Image-based modeling of the cardiovascular system

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COLLEGE OF ENGINEERING & MEDICAL SCHOOL
COMPUTATIONAL VASCULAR BIOMECHANICS LAB
UNIVERSITY OF MICHIGAN

KING'S College LONDON
University of London

Outline

- Lecture 1: Introduction to function and modeling of the CV system
- Lecture 2: Techniques for Parameter Estimation in the CV system
- Lecture 3: Simulation of Transitional Physiology
- Lecture 4: Advanced Topics, Clinical Applications and Challenges

Lecture 4:
Advanced Topics, Clinical Applications and Challenges

Importance of Validation in CFD

US FDA’s CFD Challenge:

Steady flow through a nozzle at different Reynolds numbers

Stewart et al., CVET 2012

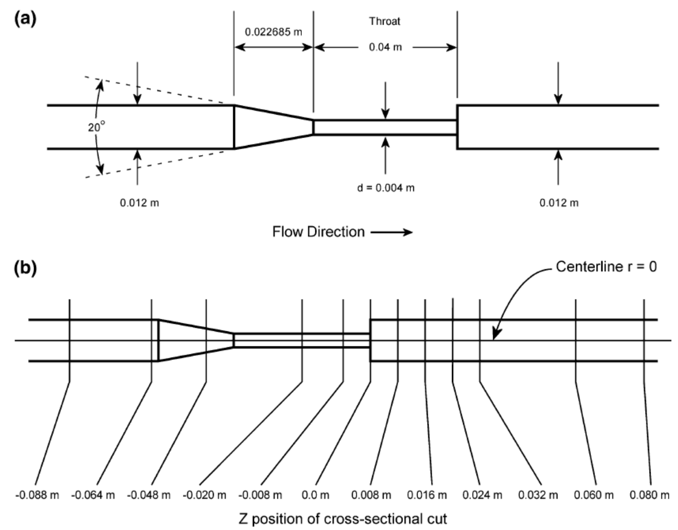


FIGURE 1. Nozzle specifications: (a) dimensions of nozzle (inlet and outlet lengths unspecified); (b) cross-sectional cuts defined for data submission for the sudden expansion.

TABLE 1. Flow rates and Reynolds numbers used in simulations.

Flow rate (m^3/s)	Throat Reynolds number (Re_t)	Inlet Reynolds number (Re_i)
5.21×10^6	500	167
2.08×10^5	2000	667
3.64×10^5	3500	1167
5.21×10^5	5000	1667
6.77×10^5	6500	2167

Steady flow through a nozzle at different Reynolds numbers

28 groups around the world submitted their results

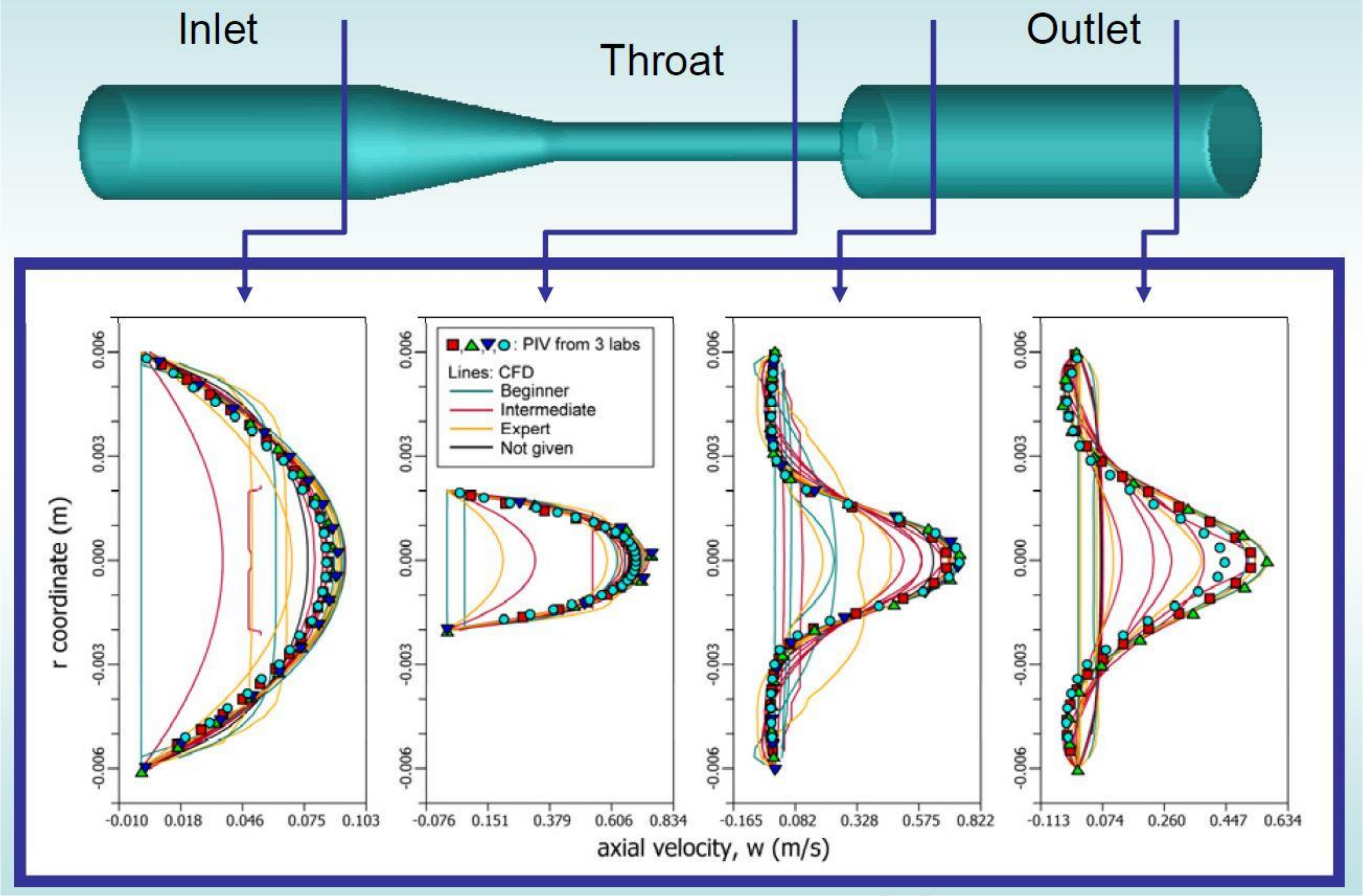
Different modeling assumptions were used: Laminar, and a number of turbulent models

Importance of Validation in CFD

Very discouraging results were reported:

Up to 5 submissions reported solutions in which the errors on **volumetric flow** were above 10%

Re (throat) = 500



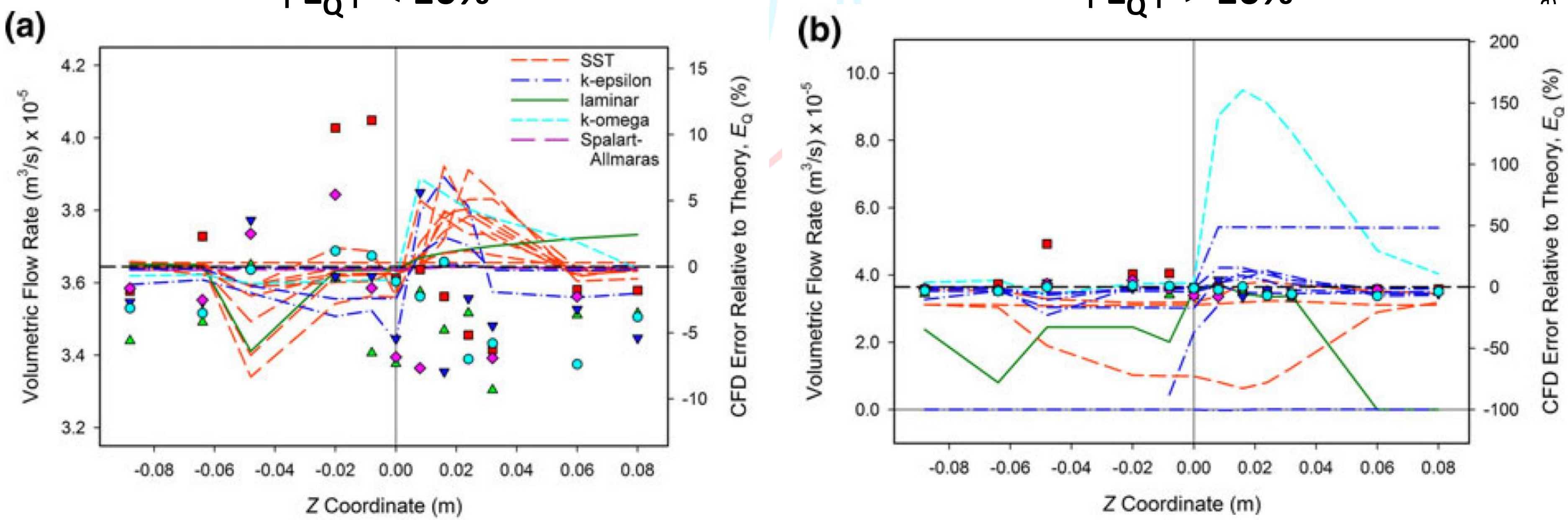
Importance of Validation in CFD

Very discouraging results were reported:

Up to 5 submissions reported solutions in which the errors on **volumetric flow** were above 10%

Re (throat) = 3500

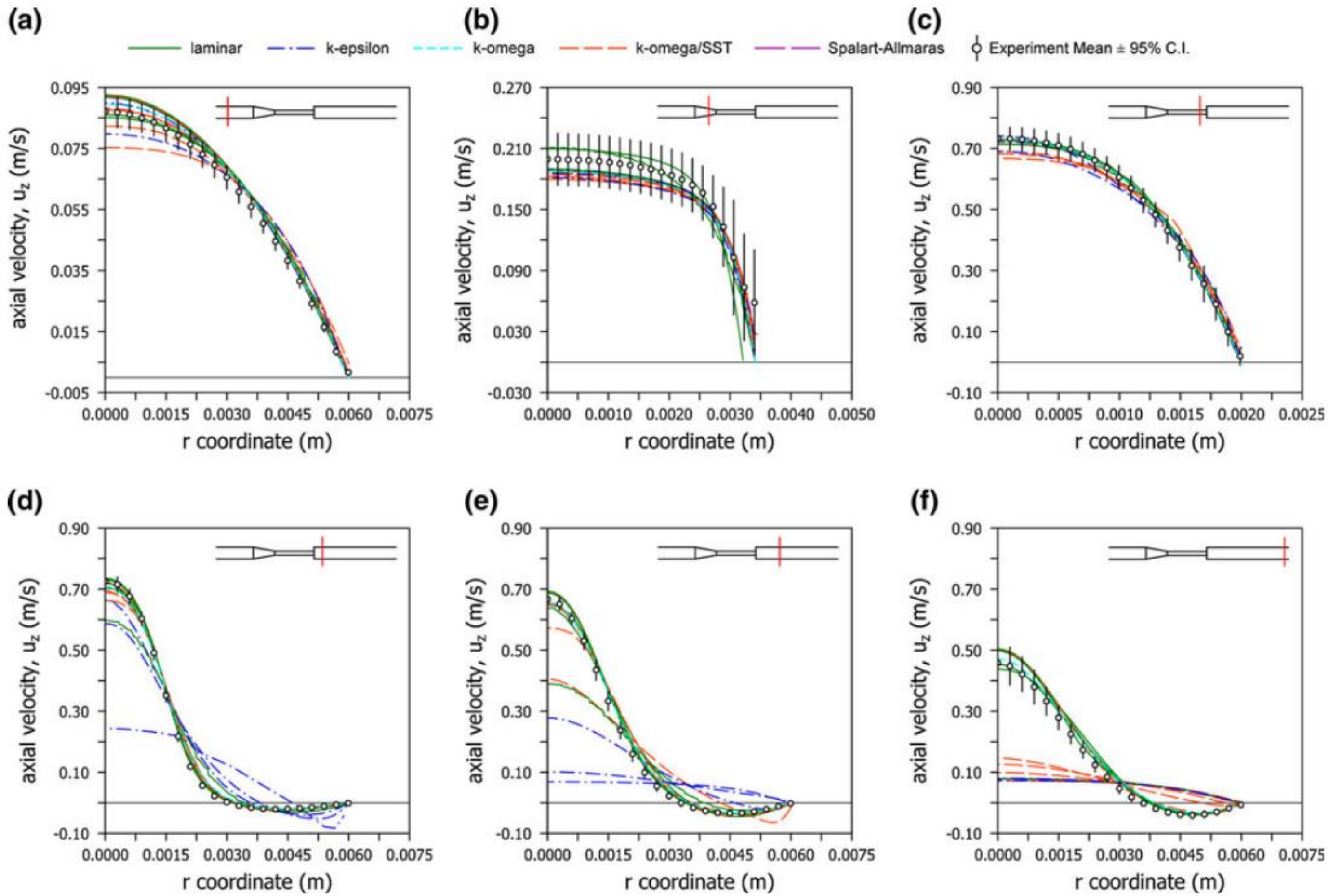
$|E_Q| < 10\%$ **$|E_Q| > 10\%$**



Importance of Validation in CFD

Axial velocity profiles for the Re = 500 (easiest case)

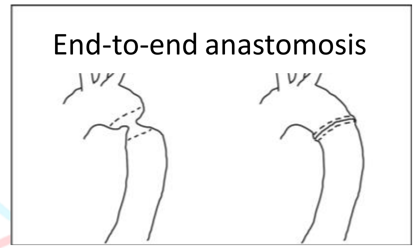
Simulations with errors > 10% are omitted

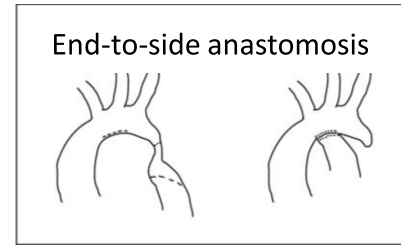


Validation in a clinical setting

Aortic Coarctation

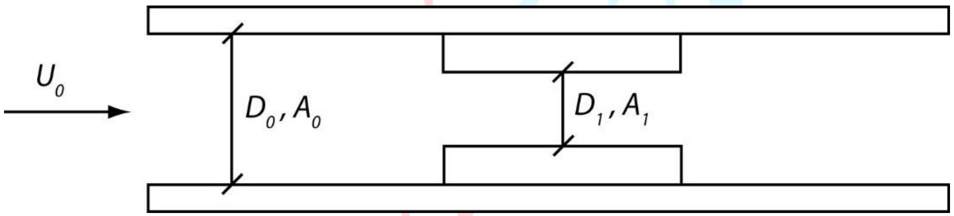
- **Aortic Coarctation (CoA)**
  - 8%-11% of congenital heart defects (10 000 patients annually in Western world)
  - Treatment: alleviate blood pressure (BP) gradient through the coarctation
  - Open repair or stenting





- **Diagnosis and treatment planning: importance of BP metrics:**
  - BP at rest:
    - Catheter-driven transducer (accurate but **invasive**)
    - Sphygmometer (less accurate but non-invasive)
    - Doppler ultrasound imaging (Bernoulli's equation)
  - BP at stress (pharmacologically-induced):
    - Catheter-driven transducer (accurate but **invasive**)
  - Current putative treatment guideline: **BP gradient > 20 mmHg at rest**

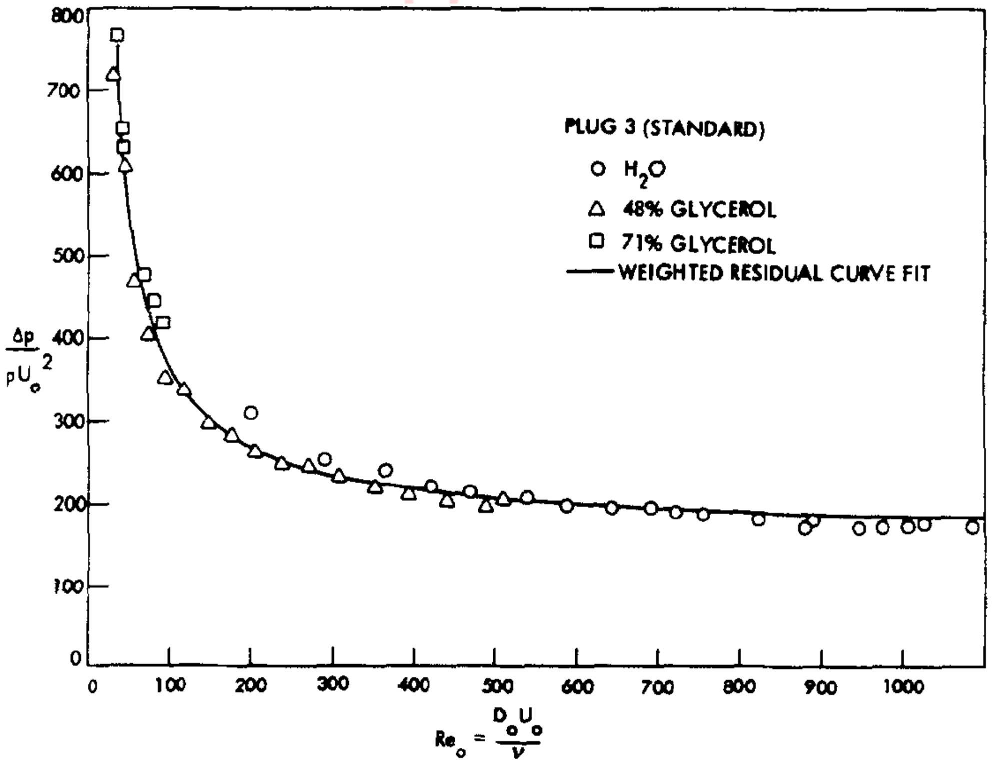
Pressure gradient (drop) through a stenosis



U_0 : mean velocity unobstructed tube

D_0 , A_0 : Diameter/Area unobstructed tube

D_1 , A_1 : Diameter/Area obstructed tube



Seeley & Young, J Biomech, 1976

Reynolds number: $\boxed{Re = \frac{D_0 U_0}{\nu}}$

ν: fluid viscosity

For medium-large ***Re***,

$$\boxed{\Delta p \sim constant \cdot \rho U_0^2 \sim constant \cdot Q_0^2}$$

Pressure gradient has a complex, nonlinear dependency on flow

MICCAI 2012: Data

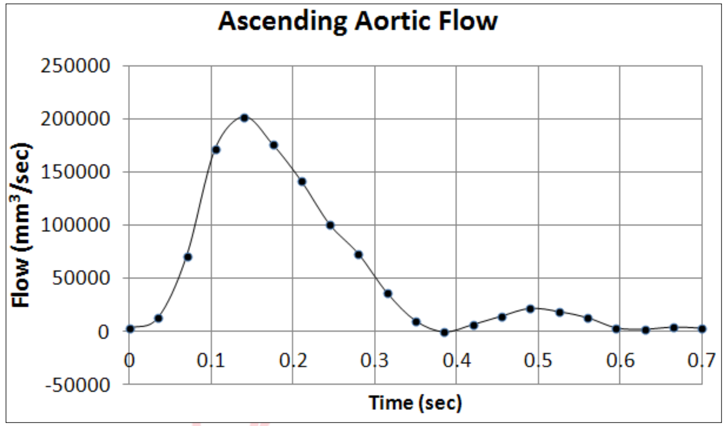
8-year old female patient, moderate thoracic aortic coarctation (≈65% area reduction) Body surface area (BSA) was 0.94 m^2.

Geometry

Gadolinium-enhanced MRA

Flow

2D PC-MRI



Cardiac output: 3.25 L/min
Cardiac cycle: 0.7 s

Flow Splits

Location	Q_{IA}	Q_{LCCA}	Q_{LSA}	Q_{DAo}
% Ascending Aortic Flow	25.6	11.3	4.26	58.8

Pressure

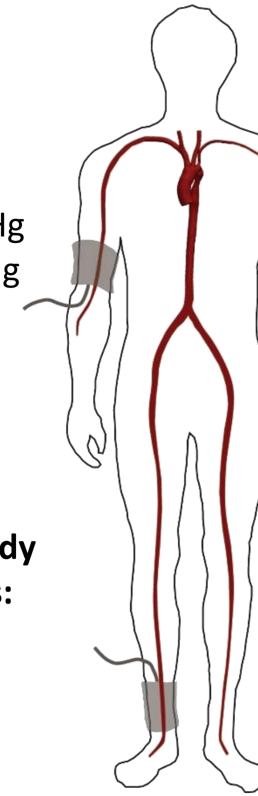
Sphygmometer

Upper Body Pressures:

SBP: 115 mmHg
DBP: 65 mmHg

Lower Body Pressures:

Hidden



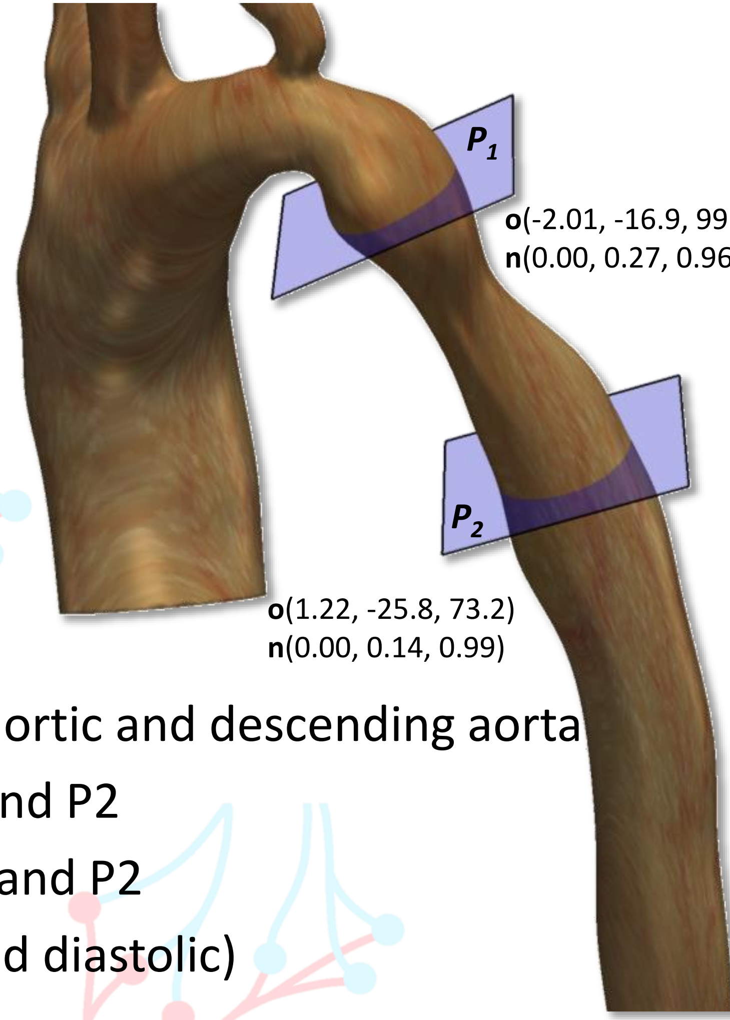
Goal: to report pressure gradient between specific locations

Assumptions

- Rigid walls (fluid computation only)
- Newtonian behavior
- Mass density: *0.001 g/mm³*
- Dynamic viscosity: *0.004 g/mm/s*

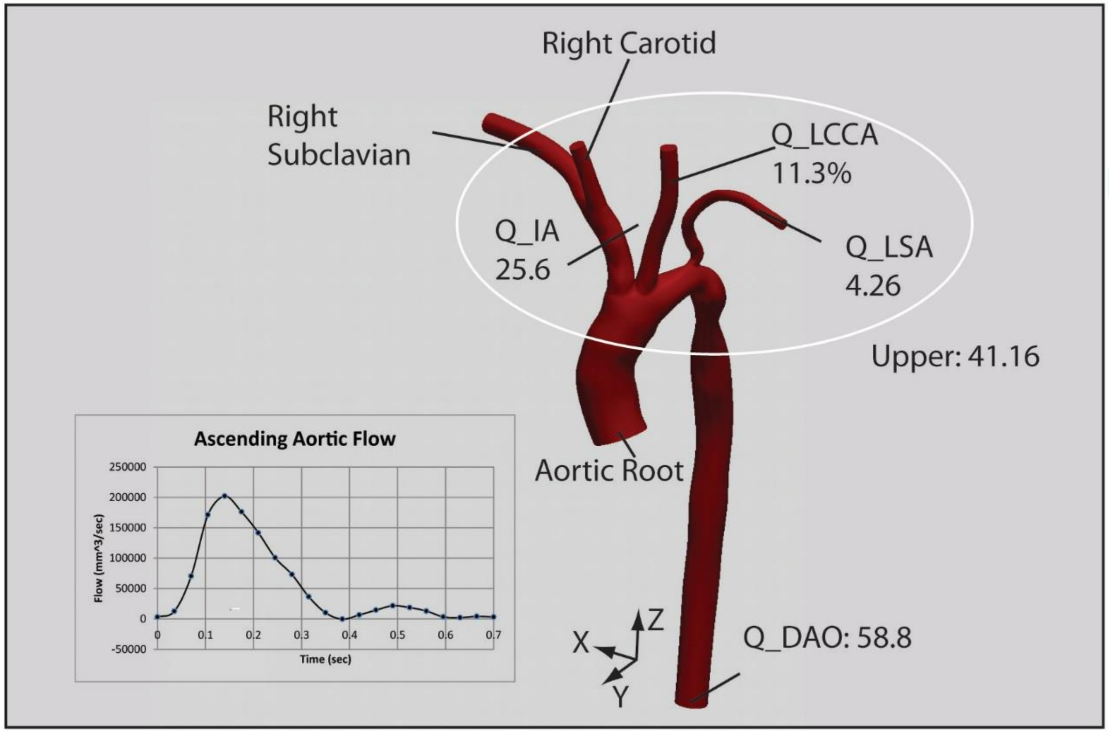
Deliverables

- Flow splits between all outlets (supra-aortic and descending aorta
- Peak pressure difference between P1 and P2
- Mean pressure difference between P1 and P2
- Pressure in ascending aorta (systolic and diastolic)



Full data – including estimated pressure gradient

Paper ID	Description	Flow Distribution						AAo Pressures		Results	
		Q_IA	Q_LCCA	Q_LSA	Upper	Q_DAO	Sum	Systolic	Diastolic	Mean ΔP	Peak ΔP
		25.6	11.3	4.26	41.16	58.8	99.96	115	65	12	

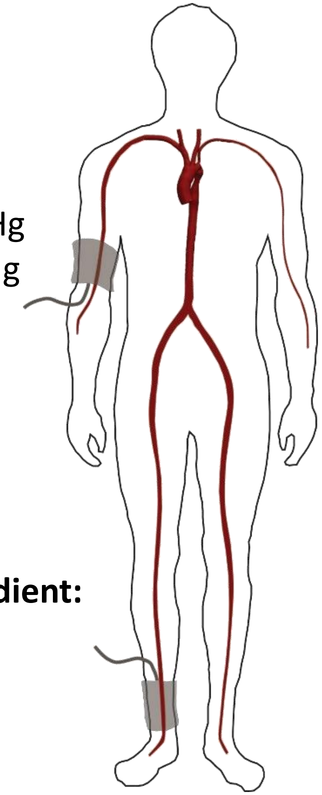


Upper Body Pressures:

SBP: 115 mmHg
DBP: 65 mmHg

Upper Body to Lower Body Gradient:

12 mmHg



Pressure amplification

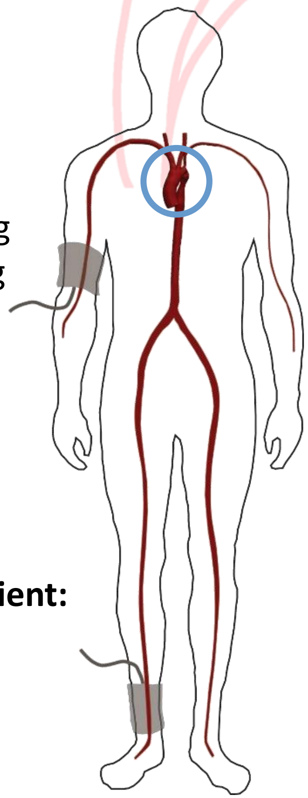
True coarctation pressure drop can only be estimated invasively or with modeling!

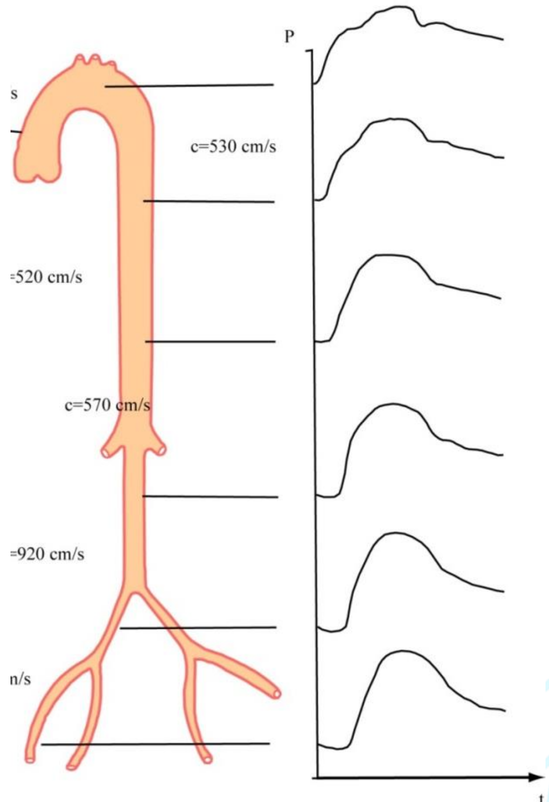
Upper Body Pressures:

SBP: 115 mmHg
DBP: 65 mmHg

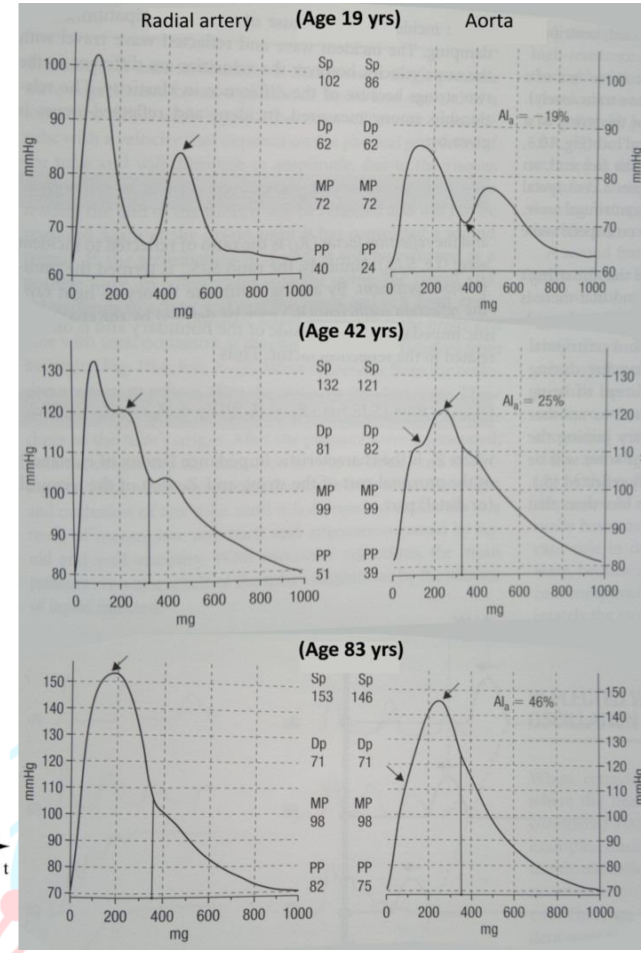
Upper Body to Lower Body Gradient:

12 mmHg





Latham et al., Circulation 1985



Amplification of the Pressure Pulse in the periphery

Nichols & Singh, Curr Opin Cardiol 2002

Results

No winners/losers: we are all ‘competing’ against ourselves… and the goal is always the same: to replicate physiology.

		Flow Distribution						AAo Pressures		Results	
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Results: 6 participants

No winners/losers: we are all ‘competing’ against ourselves… and the goal is always the same: to replicate physiology.

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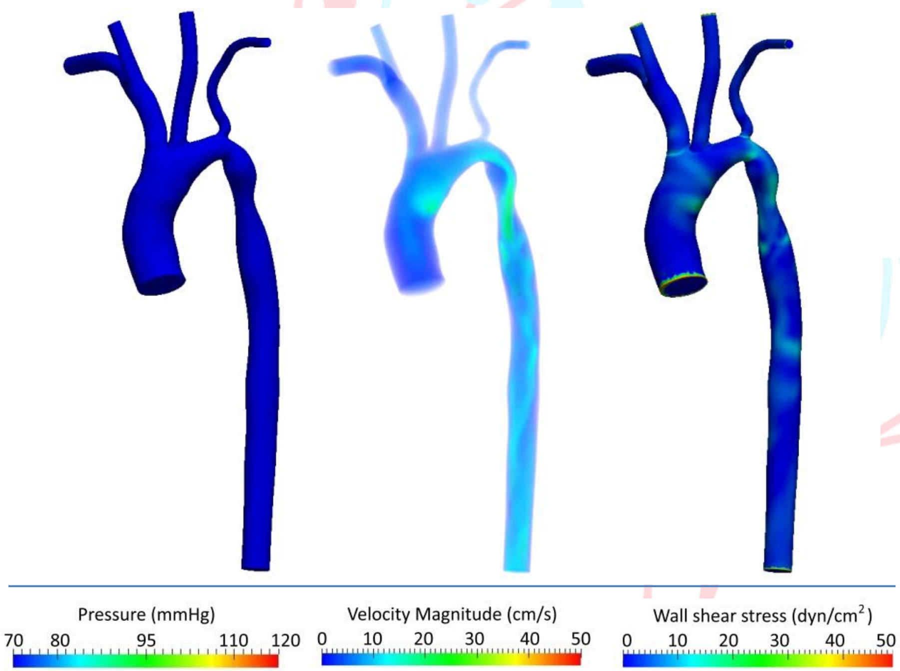
		25.6	11.3	4.26	41.16	58.8	99.96	115	65	12	
		25	12	4.5	41.5	58.5	100	115	67	7	22



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		25.6	**11.3**	**4.26**	**41.16**	**58.8**	**99.96**	**115**	**65**	**12**	
47	In-house Code (Lattice Boltzmann)	33	14.5	7.2	54.7	67.4	**122.1**	135	65	2.60	24.74
14	In-house Code (Lattice Boltzmann)	27	12	4	43	57	100	113.1	62.3	9.2	10.6
19	In-house Code (Continuum)	29.28	13.72	4.3	47.3	52.7	100	115	65	12.92	15.46

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19	In-house Code (Continuum)	29.28	13.72	4.3	47.3	52.7	100	115	65	12.92	15.46
8	Commercial Code	37.21	17.18	3.88	58.27	41.73	100	115	77	2.84	13
12	In-house Code (continuum)	25.6	11.3	4.3	41.2	58.8	100	147	65.5	5.81	30.02

Results: 6 participants

No winners/losers: we are all 'competing' against ourselves… and the goal is always the same: to replicate physiology.

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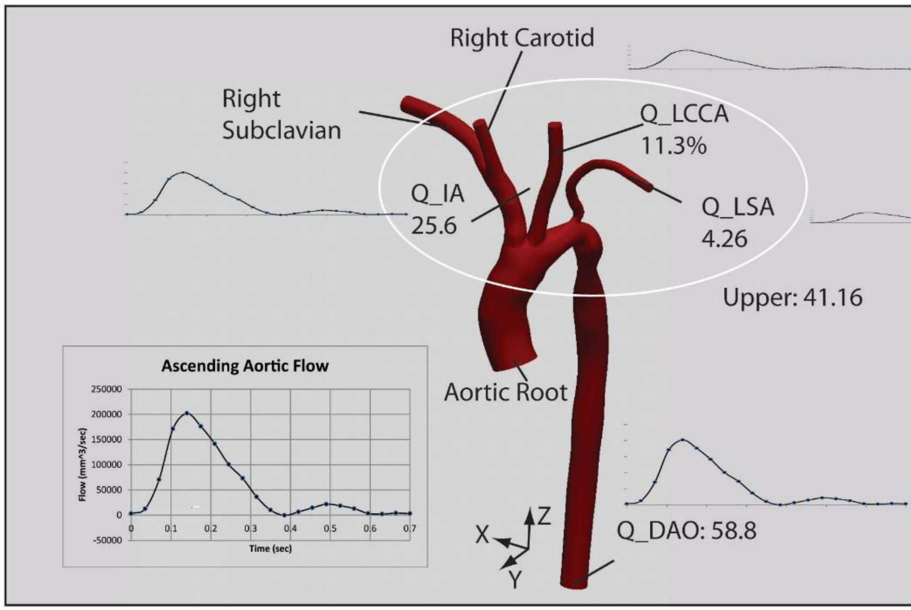
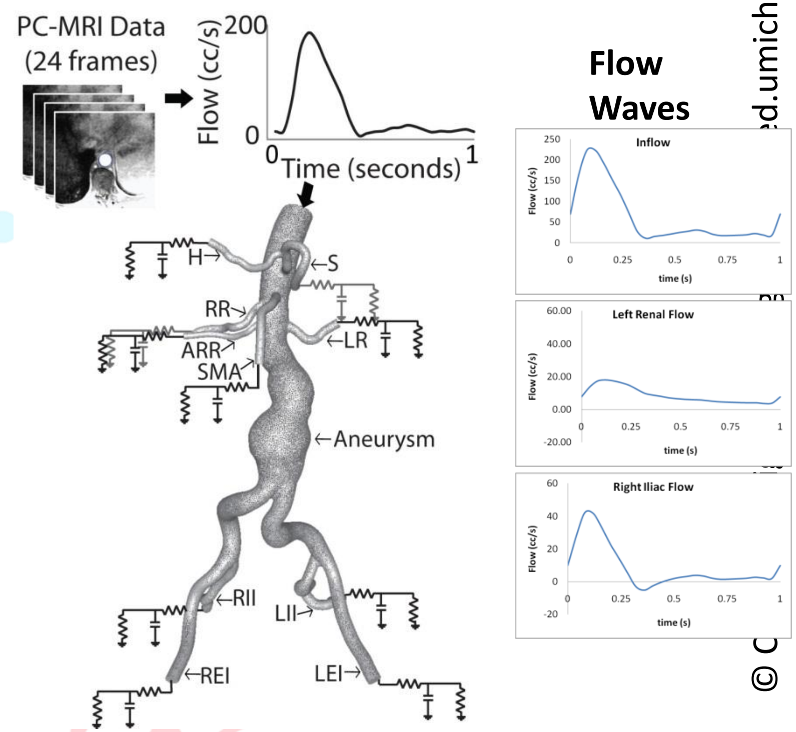
12	In-house Code (continuum)	25.6	11.3	4.3	41.2	58.8	100	147	65.5	5.81	30.02
56	In-house Code (Continuum)	26.35	11.62	4.21	42.18	57.92	100.1	120.5	67.39	2.29	12.94

Again, the issue is the boundary conditions…

Versatility of coupled outflow BCs to reproduce realistic results with scarce data

Prescribed flow splits approach VS Coupled Outflow BC approach





Les et al, Annals Biomed Eng 2010

Take-home messages

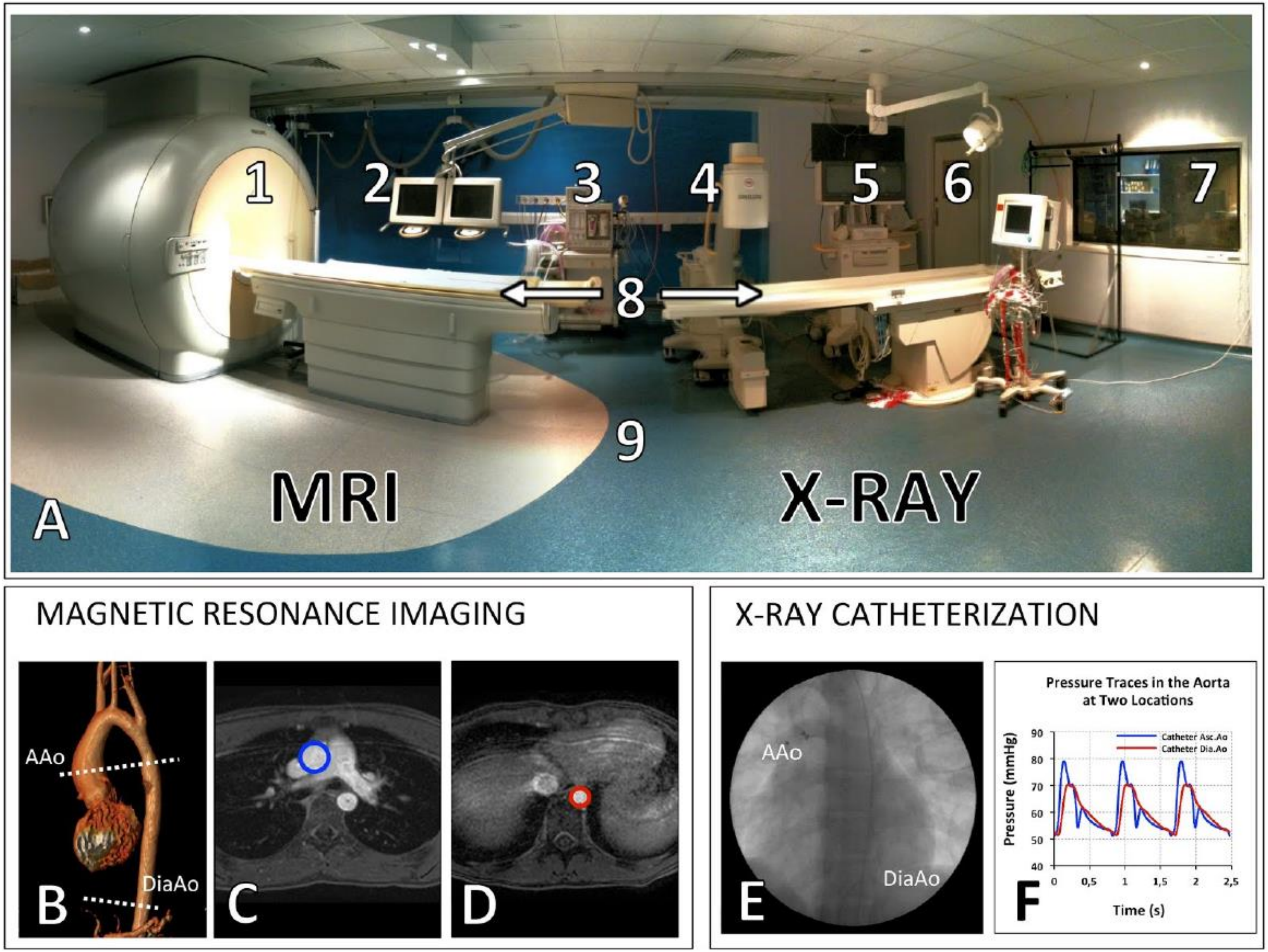
- No winners/losers: we are all 'competing' against ourselves… and the goal is always the same: to replicate physiology.
- Lack of ground truth
- Amplification of the Pressure Pulse in the periphery
- Value of Simulation (when property validated)
- 3 types of results:
  - Globally satisfy all measurements, it requires techniques that have the ability of accommodating uncertainties and lack of completeness in the data
  - Physically-plausible solution, but unable to reproduce clinical measurements
  - Non-physical solution

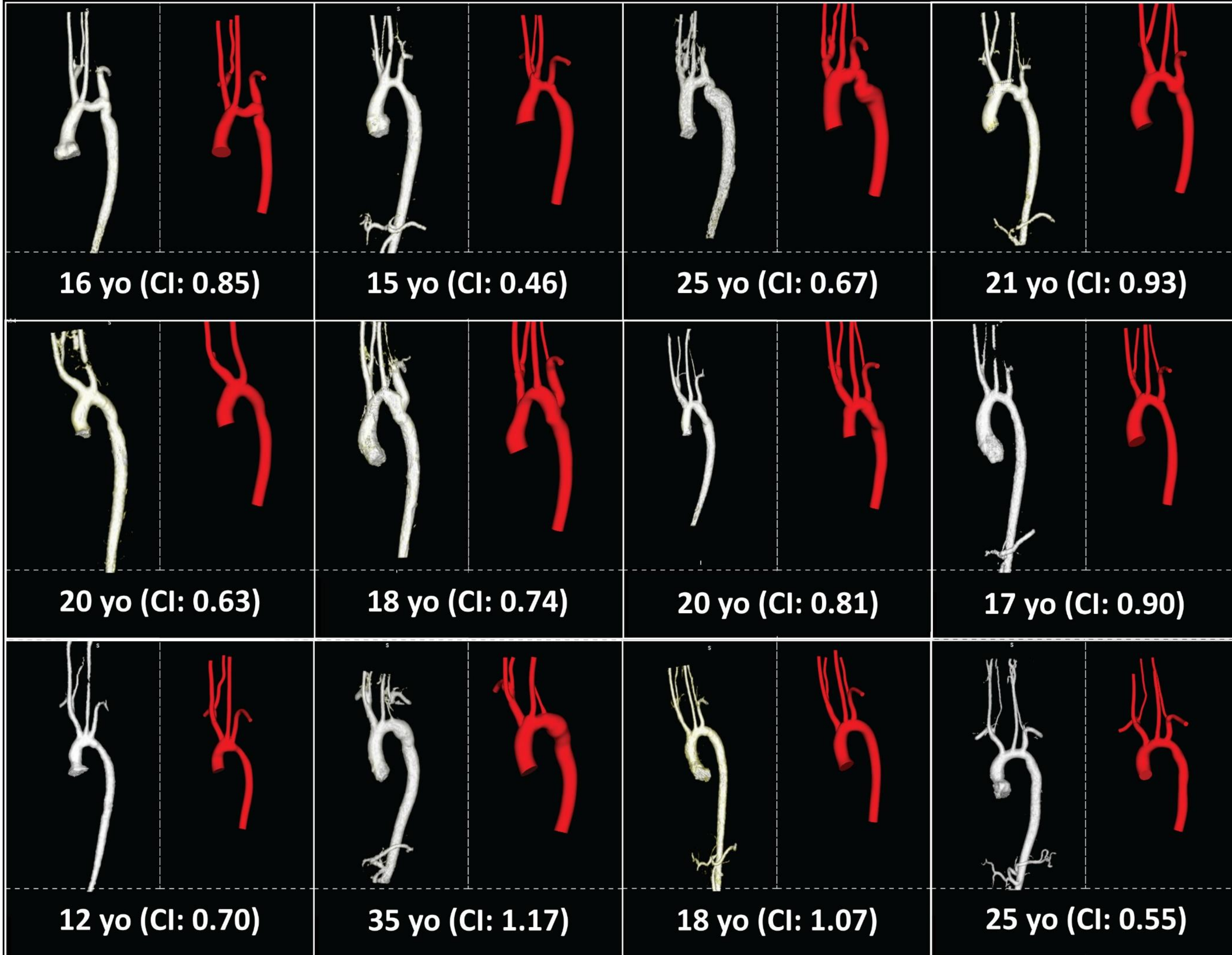
Take-home messages

- Velocity-centric submissions
- Pressures are often times ignored (set to zero!)
- Imposing flow splits when waveform is not known forces different pressure gradients in the model (even when the waveforms are known: we need to considered differences between model and measurement)
- 1D Methods not appropriate for coarctation or aneurysms
- Turbulence models or laminar flow assumptions
- Methods with uniform grid size are at a clear disadvantage
- Importance of grid independence assessment

CoA validation study at KCL with ground-truth pressure data

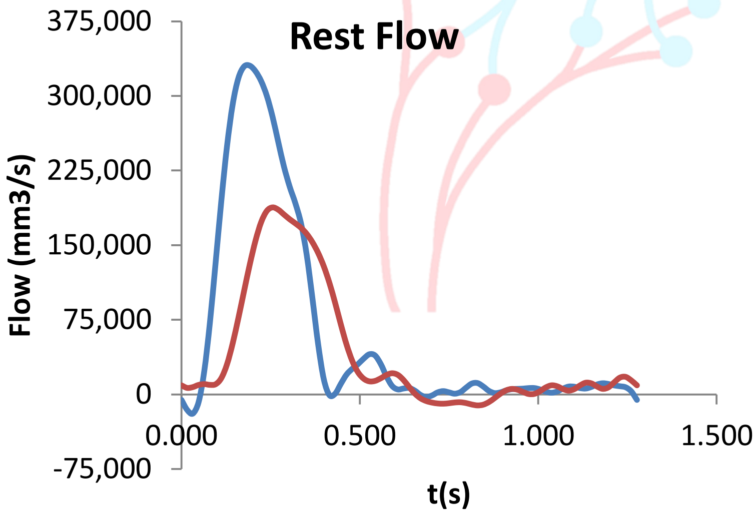
X-MR Setup at St Thomas' Hospital



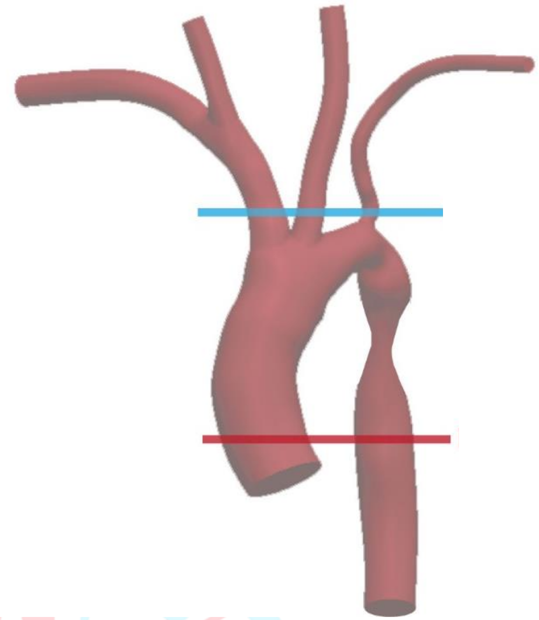

16 yo (CI: 0.85)
15 yo (CI: 0.46)
25 yo (CI: 0.67)
21 yo (CI: 0.93)
20 yo (CI: 0.63)
18 yo (CI: 0.74)
20 yo (CI: 0.81)
17 yo (CI: 0.90)
12 yo (CI: 0.70)
35 yo (CI: 1.17)
18 yo (CI: 1.07)
25 yo (CI: 0.55)

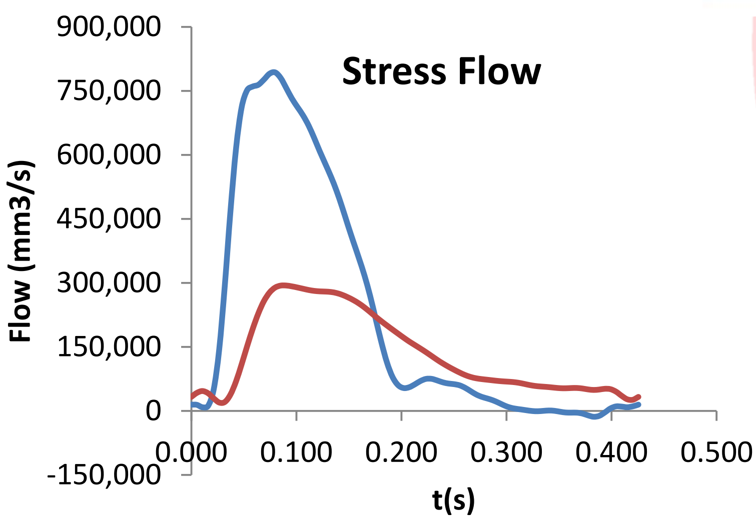
CMR & pressure data in repair CoA patients at rest & stress

2D PC-MRI data



	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

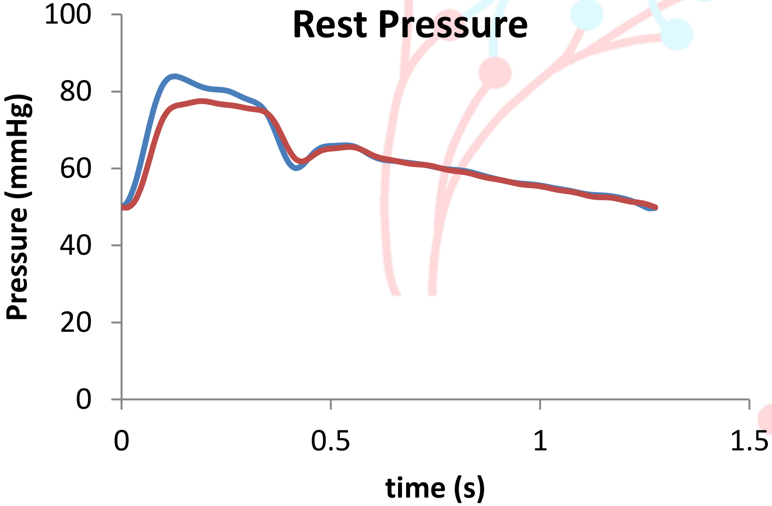




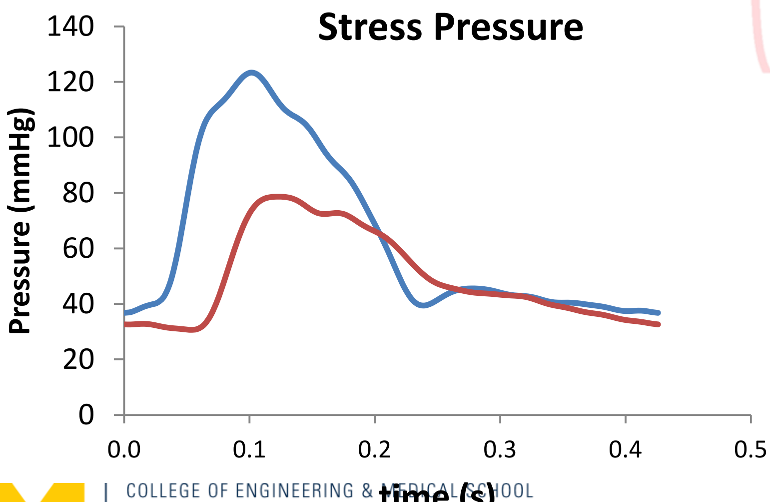
	AscAo	Innominate	LCC	LS	DiaphAo
Total Flow (L/min)	13.53	3.38	0.68	1.49	7.98
% AscAo	100	25	5	11	59

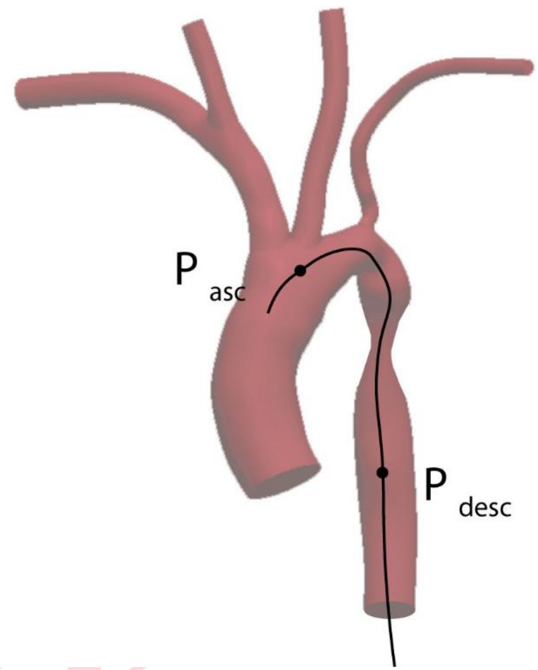
CMR & pressure data in repair CoA patients at rest & stress

Pressure wire data



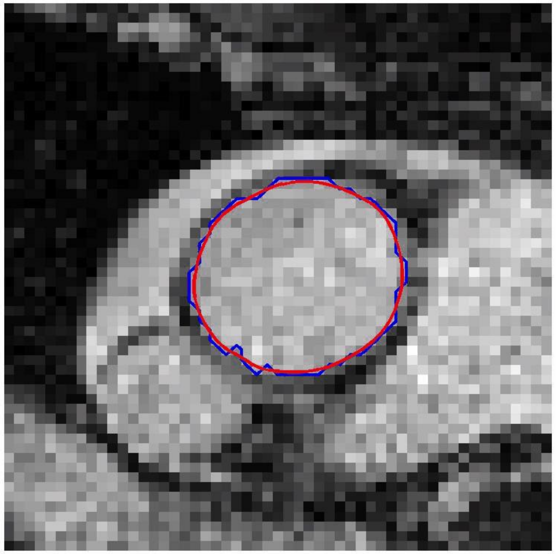
Asc
Desc



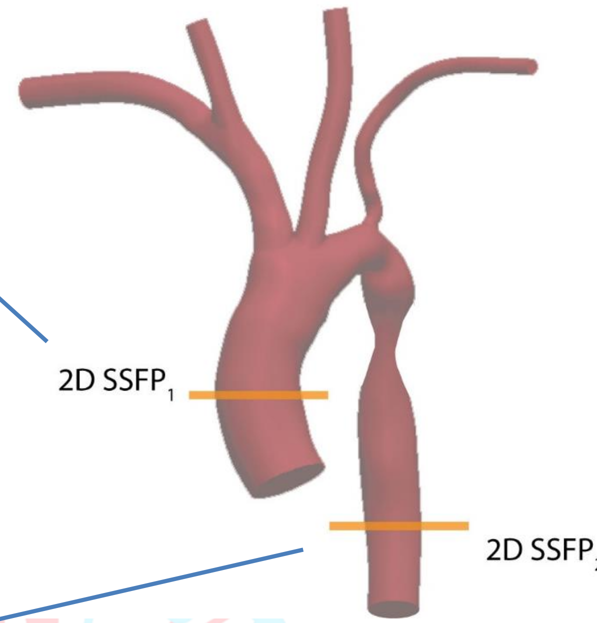


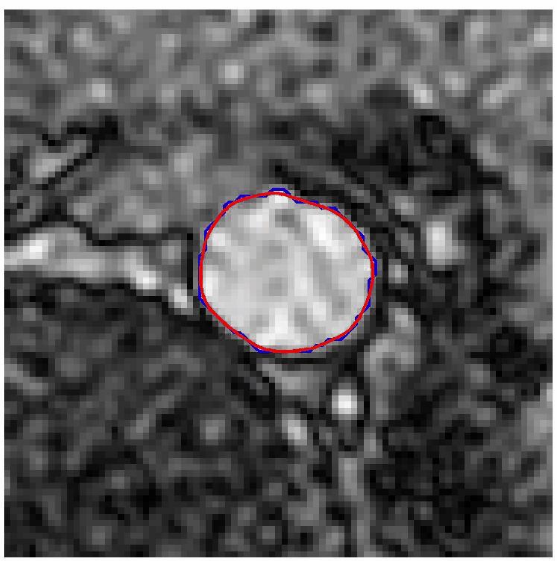
CMR & pressure data in repair CoA patients at rest & stress

2D-SSFP data



Ascending Aorta Distensibility

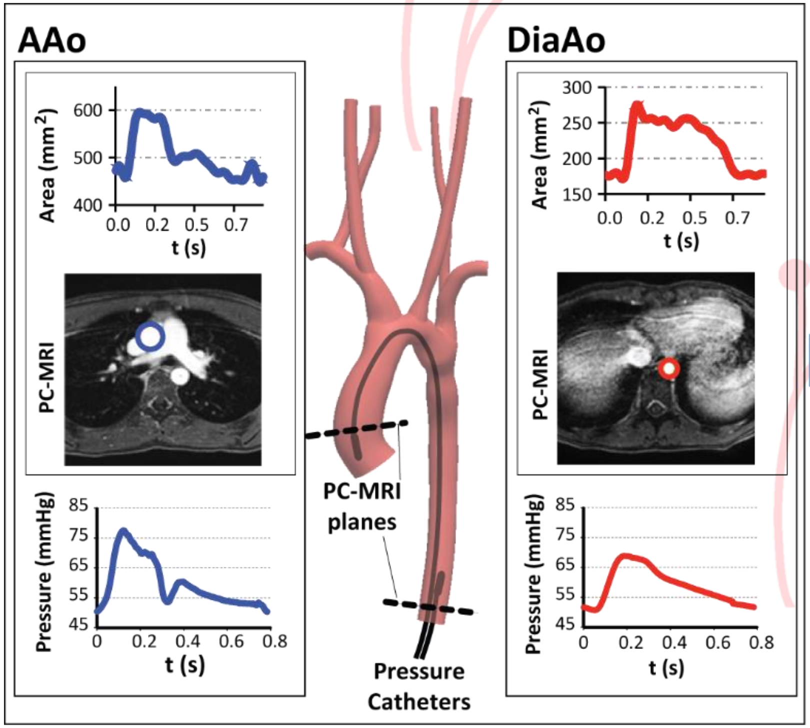


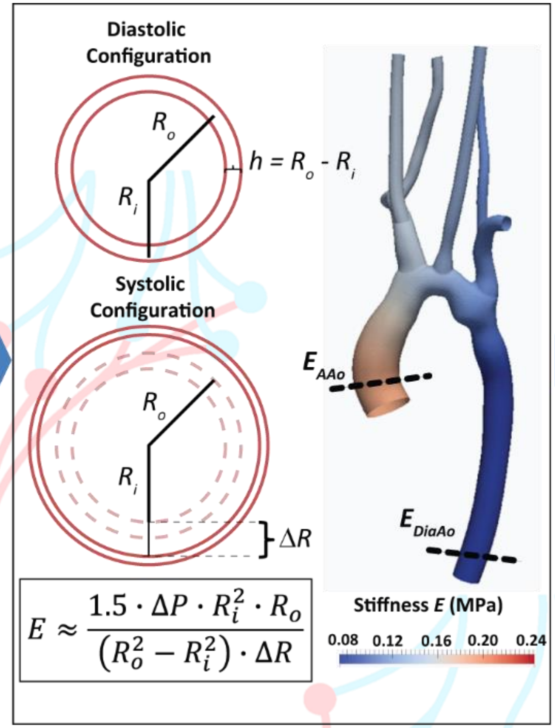


Descending Aorta Distensibility

Arterial Stiffness estimated from Pressure & Vessel Motion

Simultaneous knowledge of distensibility AND pressure is used to derived elastic properties



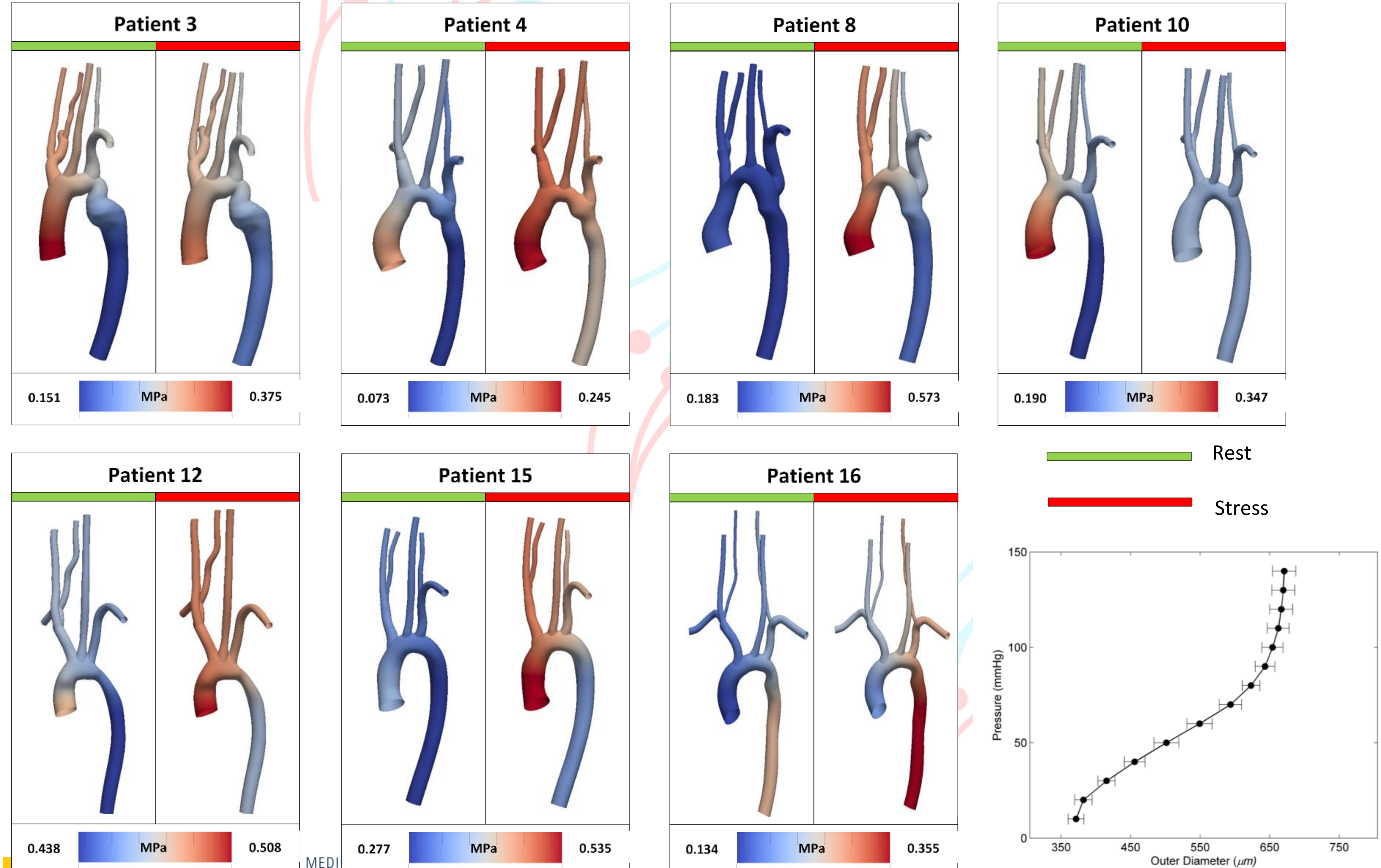


$$E \approx \frac{1.5 \cdot \Delta P \cdot R_i^2 \cdot R_o}{(R_o^2 - R_i^2) \cdot \Delta R}$$

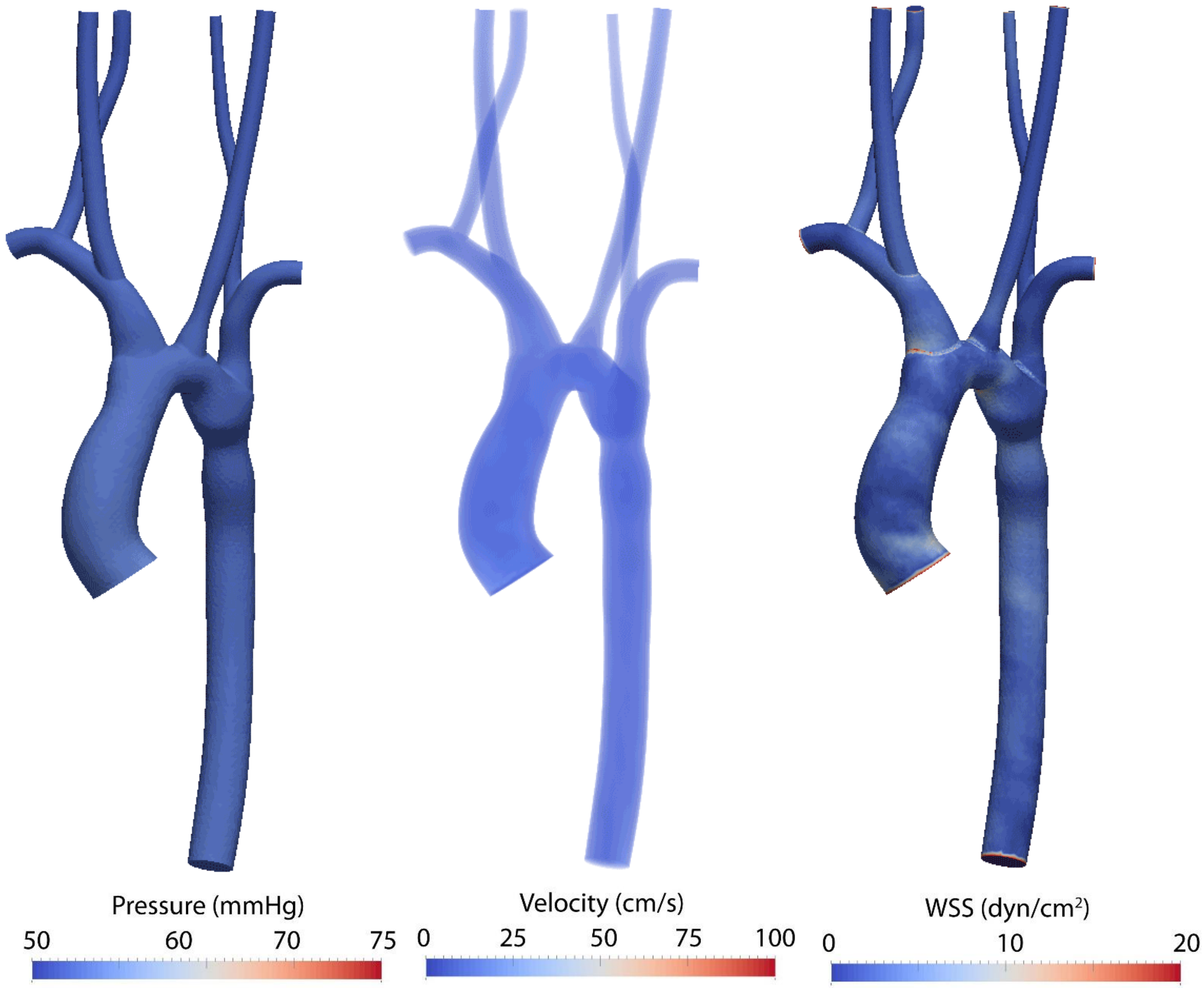
Subject	Location	Stiffness *E* (MPa) Rest	Stiffness *E* (MPa) Stress
1	AAo	0.375	0.327
	DiaAo	0.150	0.190
2	AAo	0.190	0.243
	DiaAo	0.073	0.166
3	AAo	0.208	0.573
	DiaAo	0.183	0.226
4	AAo	0.347	0.246
	DiaAo	0.189	0.240
5	AAo	0.482	0.507
	DiaAo	0.438	0.464
6	AAo	0.359	0.534
	DiaAo	0.277	0.340
7	AAo	0.134	0.180
	DiaAo	0.271	0.354

Arterial Stiffness in repaired CoA patients at rest & stress

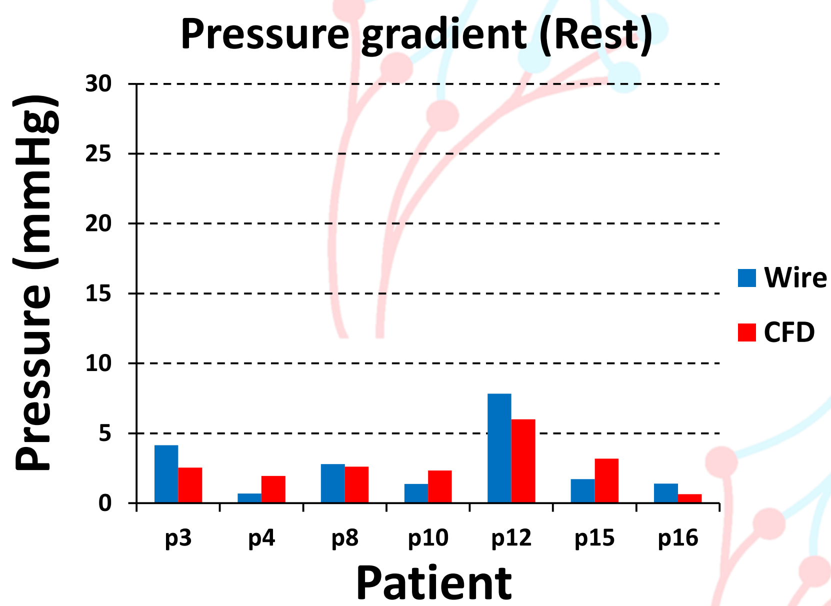
Vessel stiffness increases with stress (pressure)

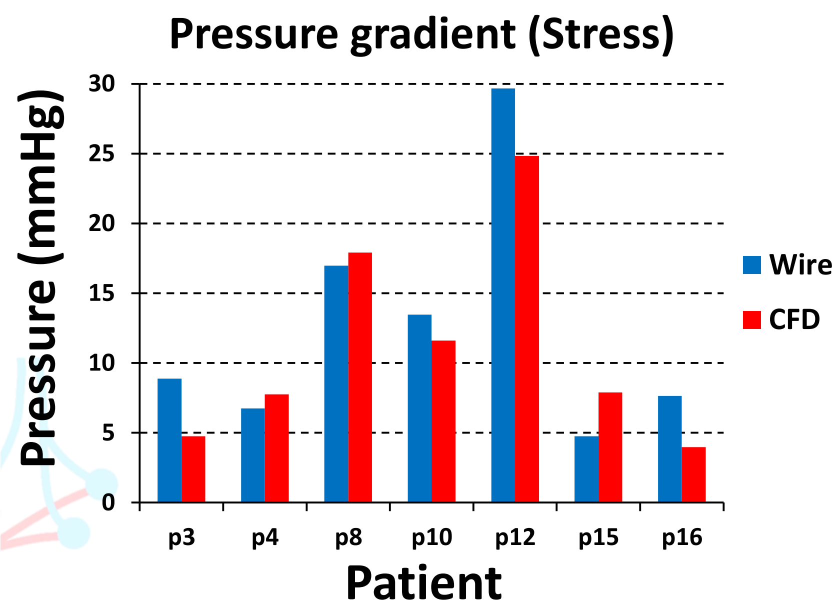


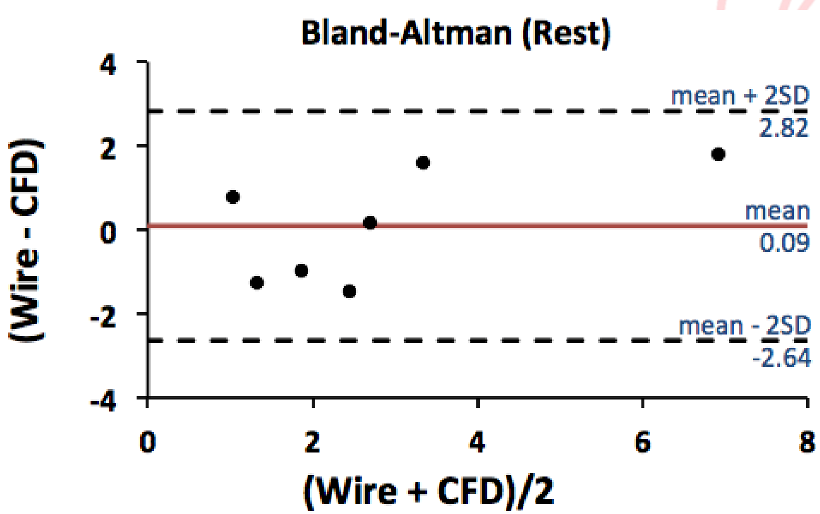
Results – CFD predictions

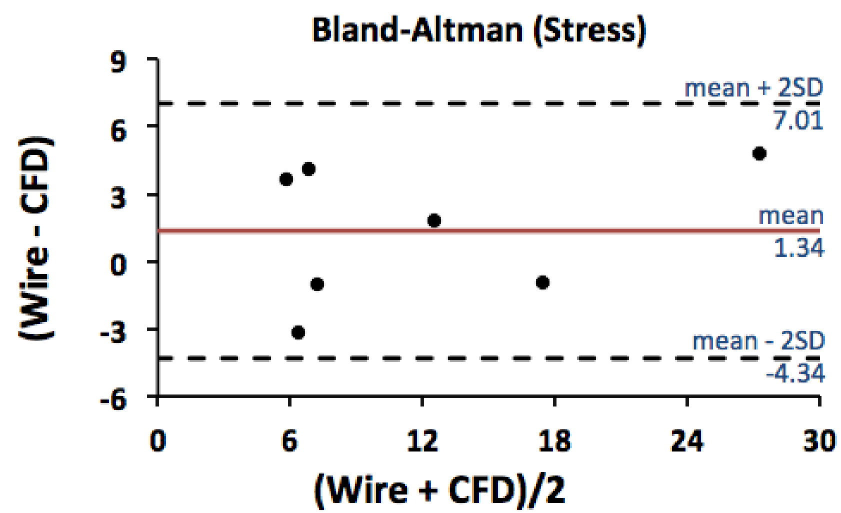


Validation of computational predictions







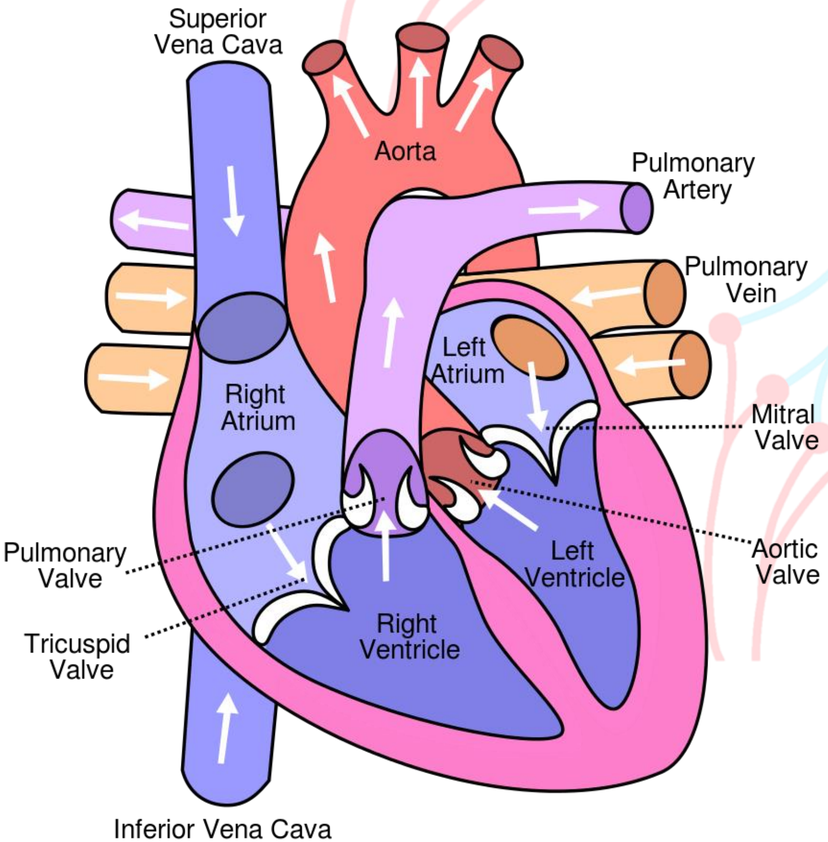


Sotelo, Valverde, Beerbaum, Grotenhius, Greil, Schaeffter, Hurtado, Uribe & Figueroa, in preparation

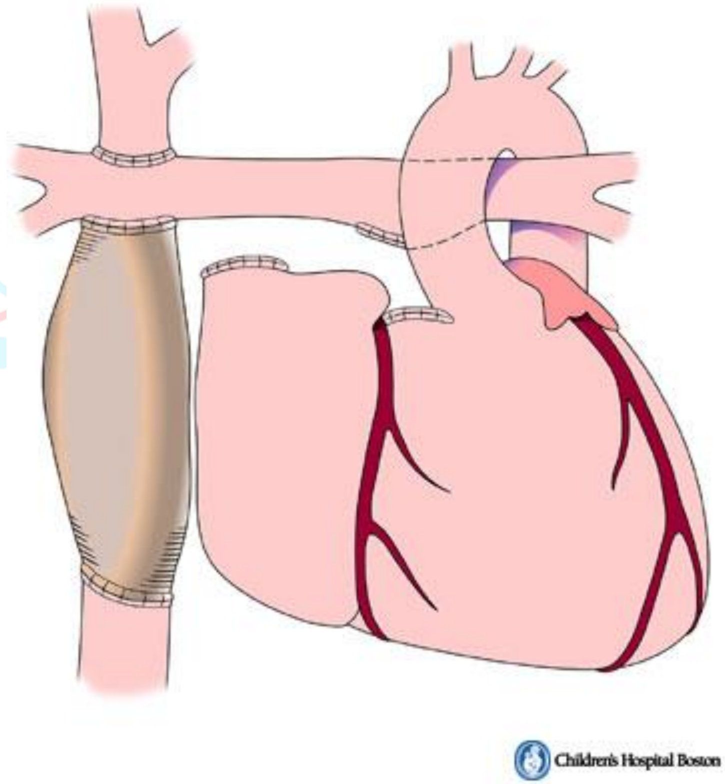
First real-life application of virtual surgical planning

Fontan patient

Normal Heart

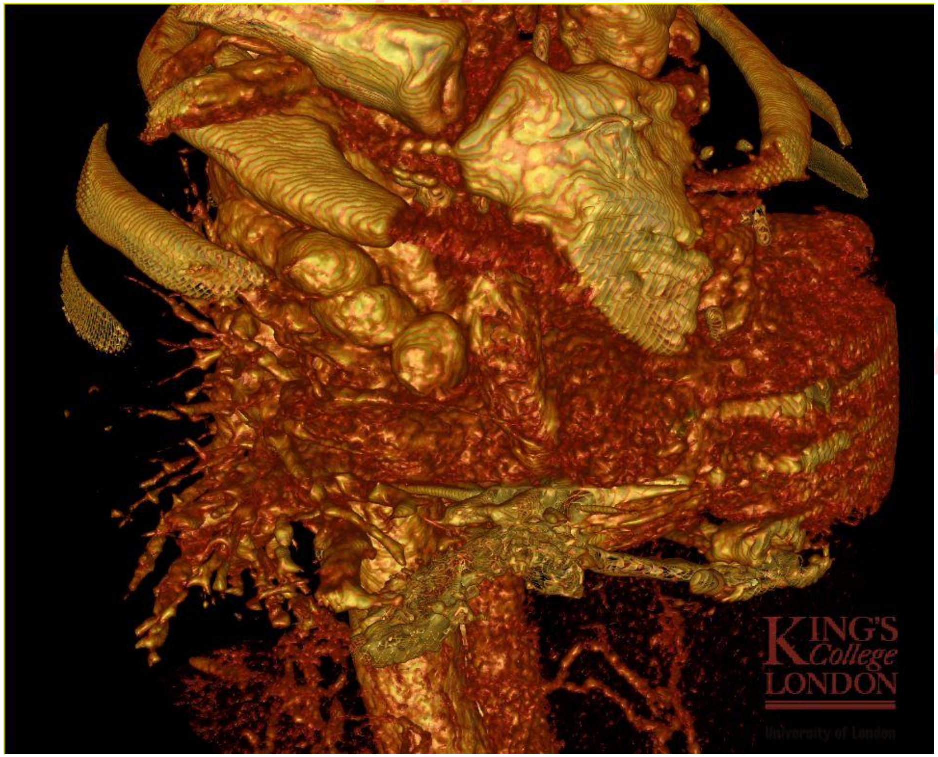


Fontan Heart

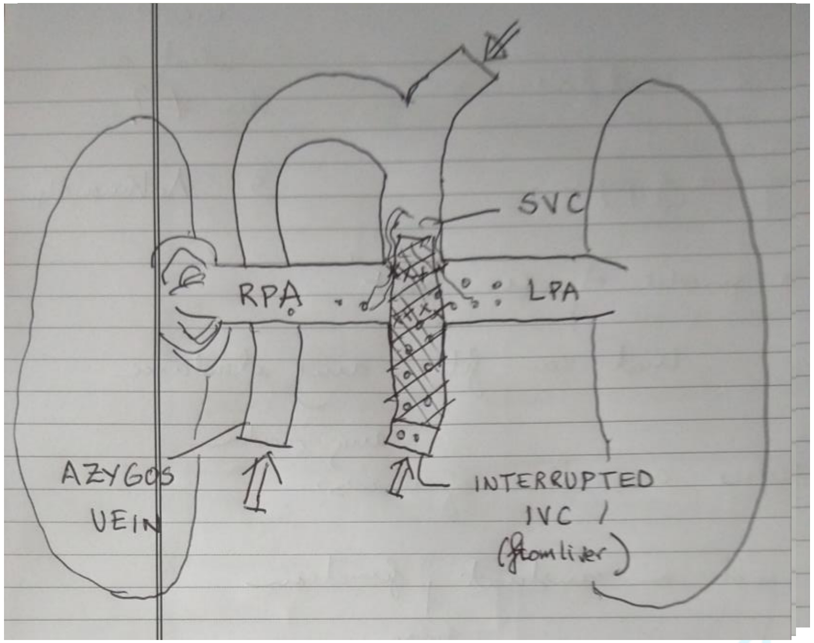


Pulmonary Arterio-venous malformations

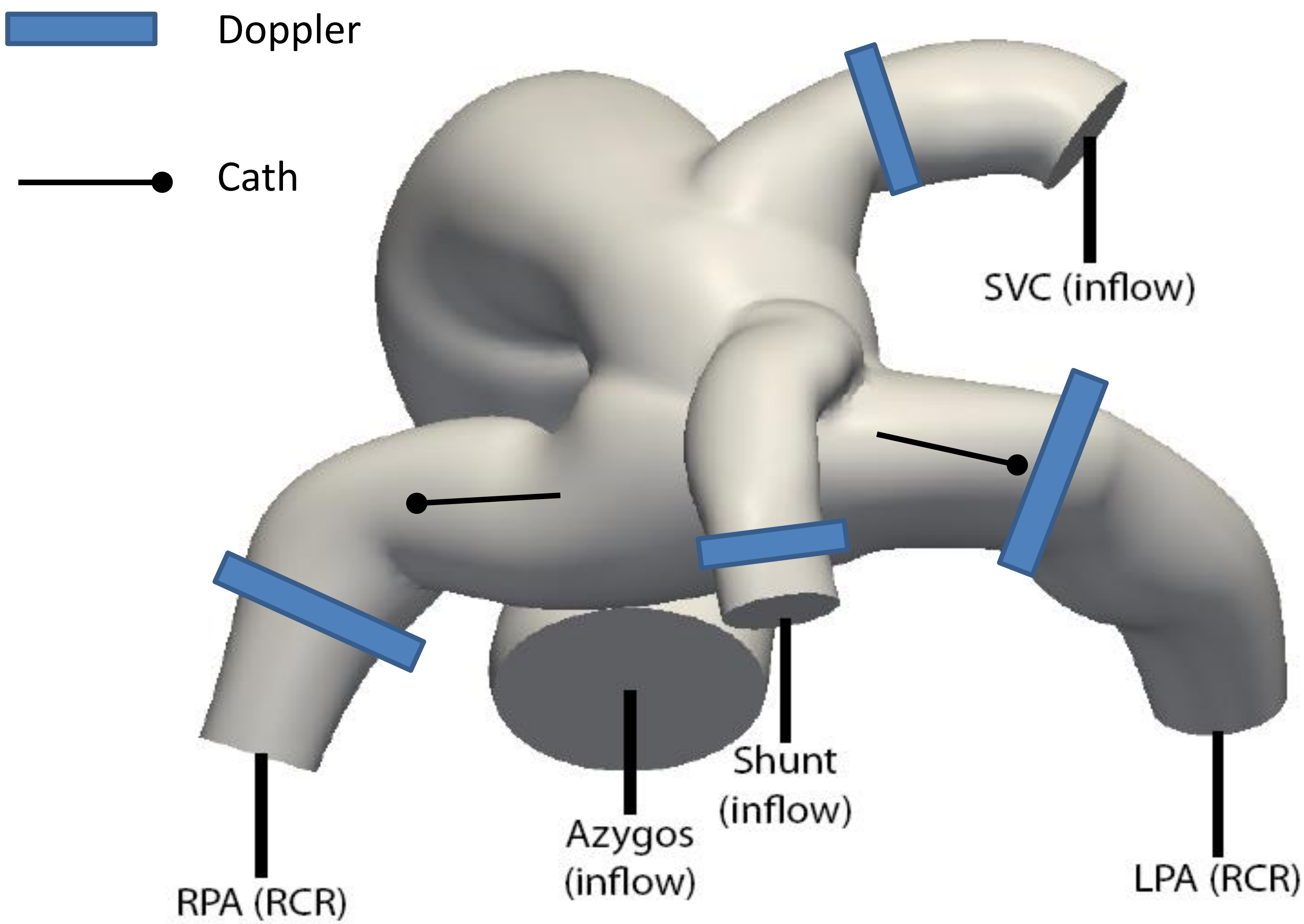
20 yo Fontan Female Patient w pacemaker & AVMs

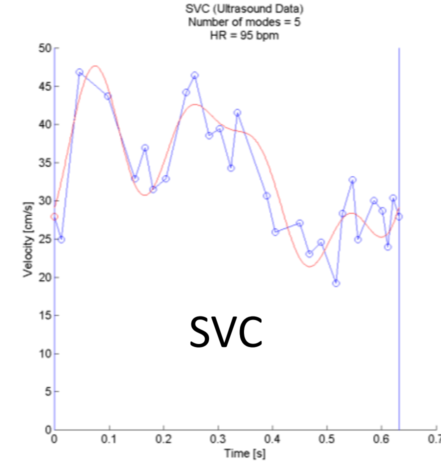


Virtual Surgical Planning Application – Congenital Disease

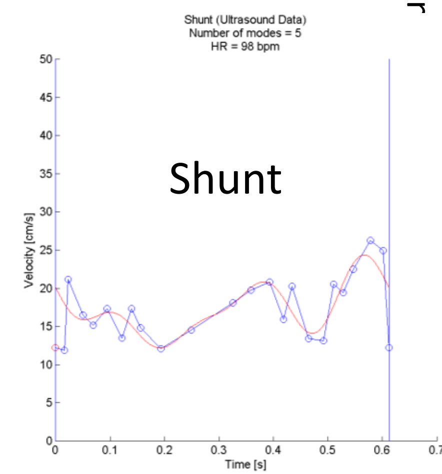


Anatomy and hemodynamic data

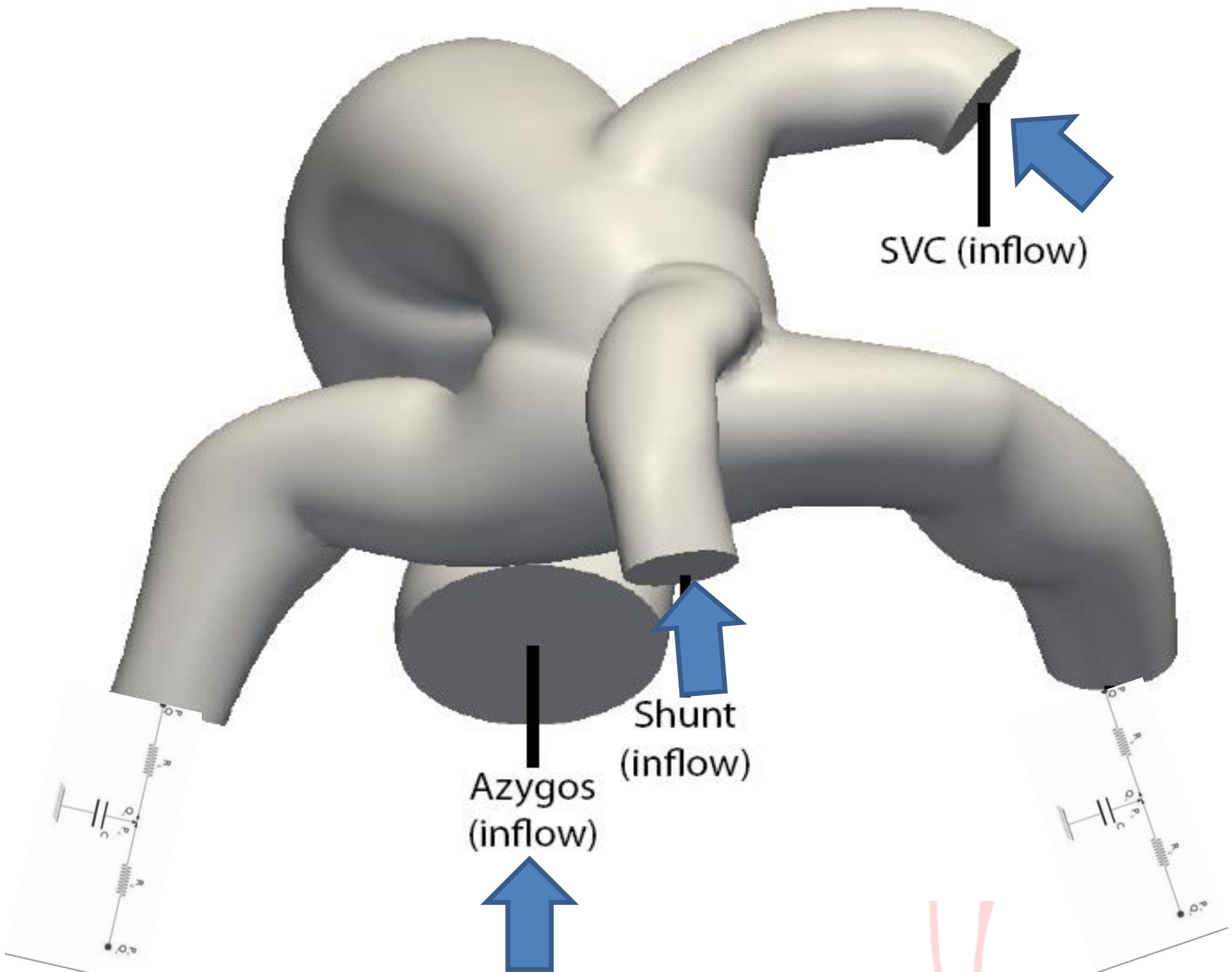




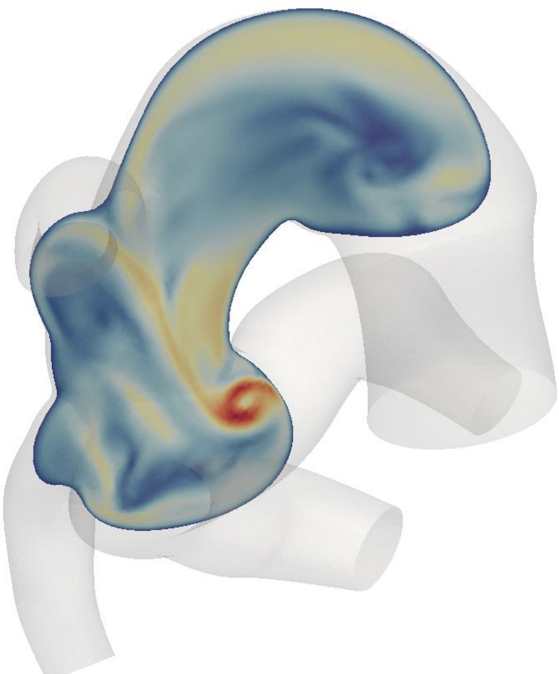
jeroa – figueroc@r



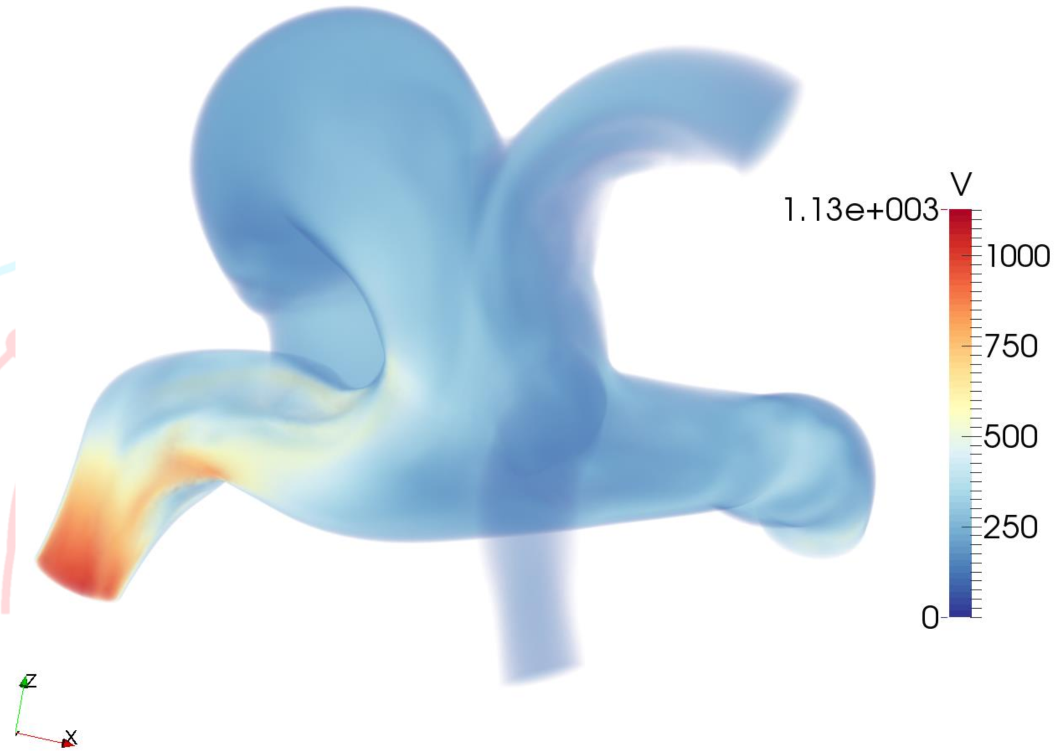
Anatomy and hemodynamic data



Hemodynamic Verification

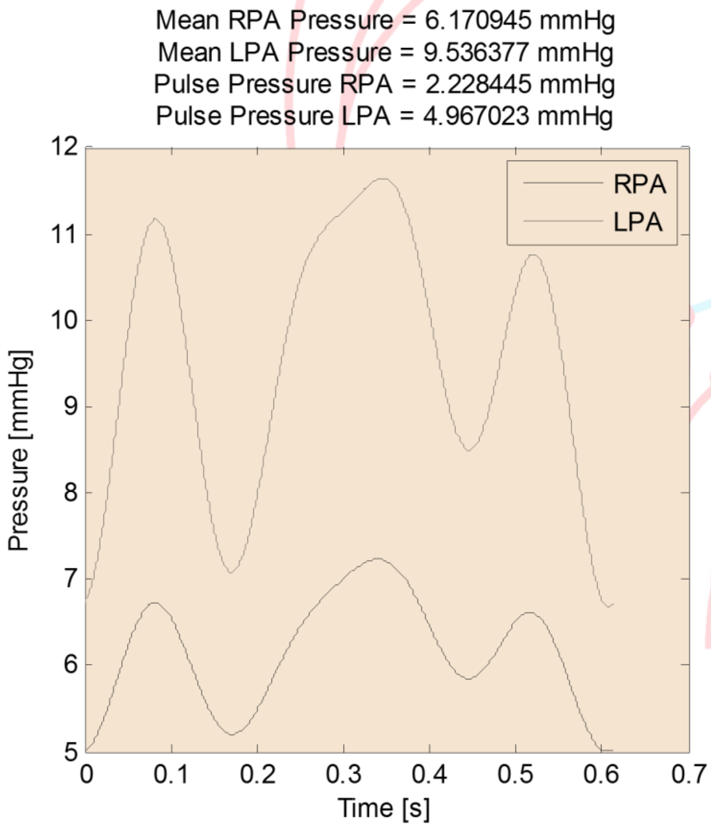


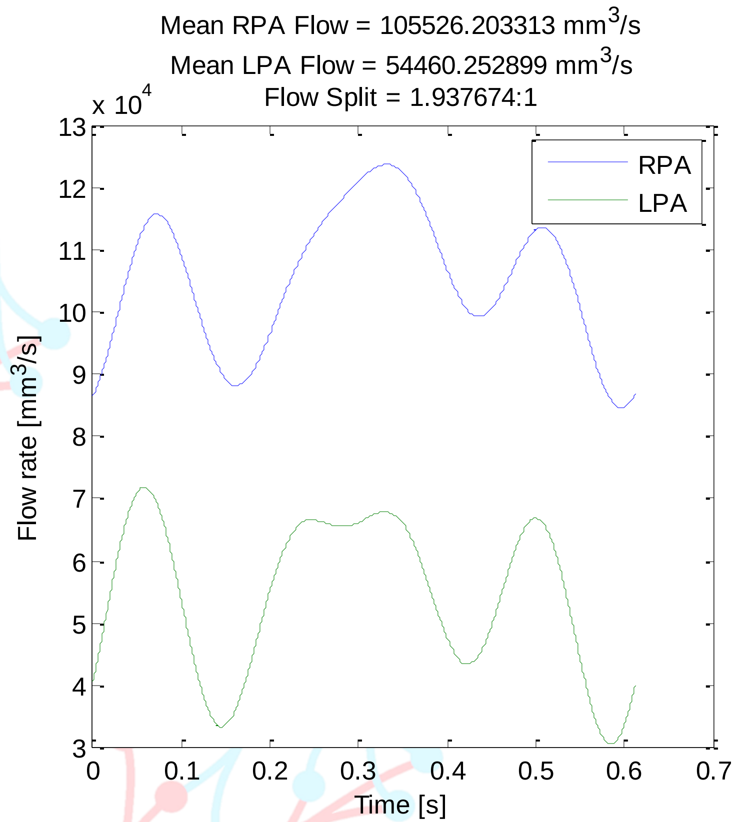
Complex mixing



Preferential RPA flow

Hemodynamic Verification



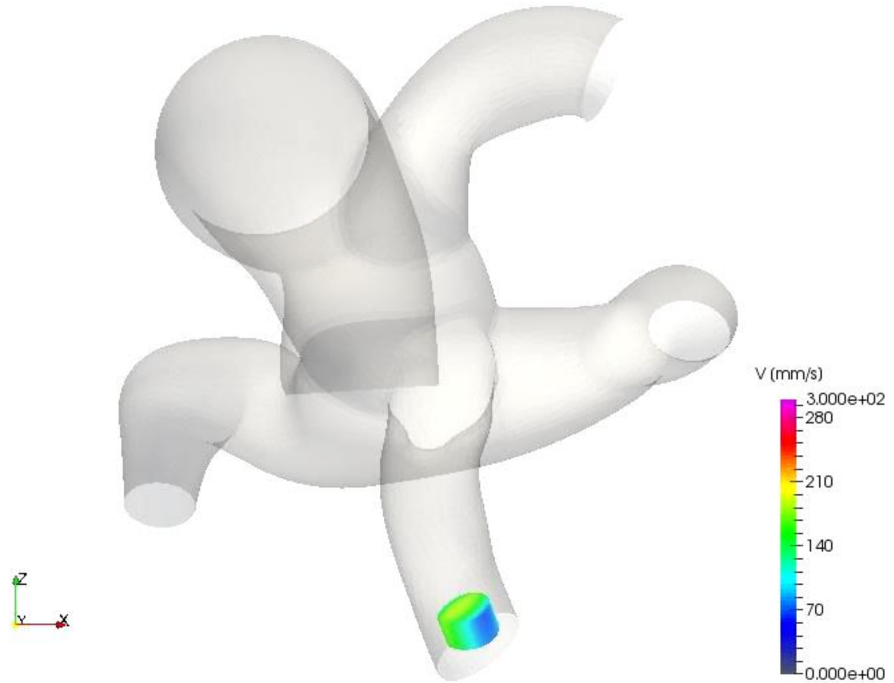


Virtual Graft Insertion – Optimal Protrusion Length?

13mm x 5 cm graft – various fixation lengths @ IVC

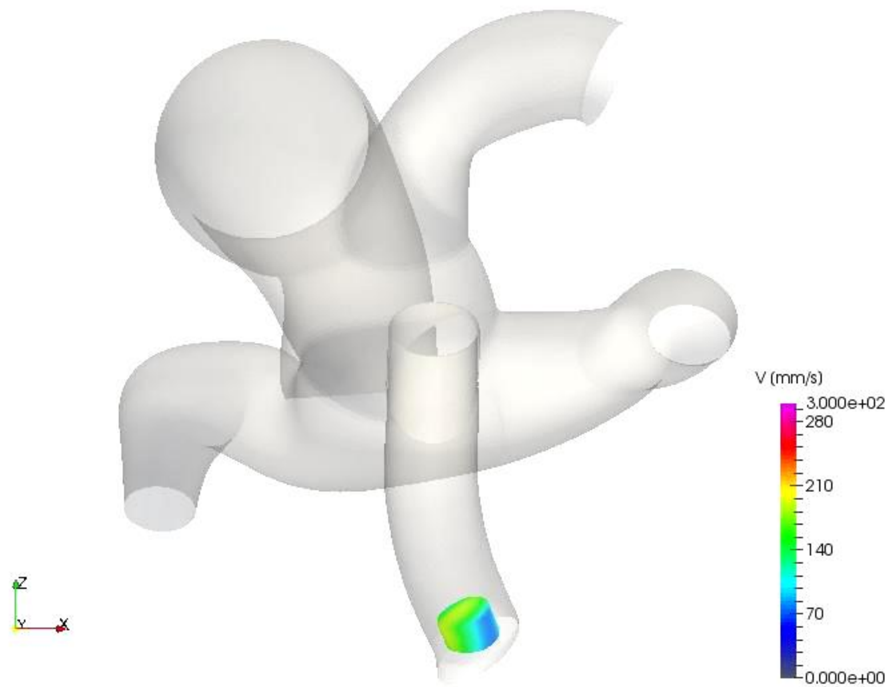
Particle tracking of different configurations

Pre-Operative Model



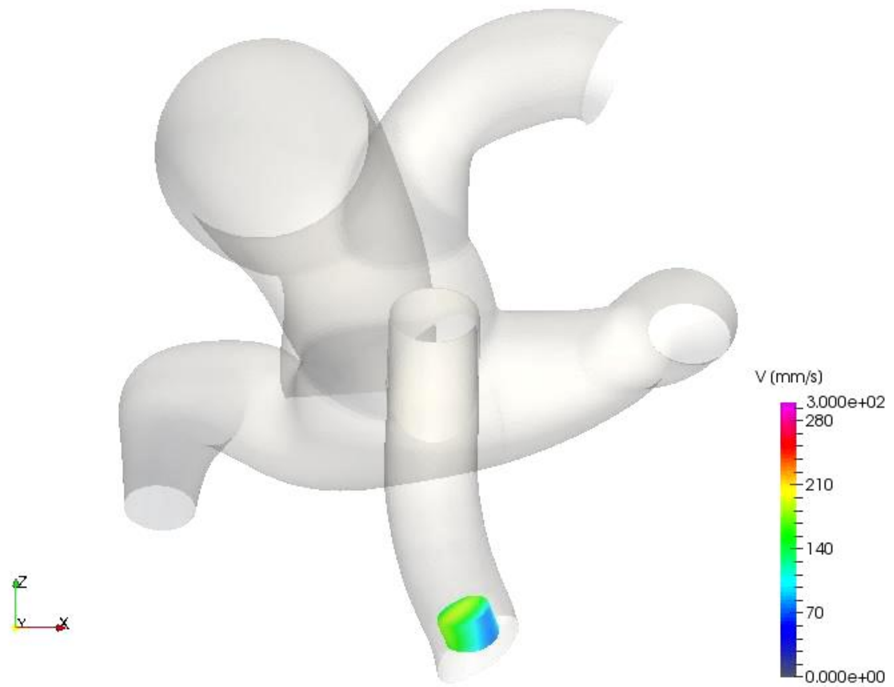
Particle tracking of different configurations

17.5 mm protrusion



Particle tracking of different configurations

20.0 mm protrusion



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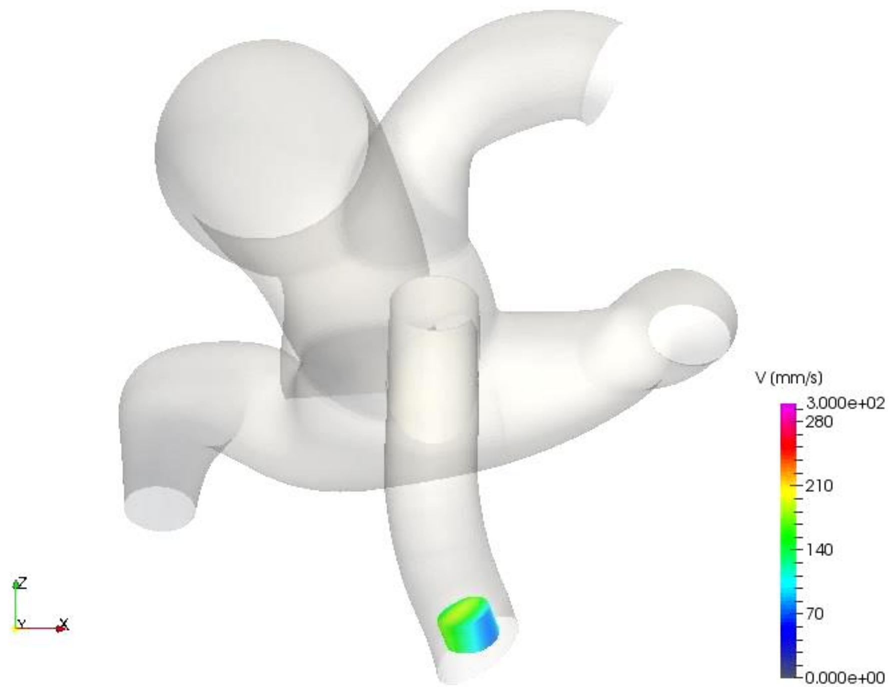
Particle tracking of different configurations

22.5 mm protrusion



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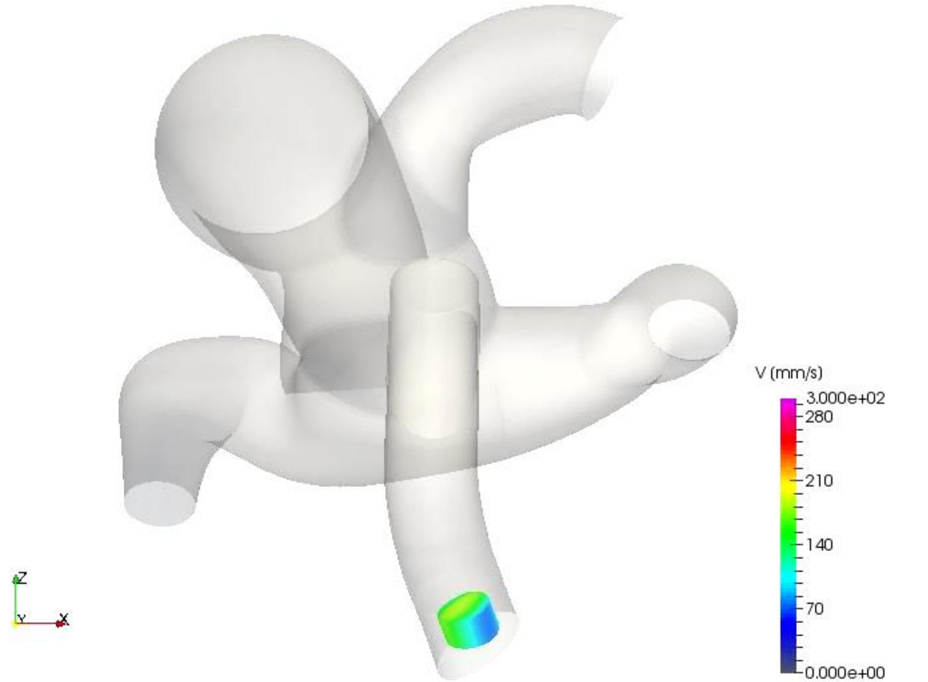
Particle tracking of different configurations

25.0 mm protrusion

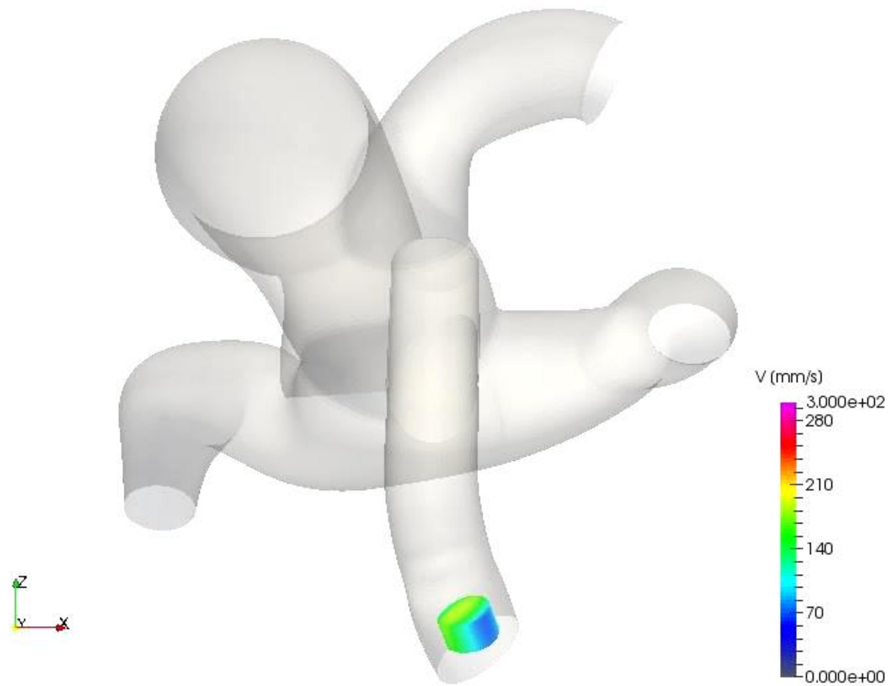


Particle tracking of different configurations

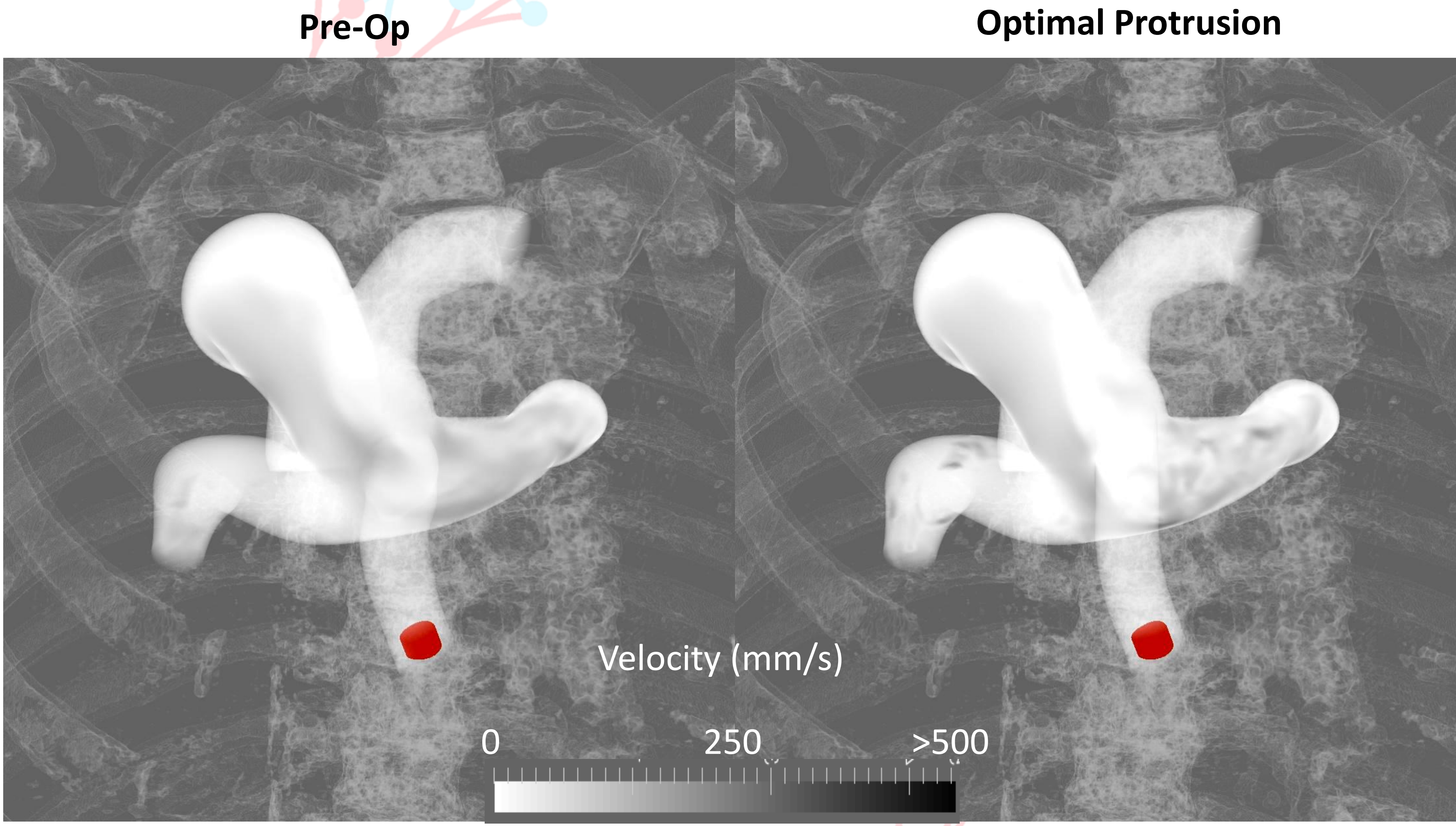
27.5 mm protrusion

Particle tracking of different configurations

30.0 mm protrusion

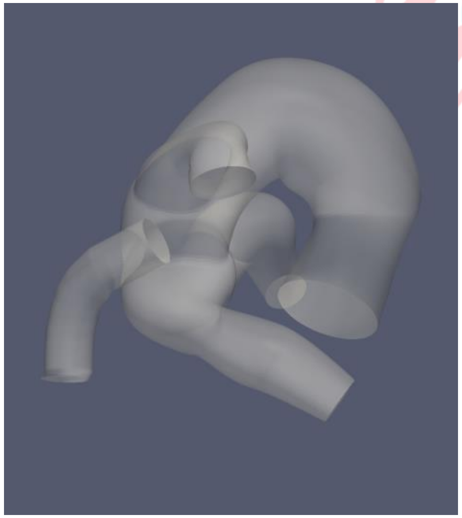


Particle tracking of different configurations

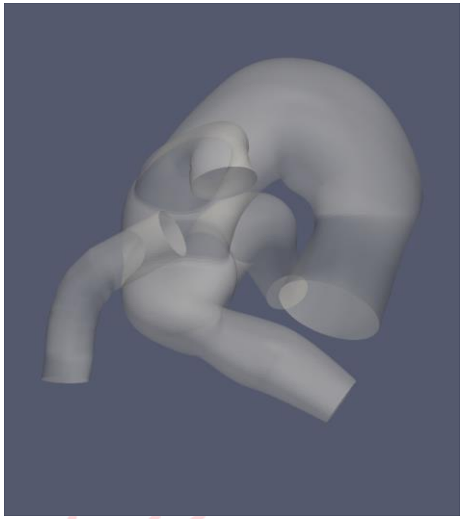


Split of hepatic factors as a function of protrusion length

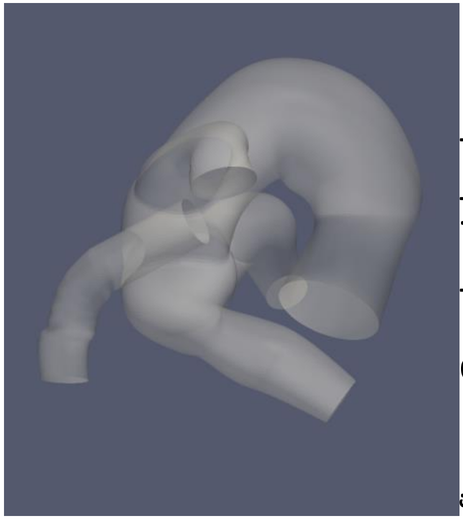
17.5 mm



22.5 mm



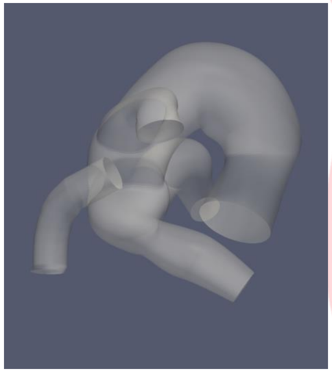
30.0 mm



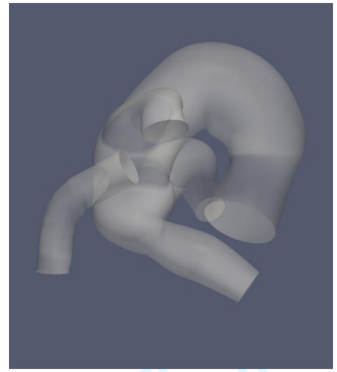
			Number of Particles at:			Percentage of Particles at:			
Model	Protrusion Length	# of Particles	Right PA	Left PA	Elsewhere	Right PA	Left PA	Elsewhere	RPA % Increase
Pre-Op	-	101222	18566	82543	113	**18.34%**	**81.55%**	0.11%	0.00%
Post-Op	17.5	101222	34654	65867	701	34.24%	65.07%	0.69%	86.65%
	20	101222	39377	60928	917	38.90%	60.19%	0.91%	112.09%
	22.5	101222	46279	53573	1370	45.72%	52.93%	1.35%	149.27%
	25	101222	39237	59836	2149	38.76%	59.11%	2.12%	111.34%
	27.5	101222	27560	70392	3270	27.23%	69.54%	3.23%	48.44%
	30	101222	18316	79754	3152	18.09%	78.79%	3.11%	-1.35%

Split of hepatic factors as a function of protrusion length

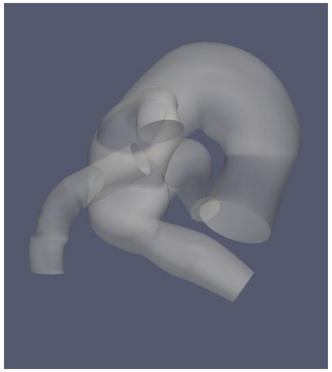
17.5 mm

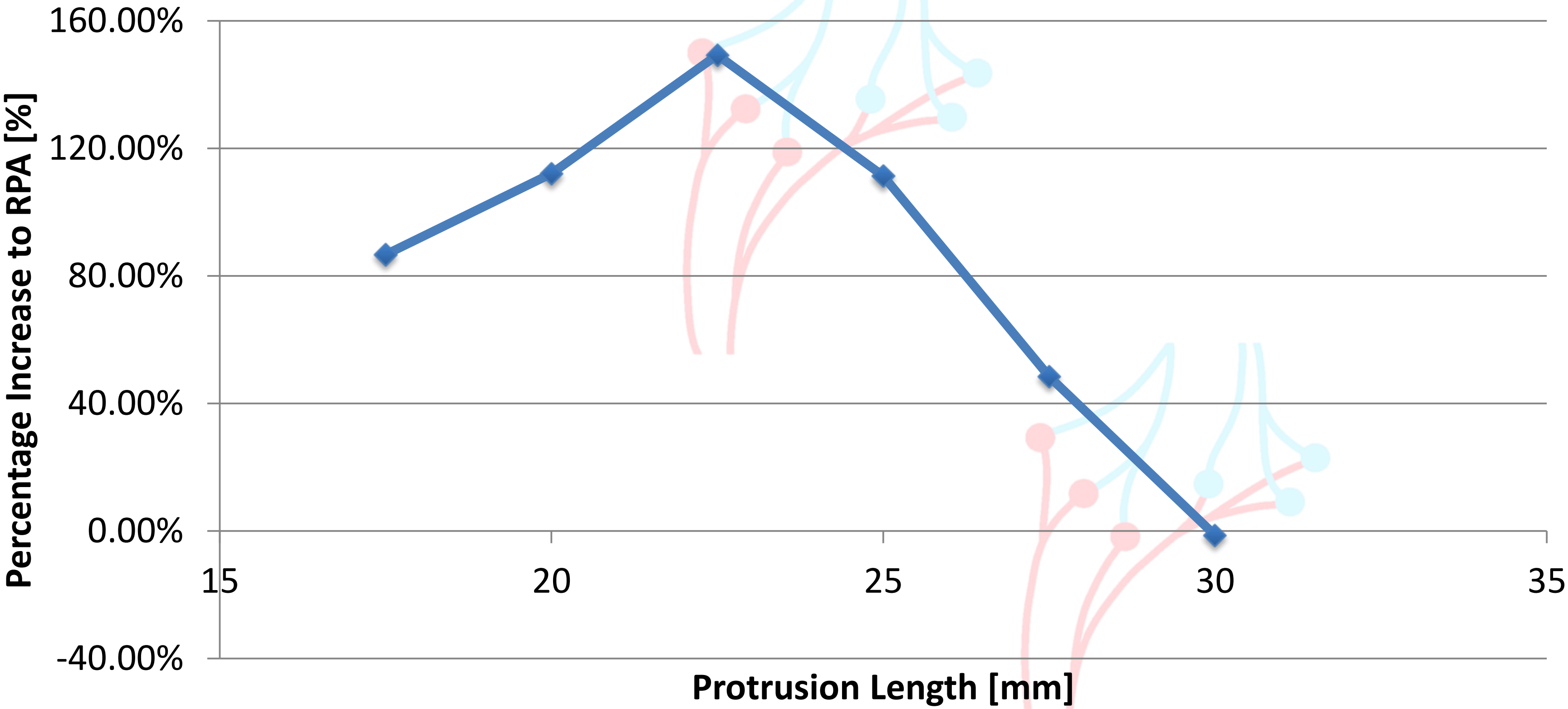


22.5 mm

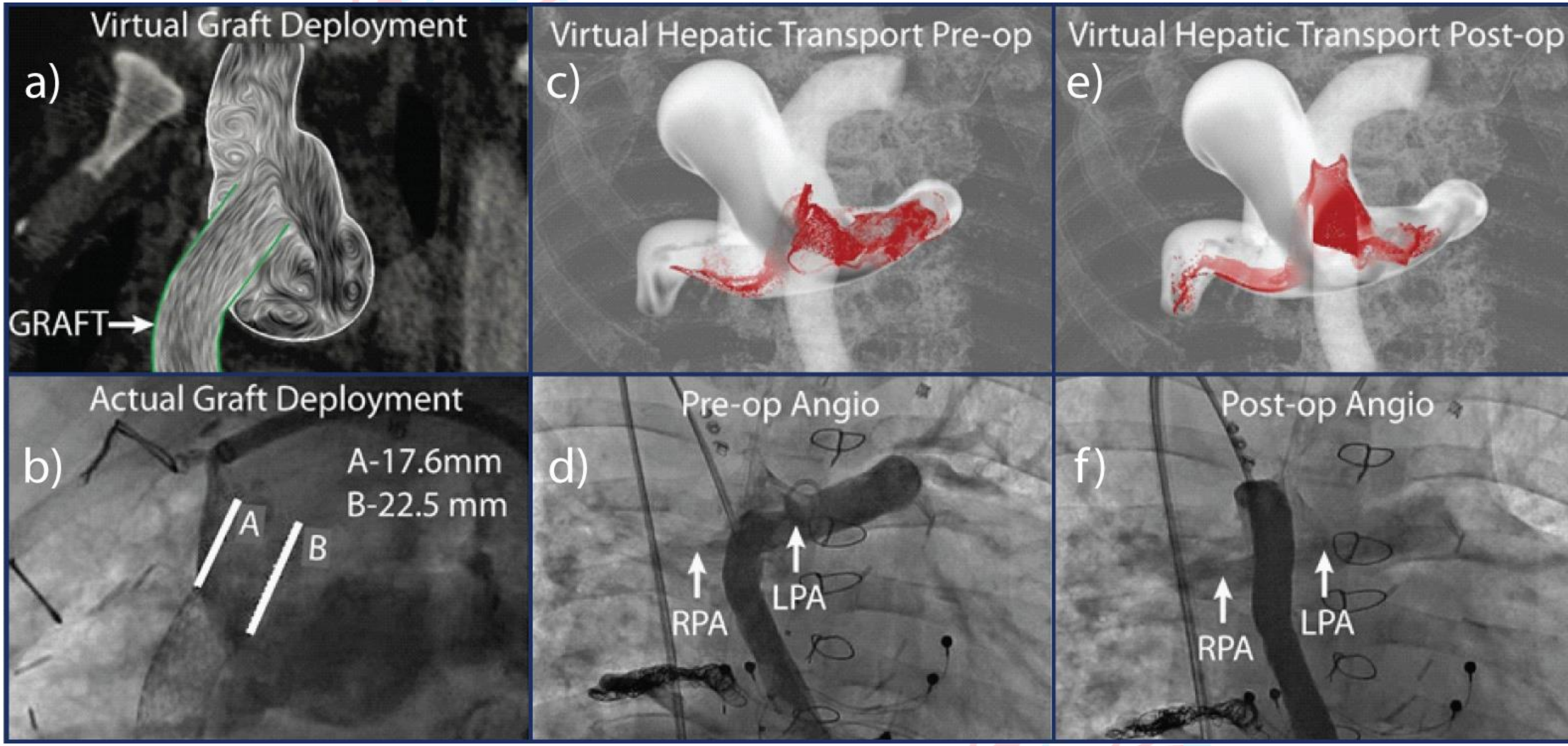


30.0 mm





Procedure done on July 10th 2015



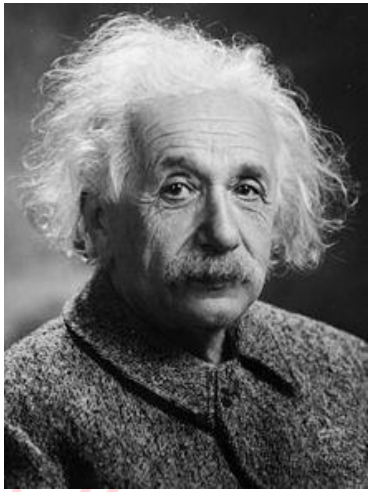
Patient is doing well and is being monitored for changes in AVMs and pulmonary flow

Conclusions

- Mathematical modeling of blood flow can have an impact on:
  - Disease research
  - Medical device design
  - **Surgical planning**
- A trial-and-error paradigm can be replaced by a virtual design and optimization paradigm

Conclusions

- "Everything should be made as simple as possible, but no simpler"



- Parameter estimation is a key effort in the CV modeling field: your model will only be as good as your parameters!

Acknowledgements

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Integrated Cardiac Care using Patient-specific Cardiovascular Modelling

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