ERCOFTAC Autumn Festival

10th October 2024

MODELLING TURBULENCE IN CARDIOVASCULAR DISEASE

EMILY MANCHESTER

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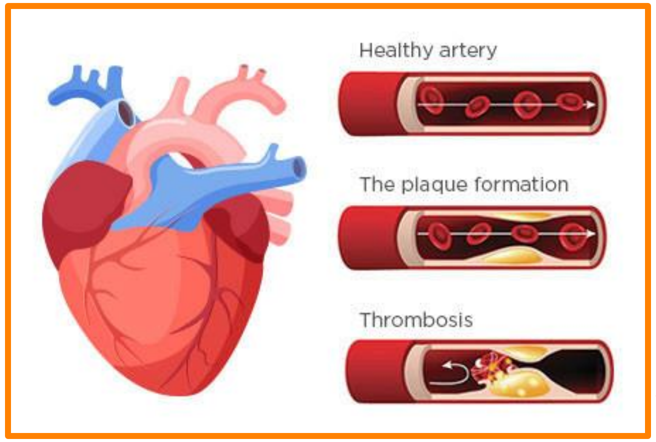
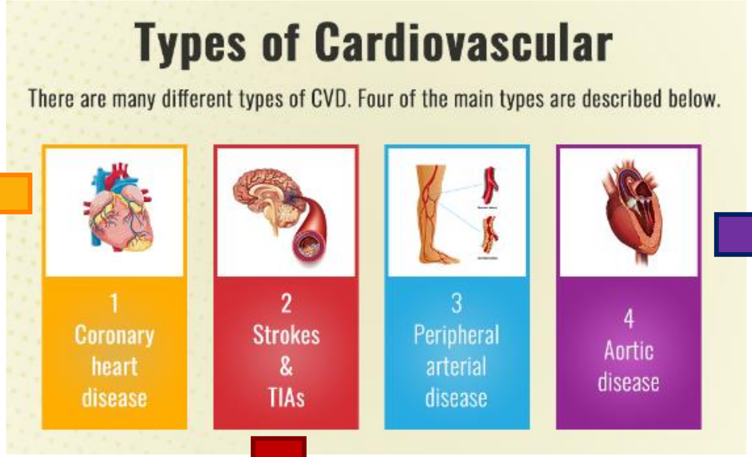
CARDIOVASCULAR DISEASE





Types of Cardiovascular

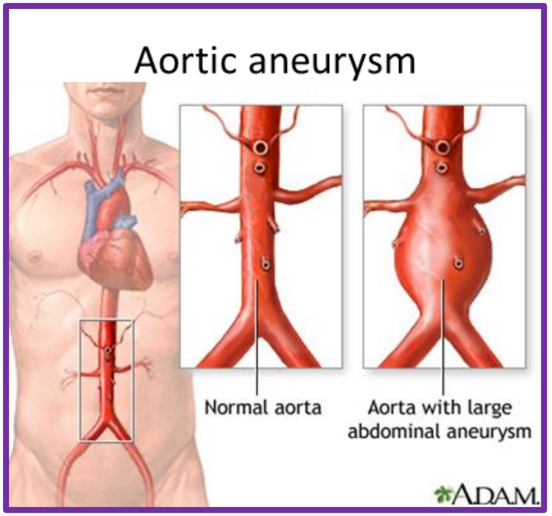
There are many different types of CVD. Four of the main types are described below.

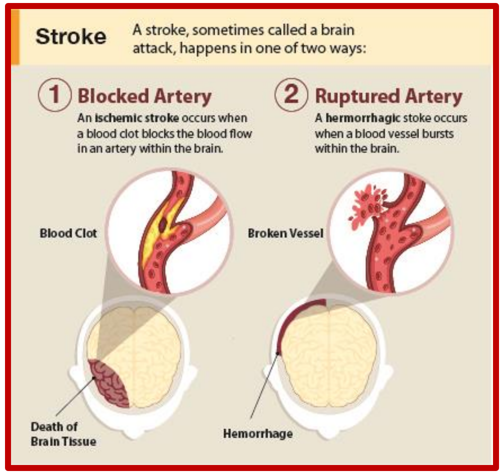
1 Coronary heart disease

2 Strokes & TIAs

3 Peripheral arterial disease

4 Aortic disease





Stroke A stroke, sometimes called a brain attack, happens in one of two ways:

① **Blocked Artery** An **ischemic stroke** occurs when a blood clot blocks the blood flow in an artery within the brain.

② **Ruptured Artery** A **hemorrhagic** stoke occurs when a blood vessel bursts within the brain.

Figures: (1) https://blogs.allizhealth.com/cardiovascular-disease/, (2) https://www.heartpatientalliance.ca/general-information/types-of-cardiovascular-disease/, (3) https://www.cdc.gov/stroke/about, (4) https://medlineplus.gov/ency/article/000162.htm

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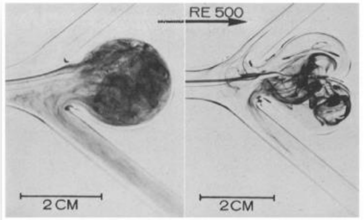
CLINICAL EFFECTS OF TURBULENCE

- ○ Blood flow can transition to turbulence and relaminarize within a single cardiac cycle
- ○ Due to computational complexity, blood flow is often assumed laminar, neglecting turbulence effects
- ○ Turbulence-related haemodynamics are correlated with disease progression – but not fully understood



Immediate Effect

<u>Mechanical Loads</u>
Abnormally high and fluctuating shear stresses acting on the fluid and arterial wall

<u>Energy Loss</u>
Heart must work harder to overcome additional energy losses

Long-Term Effect

- Haemolysis (red blood cell rupture)
- Progressive arterial wall disease – e.g., atherosclerosis, dilation, rupture

Left ventricular hypertrophy – reduced pumping efficiency

Figure: Ferguson G.G. et al. (1970). Turbulence in human intracranial saccular aneurysms. *J Neurosurg.*

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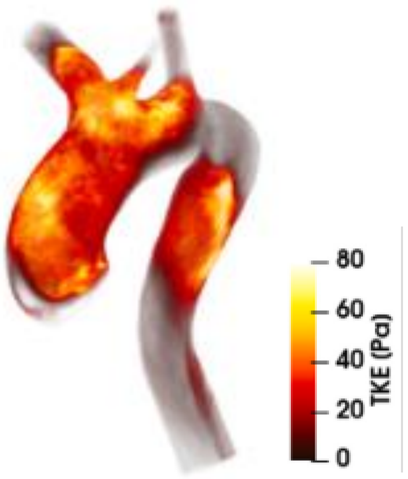
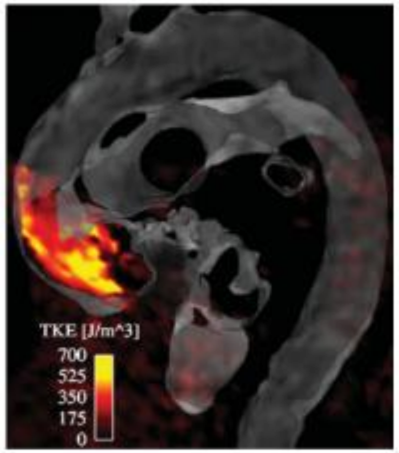
METHODS TO EVALUATE TURBULENCE

CFD
e.g., RANS, LES, DNS



In vivo experiment
e.g., *MRI or CT scan of patient*



In vitro experiment
e.g., *flow phantom*

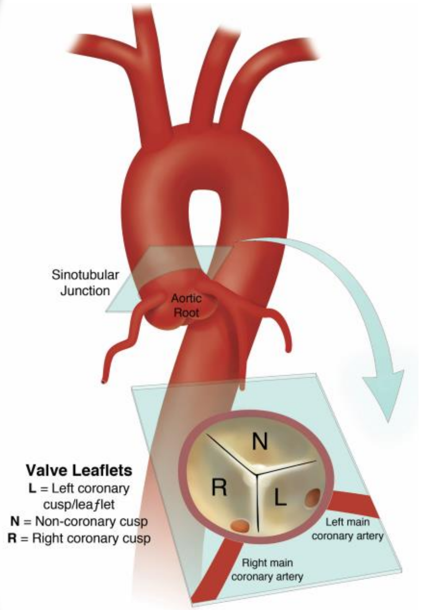
Figures (Left-to-right): (1) Manchester, E.L., et al. (2024). *Computers in Biology and Medicine*. (2) Dyverfeldt, P. et al. (2008). *Journal of Magnetic Resonance Imaging*. (3) Puiseux, T. et al. (2019). *NMR in Biomedicine*

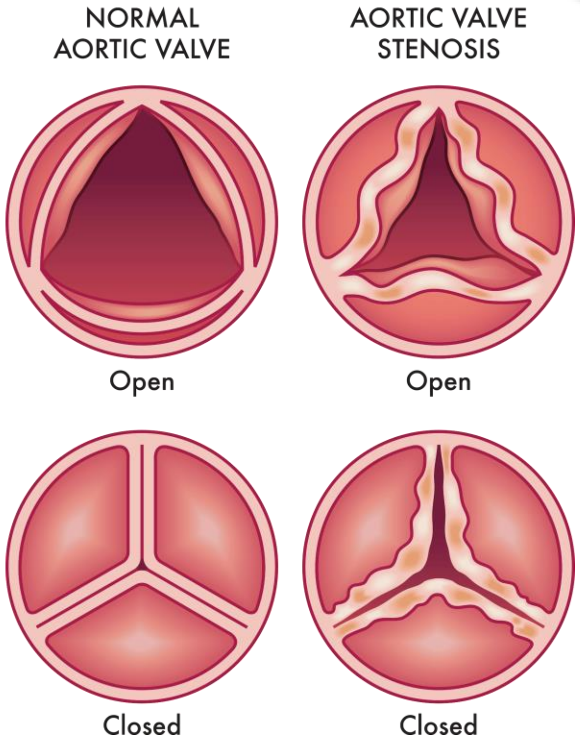
MODELLING TURBULENCE IN AORTIC VALVE DISEASE

PATIENT-SPECIFIC SIMULATIONS

AORTIC VALVE DISEASE

Anatomy and Disease



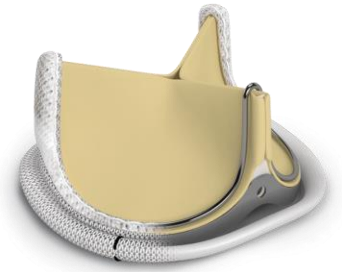


Surgical Valve Treatments

Well established

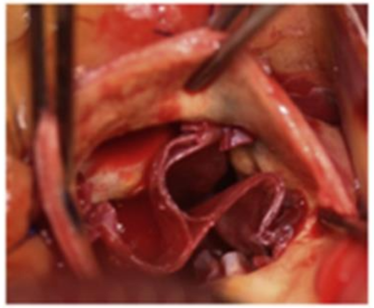
Mechanical

Biological (BV)



New

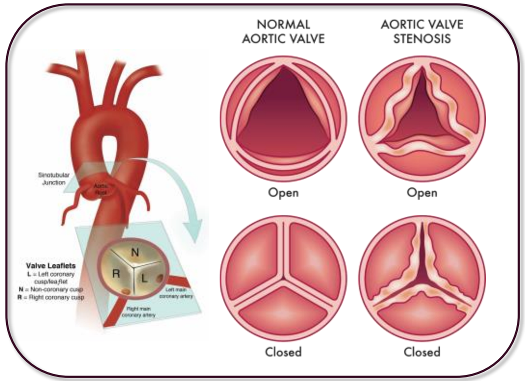
Aortic valve neocuspidisation (AV-Neo)



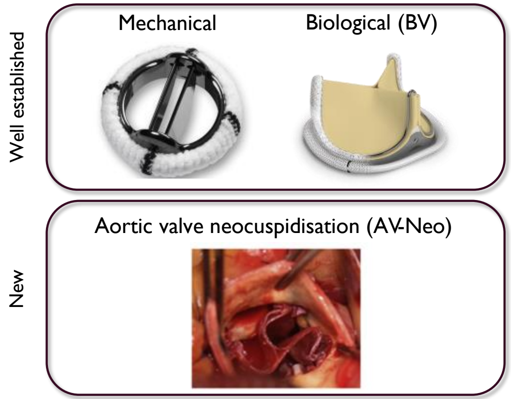
Figures adapted from 1. https://ufhealth.org/uf-health-aortic-disease-center/aorta-anatomy

AORTIC VALVE DISEASE

Anatomy and Disease



Surgical Valve Treatments



Mechanical

Biological (BV)

Aortic valve neocuspidisation (AV-Neo)

Motivation

- Few studies which consider turbulence effects in aortic valve replacements and none in patient-specific settings.
- Haemodynamics in AV-Neo have not yet been evaluated, let alone compared with other valve types.

Objective

- Perform large-eddy simulations of real patient aortas having undergone valve surgery with bioprosthetic valve types and AV-Neo repair to evaluate valve-performance related haemodynamics.

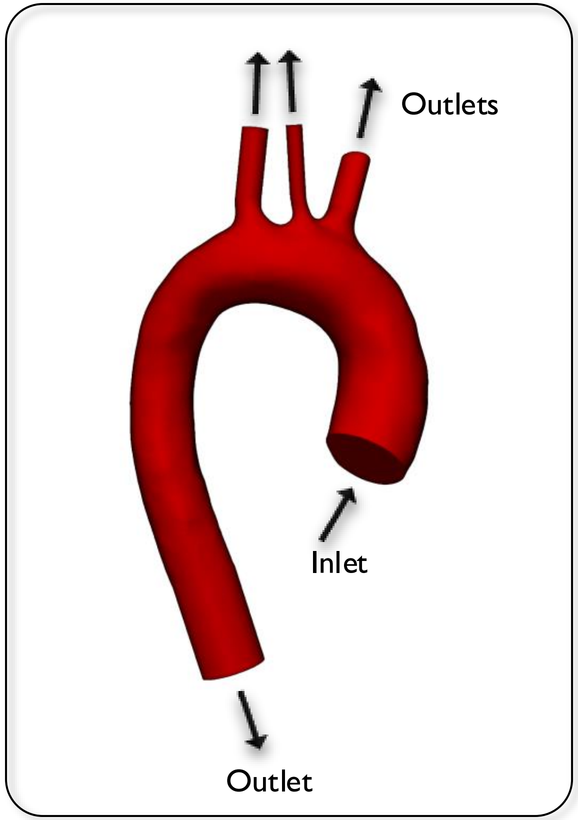
GEOMETRY RECONSTRUCTION

MAGNETIC RESONANCE IMAGING (MRI)

Raw MR Images

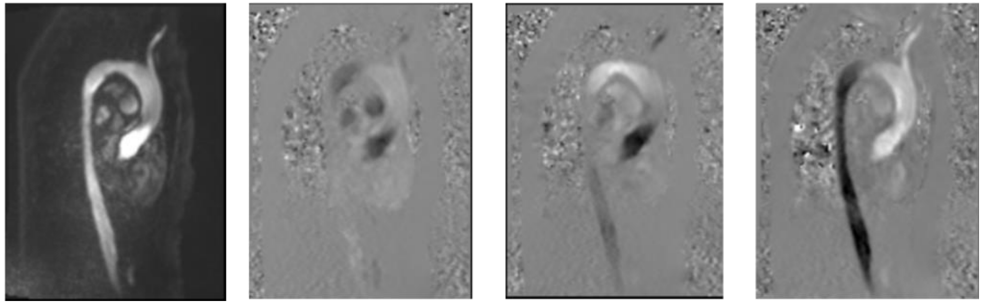
Segmentation

CFD Geometric Model



4D FLOW MRI

MR Images



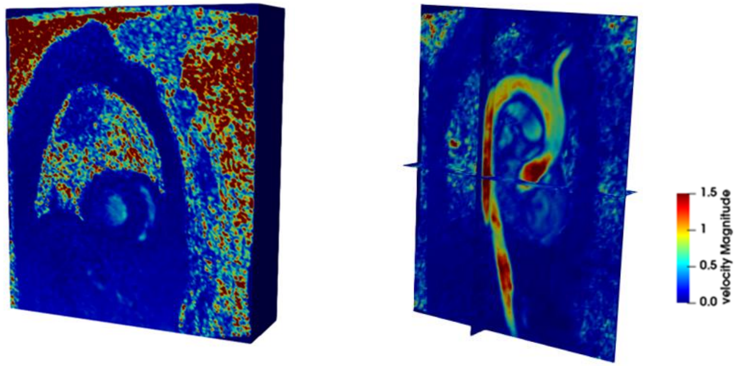
Magnitude

Phase: right-left

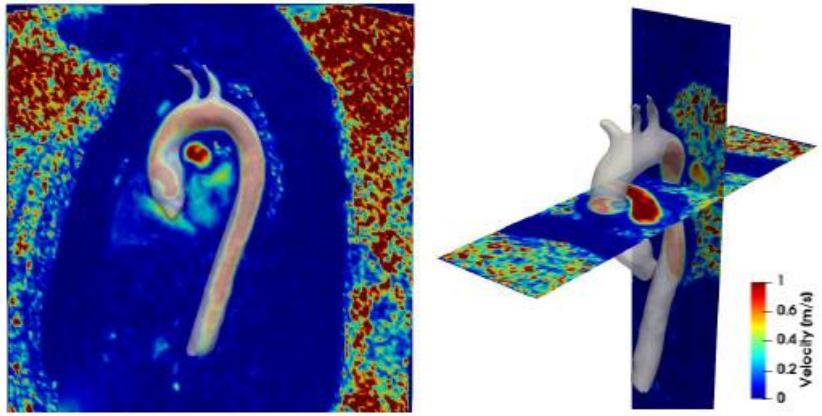
Phase: anterior-posterior

Phase: foot-head

Velocity field reconstruction

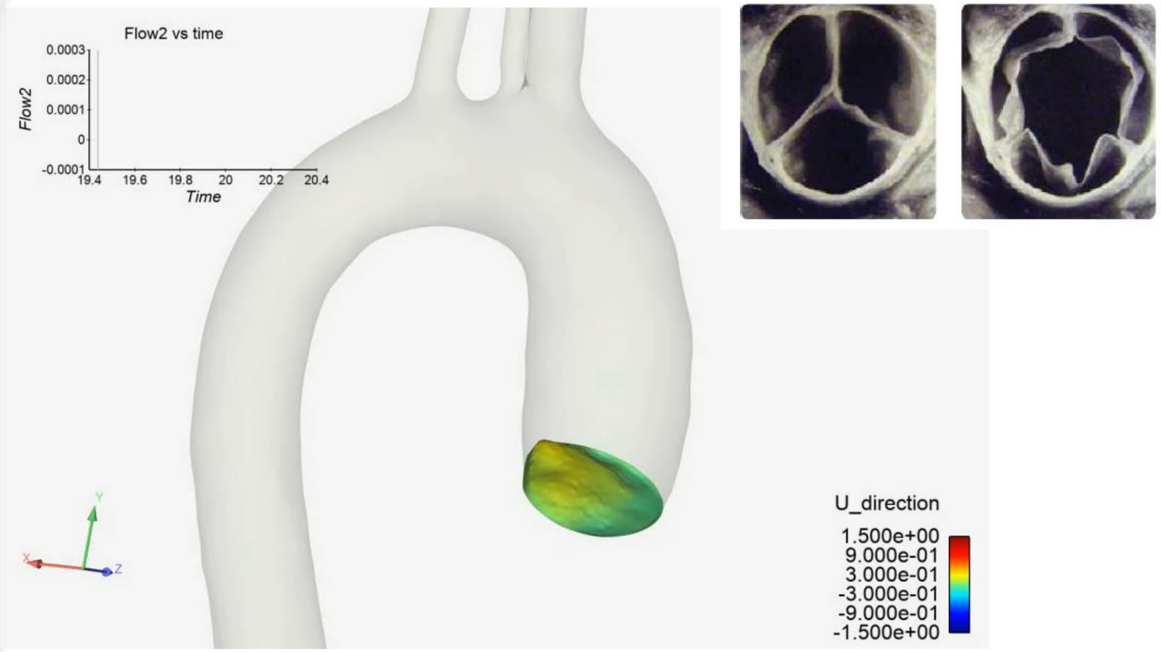


Registration



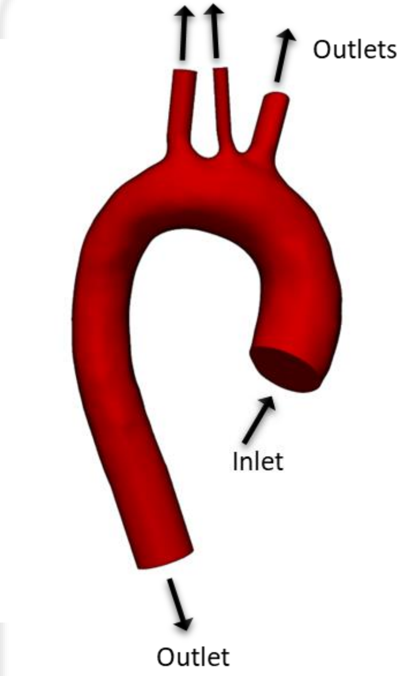
BOUNDARY CONDITIONS

Inlet



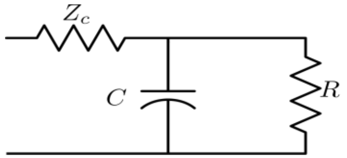
Pulsatile, velocity contours extracted from 4D flow MRI

Outlets



3-element Windkessel model:

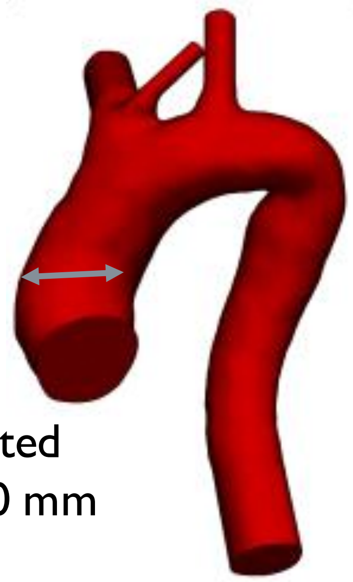
Based on blood pressure, inlet flowrate and flow split to branches



STUDY COHORT

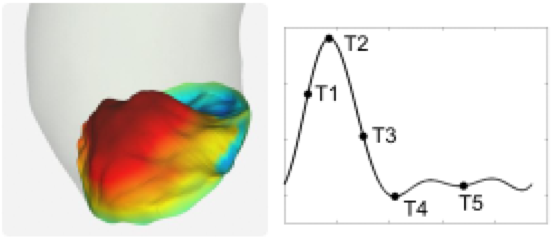
BIOPROSTHETIC VALVES (BV) & AORTIC VALVE NEOCUSPIDIZATION (AV-NEO)

BV-1

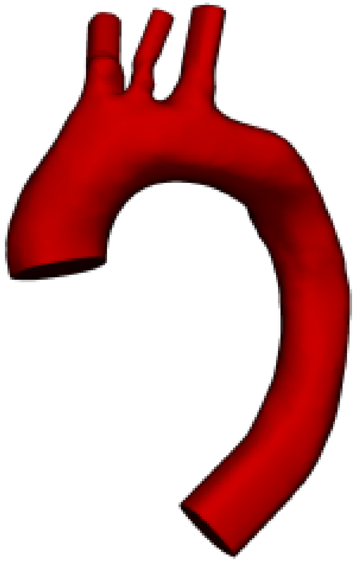


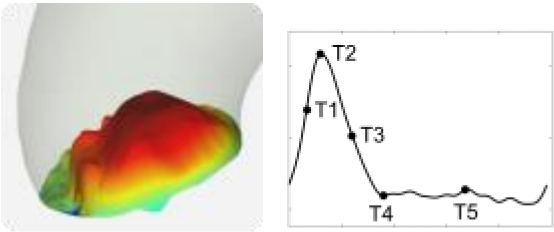
Dilated
> 40 mm

Inlet velocity contours

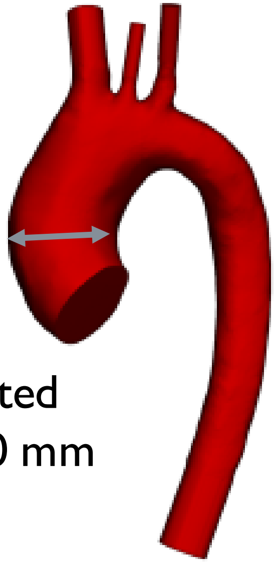


BV-2

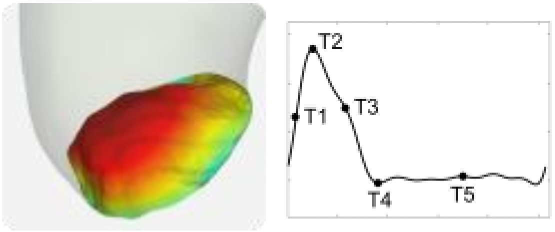




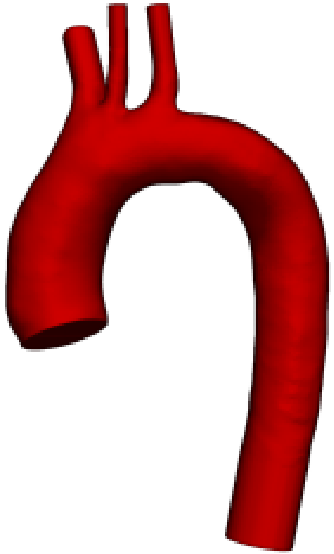
AV-Neo-1

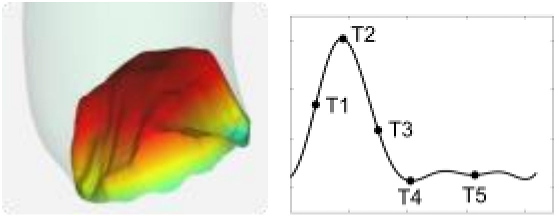


Dilated
> 40 mm



AV-Neo-2





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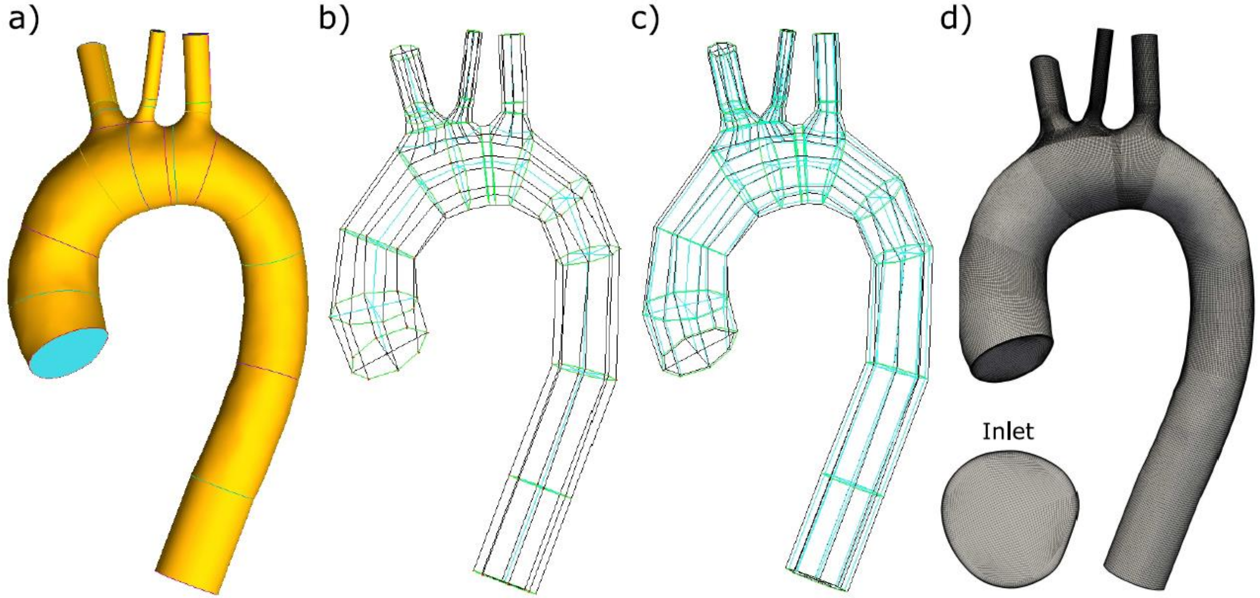
NUMERICAL DETAILS

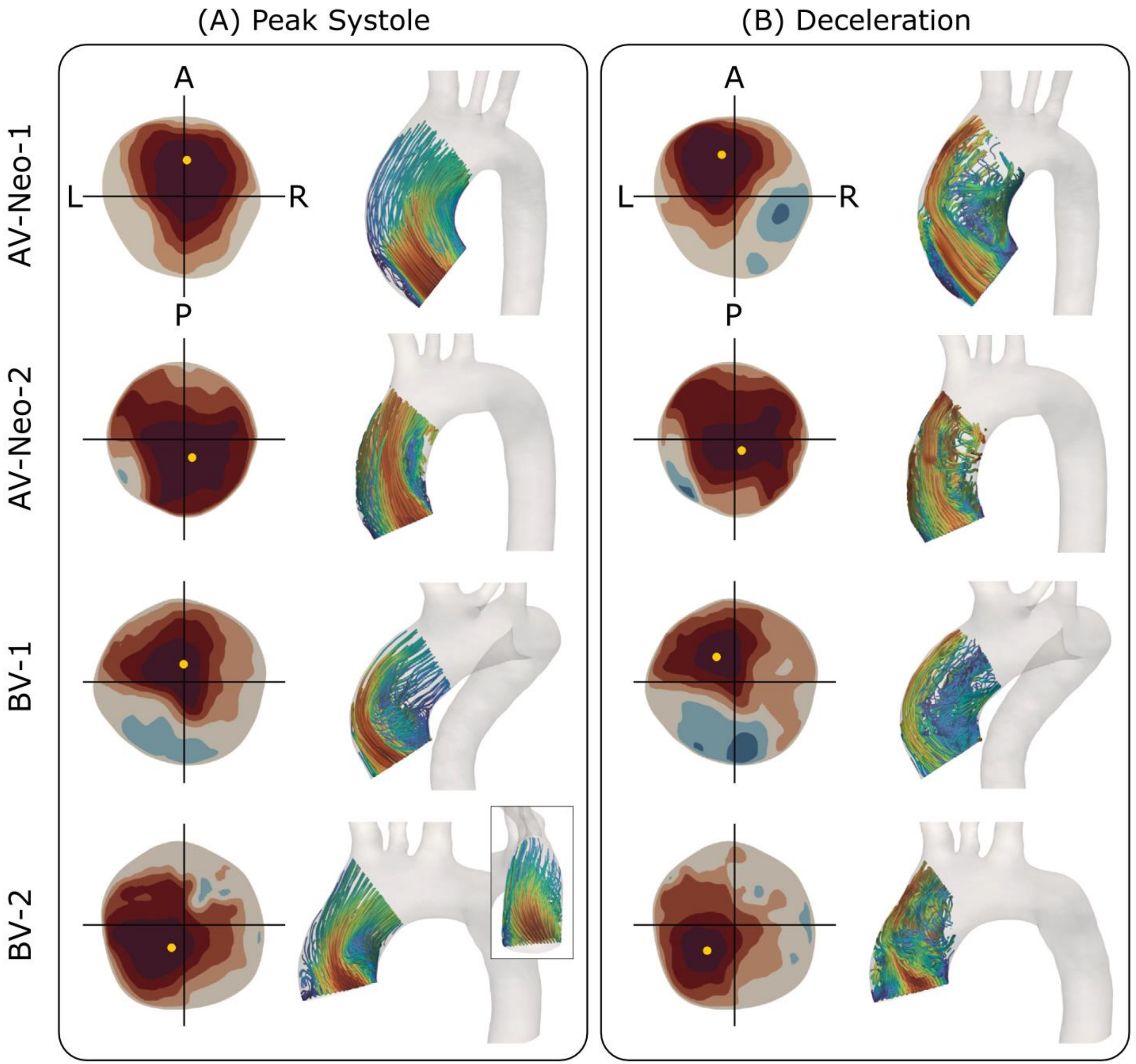
- Large-eddy simulation with WALE subgrid-scale model ($C_W = 0.325$) in OpenFOAM
- Structured meshes: 4.5 – 7.0 million cells



- Time-step: 0.2 ms
- Blood flow incompressible and Newtonian
  ρ=1060 kg/m^3 and μ=0.0035 $Pa\ s$
- Simulations performed on Cirrus: 216 – 252 cores, 7 – 14 days sim time

VELOCITY STREAMLINES

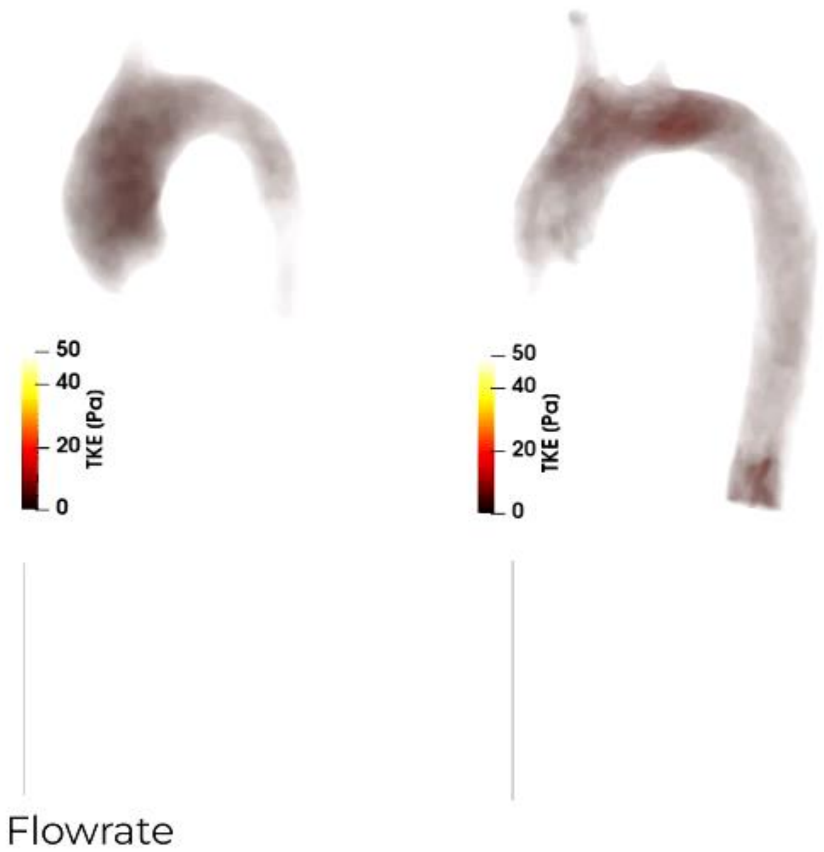
- Valvular flow entering the aorta should be central and streamlines should align with curvature of the ascending aorta.
- Valvular flow is skewed in both biological valves.



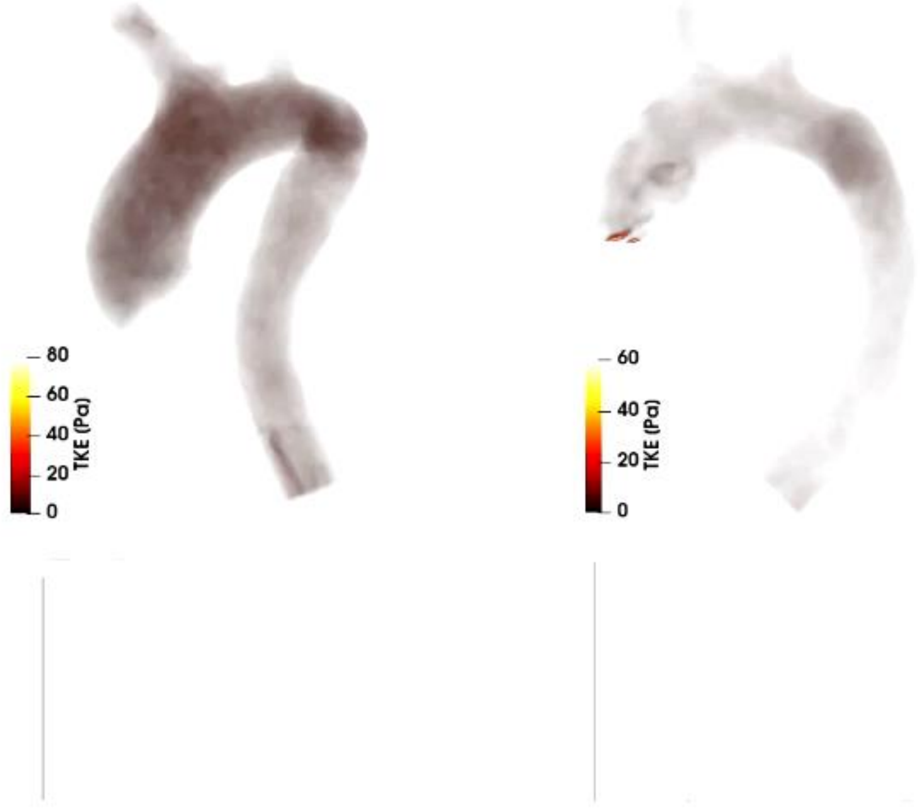
Manchester, E.L., et al. (2024). *Computers in Biology and Medicine.*

TURBULENCE KINETIC ENERGY

AV-Neo



Biological Valves



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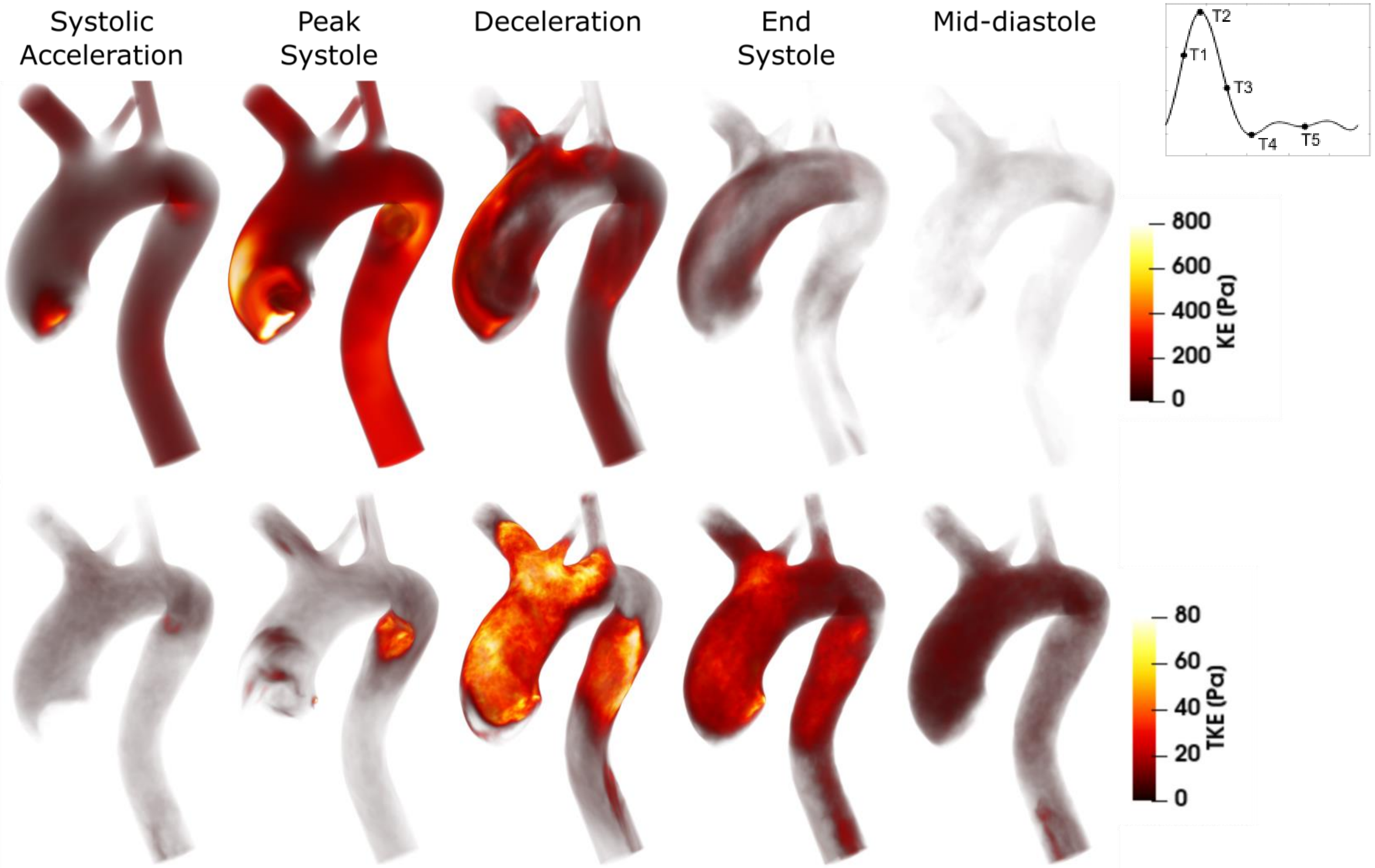
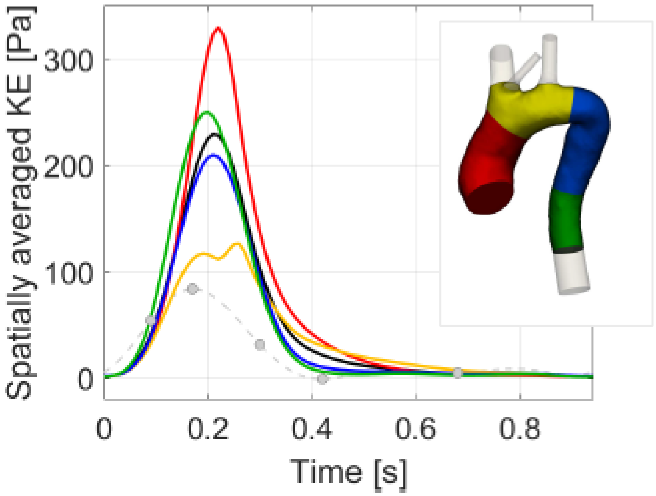
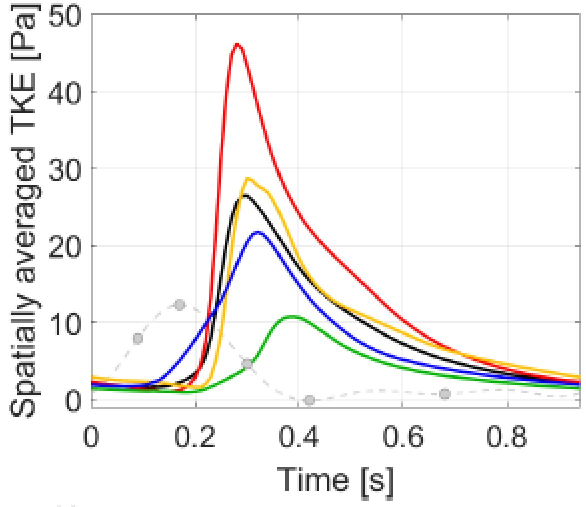
KINETIC ENERGIES OVER A CYCLE

BV-1


Systolic Acceleration
Peak Systole
Deceleration
End Systole
Mid-diastole





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SUMMARY

- Turbulence production depends on valvular skew, eccentricity, dilation and arch-descending aorta connection.
- Turbulence most sensitive to valve placement rather than valve type.
- Aortic valve treatments should prioritise minimising valvular eccentricity and skew in order to mitigate turbulence generation.
- Small sample size – larger scale study needed for statistically meaningful results.
- Methods for modelling/measuring turbulence in cardiovascular flows on a large scale are under-researched.

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Aortic valve neocuspidization and bioprosthetic valves: Evaluating turbulence haemodynamics

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Computational fluid dynamics
Haemodynamics
Ozaki procedure
Blood flow
Wall shear stress

ABSTRACT

Aortic valve disease is often treated with bioprosthetic valves. An alternative treatment is aortic valve neocuspidization which is a relatively new reparative procedure whereby the three aortic cusps are replaced with patient pericardium or bovine tissues. Recent research indicates that aortic blood flow is disturbed, and turbulence effects have yet to be evaluated in either bioprosthetic or aortic valve neocuspidization valve types in patient-specific settings. The aim of this study is to better understand turbulence production in the aorta and evaluate its effects on laminar and turbulent wall shear stress. Four patients with aortic valve disease were treated with either bioprosthetic valves (n=2) or aortic valve neocuspidization valvular repair (n=2). Aortic geometries were segmented from magnetic resonance images (MRI), and 4D flow MRI was used to derive physiological inlet and outlet boundary conditions. Pulsatile large-eddy simulations were performed to capture the full range of laminar, transitional and turbulence characteristics in the aorta. Turbulence was produced in all aortas with highest levels occurring during systolic deceleration. In the ascending aorta, turbulence production is attributed to a combination of valvular skew, valvular eccentricity, and ascending aortic dilation. In the proximal descending thoracic aorta, turbulence production is dependent on the type of arch-descending aorta connection (e.g., a narrowing or sharp bend) which induces flow separation. Laminar and turbulent wall shear stresses are of similar magnitude throughout late systolic deceleration and diastole, although turbulent wall shear stress magnitudes exceed laminar wall shear stresses between 27.3% and 61.1% of the cardiac cycle. This emphasises the significance of including turbulent wall shear stress to improve our comprehension of progressive arterial wall diseases. The findings of this study recommend that aortic valve treatments should prioritise minimising valvular eccentricity and skew in order to mitigate turbulence generation.

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