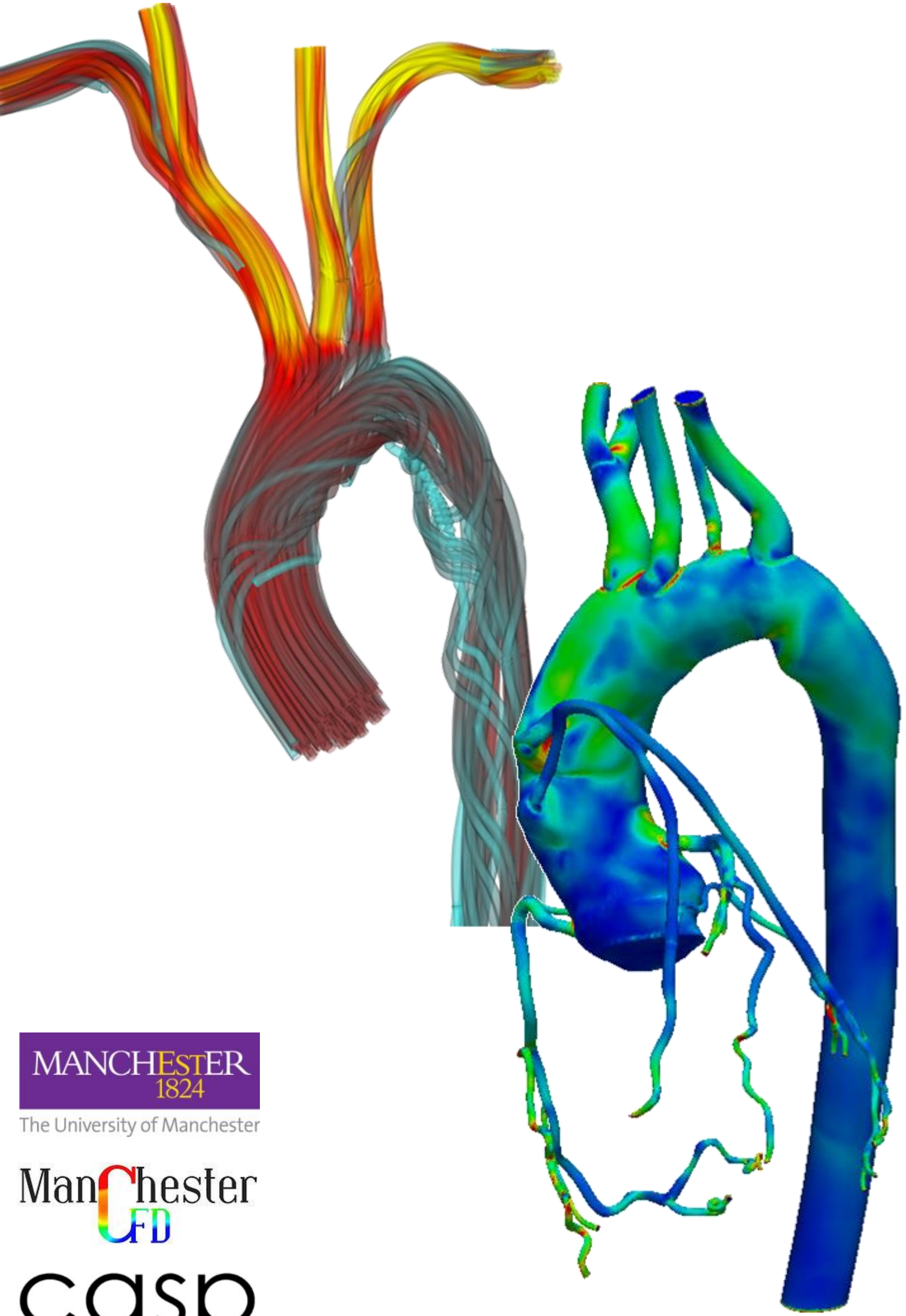

Investigating the effect of geometry on coronary artery bypass graft haemodynamics & longevity.

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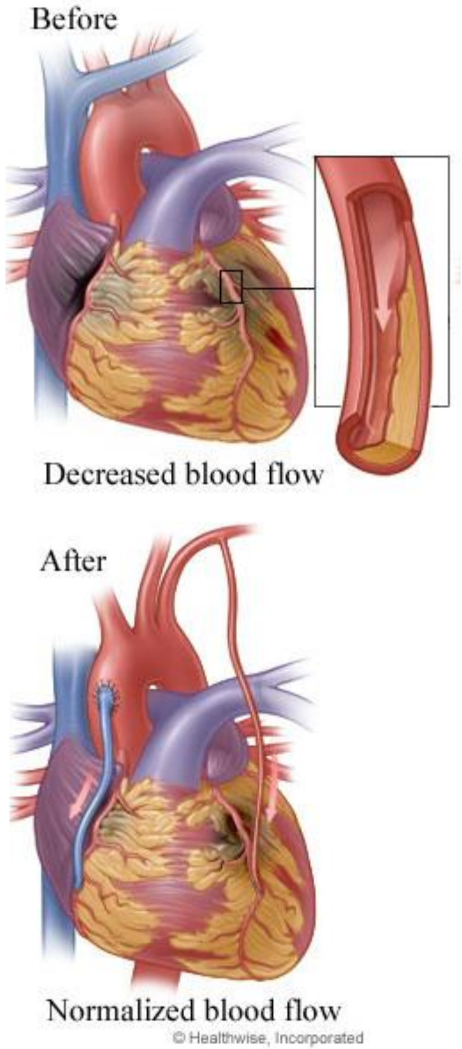
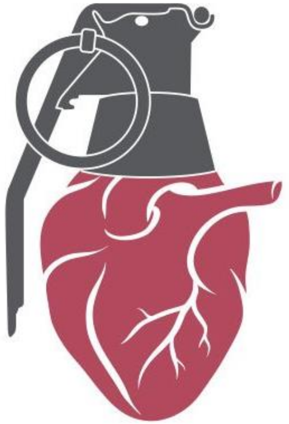
Background: What is CABG treatment?

- **Cardiovascular disease** (CVD) is the **leading cause of death** world-wide (accountable for approx. 32% of all deaths). (WHO)
  - **CVD prevalence is increasing** due to an aging population. [1]
- **Coronary artery disease** (CAD) is the **most common sub-set** of CVDs.
  - **CAD** is the leading cause of morbidity in the western world. [2]
- **Coronary artery bypass grafting** (CABG) is an effective choice of treatment for **severe and multi-vessel disease.** [3]
  - An additional vessel is attached upstream and downstream of the coronary blockage to provide a **new route for blood to flow.** [4]

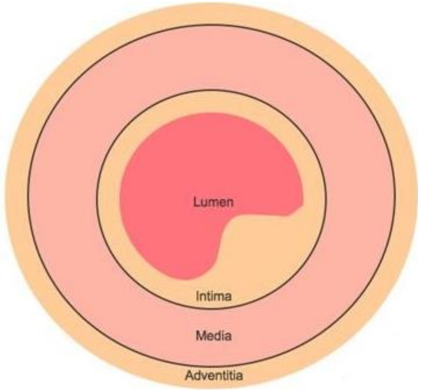


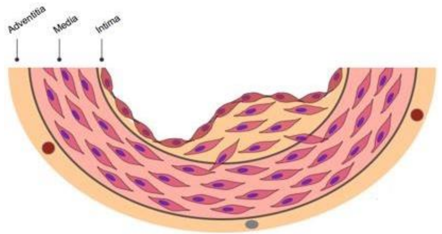
[1] Komutrattananont, P., Mahakkanukrauh, P. and Das, S. (2019) 'Morphology of the human aorta and age-related changes: Anatomical facts', Anatomy and Cell Biology, 52(2), pp. 109–114. doi: 10.5115/acb.2019.52.2.109
[2] Abu-Omar, Y. and Taggart, D. P. (2014) 'Coronary artery bypass surgery', Medicine (United Kingdom), 42(9), pp. 527–531. doi: 10.1016/j.mpmed.2014.06.008.
[3] Sankaran, S. et al. (2012) 'Patient-specific multiscale modeling of blood flow for coronary artery bypass graft surgery', Annals of Biomedical Engineering, 40(10), pp. 2228–2242. doi: 10.1007/s10439-012-0579-3.
[4] Jannati, M., Navaei, M. and Ronizi, L. (2019) 'A comparative review of the outcomes of using arterial versus venous conduits in coronary artery bypass graft (CABG)', Journal of Family Medicine and Primary Care, 8(9), p. 2768. doi: 10.4103/jfmpc.jfmpc_367_19.)

Background: Why research CABG?



- **Bypasses degenerate** through the same mechanisms as native vessels.
  - Atherosclerosis & intimal hyperplasia + increased thrombi risk. [1]
- **Bypass degeneration** has been linked to the **conduit type**: [2, 3]
  - Arterial – **Internal mammary artery** (IMA) – 90% 10 year patency.
    Radial artery (RA) – 70% 10 year patency.
  - Venous – **Saphenous vein** (SVG) **–** 50% 10 year patency.
  - Artificial/Synthetic – Under active development.
- **SVGs** are the **most commonly used** vessel. [2 , 3]
  - A large portion of bypasses are at elevated risk levels.





[1] Ghista, D. N. and Kabinejadian, F. (2013) 'Coronary artery bypass grafting hemodynamics and anastomosis design: A biomedical engineering review', BioMedical Engineering Online, 12(1). doi: 10.1186/1475-925X-12-129
[2] Abu-Omar, Y. and Taggart, D. P. (2014) 'Coronary artery bypass surgery', Medicine (United Kingdom), 42(9), pp. 527–531. doi: 10.1016/j.mpmed.2014.06.008.
[3] Tatoulis, J. et al. (2015) 'Total Arterial Revascularization: Achievable and Prognostically Effective — A Multicenter Analysis', The Annals of Thoracic Surgery, 100(4), pp. 1268–1275. doi: 10.1016/j.athoracsur.2015.03.107.

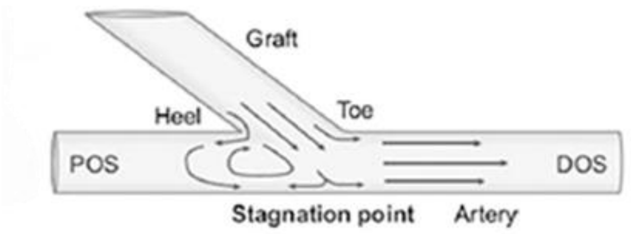
Background: Bypass failure implications.

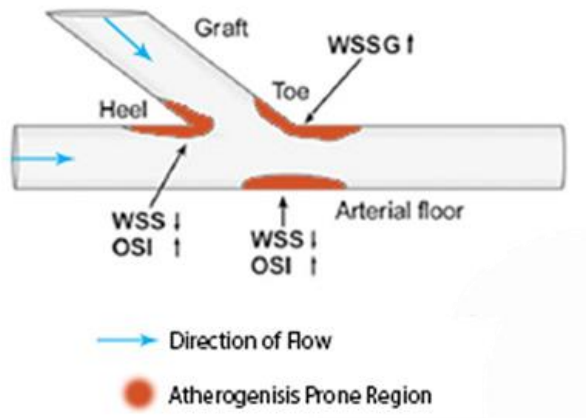
- Graft complications lead to:
  - **Decreased quality of life** (symptomatic).
  - Need for **further medical intervention.**
  - **Increased cost of care** (primary/secondary).
- **14,000** CABG surgeries performed each year in the UK;
  Each costing an average of **£8,470**. (British Heart Foundation, Department of Health, Statista)
- Up-to **17%** of cases **require re-do** surgery **within 12 years**. [1]
  - Improvements to CABG safety, therefore reductions in re-do rate, can achieve >**£20 million** annual healthcare savings in the UK alone.
  - Worldwide, the estimated savings exceed **£1 billion** (Grand View Research)**.**

[1] Machiraju, V.R., 2012. Practical Approaches to the Current "On-Pump" Redo Coronary Artery Bypass Surgery. In *Redo Cardiac Surgery in Adults* (pp. 7-19). Springer, New York, NY.

Background: Bypass failure identification.

- Clinical observations have identified several factors with an increased risk of disease propagation: [1, 2]
  - **Biomechanical forces**.
  - **Haemodynamic indices** (flow characteristics).
- **Safe values** for these metrics are approximated in the literature.
- **Computational fluid dynamics** (CFD) allows us to non-invasively measure the haemodynamics within a bypass.
- We can then **compare** the CFD results to the **safe-limits** to identify the risk of early-failure.





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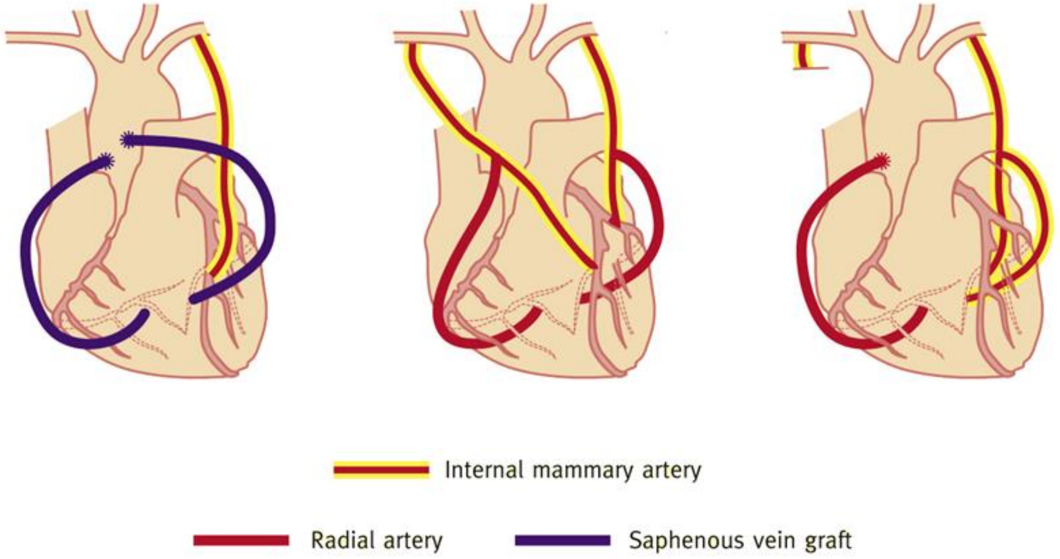
Objective: Linking CABG shape with failure.

- The **primary objective** of this work is to **provide surgical guidance** where there currently is none.
  - **Surgeons rely on training & intuition** to decide the length and lie of a bypass graft.
  - This results in **inconsistent treatment** between surgeons and institutions.

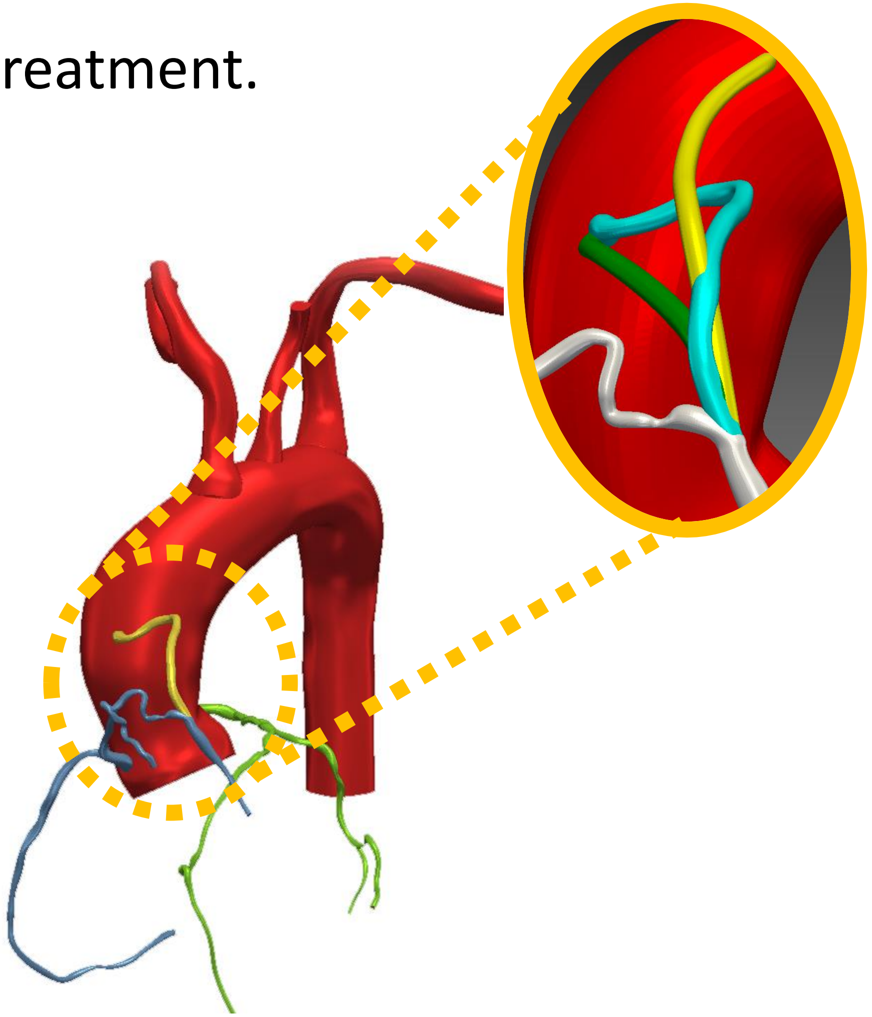


[1]

[1] Abu-Omar, Y. and Taggart, D. P. (2014) ‘Coronary artery bypass surgery’, Medicine (United Kingdom), 42(9), pp. 527–531. doi: 10.1016/j.mpmed.2014.06.008.
[2] Tatoulis, J. et al. (2015) ‘Total Arterial Revascularization: Achievable and Prognostically Effective — A Multicenter Analysis’, The Annals of Thoracic Surgery, 100(4), pp. 1268–1275. doi: 10.1016/j.athoracsur.2015.03.107.
[3] Ramachandra, A. B., Kahn, A. M. and Marsden, A. L. (2016) ‘Patient-Specific Simulations Reveal Significant Differences in Mechanical Stimuli in Venous and Arterial Coronary Grafts’, Journal of Cardiovascular Translational Research, 9(4), pp. 279–290. doi: 10.1007/s12265-016-9706-0.

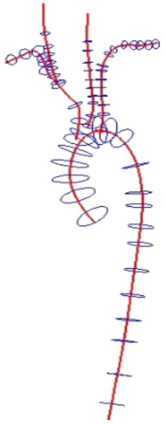
Methodology: The plan.

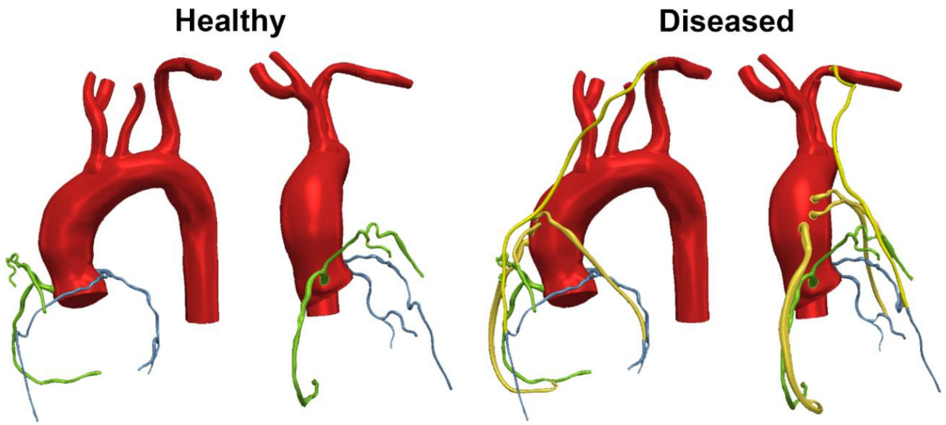
- Generate several bypass variations for the same treatment.
  - Altering:
    - **Length**
    - **Shape**
    - **Proximal anastomosis location**
  - Maintaining:
    - **Calibre**
    - **Anastomosis angles**
    - **Distal anastomosis location**
- Quantify the haemodynamic differences.



Methodology: Patient reconstruction.

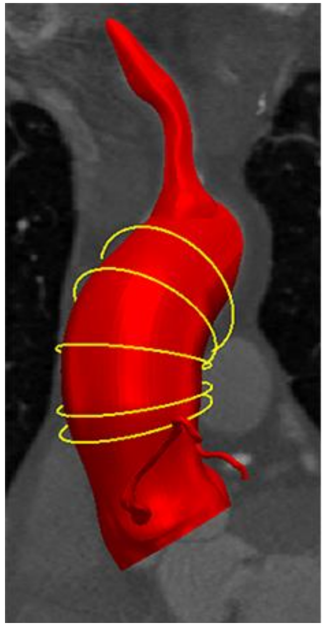
- **Post-operative CT** images were taken of a quadruple bypass patient (3/4 were SVGs).
- Using **SimVascular** (SV) their cardiac anatomy was manually reconstructed.
- **A healthy counterpart** was generated by digitally removing the in-situ bypasses and coronary stenoses.
- Severe stenosis (75% area reduction) was returned to a single coronary artery ready for **virtual surgery**.

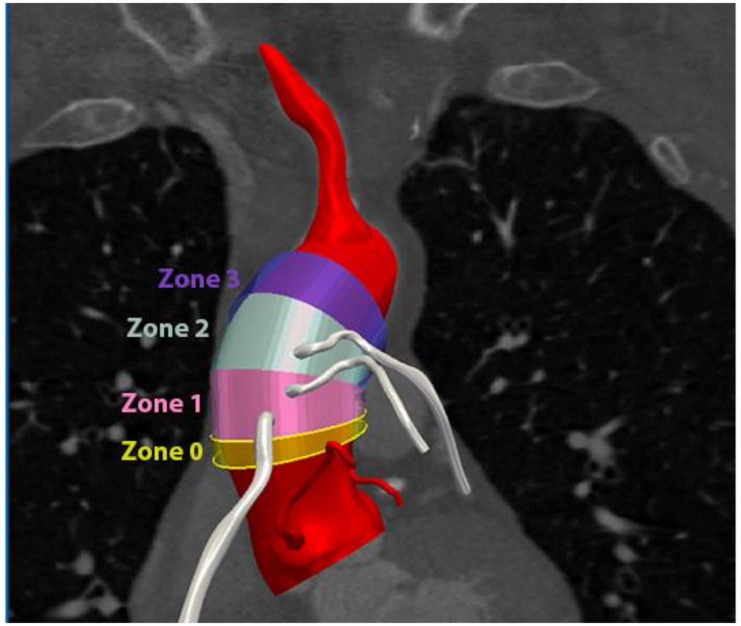


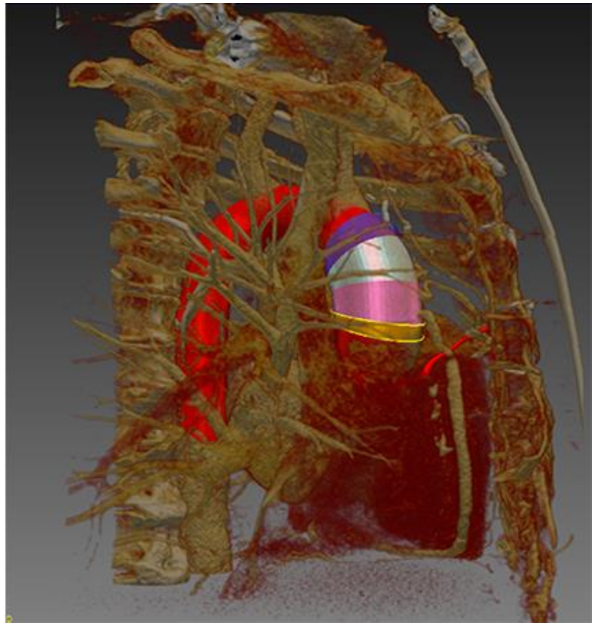


Methodology: Novel bypass attachment.

- The aorta was discretised into **three zones** for proximal anastomosis.
  - Zone 0 was ignored due to surgical inaccessibility.
- Each zone would hold 3 bypass designs of different length & shapes.

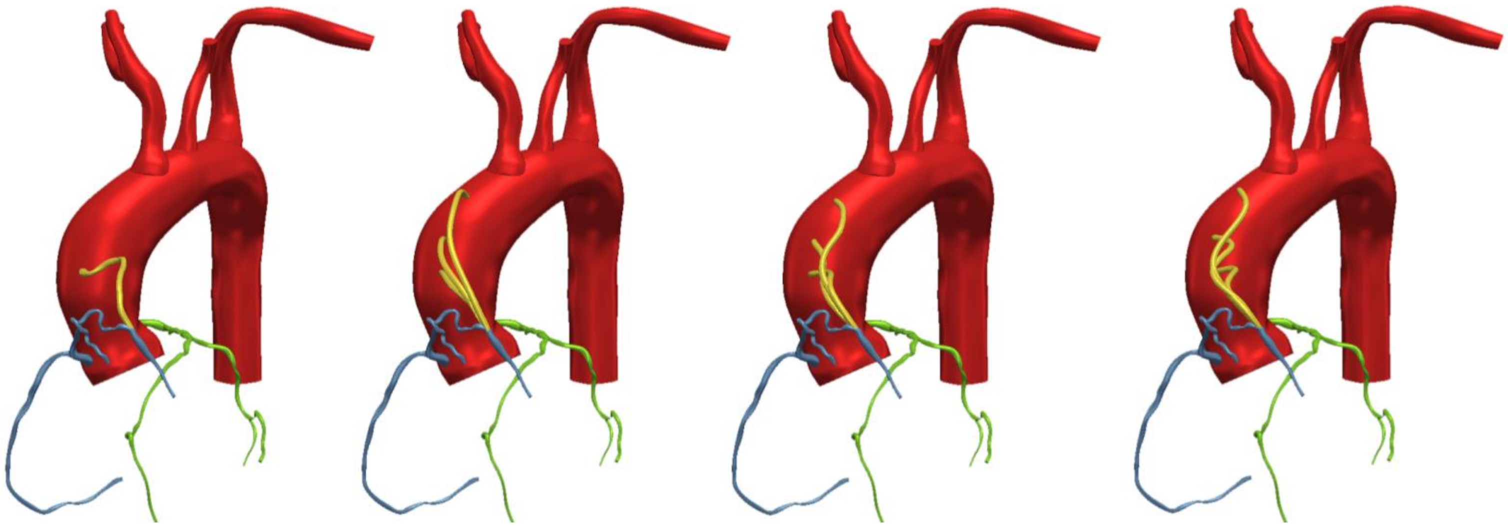






Methodology: Novel bypass design.

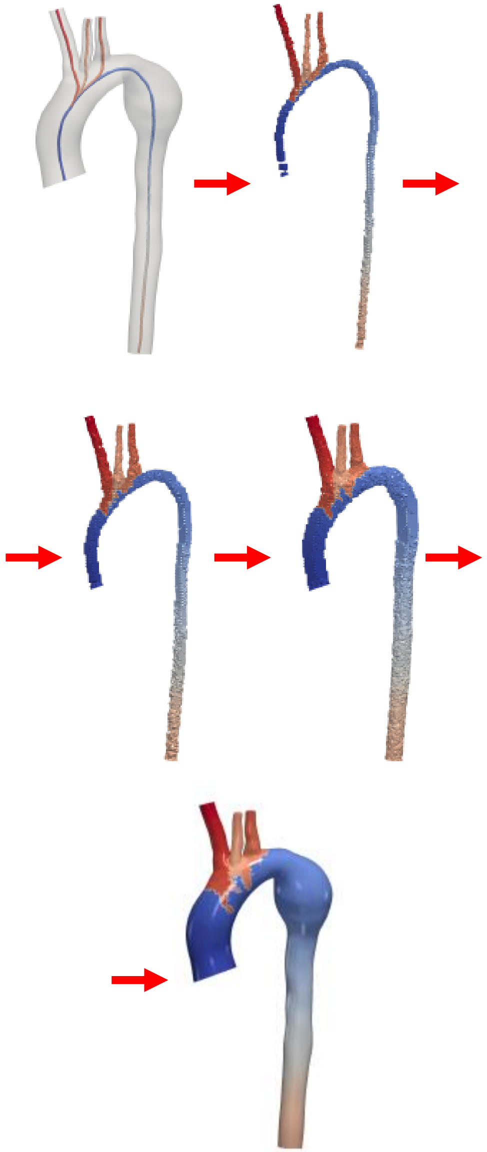
- Three CABG shapes were selected – **direct**, **slight deviation**, and **severe deviation**.
- Each shape variant was generated per zone.
- The bypasses were **idealised** with circular cross-sections and uniform calibre.
  - (Grafts taper at the anastomoses).



In-Situ Bypass (idealised) | **3 Direct Bypass Lengths** | **3 Slight Deviation Bypass Lengths** | **3 Severe Deviation Bypass Lengths**

Methodology: Simulations.

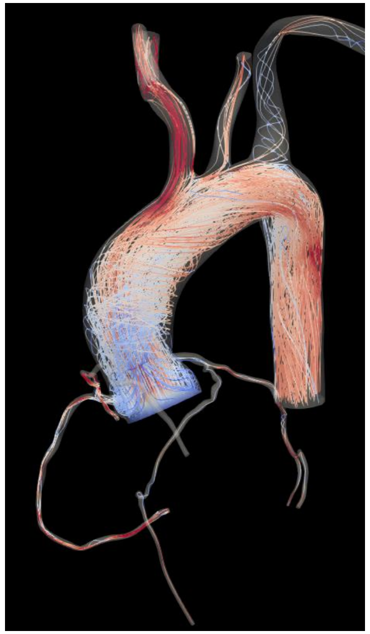
- The healthy model was **tuned** to match clinical measurements: **pressure** and **flow-distribution**.
- The prescribed **boundary conditions** were:
  At the inlet - a volumetric flowrate with parabolic profile.
  At the outlets - 3-element Windkessel.
- A **1D simulation** was run for **10 cardiac cycles**, stabilising the pressure and flow fields.
- The 1D results were then extrapolated to the 3D mesh to use as initial conditions. [1]
- The **3D simulation** was run for a further **2 cardiac cycles**.

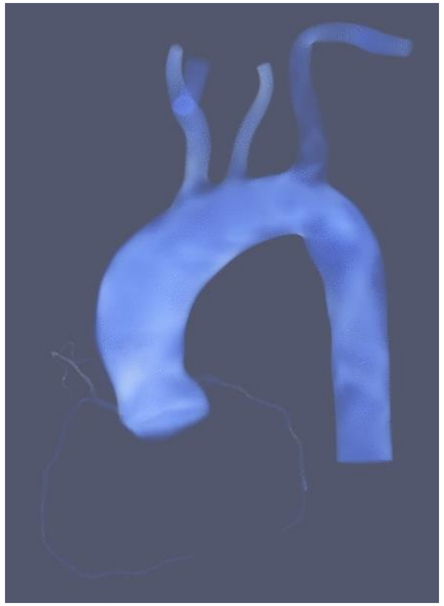


[1] Pfaller, M. R. et al. (2021) 'On the Periodicity of Cardiovascular Fluid Dynamics Simulations', Annals of Biomedical Engineering, pp. 1–19. doi: 10.1007/s10439-021-02796-x.

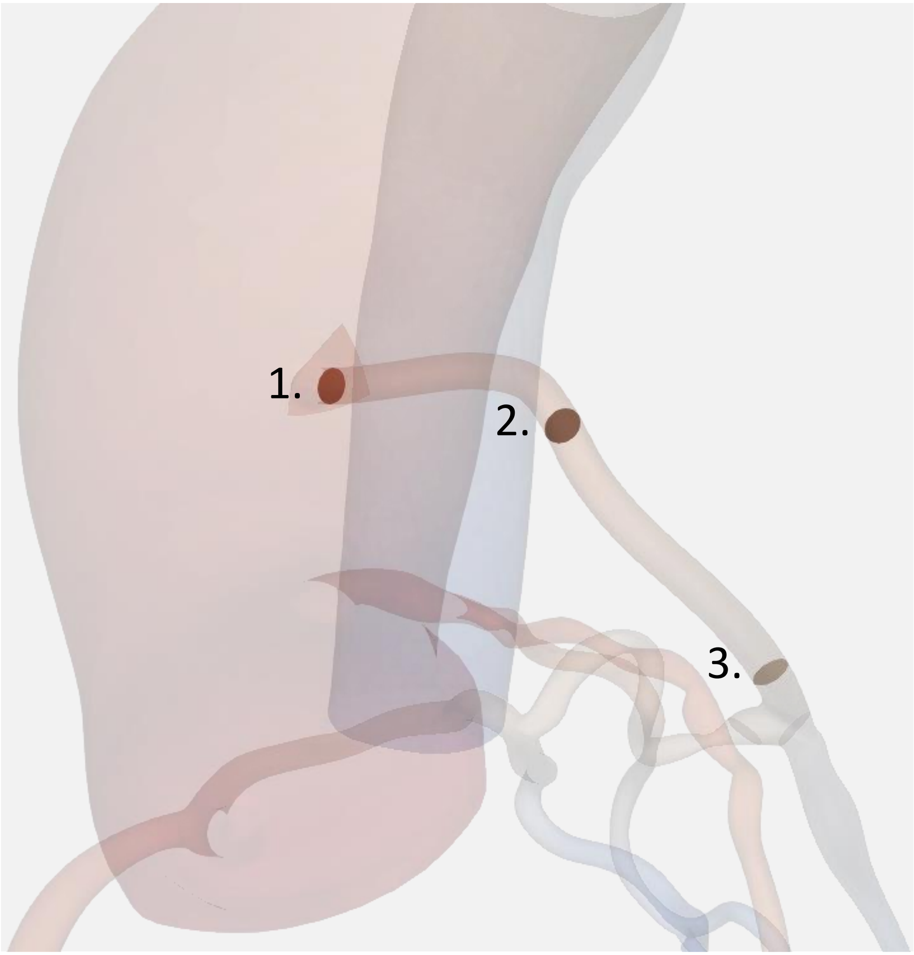
Methodology: Simulations.

- **Blood** was modelled as an **incompressible Newtonian fluid**.
- A **mesh** independency analysis concluded **6.8 million elements** was sufficient for the healthy model.
  - CABGs increased cell count by several hundred thousand.
  - The near-wall region contained 5 layers of prism-cells.
- A **timestep** independency analysis concluded a timestep size of **0.001s** was sufficient.
- A residual independency analysis concluded a **RMS residual** criteria of **$1x10^{-4}$** was sufficient.





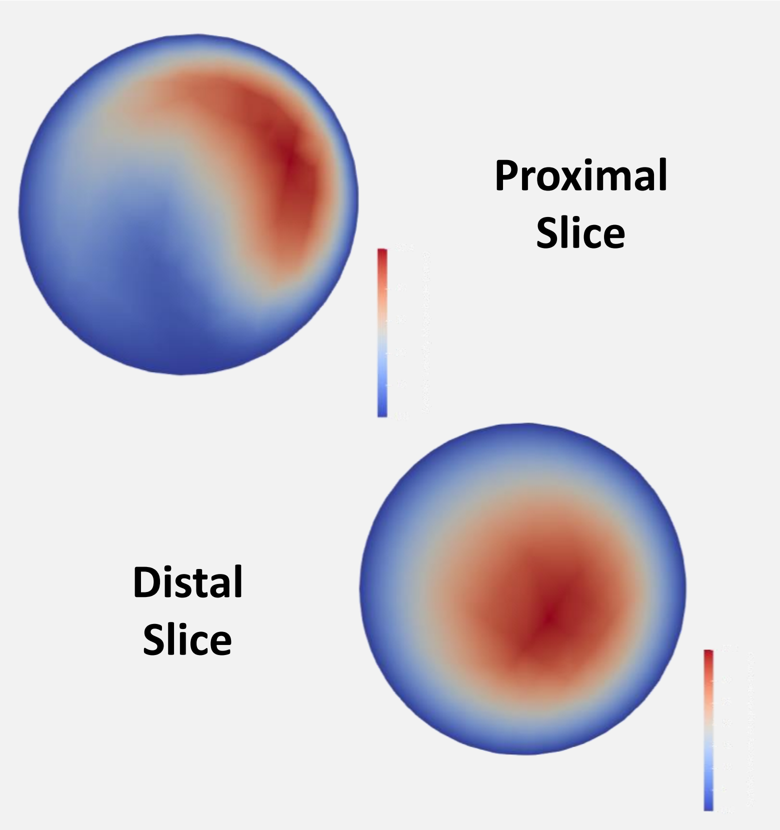
Methodology: Metrics – Axial velocity.



- Each bypass was sliced in 3 locations:
    1. Distal-to-proximal anastomosis.
    2. Mid-section.
    3. Proximal-to-distal anastomosis
- Velocity was recorded during peak-systole:
    - (3-element WK does not reproduce the out-of-phase coronary flow).
- Used to better understand the wall forces.

Results: Axial velocity.

- At the **proximal** anastomosis:
  - The **velocity** distribution was **asymmetrical.**
  - Very large **peak-flowrates** were present at the **outside wall**.
- At the **distal** anastomosis:
  - The **velocity** distribution was more **evenly distributed.**
  - The **peak-flowrate** was **centralised** and **smaller magnitude**.
- **Bypass shape** was **insignificant** to **distal coronary flowrate**.
- A **higher** aortic **anastomosis** resulted in **larger peak-flow** velocities throughout the bypass.
- Longer bypasses exhibited fully developed flow profiles distally.



Methodology: Metrics – TAWSS.

- Wall shear stress was averaged through the final cardiac cycle.

- Literature classifies **pathological TAWSS** values as:
- $\mathrm{TAWSS} < 4\, dyn \cdot cm^{-2}$:
  - Increased particle residence time.
  - Encourages IT, atherosclerosis, and thrombi formation.

- $\mathrm{TAWSS} > 25\, dyn \cdot cm^{-2}$:
  - Endothelial damage. [1, 2]

[1] Ghista, D. N. and Kabinejadian, F. (2013) 'Coronary artery bypass grafting hemodynamics and anastomosis design: A biomedical engineering review', BioMedical Engineering Online, 12(1). doi: 10.1186/1475-925X-12-129
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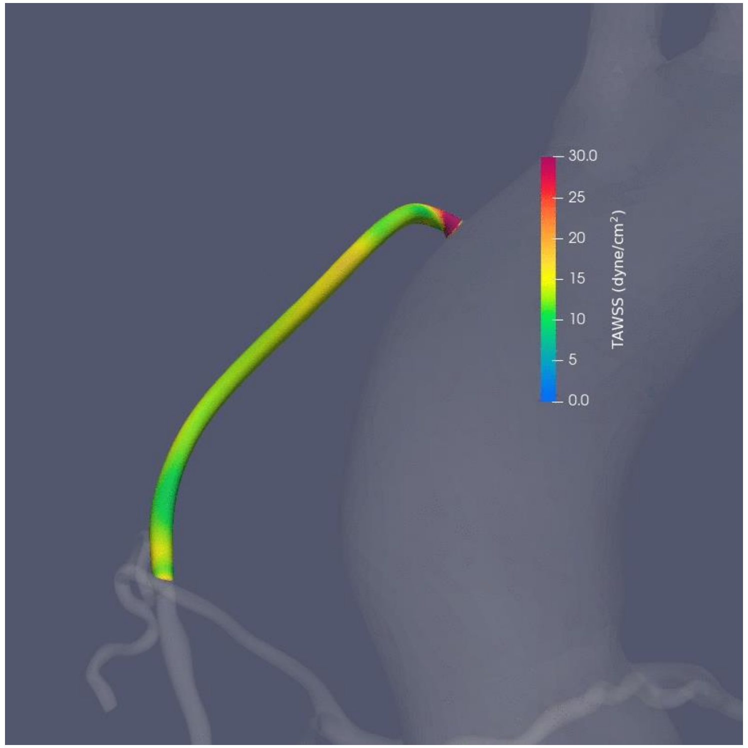
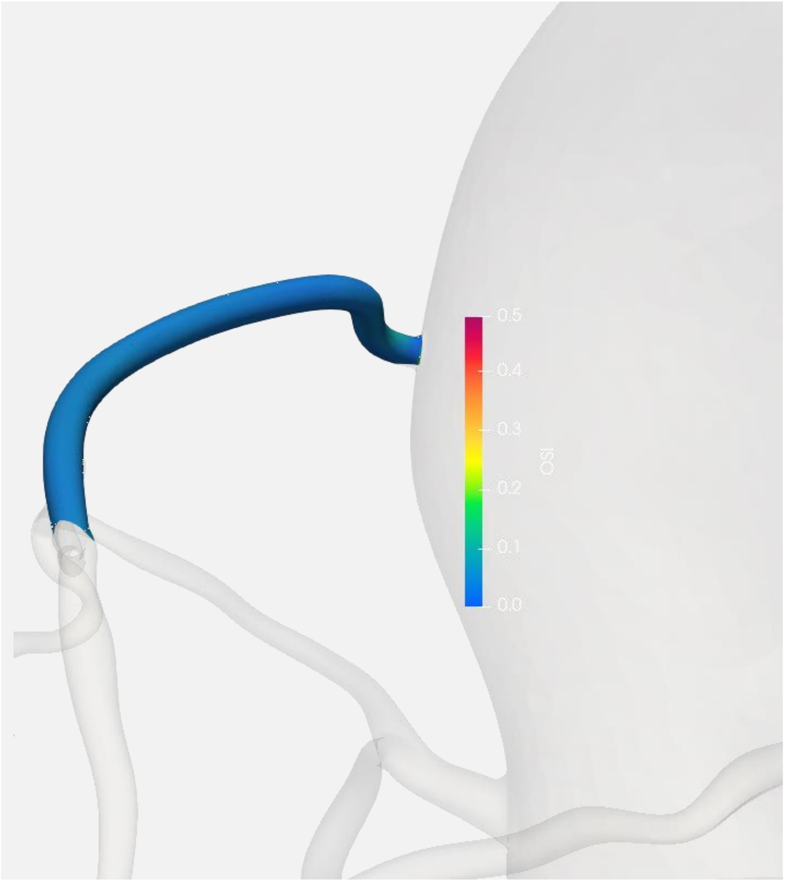
Results: TAWSS.

- A **higher** aortic **anastomosis** resulted in **larger TAWSS** throughout the vessel.
- The **largest TAWSS** was located at the **proximal anastomosis** the largest peak-flowrate were found at the outside curvature.
- **Bypass shape** was **significant** to **TAWSS**:
  - The outside bends saw an increase in TAWSS.
  - The inside bends saw a decrease in TAWSS.
- This suggests that **too severe deviation** may **propagate atherosclerotic progression** through multiple mechanisms.



Methodology: Metrics – OSI.



- OSI was calculated across the final cardiac cycle.
- Literature classifies **pathological OSI** as $\mathrm{OSI} > 0.15$.
    - Where a pairing of low-TAWSS and high-OSI has been identified to be preferential for atherosclerosis development. [1, 2]

[1] Ghista, D. N. and Kabinejadian, F. (2013) 'Coronary artery bypass grafting hemodynamics and anastomosis design: A biomedical engineering review', BioMedical Engineering Online, 12(1). doi: 10.1186/1475-925X-12-129
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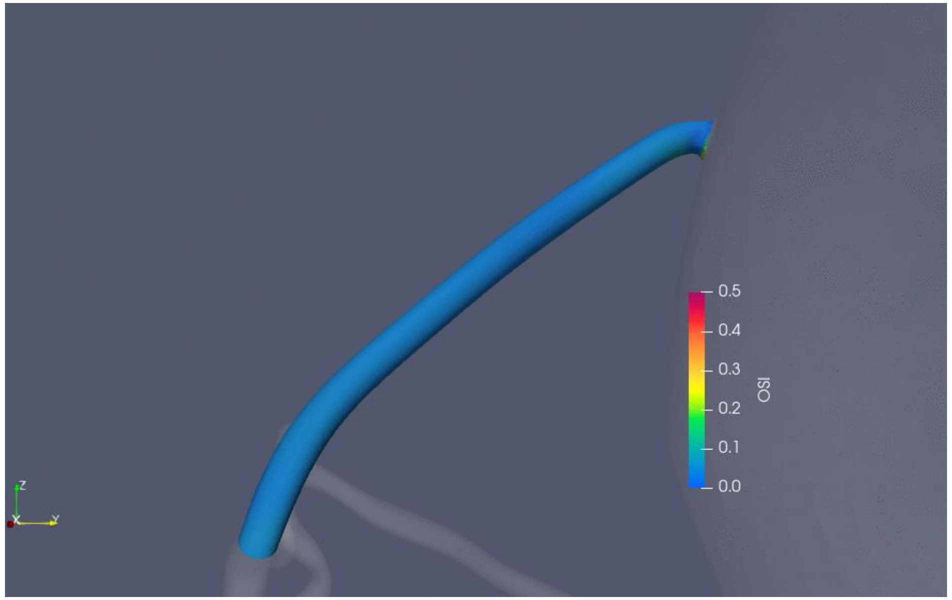
Results: OSI.

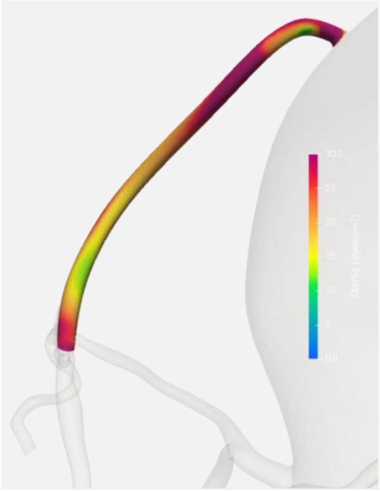
- **Bypass shape** was **insignificant** to the **observed OSI**.
- The **largest OSI** values were located at the **proximal anastomosis.**
- This suggests that the local aortic backflow may be dominant in the proximal section.



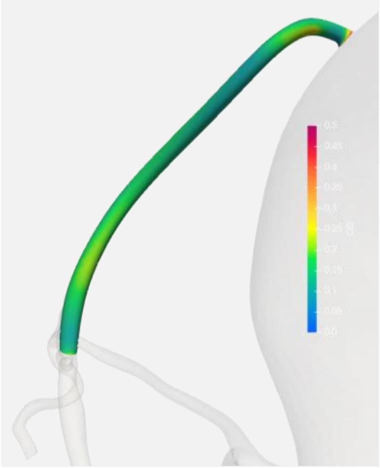
Conclusion: Discussion & future work.

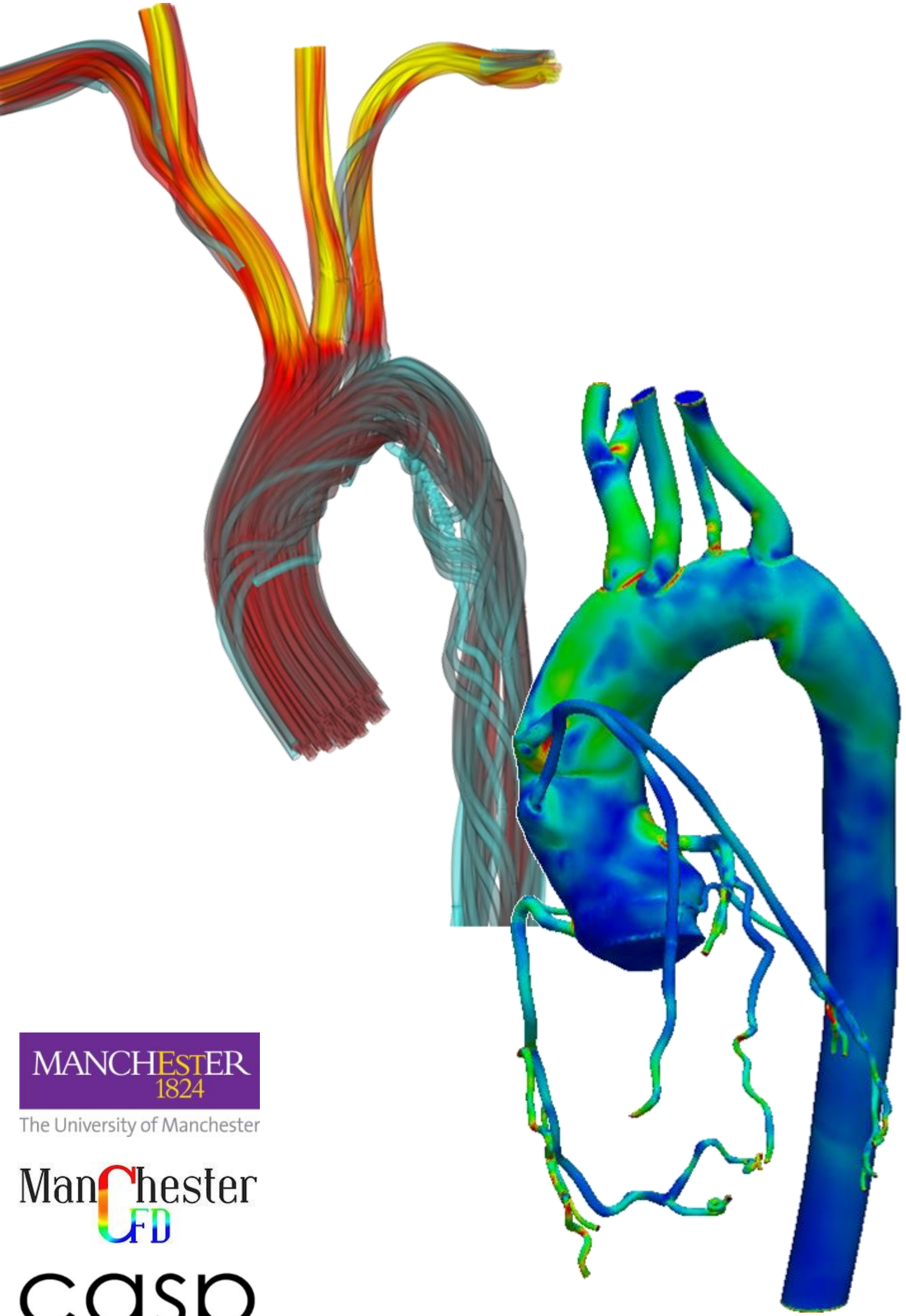
- This work found bypass geometry to be:
  - Insignificant to distal coronary run-off.
  - Significant to the values of TAWSS through the vessel.
  - Insignificant to the observed OSI through the vessel.
- Therefore, **extreme bypass deviation may significantly impact longevity**.
- **Future work** aims to:
  - Use BCs that **impose coronary restriction** during systole:
    - Initial results indicate a much greater effect on TAWSS and OSI range.
  - Incorporate graft imperfections:
    - Graft varicosities.
    - Tapering calibre.
  - Automate optimisation for surgical decision with minimal user input.

TAWSS



OSI





Thank you for listening.
Any questions?

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