The impact of computational and experimental integration in heart valve design

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Background and Objectives

- Current artificial heart valve designs suffer either from calcification and fatigue (biological valves) or thromboembolism (mechanical valves).
- Development of artificial heart valves is a long and expensive process, requiring many design iterations and performing costly and timely experimental testing for each design.
- New methods are currently being investigated by combining computational and experimental studies to shorten development times.
- New computational methods may reduce the need for early on experimental testing, whereas new experimental techniques may provide more insight into heart valve function without increasing the amount of experimental testing required.

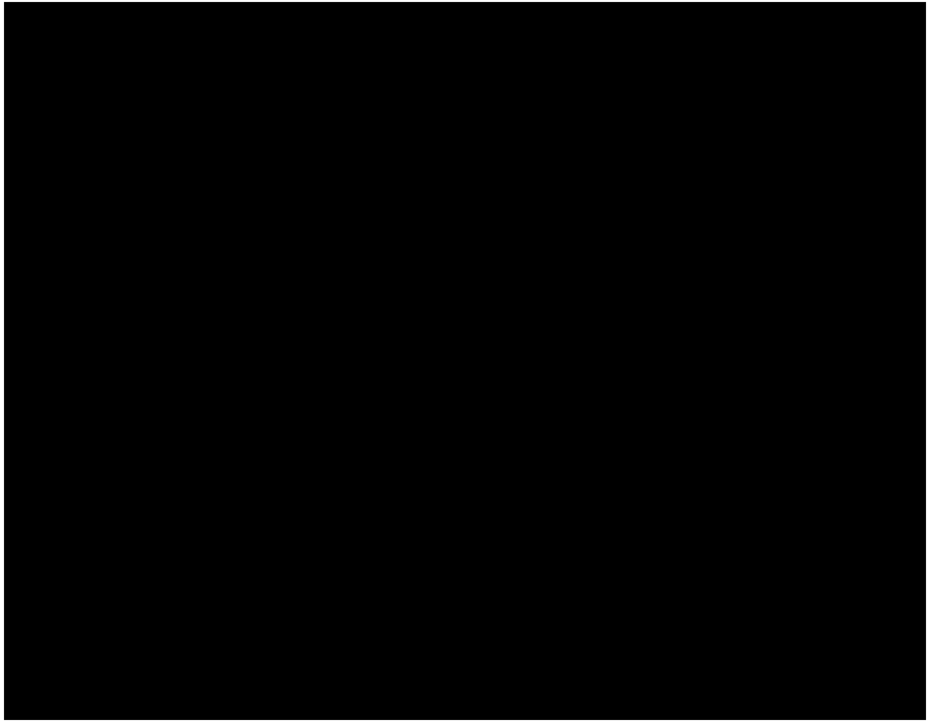
Methods

- To test the new design methods, a trileaflet polyurethane valve was tested using a combination of pulse duplication (ViVitro Labs pulse duplicator[1]) and a custom built pulse duplicator with a particle image velocimetry (PIV) system at Stellenbosch University.
- The polyurethane valve enabled for fast design alteration turnaround times through 3D printing and dip moulding procedures.
- Computational fluid dynamics (CFD) simulations were performed using foam-extend-3.2 with the FOAM-FSI adapter[2], CalculiX v2.10[3] and preCICE[4].
- The CFD results were validated against experimental data and used to evaluate the performance of the heart valve

1. https://vivitrolabs.com/
2. https://github.com/davidsblom/FOAM-FSI
3. http://www.calculix.de/
4. https://www.precice.org/

Vortex formation in turbulent flow

- Turbulent flow is characterised by vortices that break down from larger to smaller vortices, dissipating the kinetic energy in the vortices as heat.
- This phenomenom is utilised in the sub-grid scale (SGS) model utilised in the experimental investigation using PIV.
- The SGS model captures information of the large vortices that we can see, and computes what is happening in the small vortices that we can't see.



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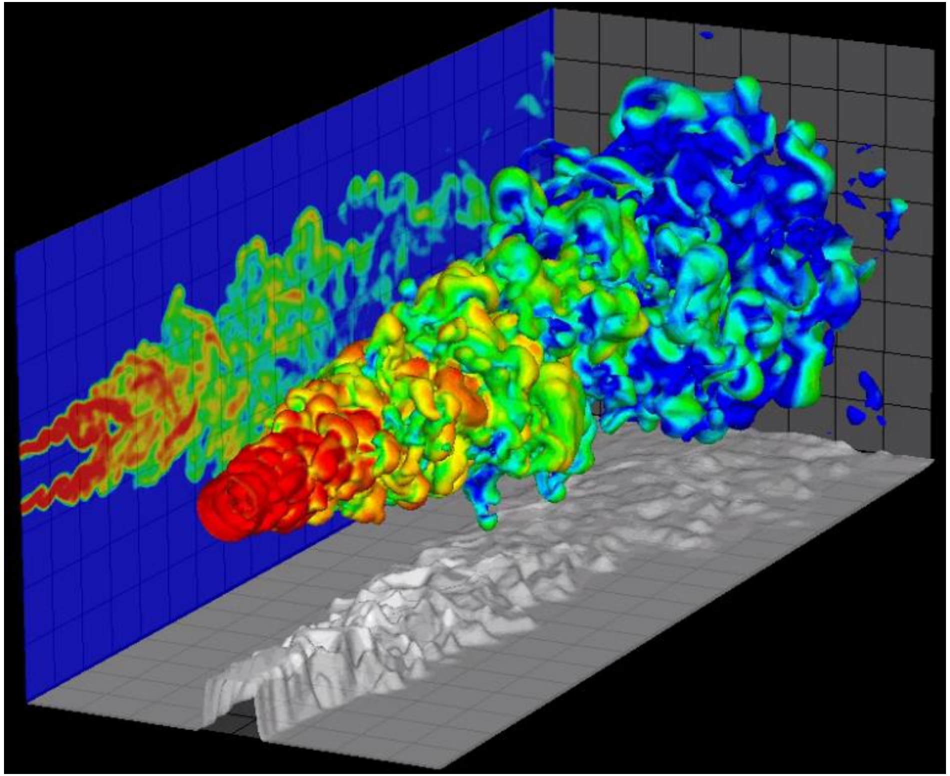

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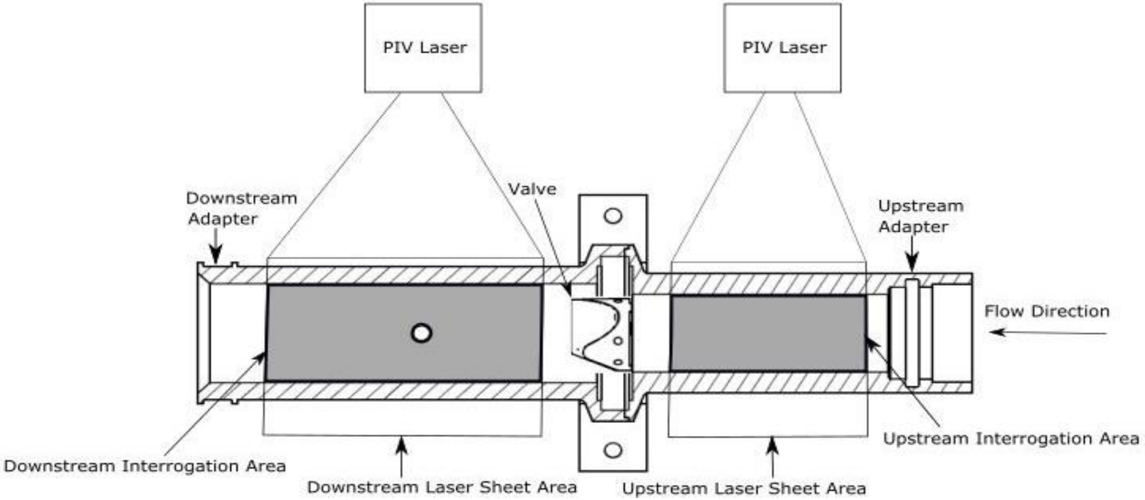
PIV Experimental setup

- The PIV was performed upstream and downstream of the valves using a PIV system from Dantec Dynamics
- The valves were all tested at 5 L/min, 70 beats per minute, 72 ml stroke volume.
- The camera had a resolution of 2048 x 2048 pixels
- Final interrogation window of 32 x 32 with 50% overlap
- The results were phase averaged over 300 cycles



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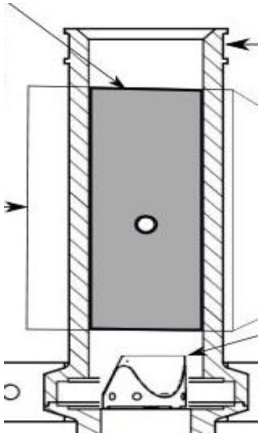
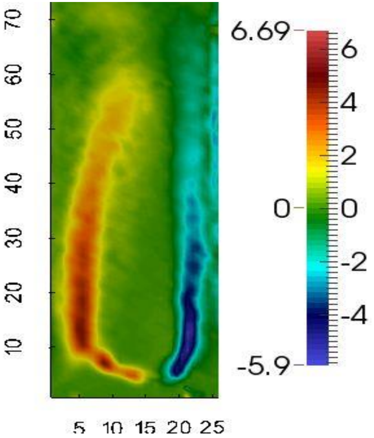
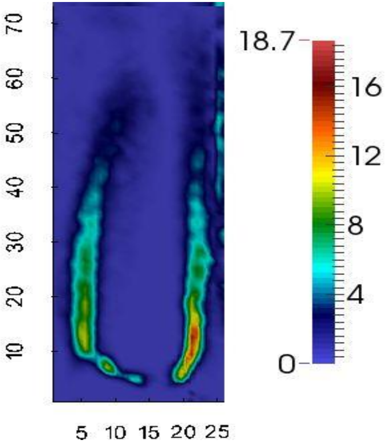
Shear stress evaluation

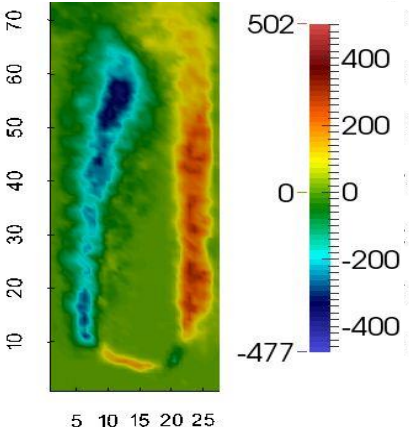




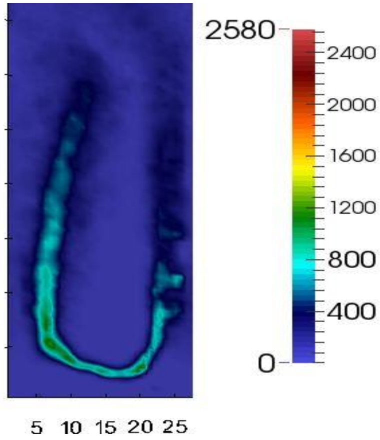
VSS



SGS



RSS

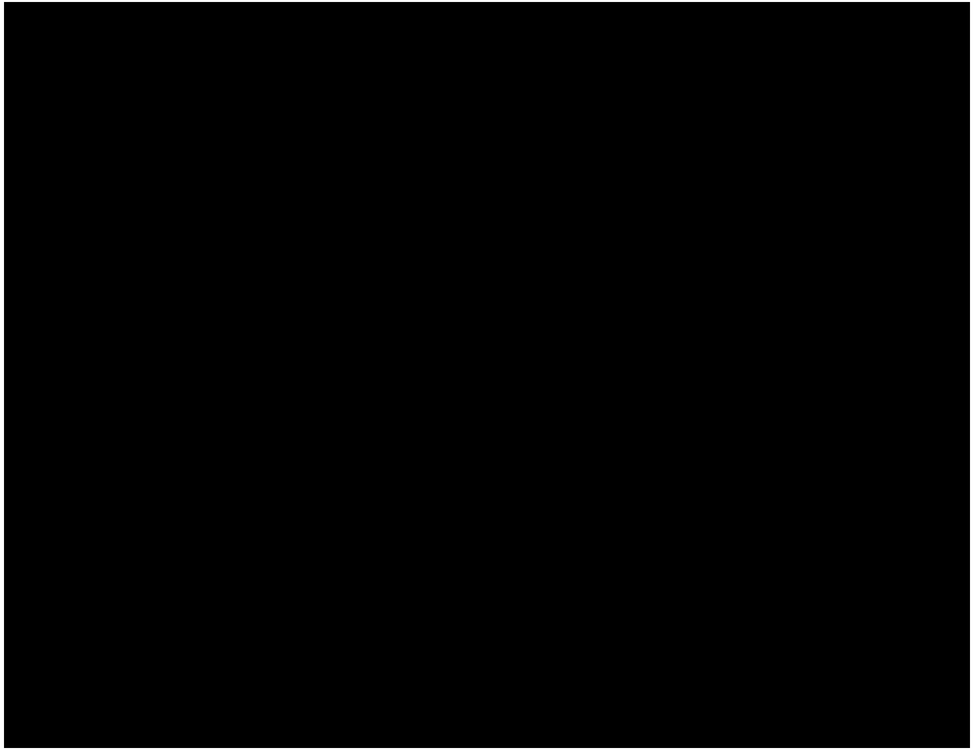


RSS_{maj}

- Viscous shear stress (VSS) value below platelet activation level of 10 Pa, however SGS value is well above 10 Pa.
- Reynolds shear stress (RSS) value below threshold of 800 Pa, however RSS_{maj} is well above 800 Pa.
- RSS and RSS_{maj} are two different formulas and are often used interchangeably in experimental testing.
- This results in errors in platelet activation and hemolysis prediction calculation.

Computational simulation

- The numerical simulations included simulating the full 3D flow field with moving boundaries.
- The moving boundary began with a closed valve that opened due to forces in the fluid domain, and closed once the flow had decelerated and moved backwards.



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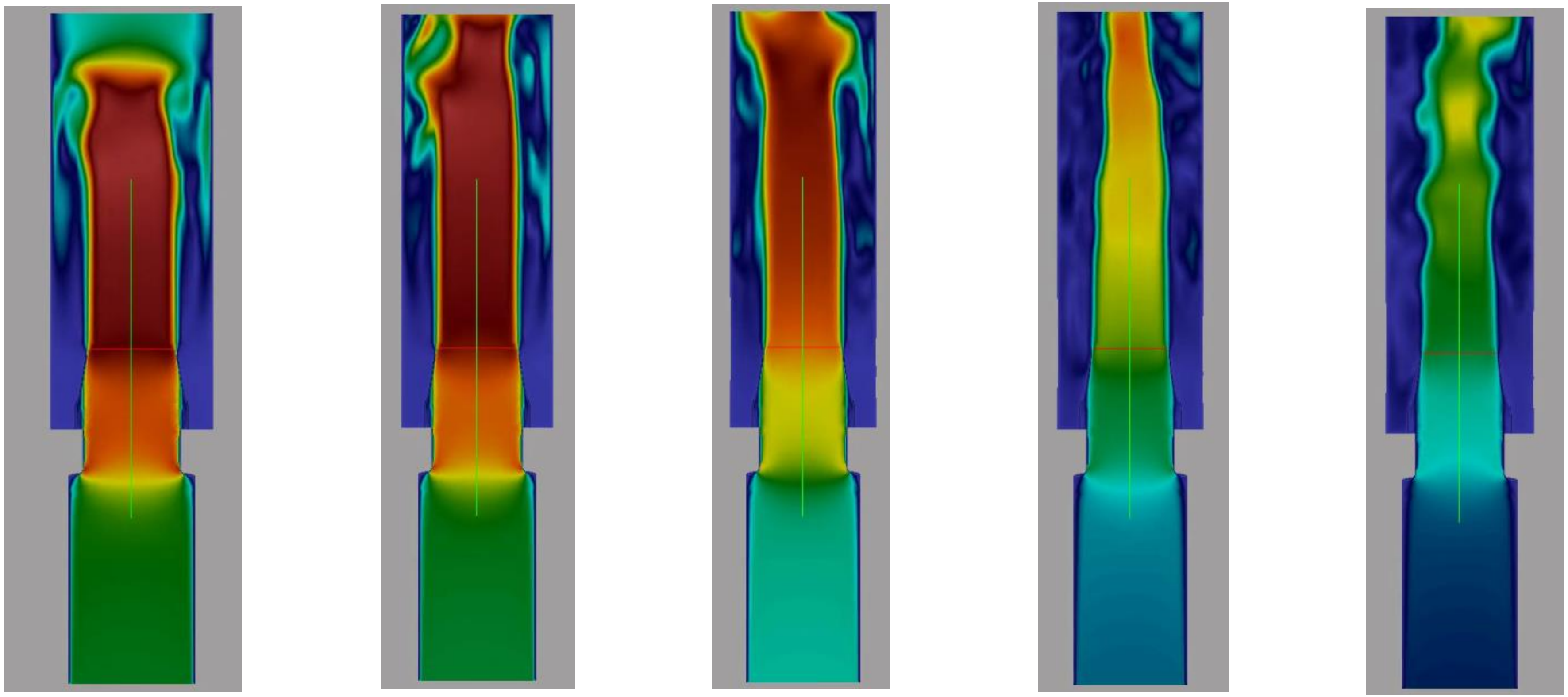
Computational simulation



Accelerating ⟶ Peak ⟶ Decellerating

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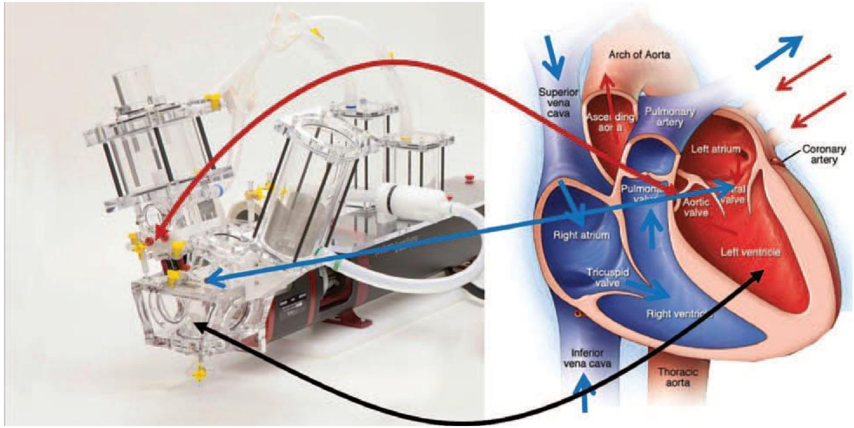
Pulse duplication pressure drop

- The average pressure drop of the heart valve is required to evaluate the hemodynamic performance for ISO and FDA accreditation
- The pressure drop was experimentally measured using a pulse duplicator (ViVitro Labs) and compared to the laminar and turbulent flow (κ-ω *SST* model) simulations
- The turbulent flow simulation provided a reasonable approximation for the average pressure drop



	Average Pressure Drop [mmHg]		
	Experiment	Laminar	Turbulent
Method 1	15.18	12.53	13.49
Method 2	7.53	12.40	13.80
ViVitro	15.28	-	-

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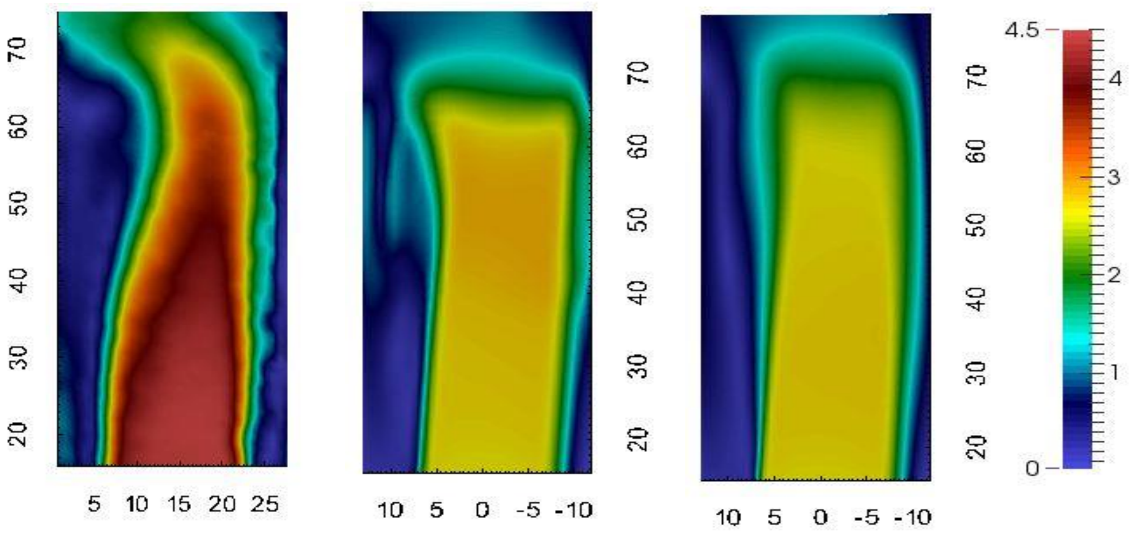
Comparison of computational and experimental results

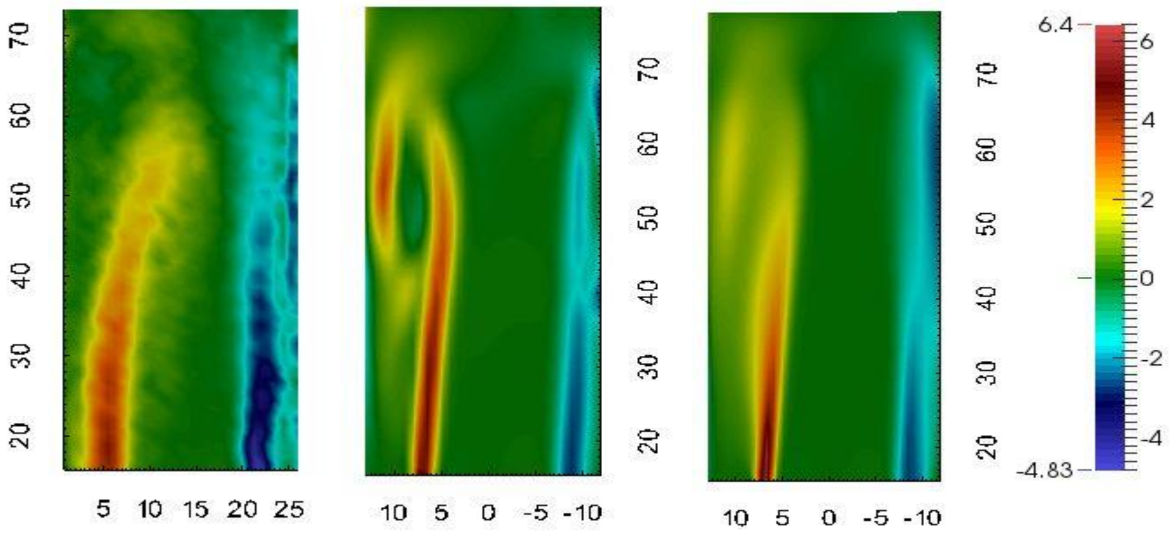
- The velocity profile was obtained on a pulse duplicator at the Stellenbosch University whilst simultaneously performing PIV.
- The numerical velocity magnitude did not match the experimental results (experiment = 4.5 m/s, laminar = 2.86 m/s, turbulent = 2.69 m/s).



Experiment Laminar Turbulent

Comparison of computational and experimental results

- The VSS for the numerical results was in good agreement with the experimental results.
- A shear stress larger than 10 Pa indicates potential platelet activation and thrombosis.



Experiment Laminar Turbulent

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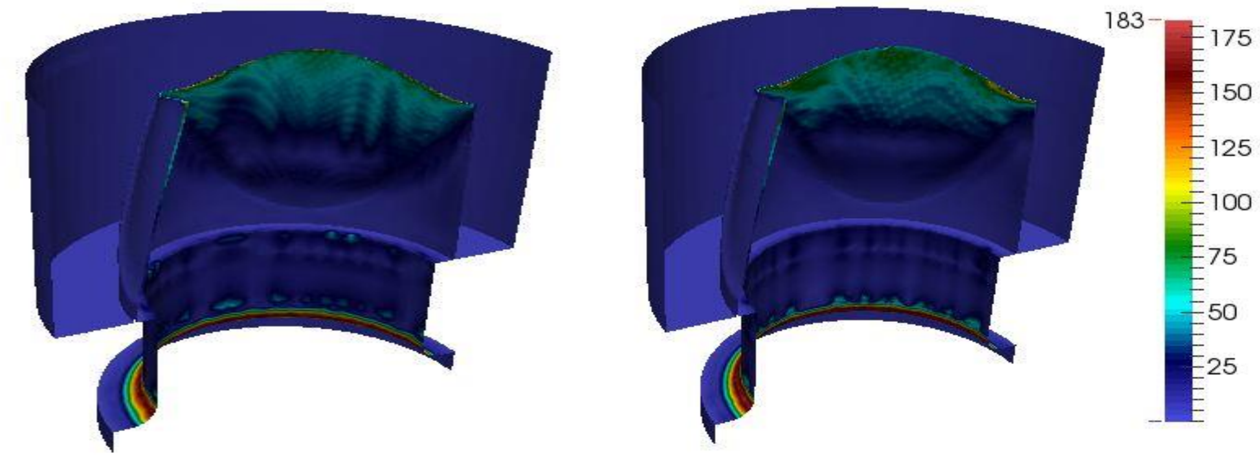
Computational WSS evaluation

- The wall shear stress (WSS) is also a potential indicator of platelet activation.
- The results upstream of the valve is much larger than 10 Pa, however the heart valve leaflets themselves have a maximum WSS of approximately 75 Pa – 100 Pa near the leaflet edge.
- This indicates potential platelet activation and potentially hemolysis, and the WSS values are similar in magnitude with results in literature.



Laminar Turbulent

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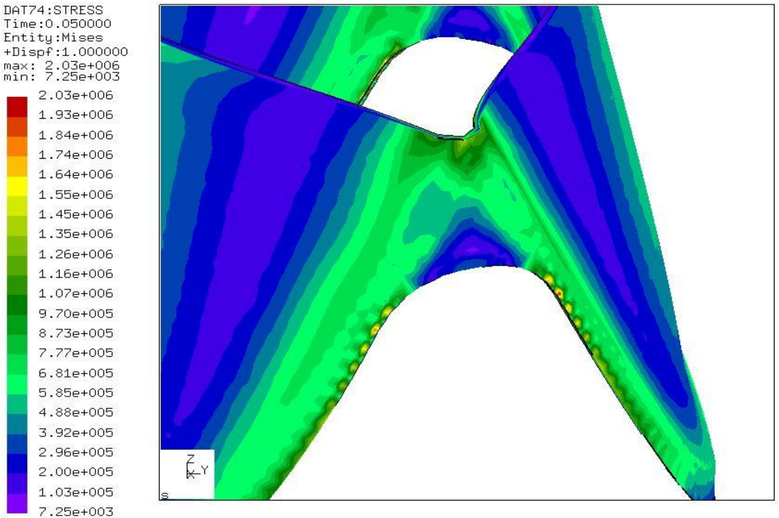
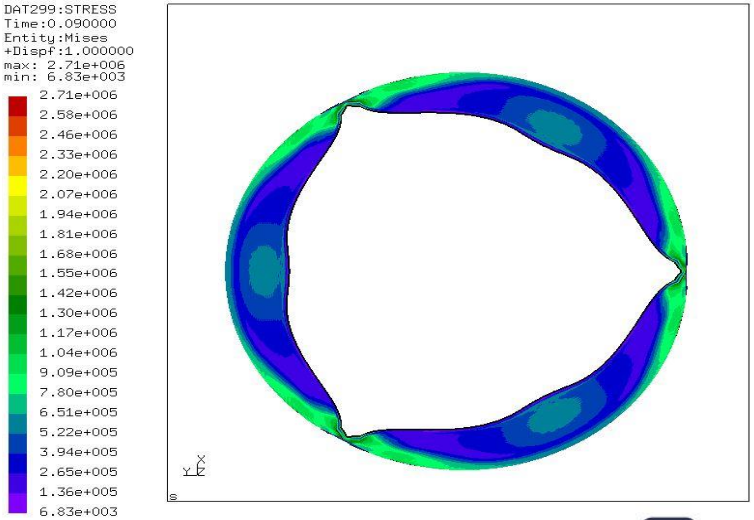
Computational material stress evaluation

- The von Mises stress within the leaflets shows that the largest stress occurs where the polyurethane material attaches to the leaflets.
- Utilising computational studies to reduce the stress in these regions can avoid lenghthy manufacturing and expereimental lead times on fatigue testing.





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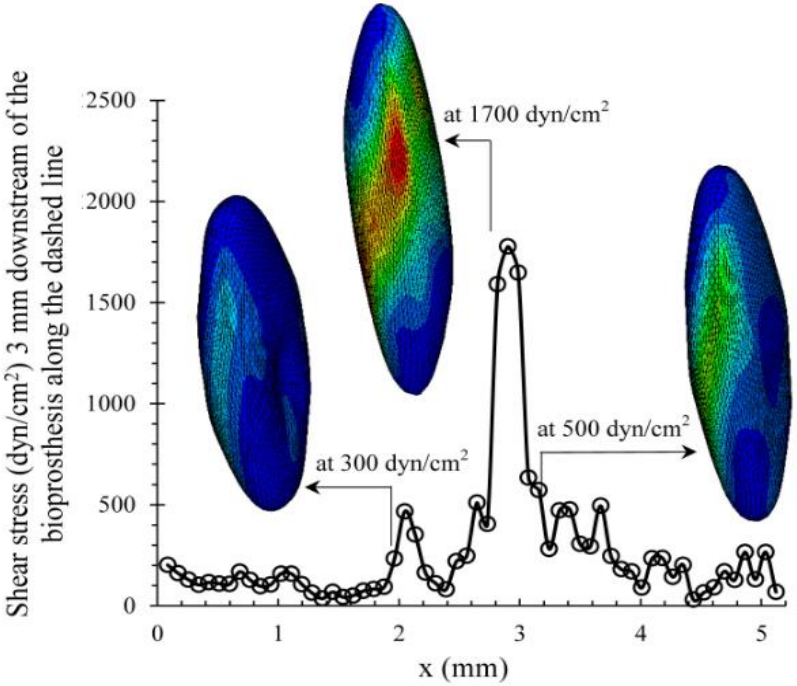
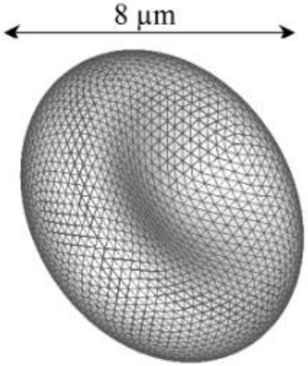
Red blood cell damage limits

- Simulations performed on red blood cells show that severe distortion of red blood cells occur at 1700 dyn/cm^2 (170 Pa) with a high chance of damaging the blood cells[6].
- Values as high as 170 Pa are present on the walls of experimental setup





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6. Koohyar Vahidkhah, Dan Cordasco, Mostafa Abbasi, Liang Ge, Elaine Tseng, Prosenjit Bagchi, **Ali Azadani**.: Multiscale Analysis of Blood Flow through Aortic Valve Stenosis: Implications on Red Blood Cell Membrane Damage. The Heart Valve Society Scientific Meeting 2016

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Conclusion

- A combination of computational and experimental testing is able to compliment each other and reduce development times on heart valves.
- Experimental testing offers limited information of the fluid mechanics through the valve, and does not provide the stress in the leaflet material (until failure in fatigue testing).
- By validating computational methods, numerical simulations provide further insight into what cannot be experimentally measured.
- This offers new ideas to explore, such as platelet activation and hemolysis shear stress thresholds.

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