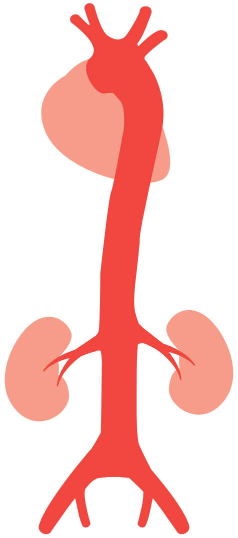
IMPERIAL

Computational Biomechanical Modelling of Thoracic Endovascular Aortic Repair



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July, 2024

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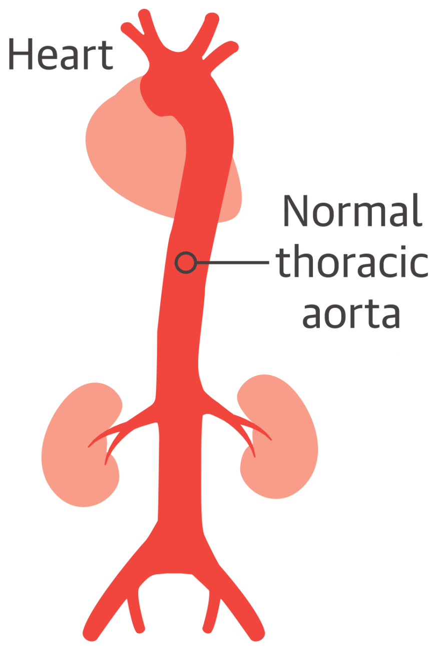
Background (1/3)

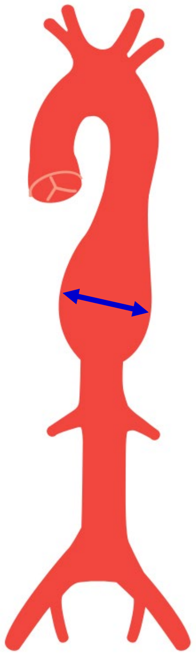
From Aortic Aneurysm to Aortic Dissection

Healthy aorta



- Largest artery in body
- Diameter: 25 ± 2 mm
- Three-layer structure: intima, media, adventitia

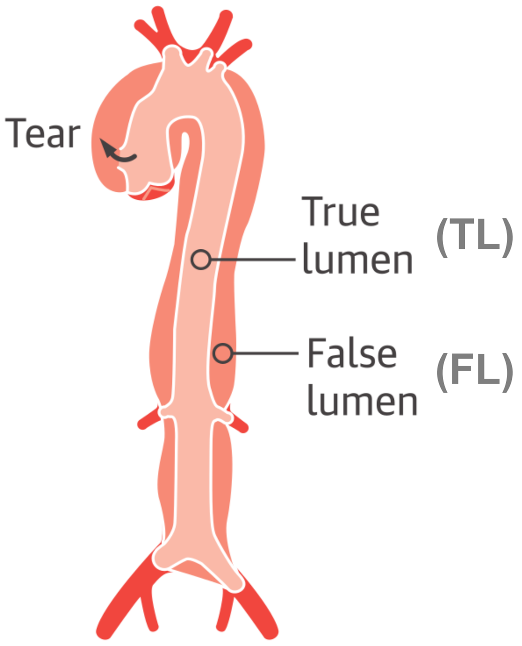
Aortic aneurysm (AA)



- Local **enlargement** of aortic segment > 50%
- 5-6 per 100,000 individuals / year
- Genetic and non-genetic attributes

5 - 10%

Aortic dissection (AD)

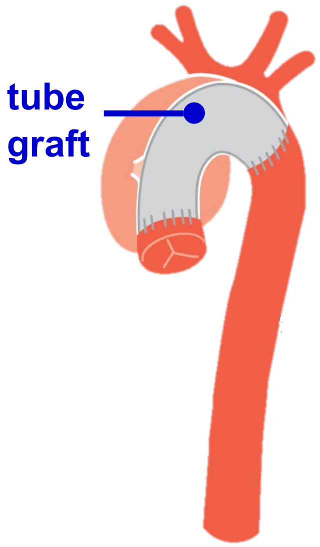


- A **tear** between intima and media diverts blood from TL to FL
- 2.9-4.6 per 100,000 individuals / year
- Intervention-free mortality increases 1% per hour, up to 90%

Background (2/3)

Clinical Management: surgical *v.s.* endovascular approaches

- Both AA and AD can be **asymptotic** until the late manifestation of **acute aortic syndrome**
  - Unsuitable for pharmacological control in most of the cases
- As suggested by AATS, an early intervention is recommended as the aortic diameter > 55 mm.

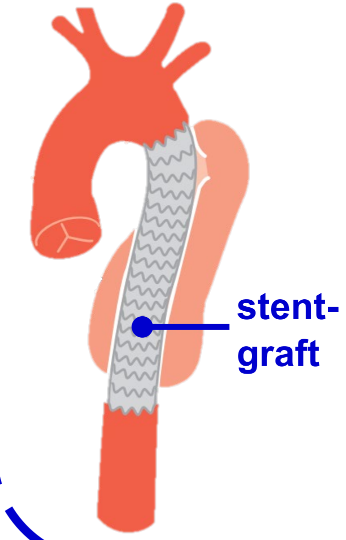


Surgical repair (arch repair)

PROs
- Good durability
- Fully removes the pathological tissue (e.g. AA sac)

CONs
- Highly invasive
- Higher perioperative risks
- Longer in-hospital stay

Endovascular Aortic Repair (EVAR)



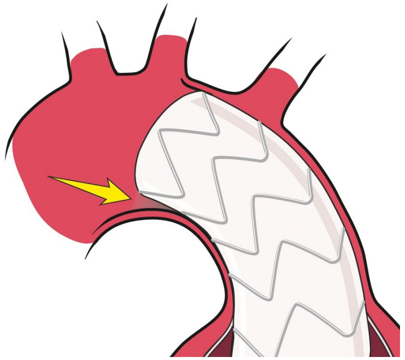
PROs
- Minimally invasive
- Reduced mortality
- Off-the-shelf availability

CONs
- Unsuitable for complex aortic anatomy
- Device-related complications

Background (3/3)

Post-TEVAR Complications and Biomechanical Risk Factors

endoleaks



- The most common device-related complications with EVAR
- Persistence of blood flow **outside** the lumen of the graft
- Attributed to the **sealing failure**, **retrograde flow**, **component failure**, undesired **graft porosity** (type I-IV)
- May lead to the subsequent development of the device **migration**, **kinking**, and **collapse**.

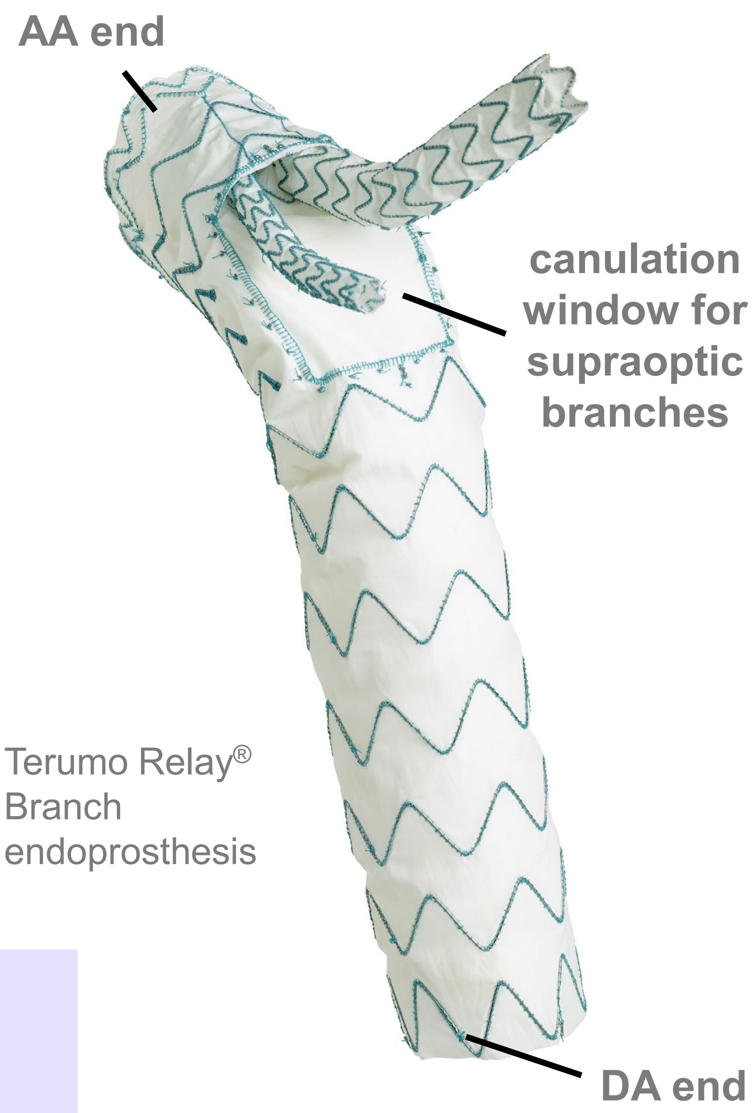
Excessive pressurization	**High oscillatory shear stress**
High displacement forces	**High wall shear stress**

biomechanical risk factors

Computational fluid dynamics

Research Objective

1. Understand the haemodynamic changes associated with the **aortic pathologies**, including AA and AD, through **computation fluid dynamics (CFD)** simulations;
2. Investigate the **haemodynamic performance of thoracic EVAR (TEVAR) devices**, with the particular focus on a newer generation *branched* devices;
3. Predicting the possible **device-related complications** through both quantitative and qualitative analysis of the haemodynamic matrices;
4. Informing and facilitating possible future clinical decisions.



- Terumo Relay® Branch endoprosthesis

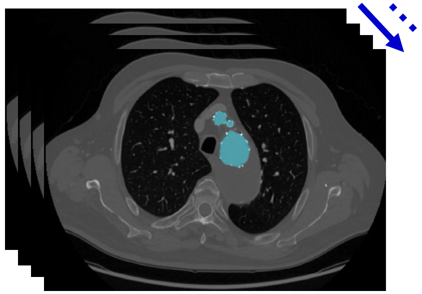
Aim

(THIS SECTION IS REMOVED FOR REVISION)

Methodology (1/4)

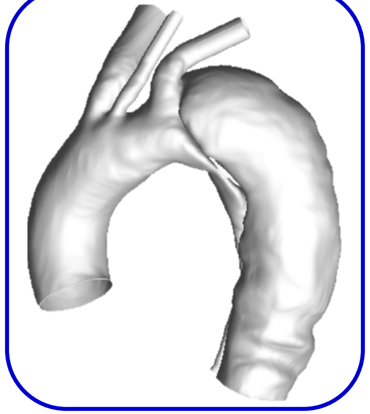
An Overview

Materialise Mimics



1 semi-automatic CTA segmentation

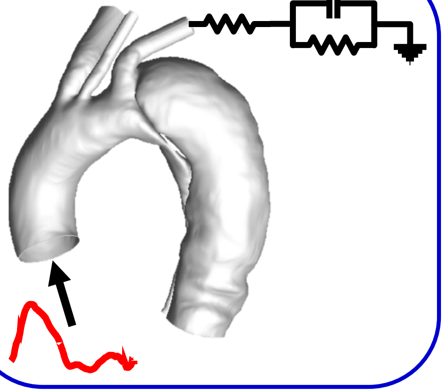
OR



2 ***direct*** **geometry reconstruction**

3 mesh generation

Ansys ICEM CFD



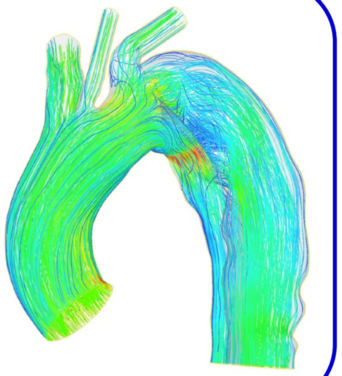
4 CFD simulation

ANSYS CFX

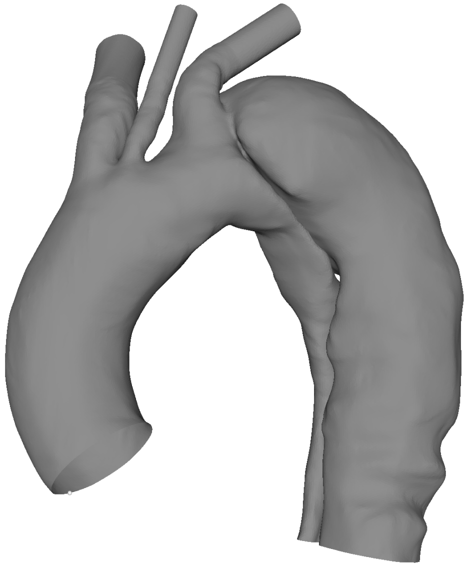
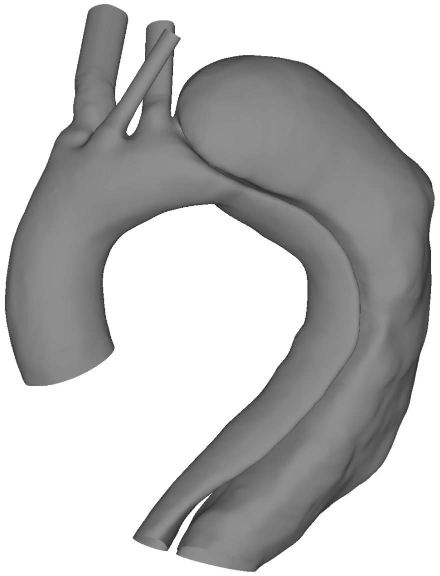
2 ***post-TEVAR*** **geometry treatment**

5 Quantification of haemodynamic matrices

Ansys ENSIGHT



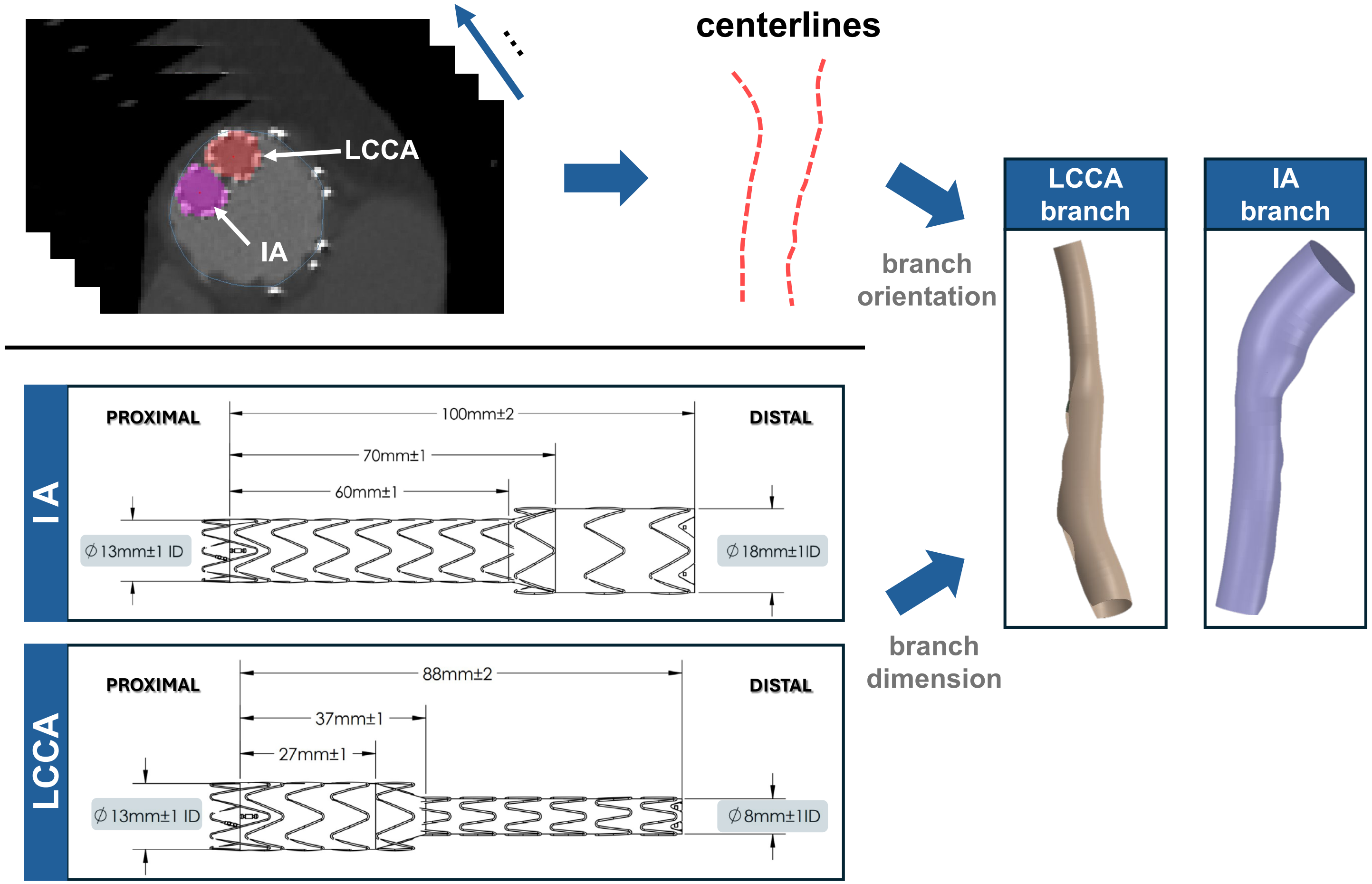
Methodology (2/4)
Patient Demographics

Patient 1	Patient 2
SV: 60 ml, EF: 54%	SV: 75 ml, EF: 62%
HR: 61 bpm	HR: 70 bpm
	

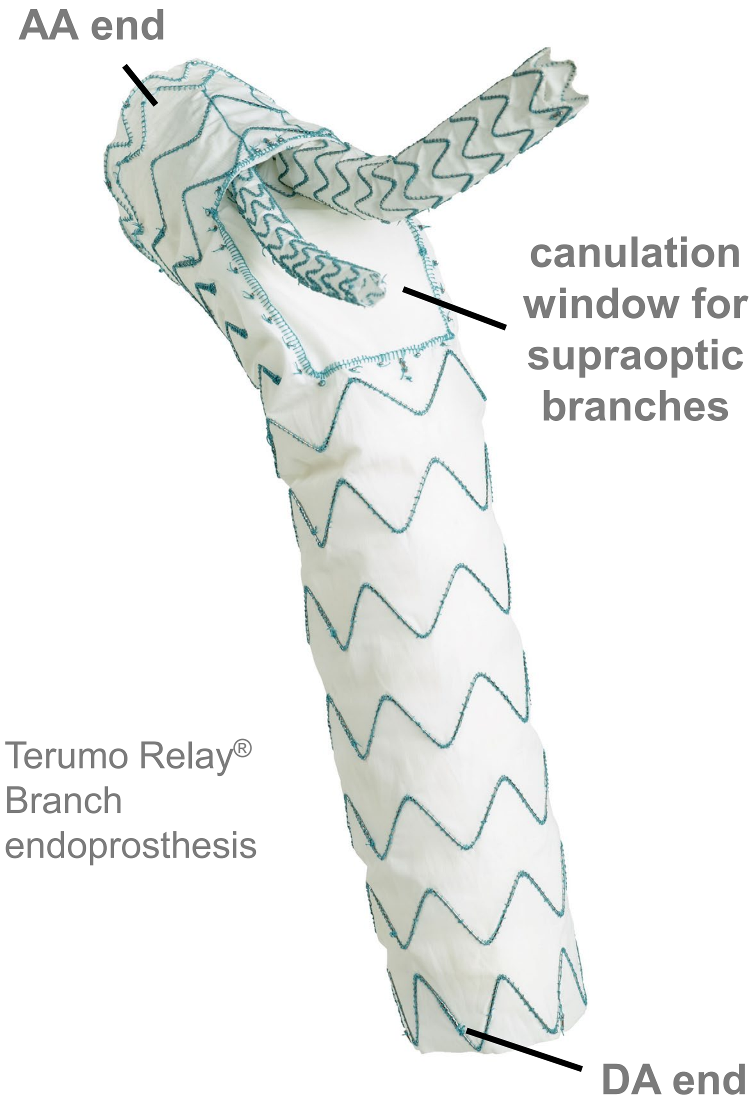
- diagnosed with the **chronic thoracic aortic dissection** progressed from the prior **aortic arch aneurysm**
- received **TEVAR treatment** with Terumo Relay® Branch endoprosthesis, both under the **dual-branch** configuration.
- post-operative CTA scans were obtained at **3 months** and **1 month** for patient 1 and 2.

By courtesy Dr M. D'Oria (Univ. of Padova, Italy)

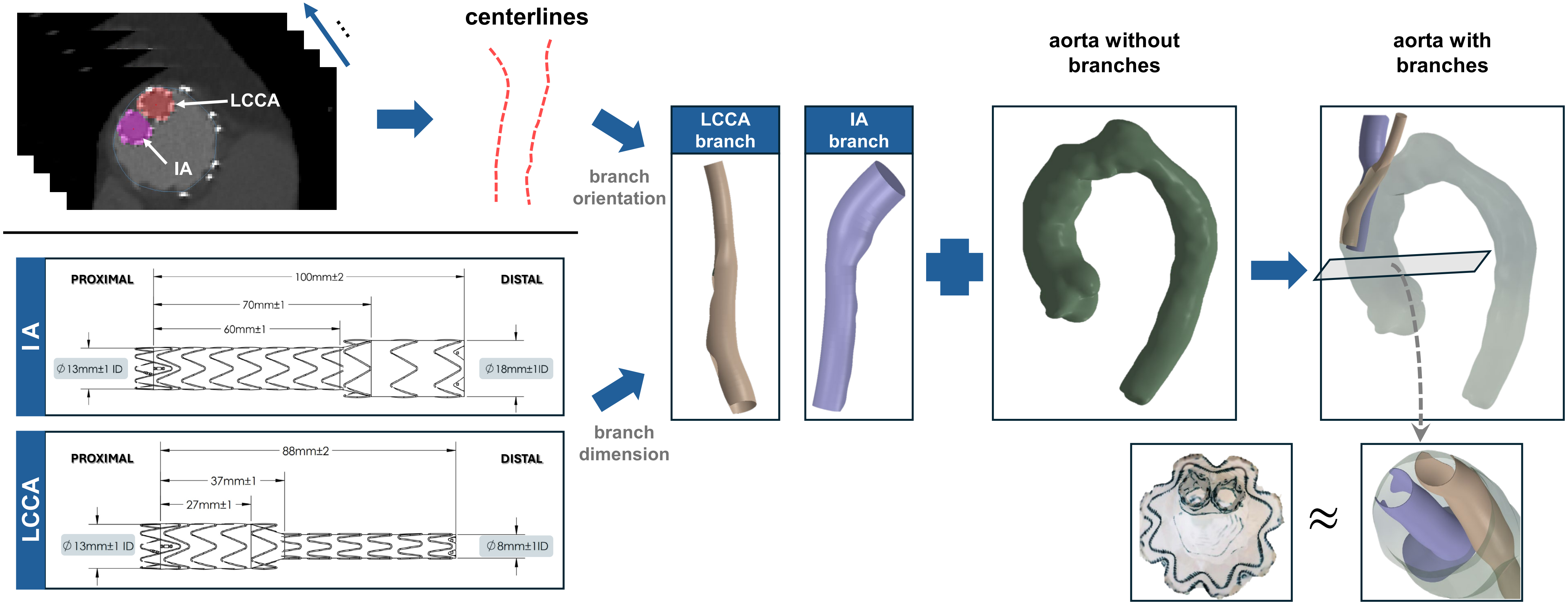
Methodology (3/4)
Post-TEVAR Geometry Treatment



- Terumo Relay® Branch endoprosthesis



Methodology (3/4)
Post-TEVAR Geometry Treatment

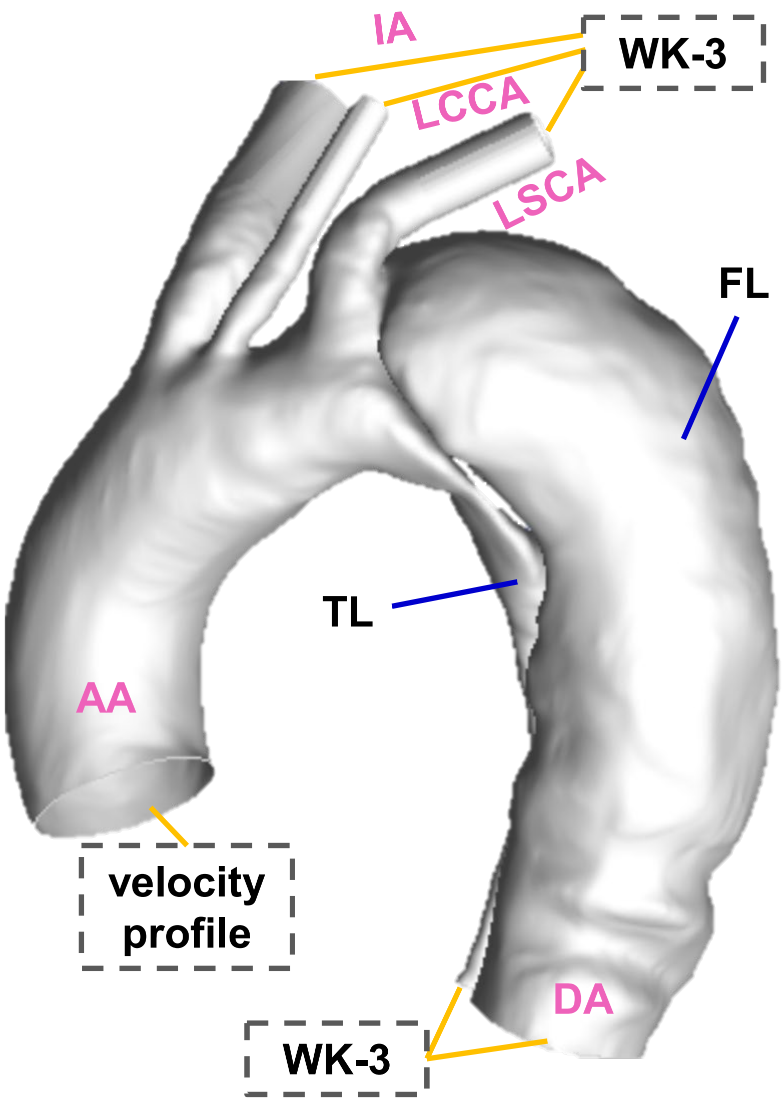


cross-sectional view of the inner tunnels

Methodology (4/4)

Simulation Setup

AA	Ascending aorta	IA	Innominate artery
LCCA	L. common carotid artery	LSCA	L. subclavian artery
CO	Cardiac output	WK-3	3-element Windkessel



NS - Continuity

$$\frac{\partial u_i}{\partial x_i} = 0,$$

Momentum

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho f_i.$$

Physiological Assumptions

- Incompressible, ρ = 1060 kg/m^3
- Non-Newtonian blood viscosity (C-Y)
- Rigid wall
- Neglected body force
- Laminar-to-turbulent transition $\gamma - Re_\theta$

Methodology (4/4)

Simulation Setup

AA	Ascending aorta	IA	Innominate artery
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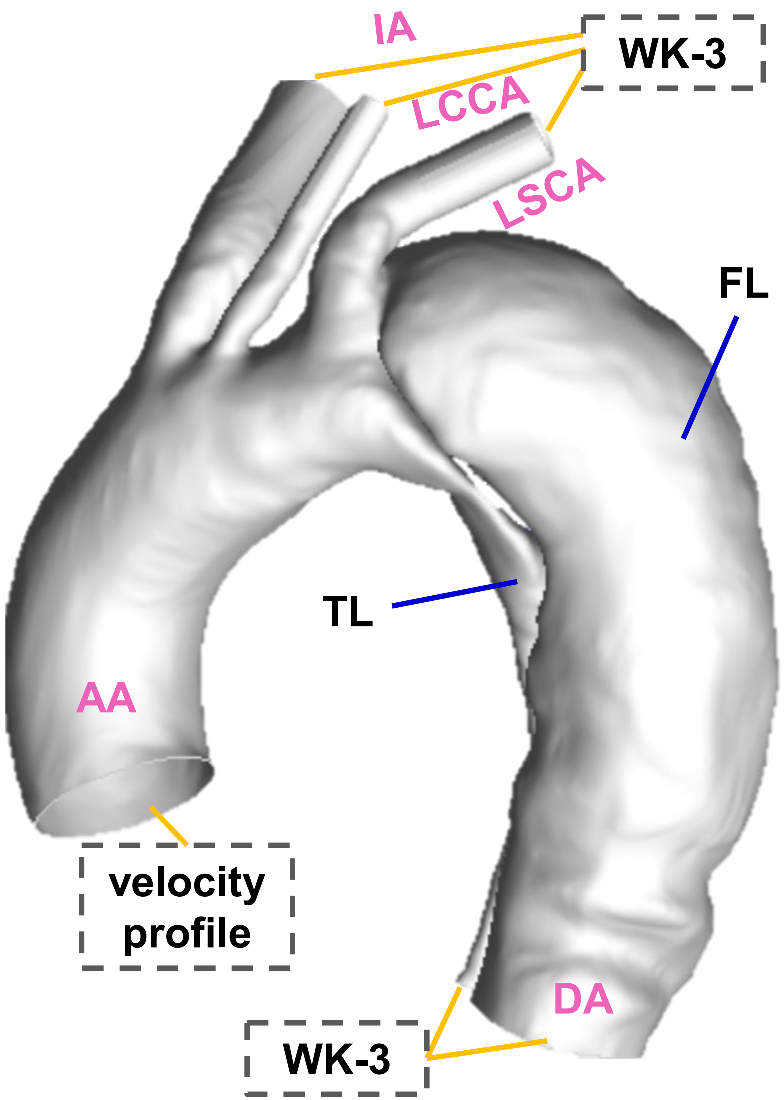
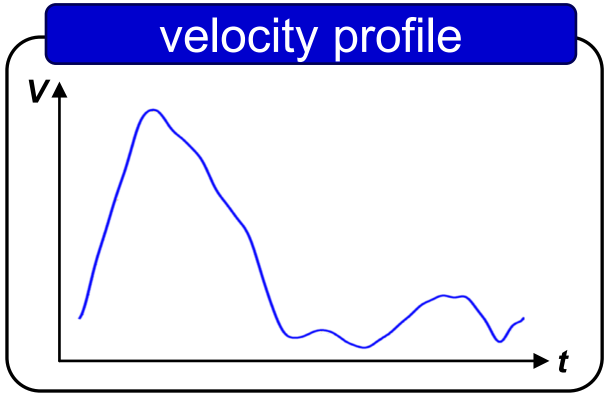
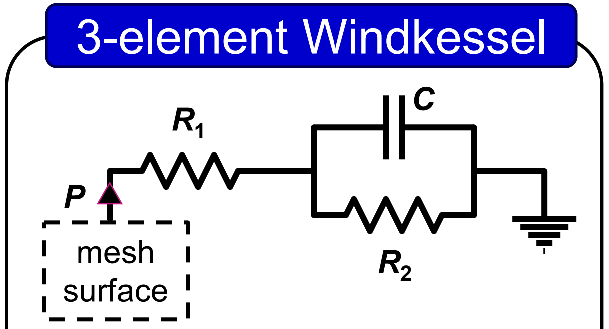




- Flat inlet profile
- Scaled from a representative TAA measurement by patient-specific CO



- R_1: characteristic impedance
- C: wall compliance
- R_2: peripheral resistance

- 0D pressure-type outlet
- Values of R_1, R_2, C calculated using surface area, CO, and brachial pressure measurement.

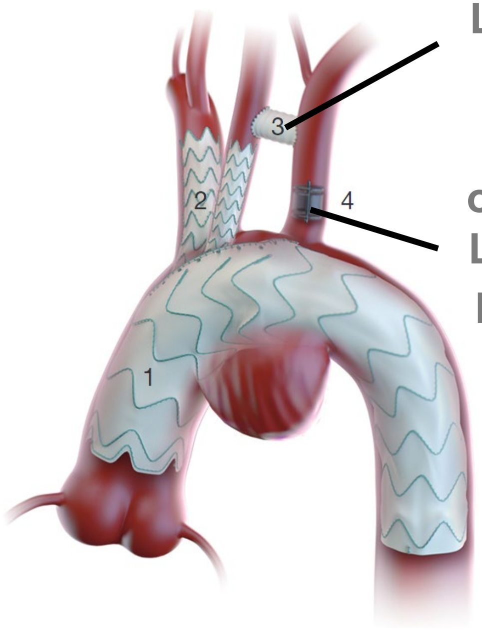
Preliminary Results (1/5)

Mass Flow Rate

outlets

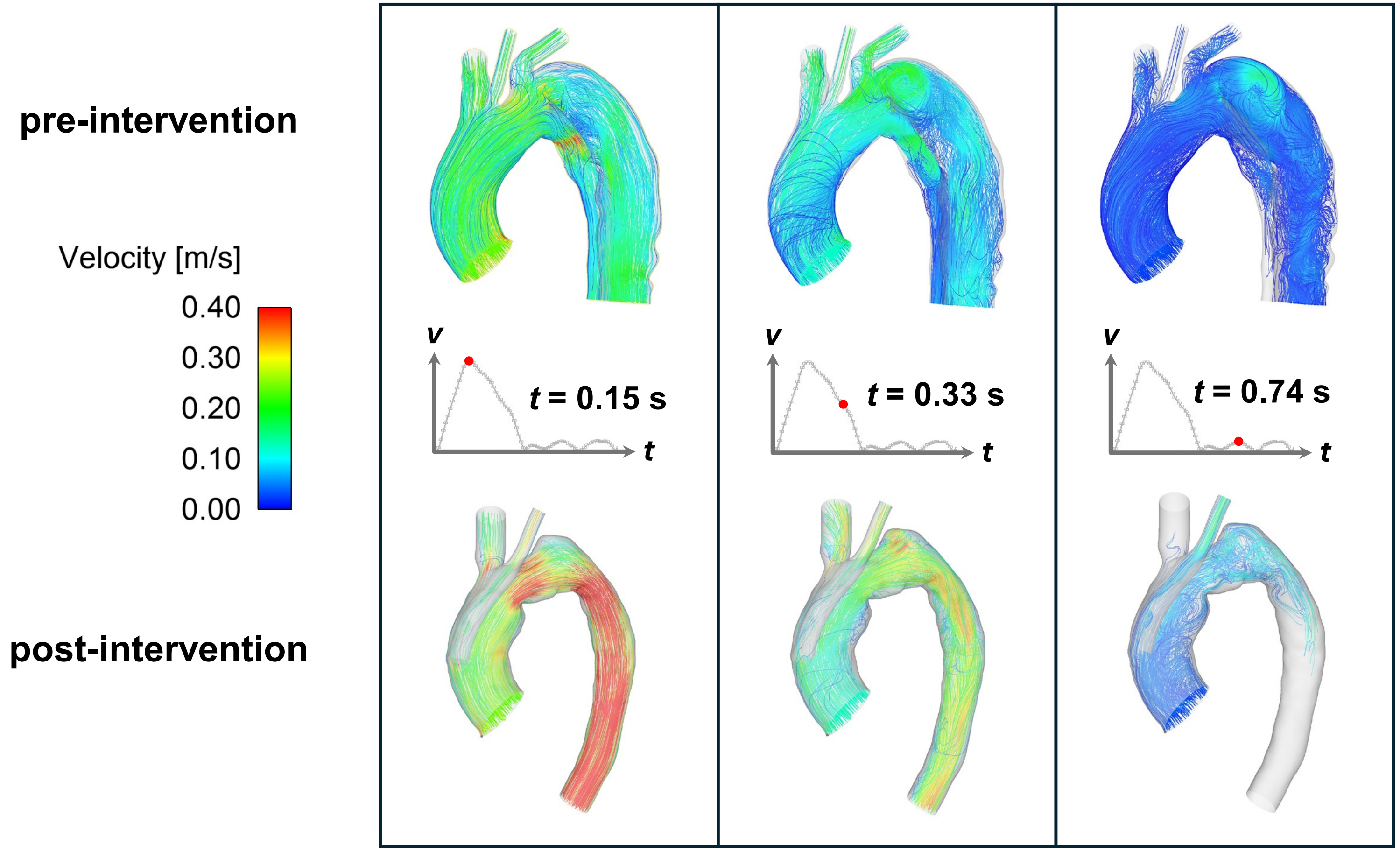
		Q_{inlet} [L/min]	Q_{DA} [L/min]	Q_{IA} [L/min]	Q_{LCCA} [L/min]	Q_{LSCA} [L/min]
Patient 1	**Pre**	3.66	2.56 (69.96%)	0.66 (17.59%)	0.13 (3.57%)	0.33 (8.89%)
	Post	3.66	2.62 (71.44%)	0.63 (17.32%)	0.41 (11.25%)	
Patient 2	**Pre**	4.50	3.19 (70.91%)	0.68 (15.17%)	0.15 (3.32%)	0.48 (10.62%)
	Post	4.50	3.24 (71.86%)	0.71 (15.72%)	0.56 (12.44%)	

- The blood perfusion in IA and LCCA are successfully preserved in both patients after TEVAR.
- $Q_{LCCA,\ \mathbf{post}} \approx Q_{LCCA,\ \mathbf{pre}} + Q_{LSCA,\ \mathbf{pre}}$, due to the flow split to LSCA is bypassed to LCCA



Preliminary Results (2/5)
Streamline Plot

Patient 1



Pre-TEVAR

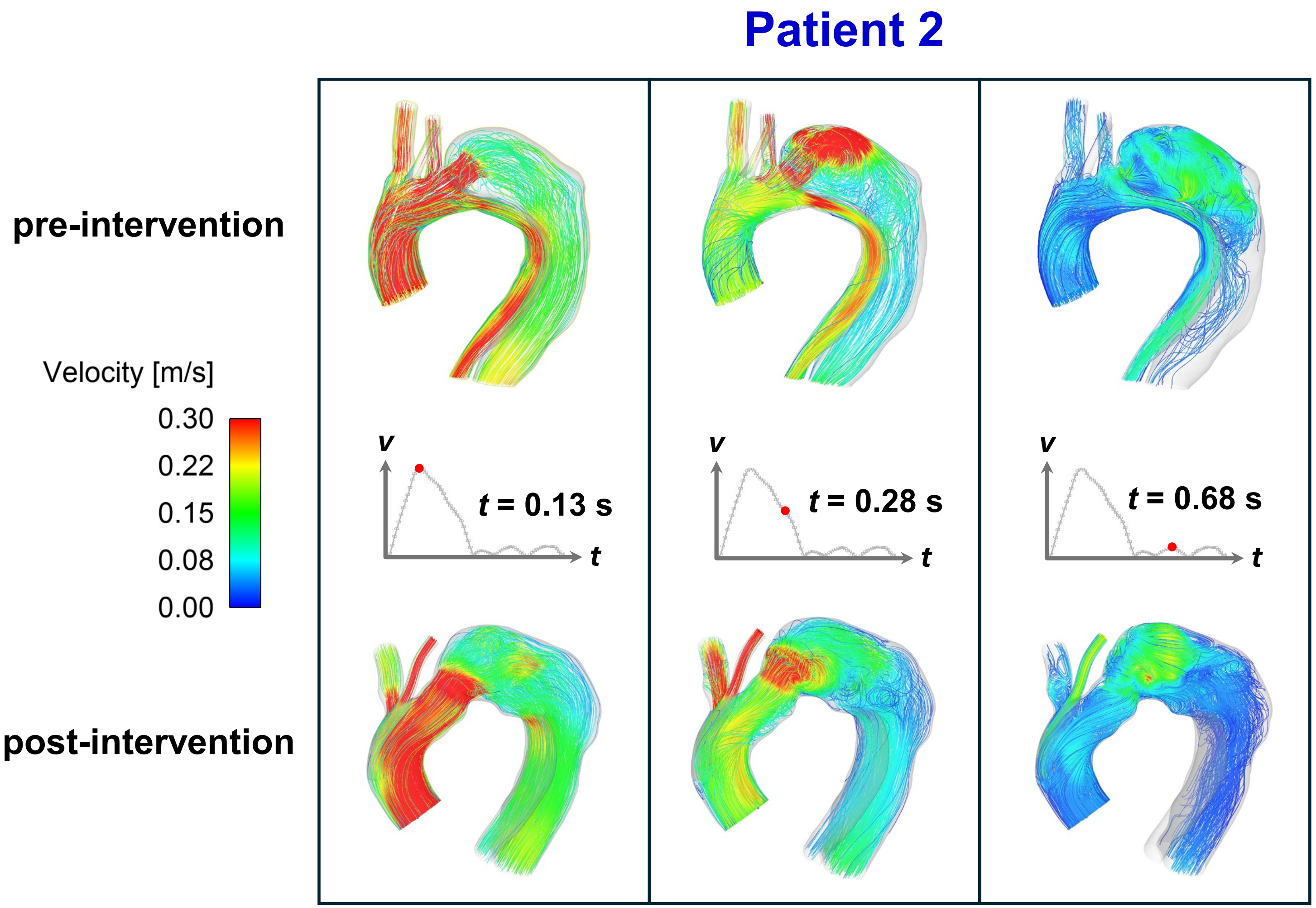
- High velocity around the tear (> 0.3 m/s)
- Blood impinged the wall as it enters FL, accompanied with strong recirculation

Pre-TEVAR

- Smooth and organized velocity streamlines in both AA and DA
- High velocity as blood enters the branch tunnels

Preliminary Results (2/5)

Streamline Plot



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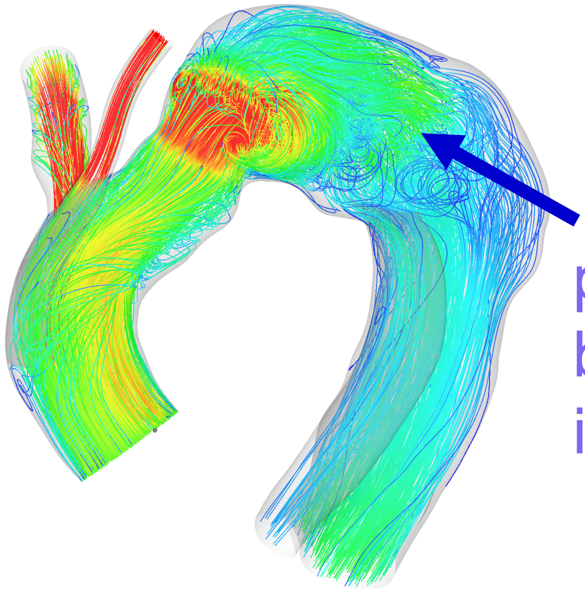
Pre-TEVAR

- Smooth and organized velocity streamlines in both AA and DA
- High velocity as blood enters the branch tunnels

Preliminary Results (2/5)

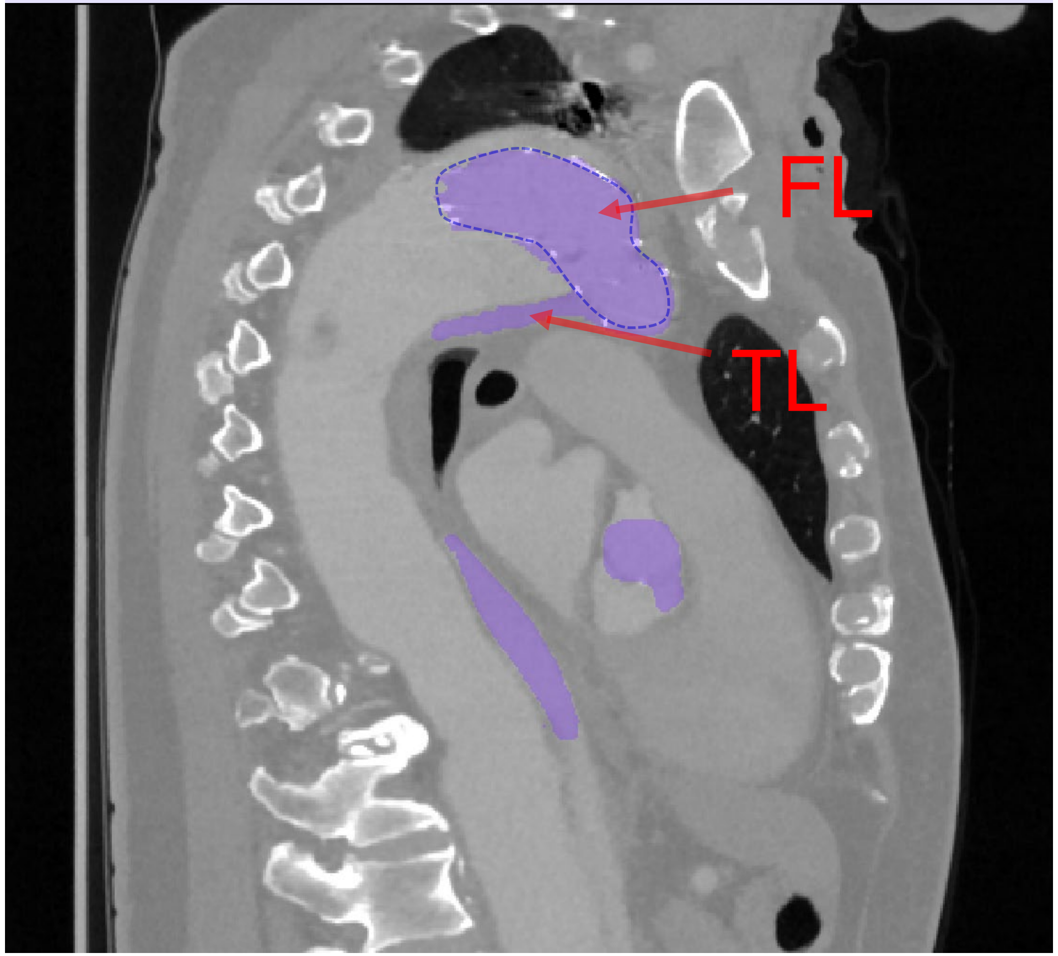
Streamline Plot, contd'

Patient 2, 1-month post TEVAR



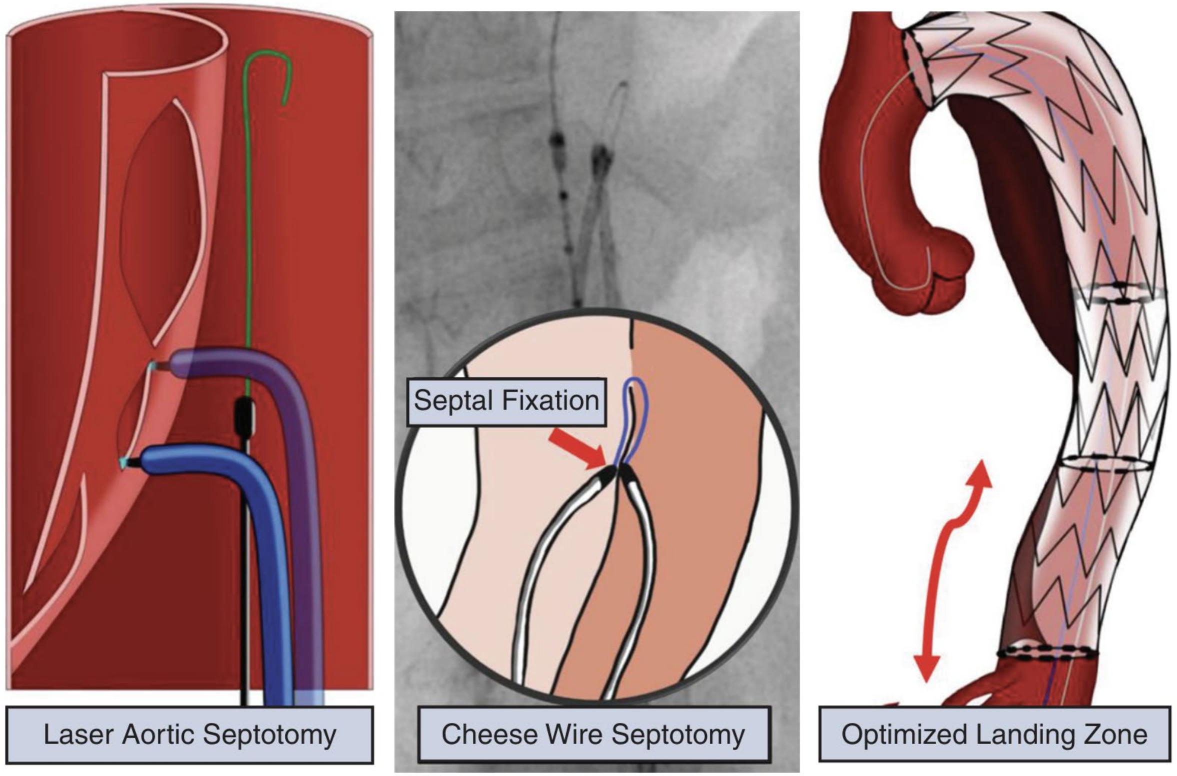
persistent blood perfusion in FL ?

CTA scan (sagittal)



Preliminary Results (2/5)

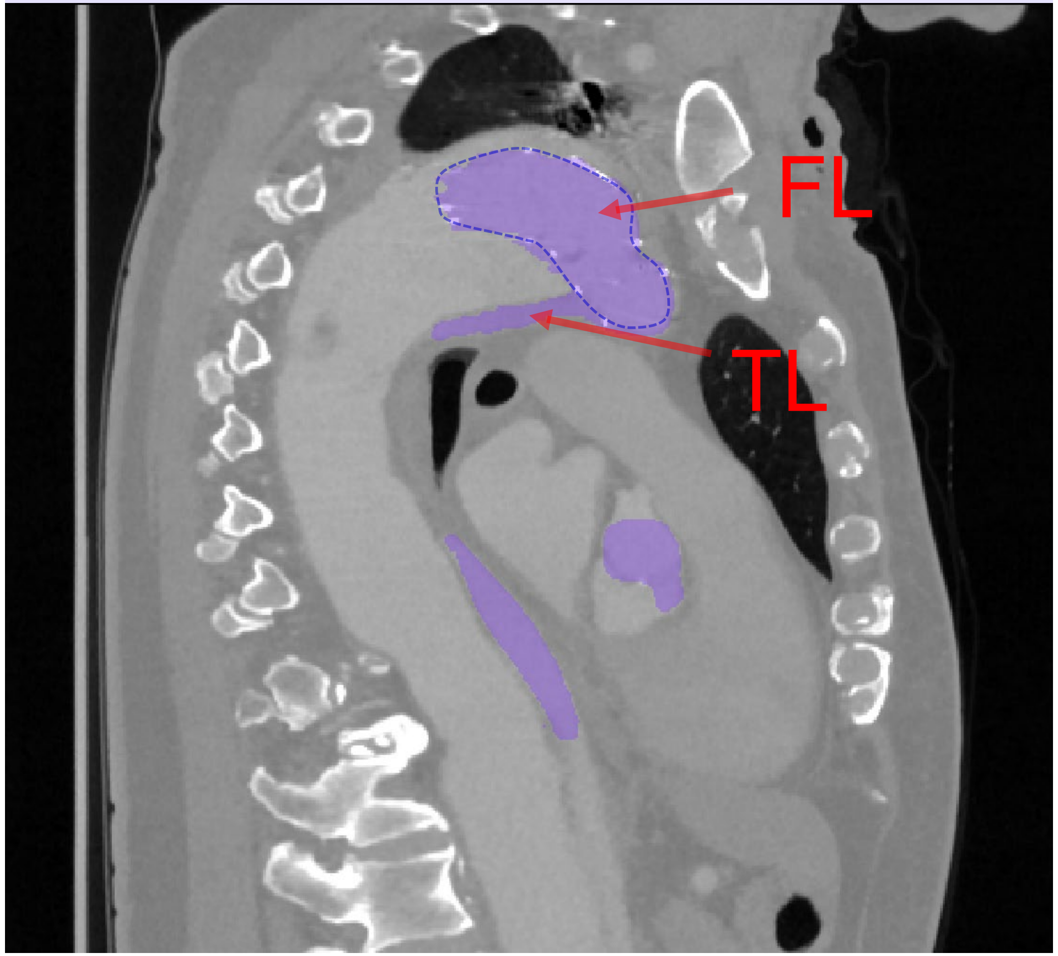
Streamline Plot, contd'



Fukuhara *et al.* (2023)

Planned for a **septostomy**: establish the flow communication between FL and TL through a hole

CTA scan (sagittal)

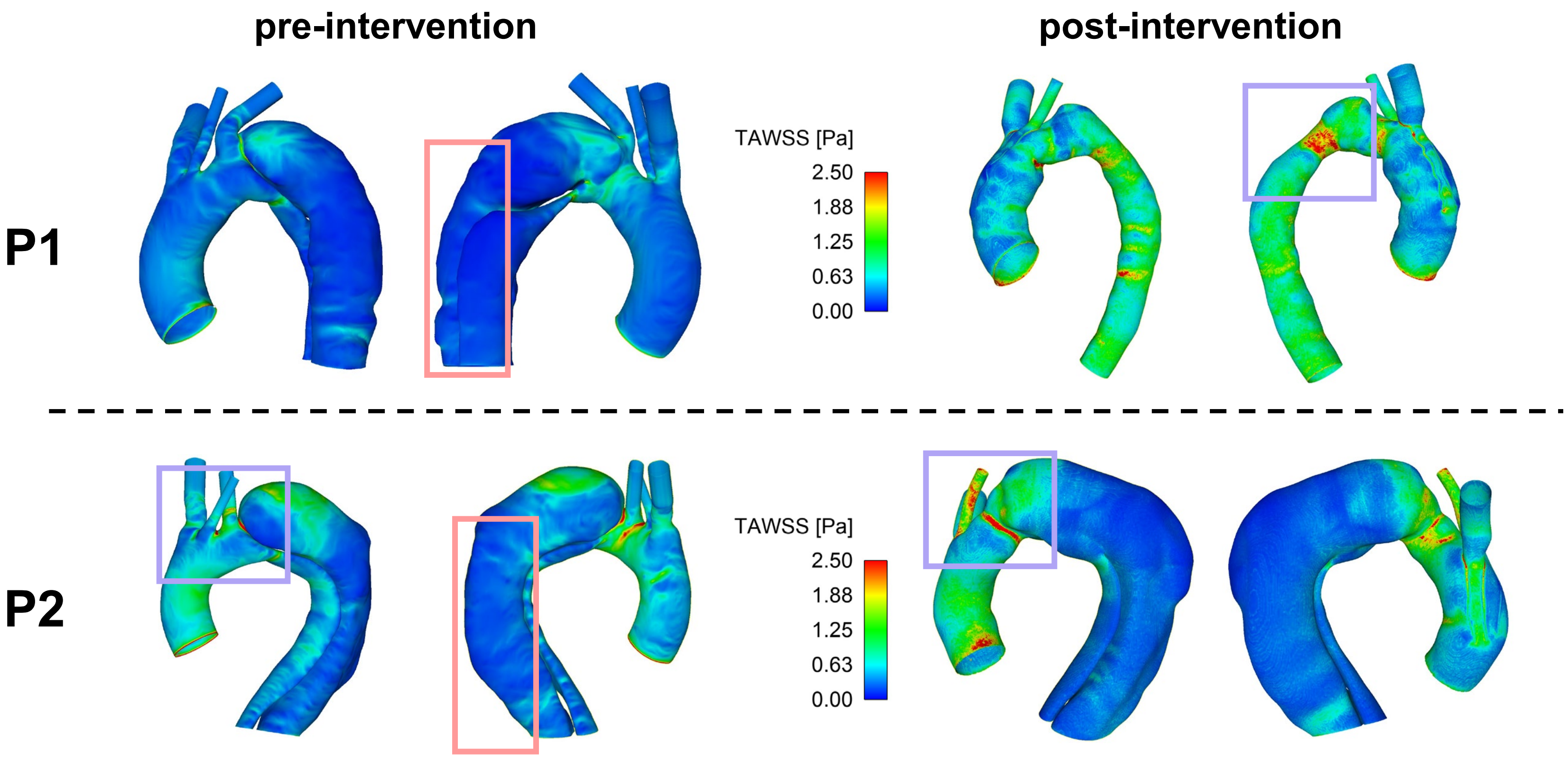


Preliminary Results (3/5)

Time-Averaged Wall Shear Stress (TAWSS)

$$\mathrm{TAWSS} = \frac{1}{T}\int_0^T |\tau_w| \cdot \mathrm{d}t$$

"the average stress (τ_w) on the aortic wall over an entire cardiac cycle *T*."



< 0.4 Pa	thrombus formation
> 2.5 Pa	aortic remodelling

Zhu *et al.* (2020)

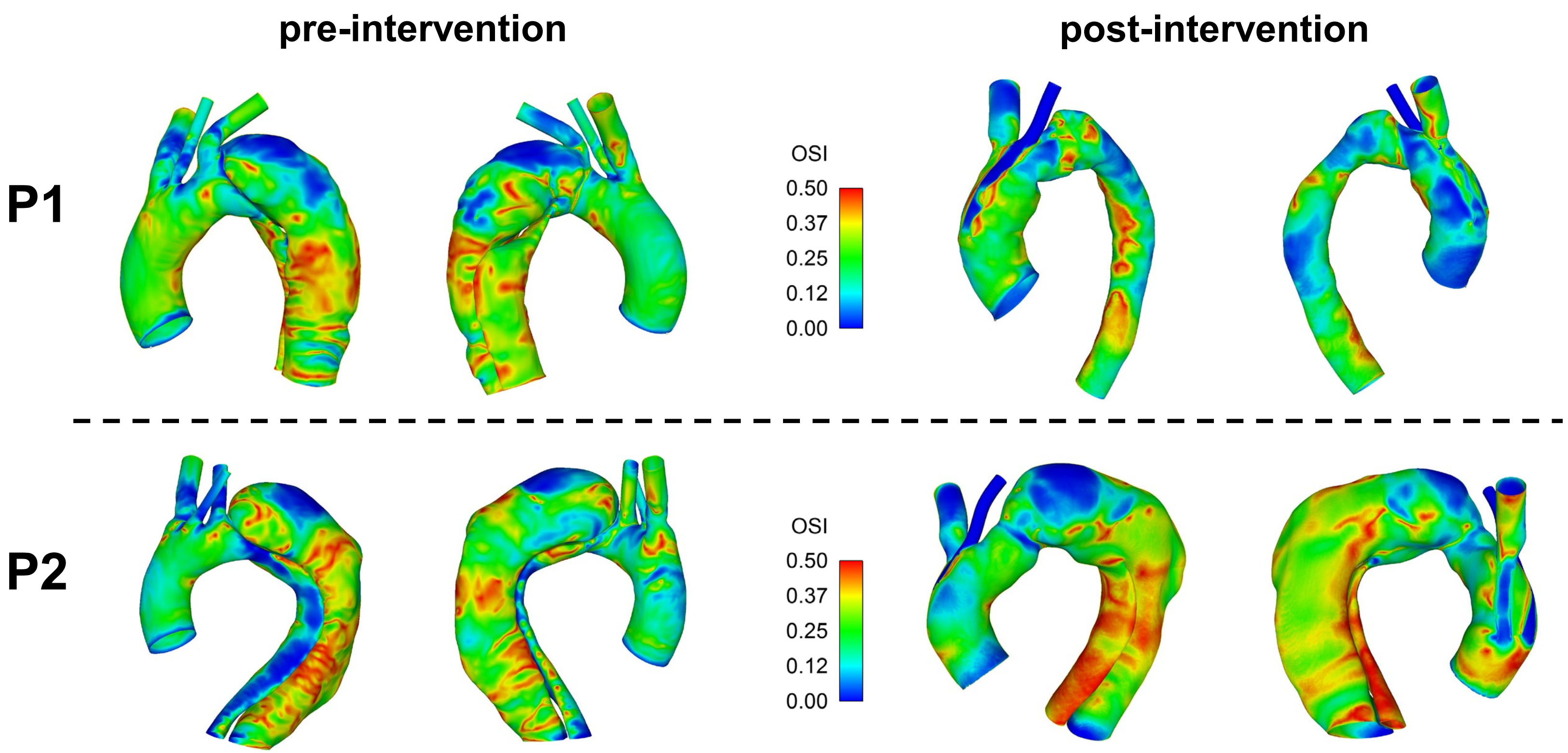
- Regions where a high TAWSS occurs are generally in agreement to the regions with a high velocity

Preliminary Results (4/5)

Oscillatory Shear Index (OSI)

$$\mathrm{OSI} = \frac{1}{2}\left(1 - \frac{\left|\int_0^T \tau_w \cdot \mathrm{d}t\right|}{\int_0^T |\tau_w| \cdot \mathrm{d}t}\right)$$

"unsteady effects of WSS by its changes in direction and magnitude."



- OSI ∈ [0, 0.5] (∝ 1/TAWSS)
  - OSI ~ 0: unidirectional flow
  - OSI ~ 0.5: highly disturbed, oscillatory flow
- Lower OSI in DA of P1, indicating a TEVAR improved the haemodynamic environment
- excessive-high OSI on TL of P2, attributed to the recent deployment of the SG

Preliminary Results (5/5)

Displacement Forces (F_d)

$$F_{d,i} = \int_S p \cdot n_i \, \mathrm{d}S + \int_S \left(-\mu \frac{\partial u}{\partial n_i}\right) \mathrm{d}S$$

$$|F_d| = \sqrt{F_{d,x}^2 + F_{d,y}^2 + F_{d,z}^2} \quad i \in \{x, y, z\}$$

"sum of the pressure force and WSS force over the stent-graft surface *S*."

	$\lvert F_d \rvert_{max}$ [N]	$\lvert F_d \rvert_{average}$ [N]	S [cm^2]
Patient 1	12.7	10.6	388.6
Patient 2	33.1	27.9	710.2

> 32 N ?

Rahmani *et al.* (2014)

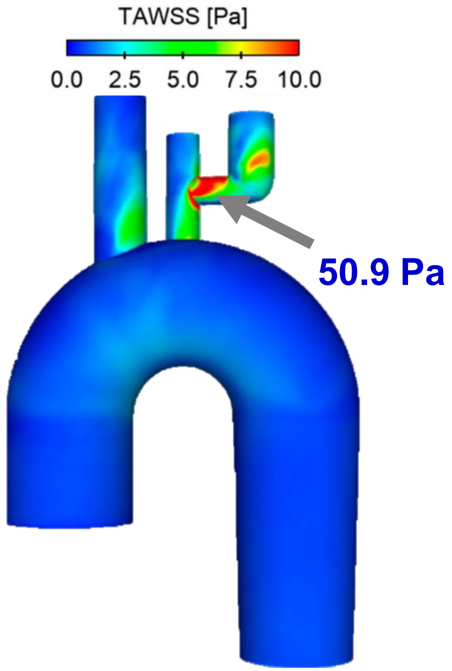
- A high displacement force may lead to the undesired device migration.
- The maximum displacement force of P2 is greater than the critical threshold 32 N
- However, P2 has ~double surface area to P1 → large surface integral
- Continuous follow-up is suggested, due to P2 may be in an ongoing aortic remodelling 1-month post-surgery.

Conclusion

- CFD reveals hidden in-vivo haemodynamics and quantifies biomechanical changes in AA and AD, as well as palliative strategies like TEVAR.
- Post-surgery, increased TAWSS and reduced OSI suggest a more stable blood flow environment and a lower risk of aneurysm rupture.
- Individual patient anatomy must be considered in stent graft stability assessments, as displacement forces vary due to anatomical differences.

Limitations

- Due to limited accessibility to patient-specific 4D flow profiles, a flat inlet velocity profile was adopted, compromising physiological fidelity.
- Image quality limitations prevented reconstruction of the LCCA-LSCA bypass, which is crucial due to the likelihood of graft material fatigue.
- The aortic wall was assumed rigid, only fluid domain is considered in the current study; The structural behaviours of the aorta and TEVAR was neglected.



Sengupta *et al.* (2022)

Future Research Plan (1/2)

Short-term outlook

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Future Research Plan (2/2)
Long-term outlook

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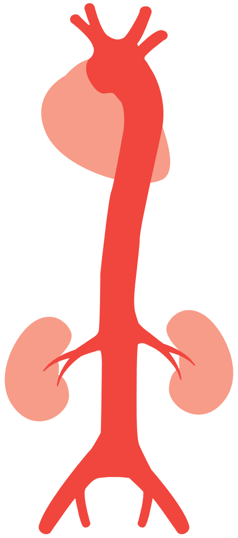

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