A Systematic Quantification of Hemodynamic Differences Persisting After Aortic Coarctation Repair

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Background

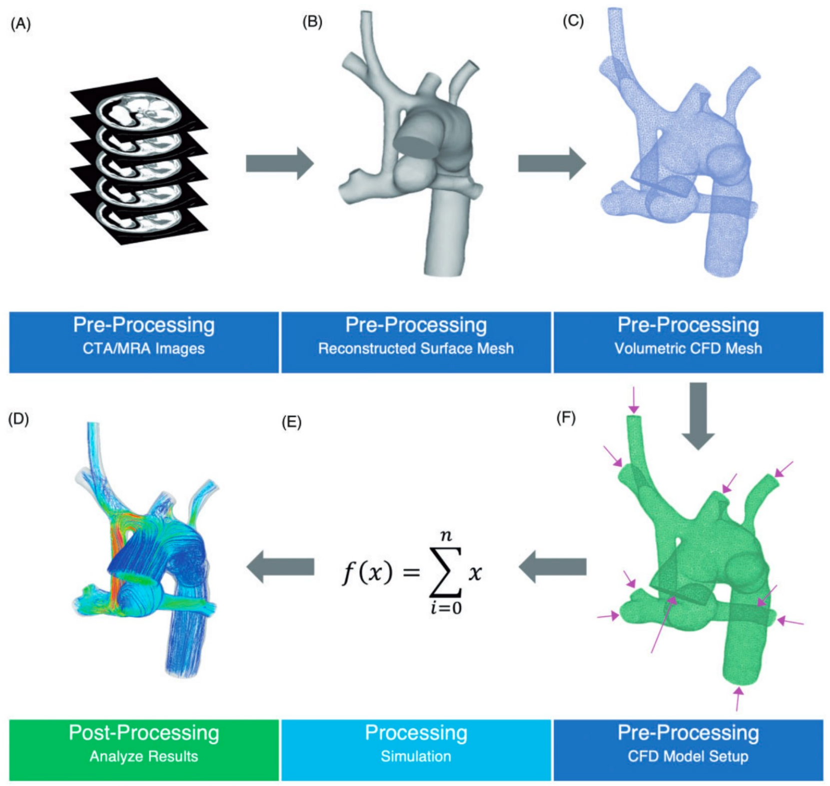
- Aortic coarctation (CoA) – surgical repair has excellent overall survival, *but*
  - High risk of long-term complications, *e.g.*, restenosis, hypertension
  - Lifelong imaging surveillance necessary for all CoA patients[1-2]

- Many possible risk factors, but evidence is mixed
  - Incomplete resection?
  - Low birth weight?
  - Abnormal hemodynamics?
  - Underlying tissue defect?

Hypothesis: *Small anatomic variations following repair can significantly alter wall shear stress (WSS) and may contribute to restenosis risk*

Background – CFD and CoA

- **Computational fluid dynamics** (CFD) is a powerful tool for modeling CoA[1-7]
  - Nearly 60 studies in last 15 years
- **The challenge**: isolating effect of anatomy on hemodynamics
  - Multiple confounders: patient age, type of repair, underlying simulation assumptions
- **Goal**: simulate flow in comparable patients while minimizing confounding factors



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[1]Aslan *et al.,* "Non-invasive prediction of peak systolic pressure drop across coarctation of aorta using computational fluid dynamics." *2020 IEEE Proceedings*

[2]Guillot *et al.*, "Computational fluid dynamics simulations as a complementary study for transcatheter stent implantation for re-coarctation of the aorta." *Cardiology in the Young* 2019

[3]Olivieri *et al.*, "Hemodynamic modeling of surgically repaired coarctation of the aorta." *Cardiovascular Engineering and Technology*, 2011

[4]Ardakani *et al.*, "Isolating the effect of arch architecture on aortic hemodynamics late after coarctation repair: a computational study." *Frontiers in CV Medicine*, 2022

[5]Keshavarz-Motamed *et al.*, "Elimination of transcoarctation pressure gradients has no impact on left ventricular function or aortic shear stress after intervention in patients with mild coarctation." *JACC: Cardiovascular Interventions*, 2015

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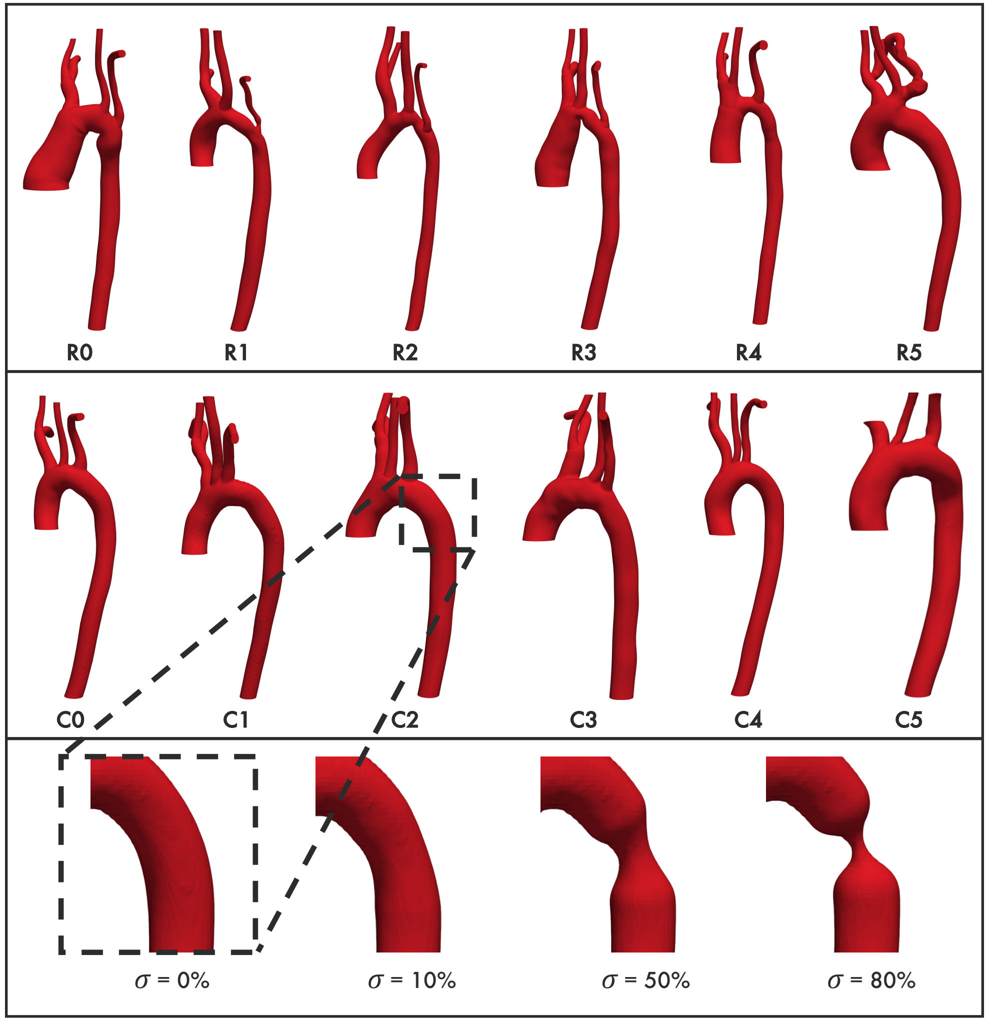
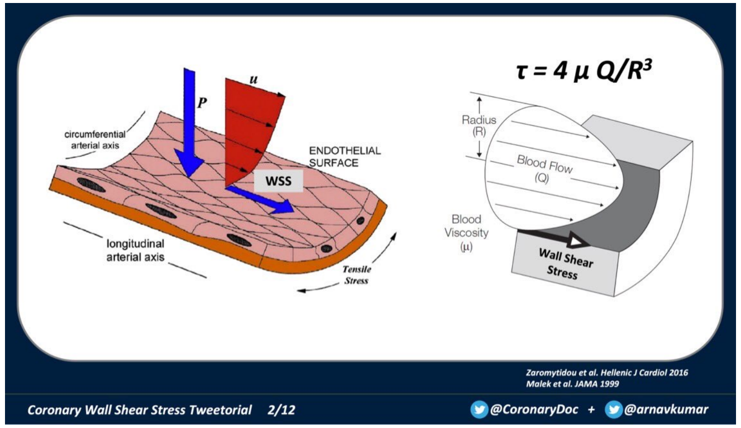
Methods

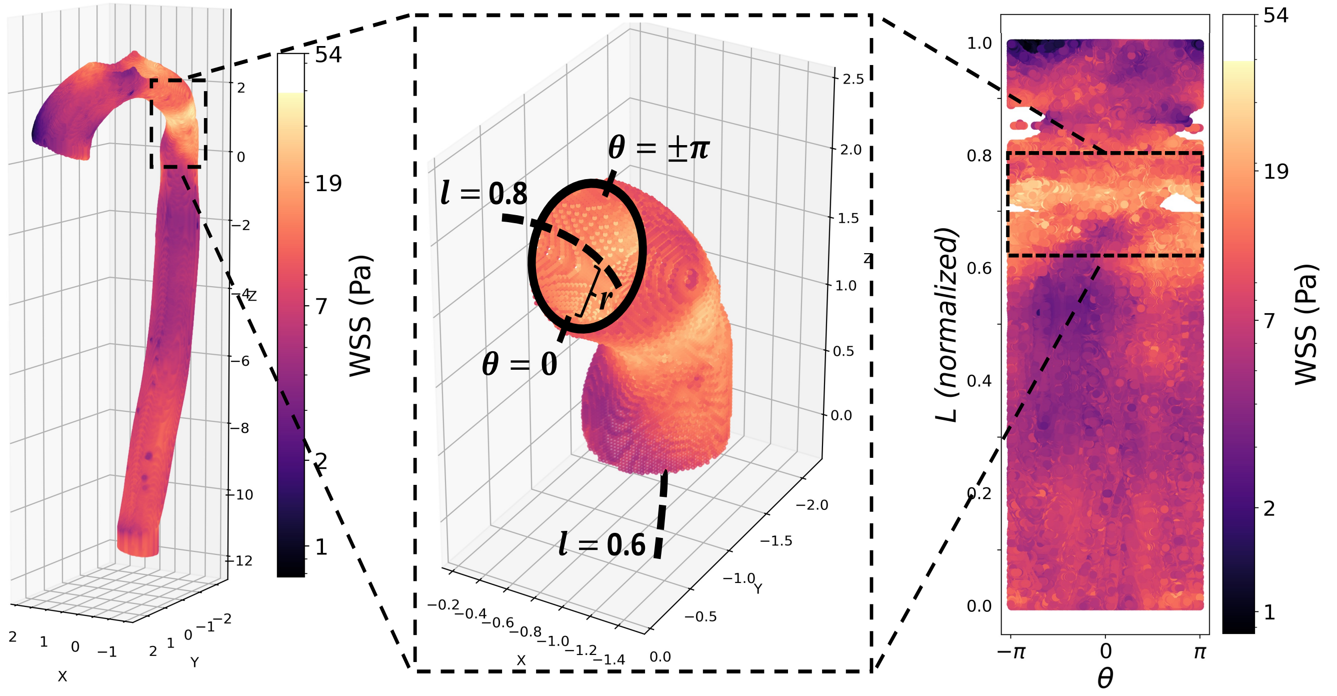
- CFD code: HARVEY
  - Massively-parallel solver that uses the lattice Boltzmann method (LBM) to solve the Navier-Stokes equations of fluid flow
- Two patient cohorts:
  - 6 CoA patients after resection with end-to-end anastomosis
  - 6 age/sex-matched healthy control patients
  - Models derived from MRI angiograms
- For each patient, simulate 4 restenosis angles:
  - 0%, 10%, 50%, 80%
  - 48 simulations total
- Assumptions:
  - rigid walls (valid for large vessel flow)
  - Newtonian blood flow
  - 0-pressure outlets

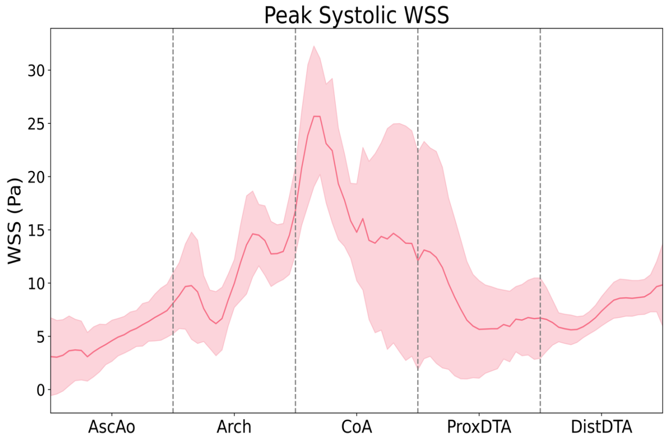


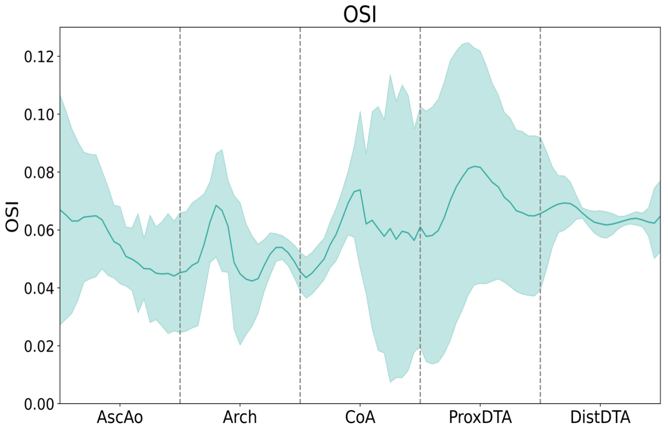
Methods

- Simulate 1 cardiac cycle
  - Heart rate: 80 bpm
  - Peak systolic velocity: 45 cm/s
- Spatial resolution: 25 microns
  - Performed on 1,024 CPUs of an institutional high-performance computing (HPC) research cluster
- Primary outcome: **time-averaged wall shear stress (TAWSS)**
  - Secondary outcome: **oscillatory shear index (OSI)**



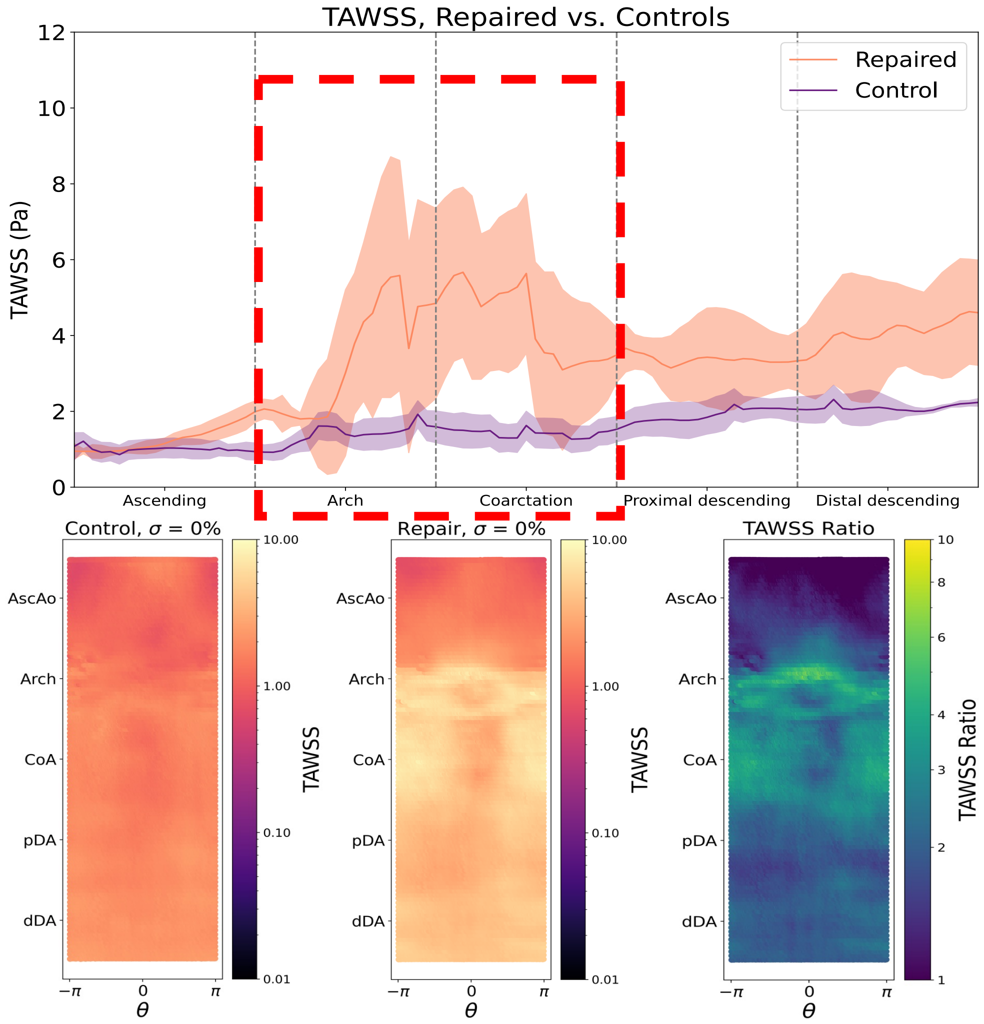






Higher TAWSS in arch and CoA repair site

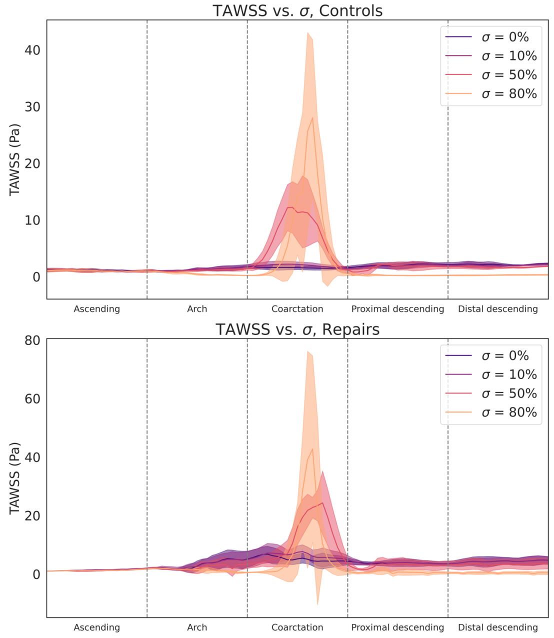
	CoA (n = 6)	Control (n = 6)	p-value
Ascending aorta			
TAWSS (Pa)	1.25	1.07	NS
OSI	0.05	0.06	NS
Aortic arch			
TAWSS (Pa)	**3.46**	**1.24**	**<0.0001**
OSI	0.05	0.05	NS
Coarctation site			
TAWSS (Pa)	**4.34**	**1.56**	**<0.0001**
OSI	0.04	0.05	NS
Proximal descending aorta			
TAWSS (Pa)	3.76	1.94	<0.01
OSI	0.06	0.06	NS
Distal descending aorta			
TAWSS (Pa)	4.31	2.09	<0.01
OSI	0.06	0.06	NS

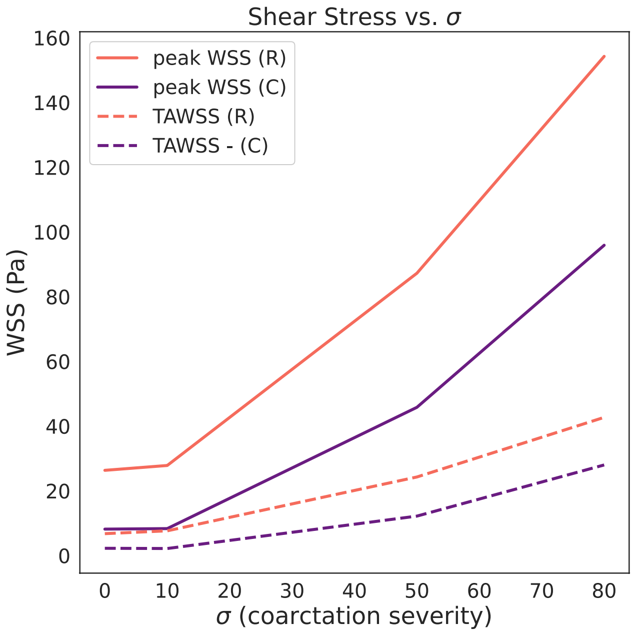


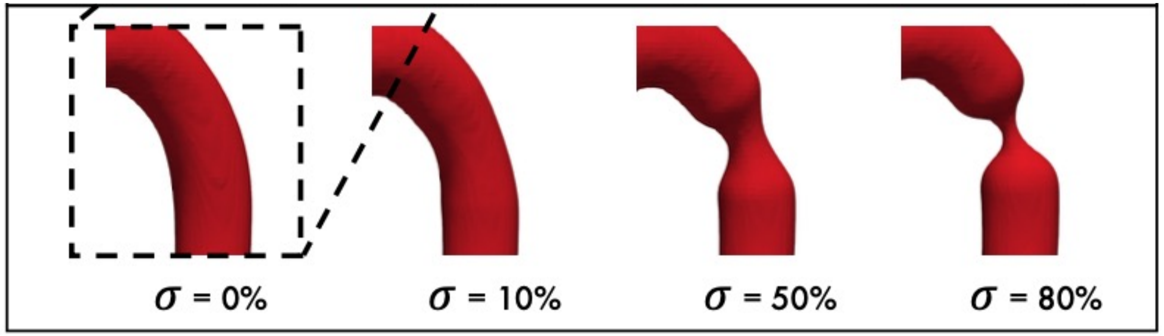
TAWSS Increases Sharply With Coarctation Severity

- Clear, nonlinear relationship between coarctation severity and TAWSS magnitude

Repaired CoA					
Stenosis	$\sigma = 0\%$	$\sigma = 10\%$	$\sigma = 50\%$	$\sigma = 80\%$	***p*-value**
TAWSS (Pa)	**4.34**	**7.64**	**24.28**	**42.70**	**<0.001**
Matched controls					
Stenosis	$\sigma = 0\%$	$\sigma = 10\%$	$\sigma = 50\%$	$\sigma = 80\%$	***p*-value**
TAWSS (Pa)	**1.56**	**2.17**	**12.19**	**27.99**	**<0.001**

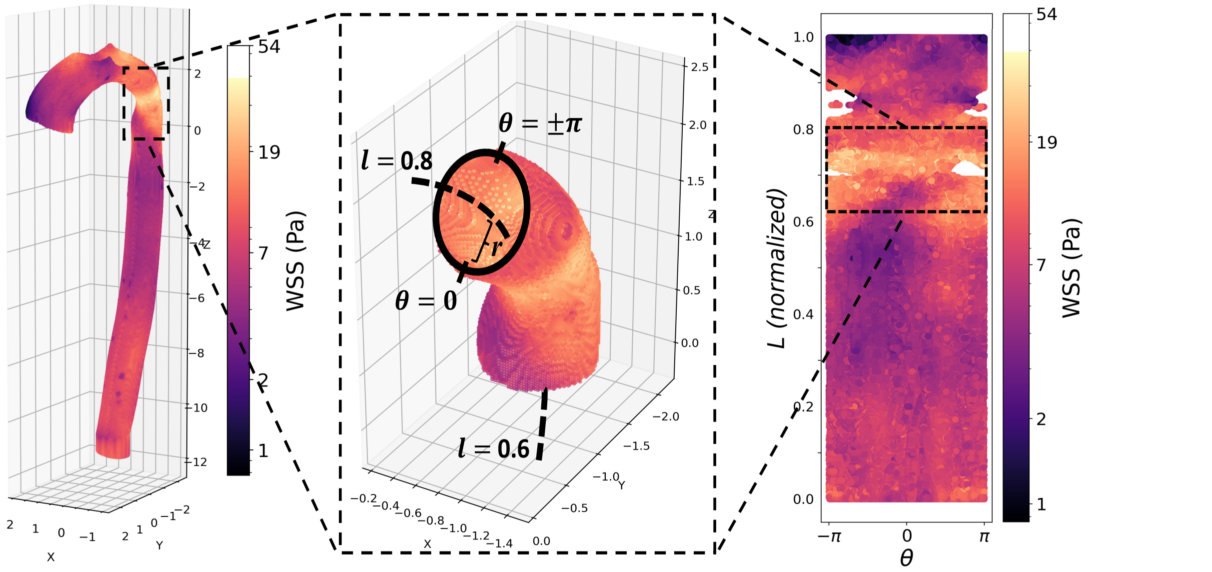






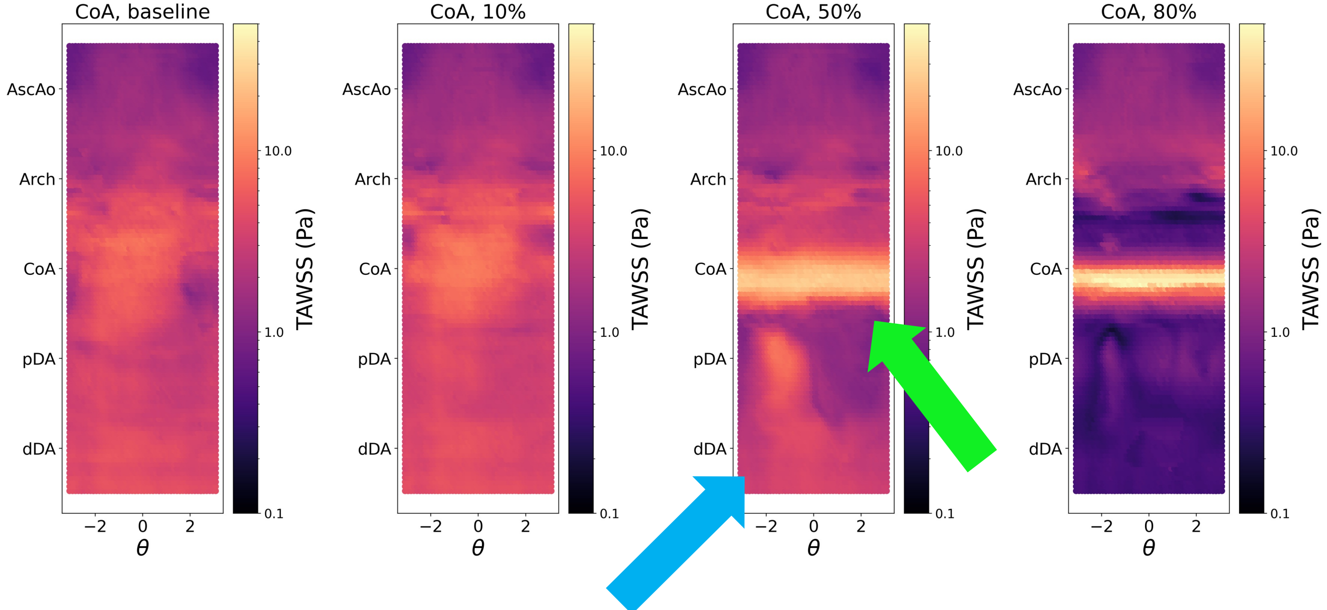
TAWSS Increases Sharply With Coarctation Severity

Unwrapping the aorta wall into a 2D plane



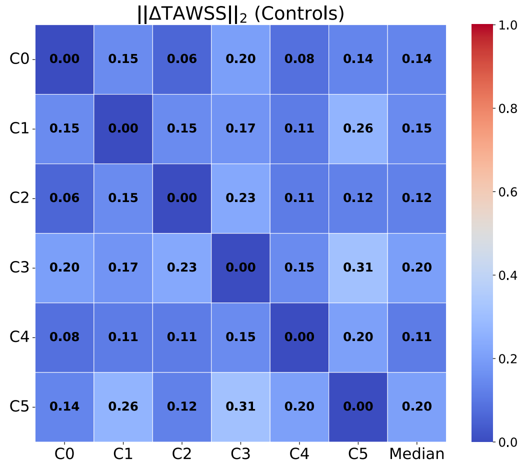
Region of elevated TAWSS clear as bright band (**green arrow**)

Jet impinging on distal outer aorta (**blue arrow**)

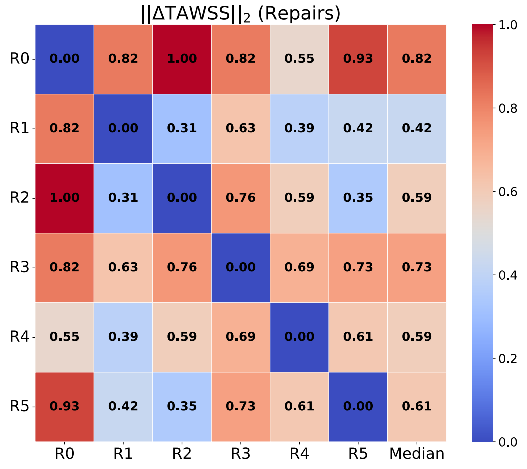


Wall Shear Stress is Highly Variable Following CoA Repair

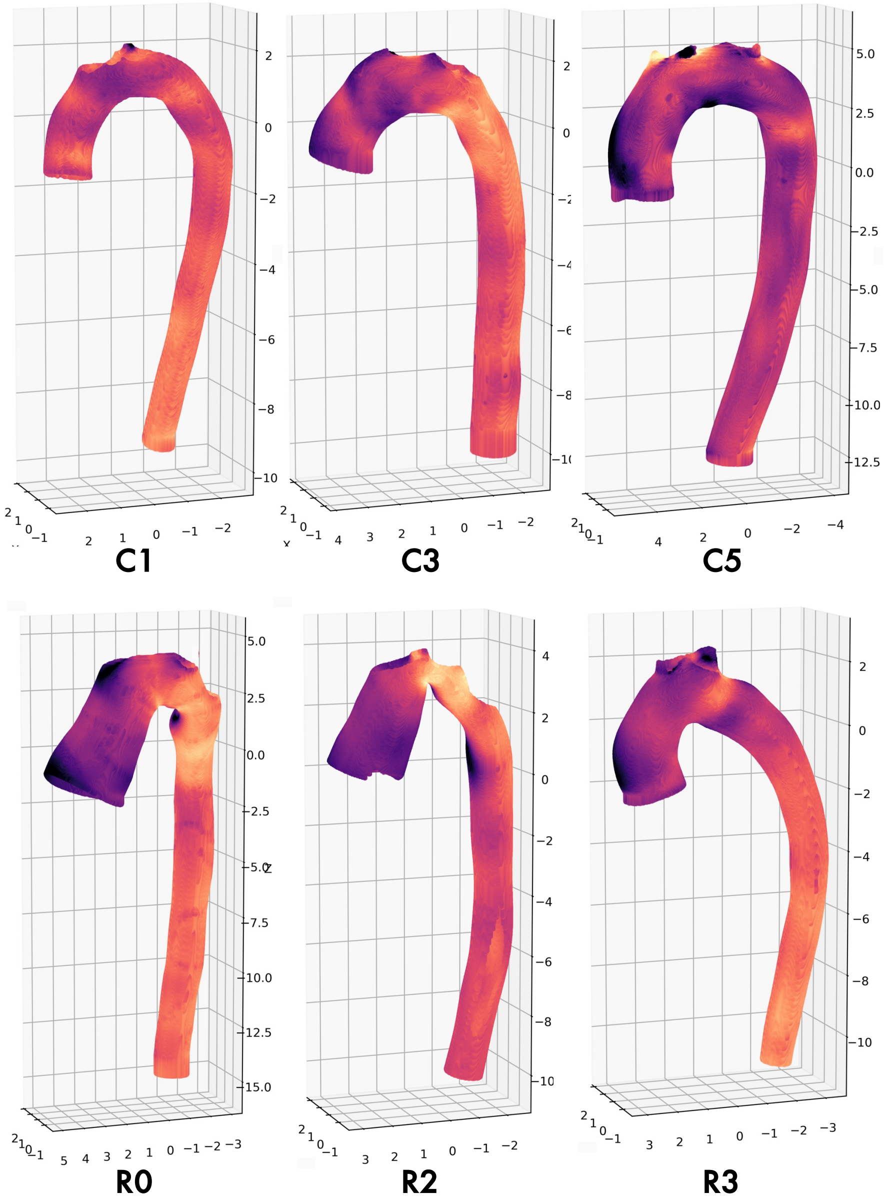
- Healthy aortas
  - Uniform flow
  - Smooth wall shear stress distribution
- Repaired aortas differ greatly
  - Wide range of hemodynamic phenotypes
  - High WSS at the repair site (R0)
  - High WSS in the aortic arch (R2)
  - Or no high WSS at all (R3)
- Intra-cohort correlation:



Healthy controls (very similar)



Repaired CoAs (very different)



Discussion

- Many CFD/imaging studies on CoA, but results are inconsistent
- Restenosis = multifactorial process
- CFD simulations must use **account for clinical confounders**
  - Patient age at repair
  - Type of repair
  - Coarctation anatomy, presence of collaterals, etc.

Abnormalities of Aortic Arch Shape, Central Aortic Flow Dynamics, and Distensibility Predispose to Hypertension After Successful Repair of Aortic Coarctation

Luca Donazzan, MD[1], Robert Crepaz, MD[1], Josef Stuefer, MD[2], and Giovanni Stellin, MD[3]

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Aortic arch shape is not associated with hypertensive response to exercise in patients with repaired congenital heart diseases

Hopewell N Ntsinjana[1], Giovanni Biglino[1], Claudio Capelli[1], Oliver Tann[1], Alessandro Giardini[1], Graham Derrick[1], Silvia Schievano[1] and Andrew M Taylor[1,2*]

Conclusion

- Simulated aortic hemodynamics following CoA repair
  - Compared to age/sex-matched controls
- Significantly higher wall shear stress following CoA repair
  - Anatomy normal, but hemodynamics are not
- Small residual stenoses = significantly higher stresses
  - Positive feedback cycle driving restenosis?
- Future work
  - Larger patient cohorts
  - Simulate aortic flow at multiple follow-up points
- Goal
  - CFD + clinical + imaging data → restenosis prediction model