Blood flow in thoracic aorta

PhD qualifier presentation

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4Department of Pediatrics, University of Cincinnati

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ACADEMIC BACKGROUND :

Bachelors and Masters in Aerospace Engineering (India)

PROFESSIONAL BACKGROUND :

Engineer (wind tunnel design) at Larsen & Toubro

DEGREE MOTIVATION :

Specialize in fluid dynamics

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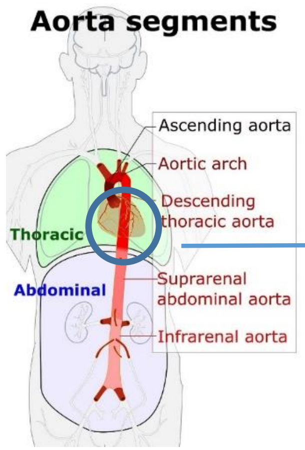
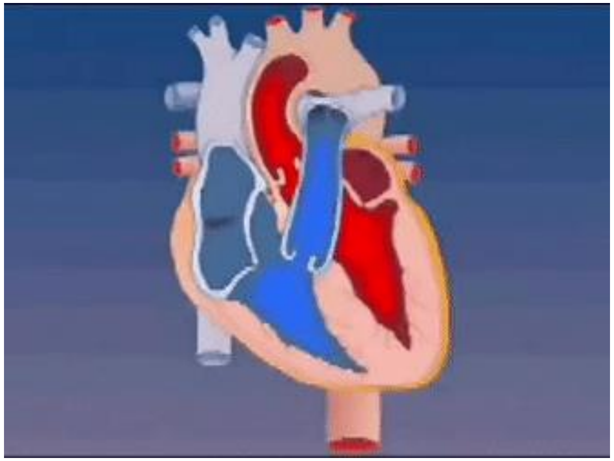
RESEARCH MOTIVATION :
Study the influence of aorta anatomy on thoracic hemodynamics



Human Aorta
SOURCE : https://en.wikipedia.org/wiki/Aorta

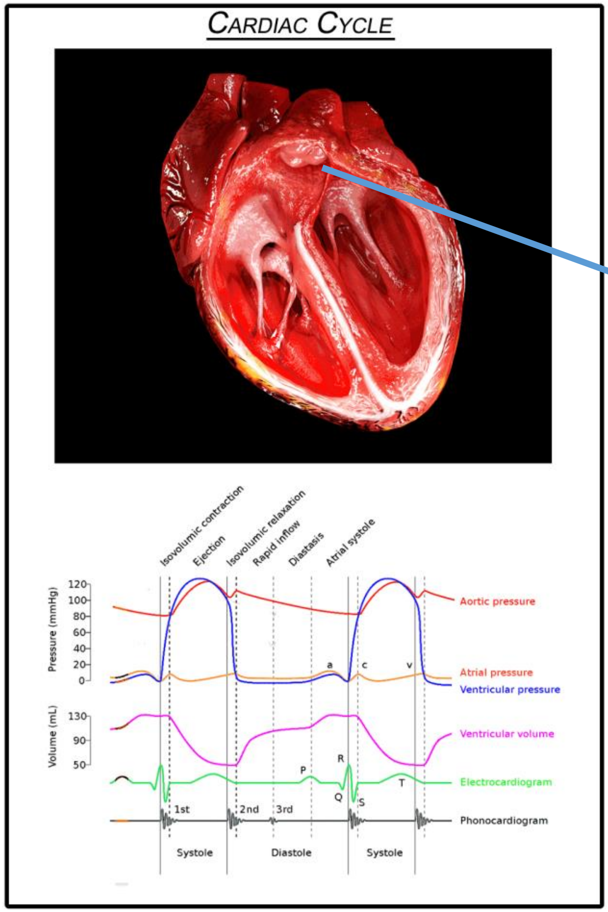


Heart
SOURCE : https://www.nationwidechildrens.org

- Every year, More than 25,000 Americans die from heart valve disease.[1]
- More than 100,000 need valve replacement surgery to survive more than two years after valve disease diagnosis[2]

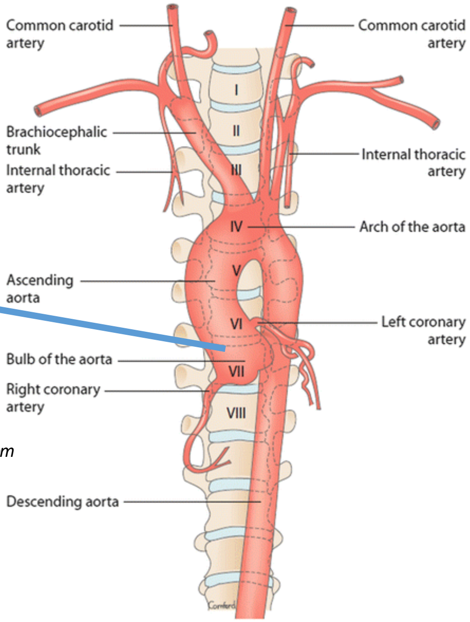
1 . https://www.cdc.gov/heartdisease/valvular_disease
2 . Otto, C. M. (2000). VALVE DISEASE: Timing of aortic valve surgery. Heart, 84(2), 211–218.

ANATOMY OF INTEREST



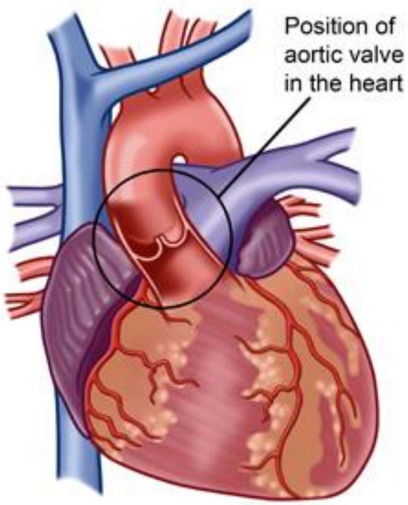
Cardiac Cycle
SOURCE : Wikimedia Commons

Tricuspid Aorta Valve (in-vitro)
SOURCE : Eric Martin Willen, http://sciencefiction-nastragull.blogspot.com



Thoracic Aorta
SOURCE : https://www.nationwidechildrens.org

TYPES OF AORTIC VALVES



Normal Aortic Valve
(3 leaflets)

Bicuspid Aortic Valve
(2 leaflets)

SOURCE : CardiacHealth.Org, CentralSydneyCardiology.com

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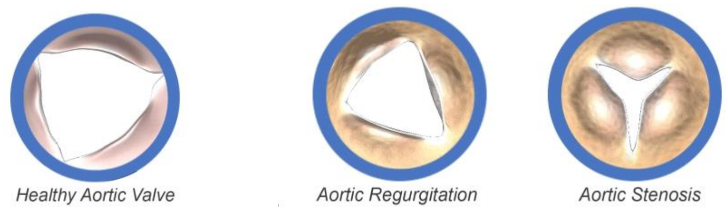
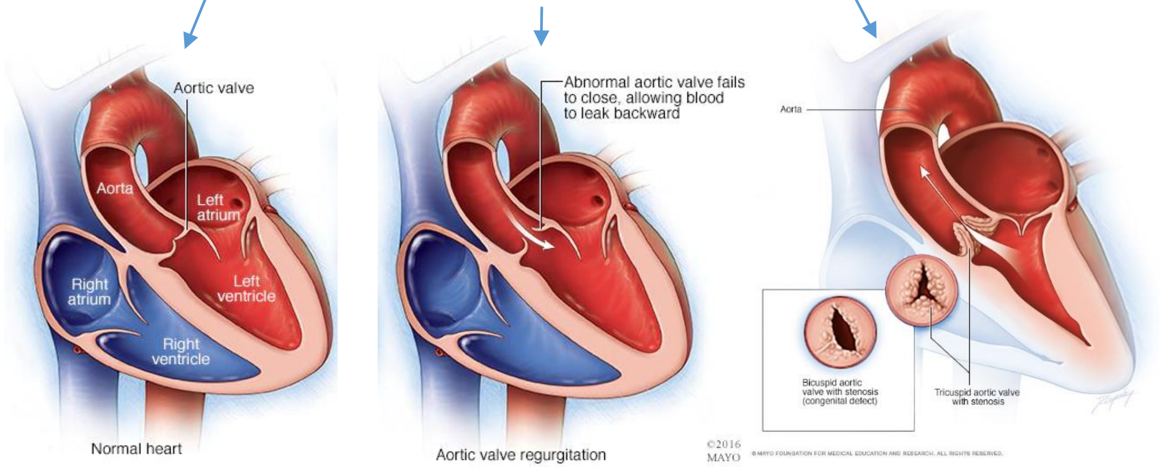
AORTIC STENOSIS AND REGURGITATION



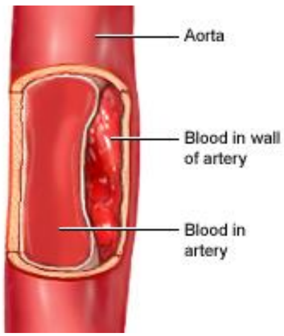
Source : https://ctsurgerypatients.org/adult-heart-disease/aortic-valve-disease



SOURCE : https://www.mayoclinic.org

- 50% of BAV subjects get aortic stenosis complications**

AORTIC DISSECTION



Aortic wall tear

SOURCE: https://medlineplus.gov/ency/article/000181.htm

Dissection in ascending aorta

SOURCE : http://www.aortarepair.com/type-a-aortic-dissection.html

- Probability of aortic dissection in Bicuspid Aortic Valve (BAV) subjects ~ 9 times that of Tricuspid Aortic Valve (TAV)*

*Luyckx and Loeys, 2015 **Paola De Mozzi et al.,2015

CURRENT GOALS :

<u>Quantify the influence of following variables on aorta blood flow</u>

- Aorta anatomy including valve shape/orientation
- Tissue compliance of aorta including the valve

<u>Correlate genetic disorders like Turner and Marfan syndrome to aorta hemodynamics</u>

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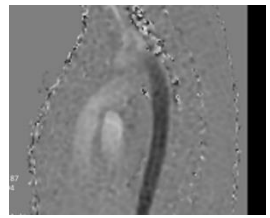
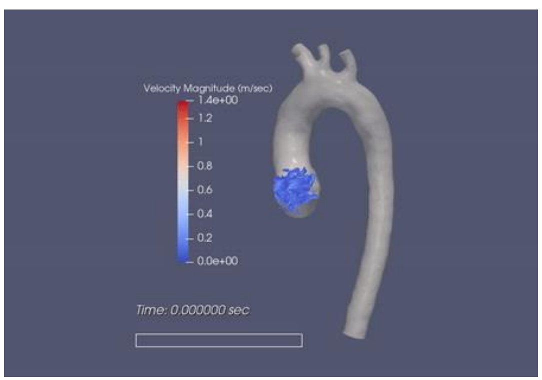
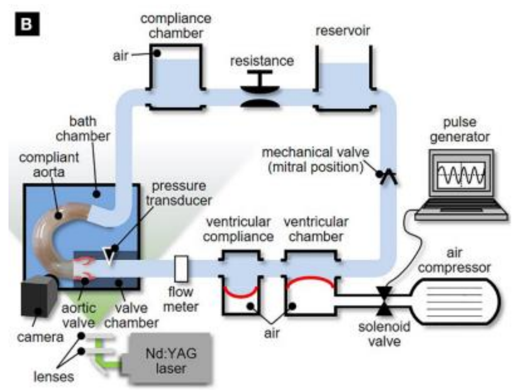
METHODS TO STUDY AORTA



MRI

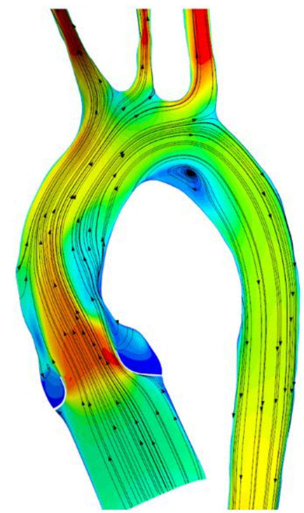


Processed PC-MRI



In-vitro analysis (PIV Setup)

SOURCE : Andrew Mcnally, Philippe Sukosky, 2017



CFD/FSI

SOURCE : Elias Sundström

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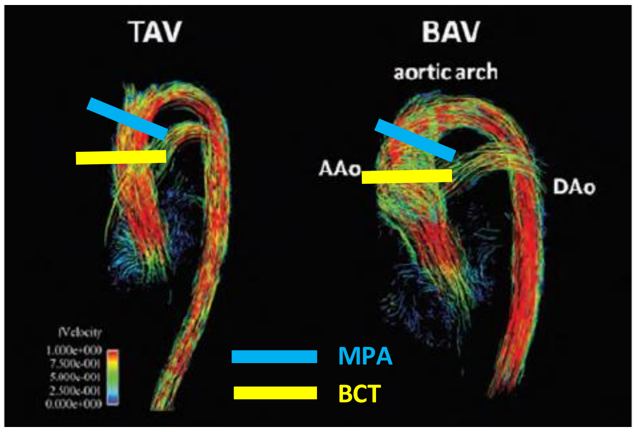
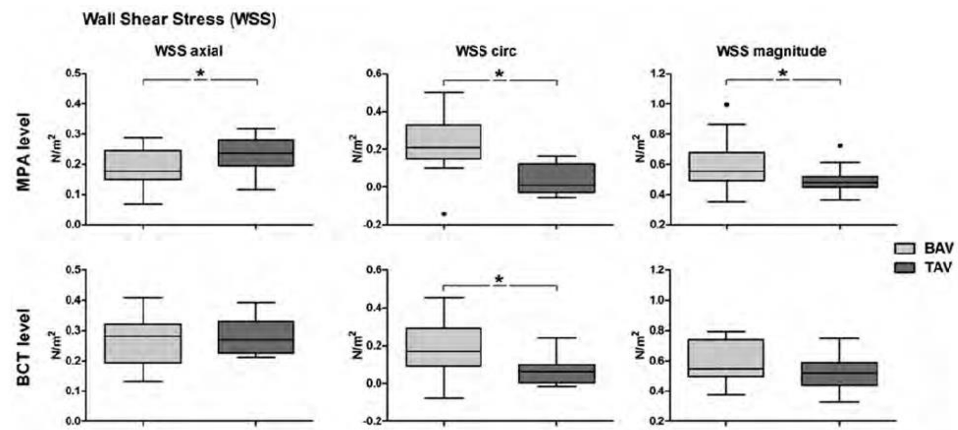
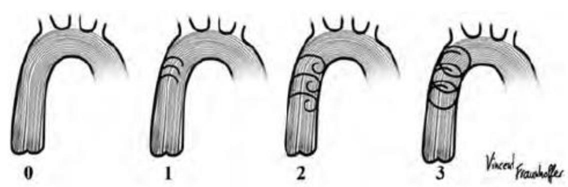
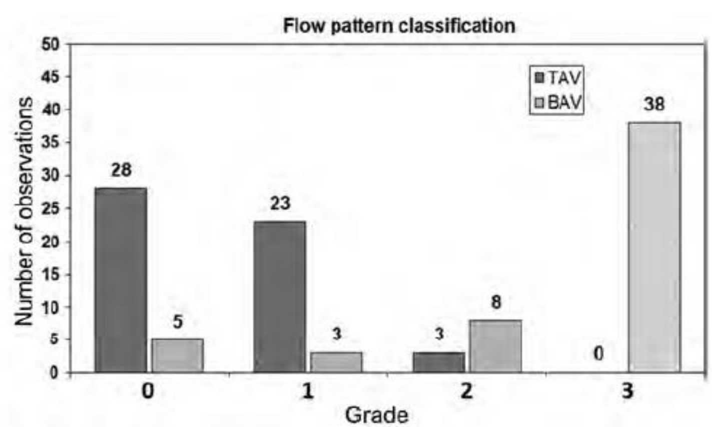
LITERATURE REVIEW – PCMRI PROCESSING





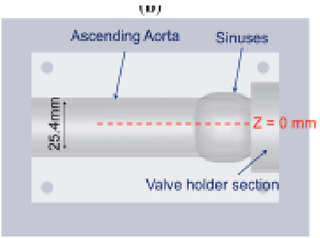


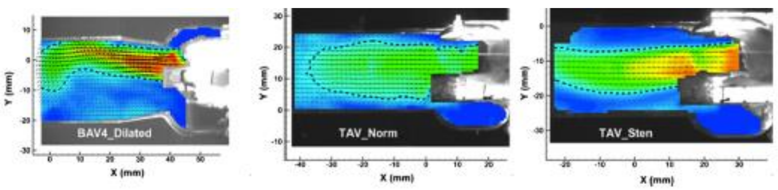


CONCLUSION : Bicuspid valve(BAV) subjects have higher shear stress than tricuspid valve (TAV) subjects, especially circumferential component. BAVs also have higher swirl in flows.

Meierhofer, C., Schneider, E.P., Lyko, C., Hutter, A., Martinoff, S., Markl, M., Hager, A., Hess, J., Stern, H., Fratz, S., 2013. Wall shear stress and flow patterns in the ascending aorta in patients with bicuspid aortic valves differ significantly from tricuspid aortic valves: a prospective study. Eur. Heart J. Cardiovasc. Imaging 14, 797–804. https://doi.org/10.1093/ehjci/jes273

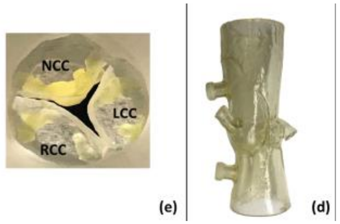
LITERATURE REVIEW – EXPERIMENTAL MODELS

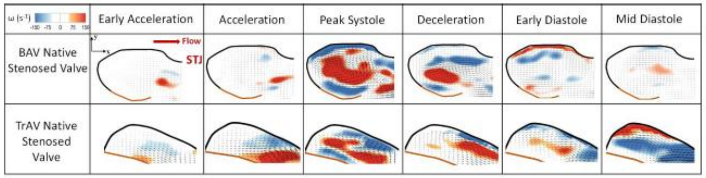




Saikrishnan, N., Mirabella, L., Yoganathan, A.P., 2015. Bicuspid aortic valves are associated with increased wall and turbulence shear stress levels compared to trileaflet aortic valves. Biomech. Model. Mechanobiol. 14, 577–588. https://doi.org/10.1007/s10237-014-0623-3

CONCLUSION : Bicuspid valve subjects have higher shear stress than tricuspid valve subjects

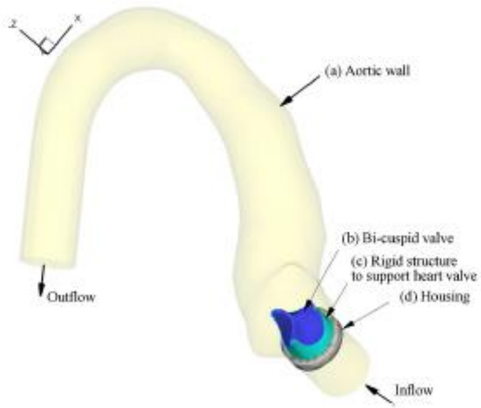


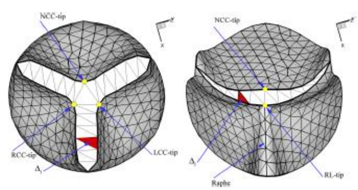


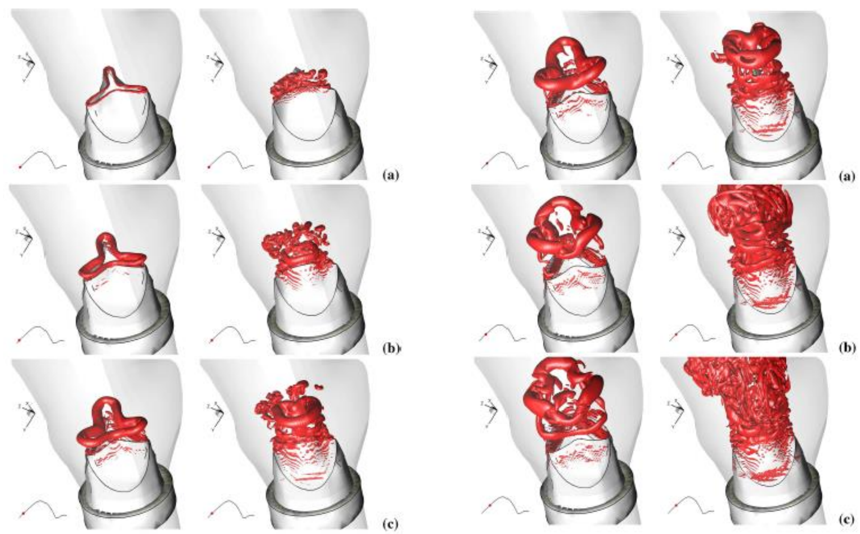
Hatoum, H., Dasi, L.P., 2018. Sinus hemodynamics in representative stenotic native bicuspid and tricuspid aortic valves: An in-vitro study. Fluids 3. https://doi.org/10.3390/fluids3030056

CONCLUSION : Sinus vortices in Bicuspid subjects are larger and persist longer in cardiac cycle when compared to Tricuspid subjects

LITERATURE REVIEW – CFD STUDIES







Gilmanov A, Satiropoulos F, 2016

CONCLUSION : Bicuspid valve(BAV) subjects have higher shear stress and higher swirl in flows. They also reach turbulence earlier than TAV subjects in a cardiac cycle.

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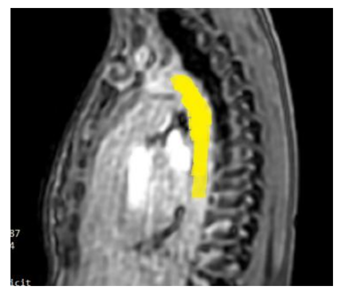
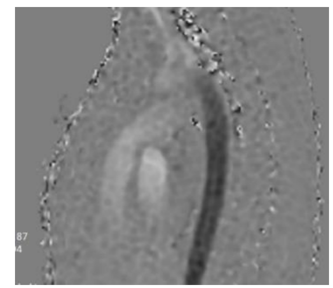
METHODOLOGY – MRI PROCESSING

Regular MRI

Phase Contrast MRI



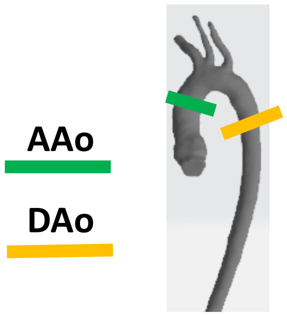
Magnitude

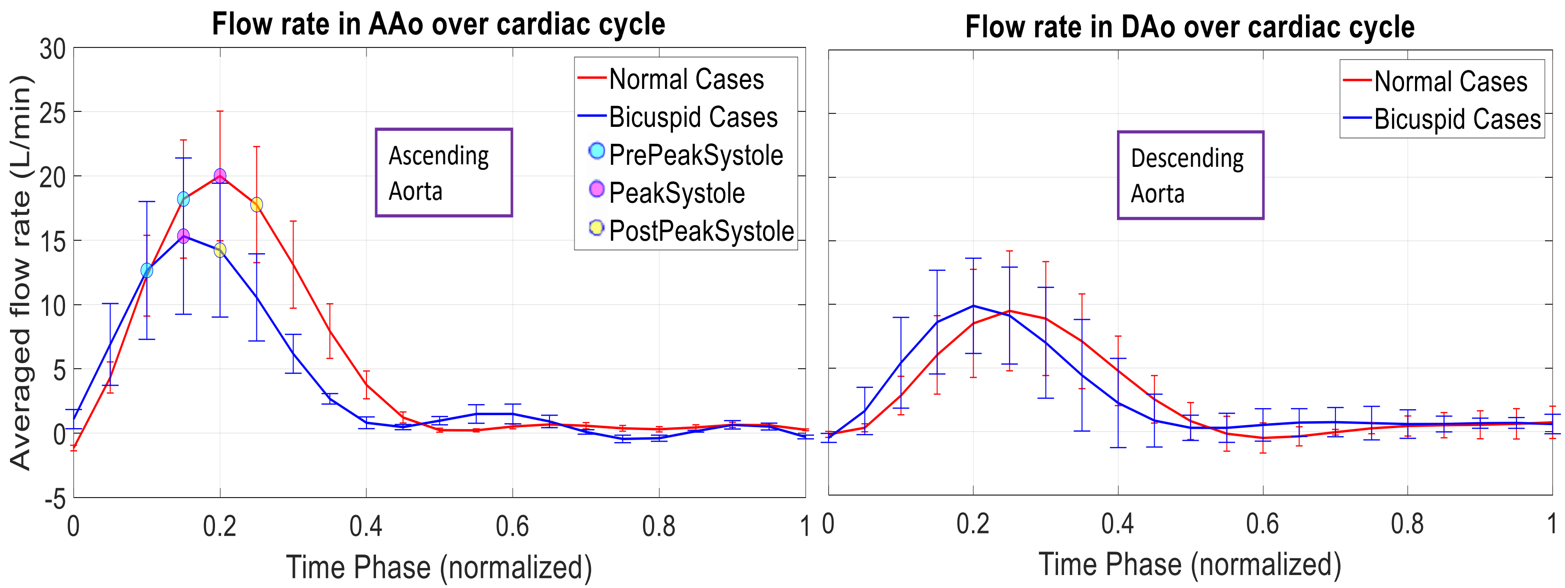


Direction

FLOW OVER A CARDIAC CYCLE

AAo - Ascending Aorta
DAo - Descending Aorta





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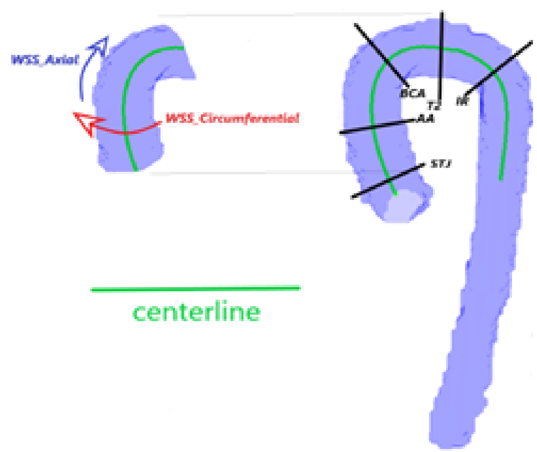
CALCULATION OF WALL SHEAR STRESS



$$\vec{\tau} = \eta \begin{pmatrix} 2n_1 \dfrac{\partial V_1}{\partial x_1} + n_2 \left(\dfrac{\partial V_1}{\partial x_2} + \dfrac{\partial V_2}{\partial x_1} \right) + n_3 \left(\dfrac{\partial V_1}{\partial x_3} + \dfrac{\partial V_3}{\partial x_1} \right) \\ 2n_2 \dfrac{\partial V_2}{\partial x_2} + n_3 \left(\dfrac{\partial V_2}{\partial x_3} + \dfrac{\partial V_3}{\partial x_2} \right) + n_1 \left(\dfrac{\partial V_2}{\partial x_1} + \dfrac{\partial V_1}{\partial x_2} \right) \\ 2n_3 \dfrac{\partial V_3}{\partial x_3} + n_1 \left(\dfrac{\partial V_3}{\partial x_1} + \dfrac{\partial V_1}{\partial x_3} \right) + n_2 \left(\dfrac{\partial V_3}{\partial x_2} + \dfrac{\partial V_2}{\partial x_3} \right) \end{pmatrix}$$

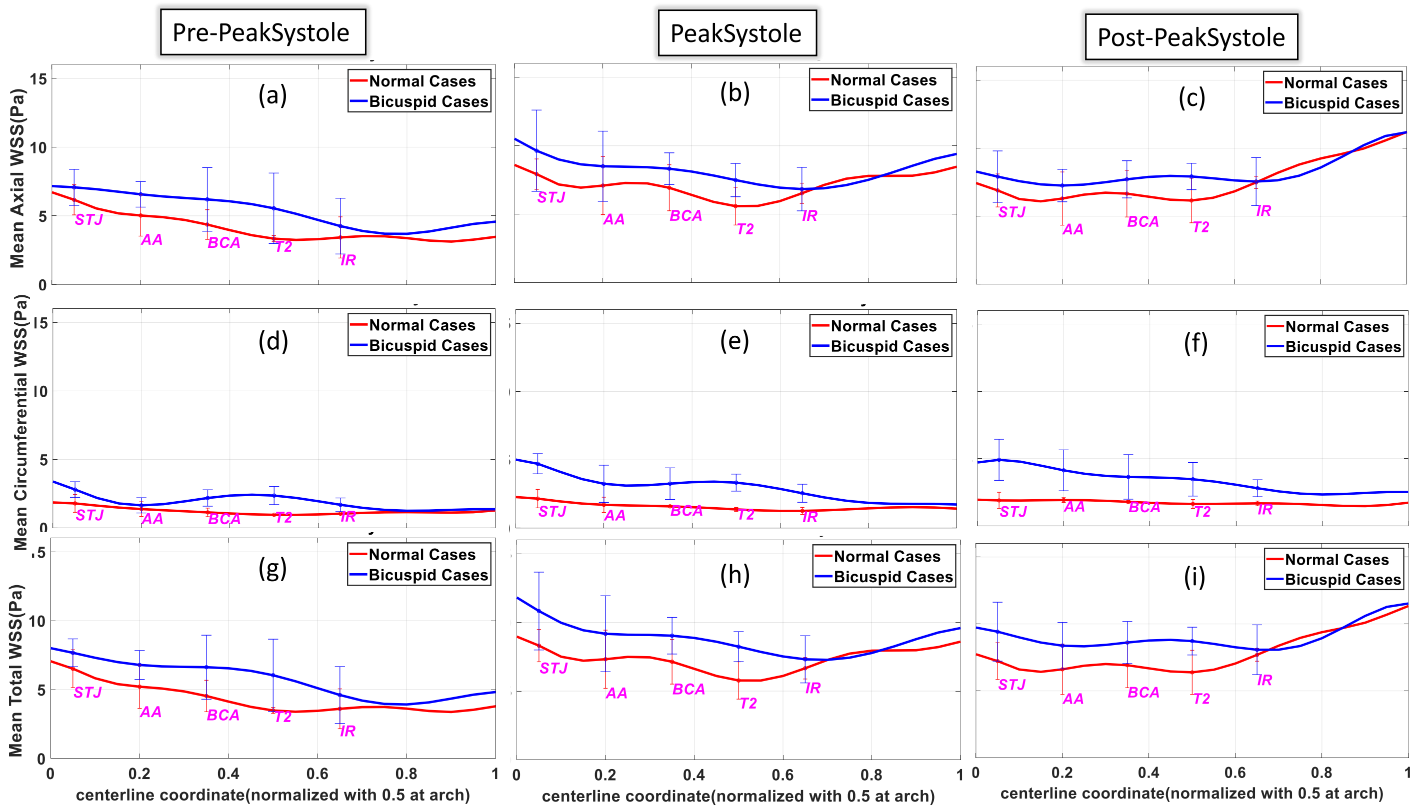
Where $\vec{\tau}$ is WSS vector , $\vec{n} = (n_1, n_2.n_3)$ is inward normal vector to the wall surface, η is dynamic viscosity of blood.

MRI pixel size : 1.5-3 mm

Esimated boundary layer thickness of aorta : 2 mm

Cubic spline interpolation was used (accepted standard in aorta research community) to ensure atleast 10 data points in boundary layer.

NORMAL vs BICUSPID : WALL SHEAR STRESS



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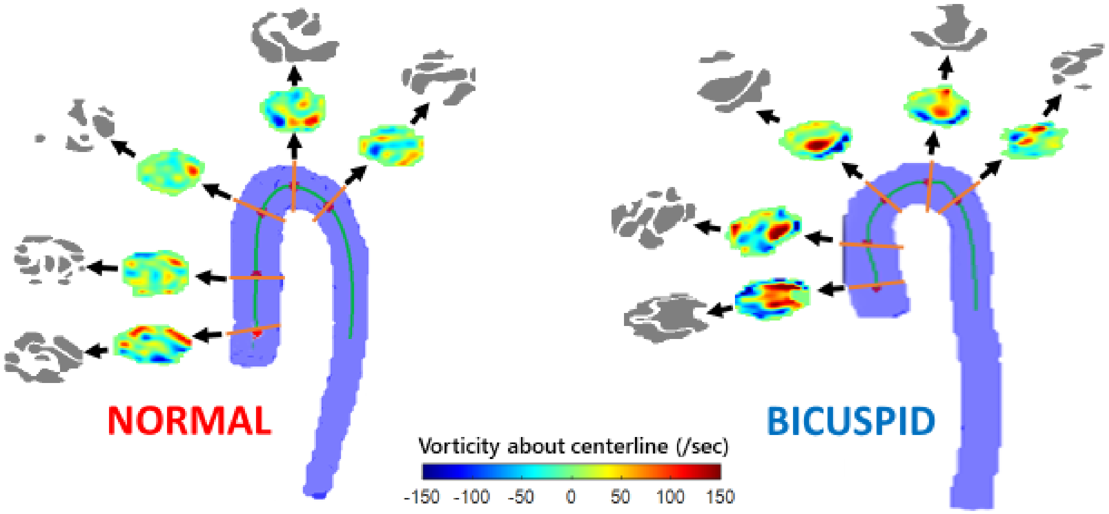
VORTICITY

Vorticity = $(\nabla \times \text{Velocity}) \cdot \overrightarrow{Centerline}$



Each segment with continuous vorticity direction is considered as a ***flow structure***

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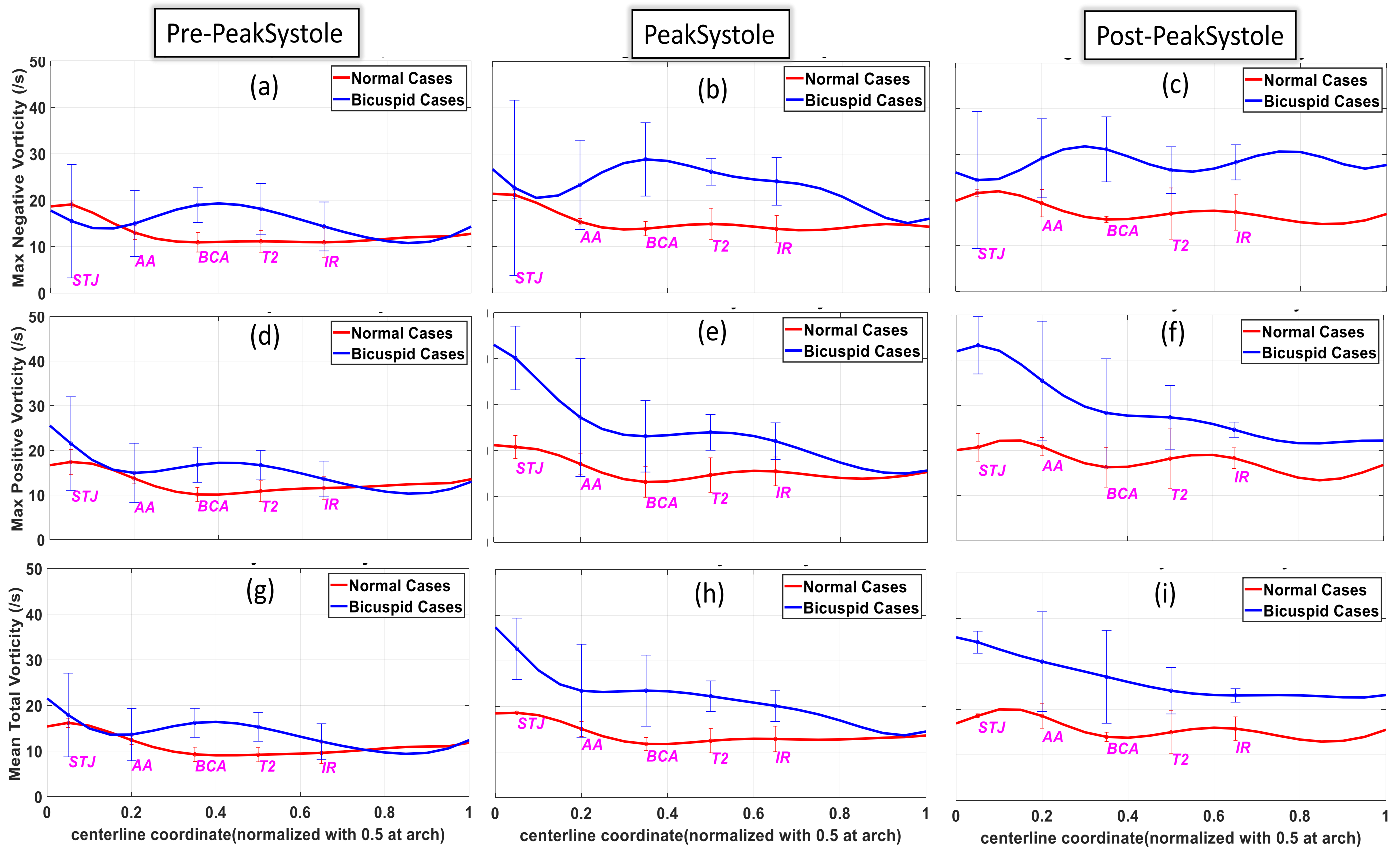
NORMAL vs BICUSPID : VORTICITY



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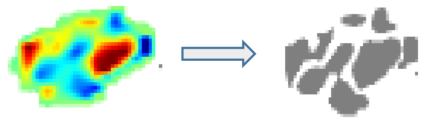
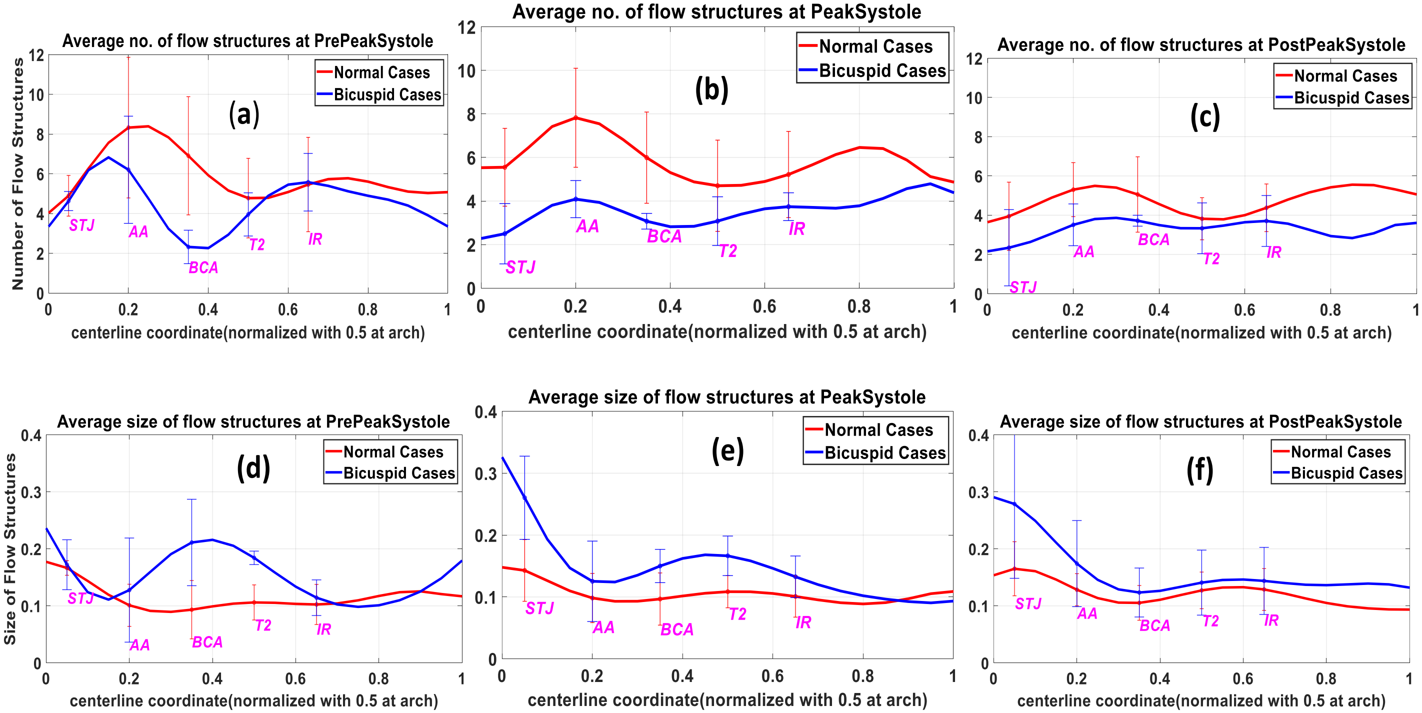
NORMAL vs BICUSPID : NUMBER/SIZE OF *flow structures*





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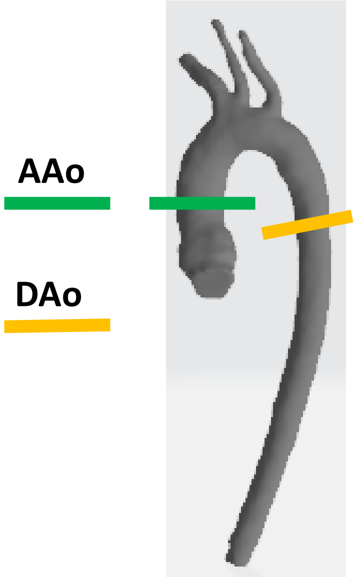
NORMAL vs BICUSPID : FLOW RATES

AAo - Ascending Aorta
DAo - Descending Aorta



	DAo/AAo (Peak)	DAo/AAo (whole cycle integrated)		DAo/AAo (Peak)	DAo/AAo (whole cycle integrated)
Normal 1	51%	53%	Bicuspid 1	62%	65%
Normal 2	40%	46%	Bicuspid 2	58%	70%
Normal 3	57%	56%	Bicuspid 3	68%	80%
Normal Avg	**49%**	**51%**	**Bicuspid Avg**	**62%**	**71%**

Typical Flow ratio of DAo/AAo used for previous research is *60%*

BLOOD FLOW CHARACTERISTICS

- <u>Reynolds Number</u>

$$\frac{\rho * Velocity * Diameter}{\mu} = \frac{1000\left(\frac{kg}{m^3}\right)*0.5\left(\frac{m}{s}\right)*0.02(m)}{3*10^{-3}(Pa.s)} \sim 3000$$

Turbulence transition Re for pipe flows ~ 2300 -4000

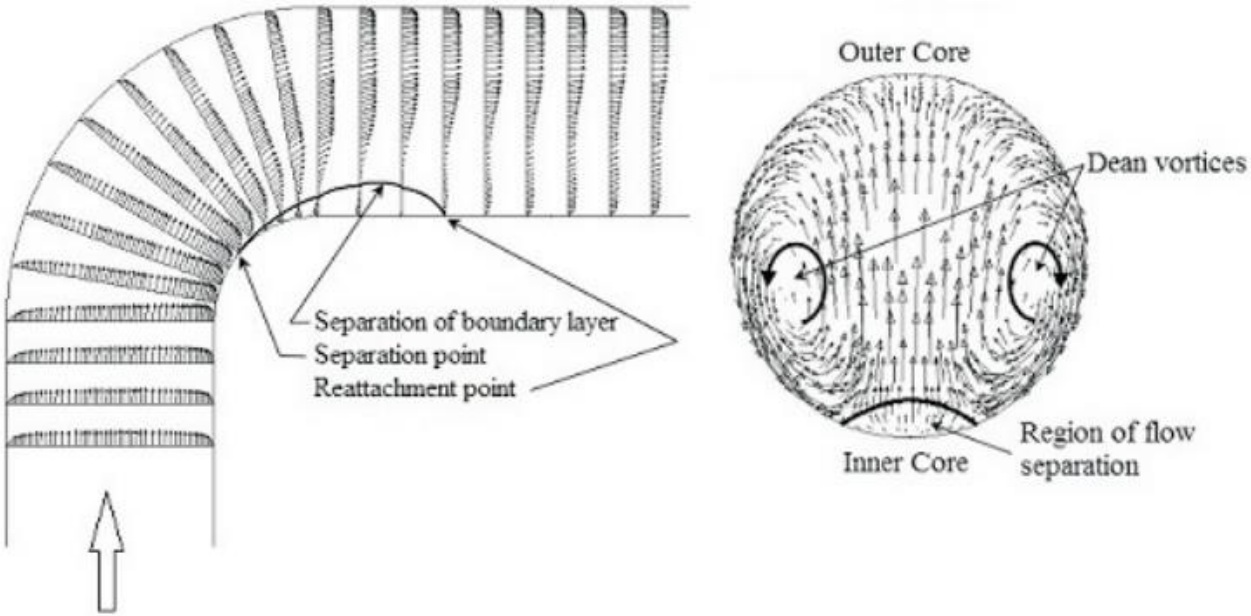
- <u>Newtonian/non-Newtonian behavior</u>

$$\tau = \mu * \frac{du}{dy} \quad , \mu \; is \; constant \; for \; newtonian \; fluids$$

Blood is a *shear thinning* fluid i.e., viscosity decreases with increase in shear strain. But, for large arteries, impact of non-Newtonian affects is still up for debate*.

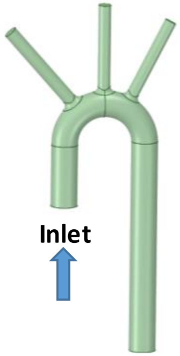
* (Amirhossein Arzani, 2018; Mohammed G Al-Azawy, 2017).

DEAN VORTICES



SOURCE : *Dutta P, Nandi N, 2015*

CFD MODELLING



- <u>Steady k-ω SST turbulence model with intermittency transition</u>
  - Well validated* RANS model for flows in aorta
  - $Y^+ \sim 2.5$, resolving laminar sublayer
  - 2nd order upwind method for spatial discretization with pressure-velocity coupling
  - Mass flow inlet of 20 Lit/min and pressure outlet conditions of 1 atm

* (FPP Tan et al., 2008; Mahalingam A et al.,, 2016).

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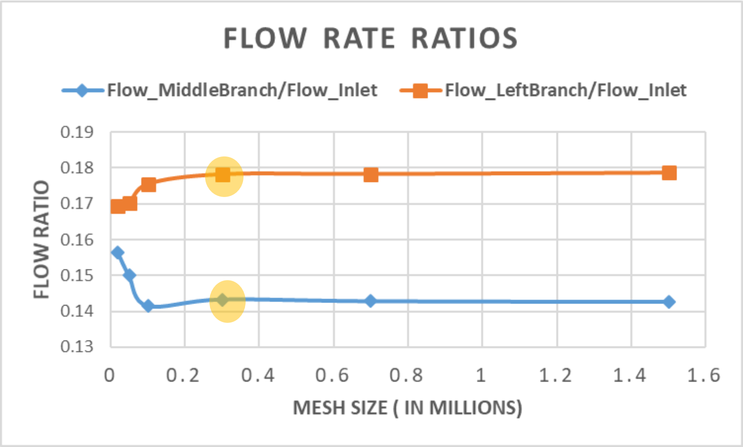
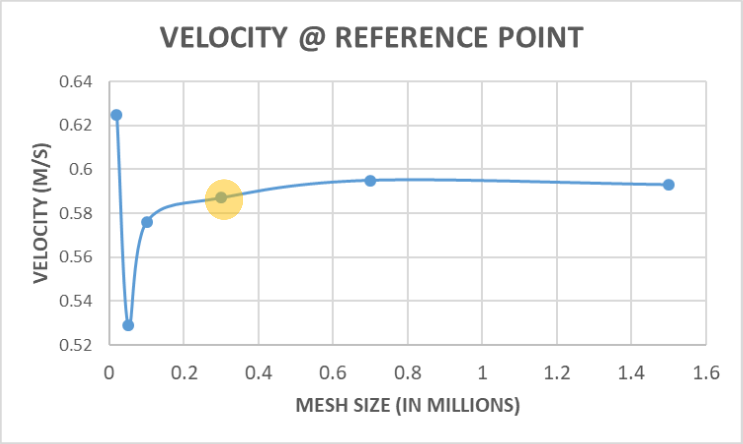
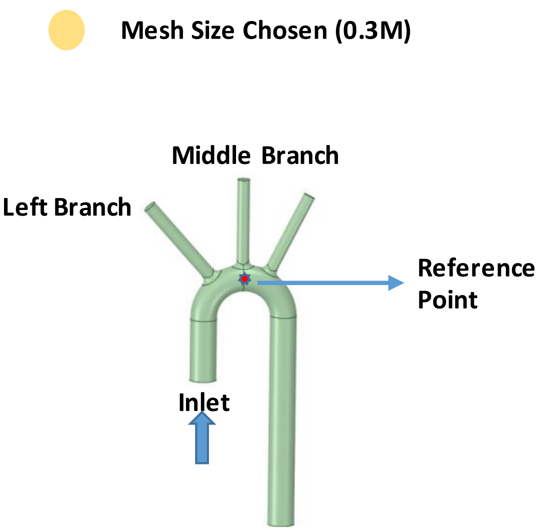
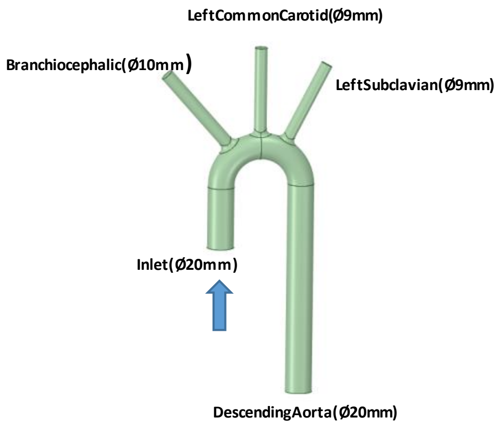
GRID INDEPENDENCE

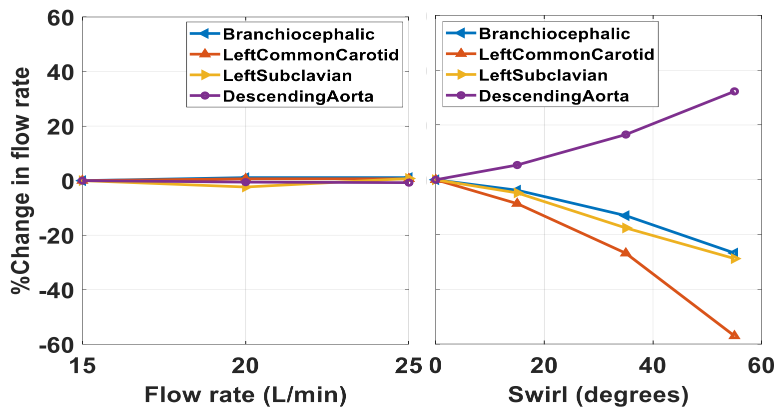




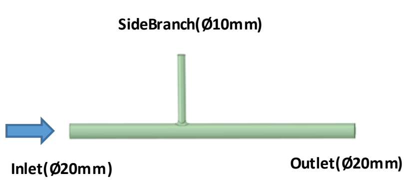


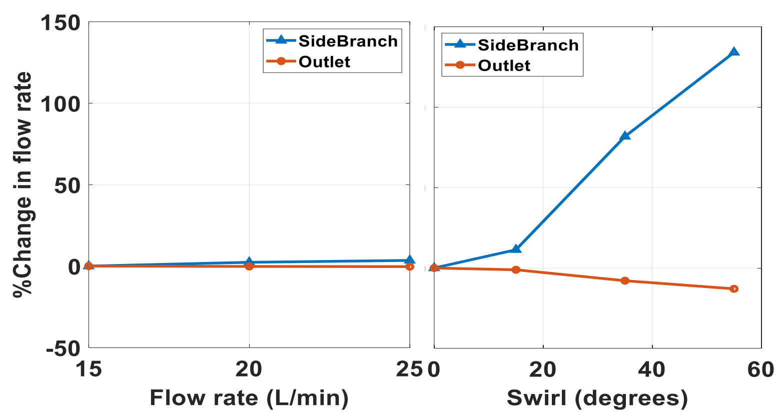
INFLUENCE OF SWIRL ON BRANCH FLOW DISTRIBUTION





<u>Bent Pipe</u> :
Swirl *decreases* side flows on outer curve





<u>Straight Pipe</u> :
Swirl *increases* side flows

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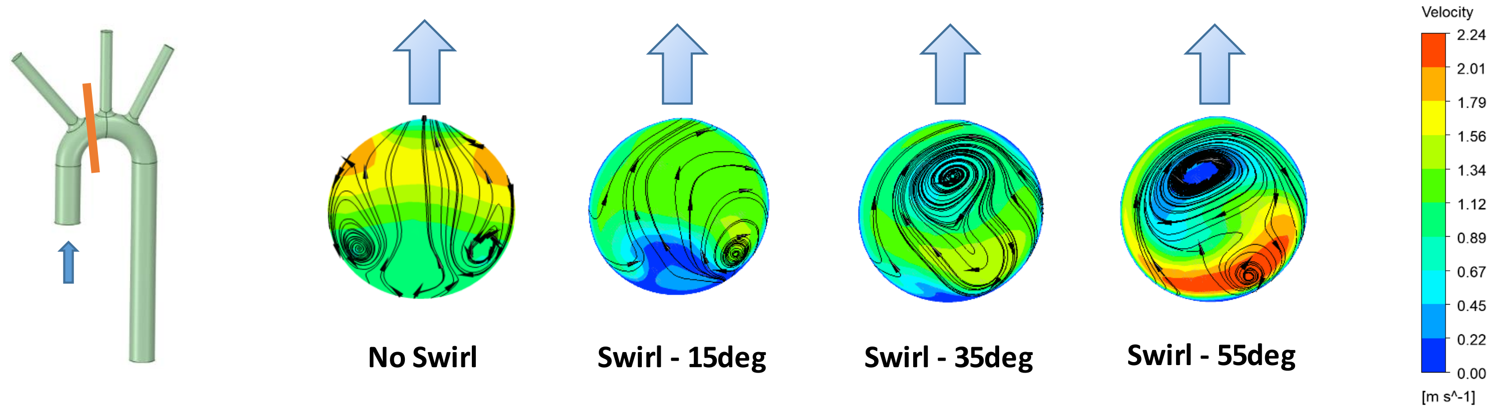
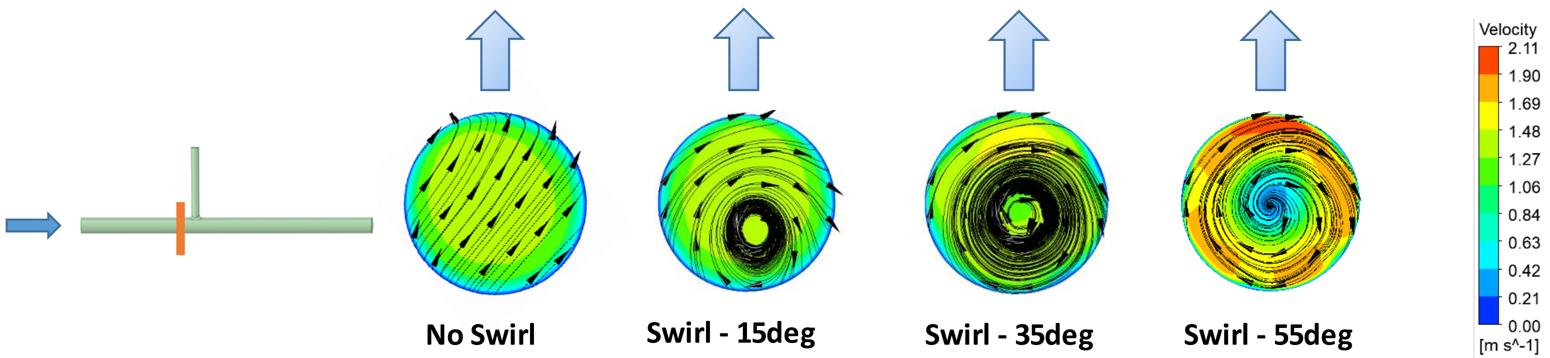
INFLUENCE OF SWIRL ON BRANCH FLOW DISTRIBUTION





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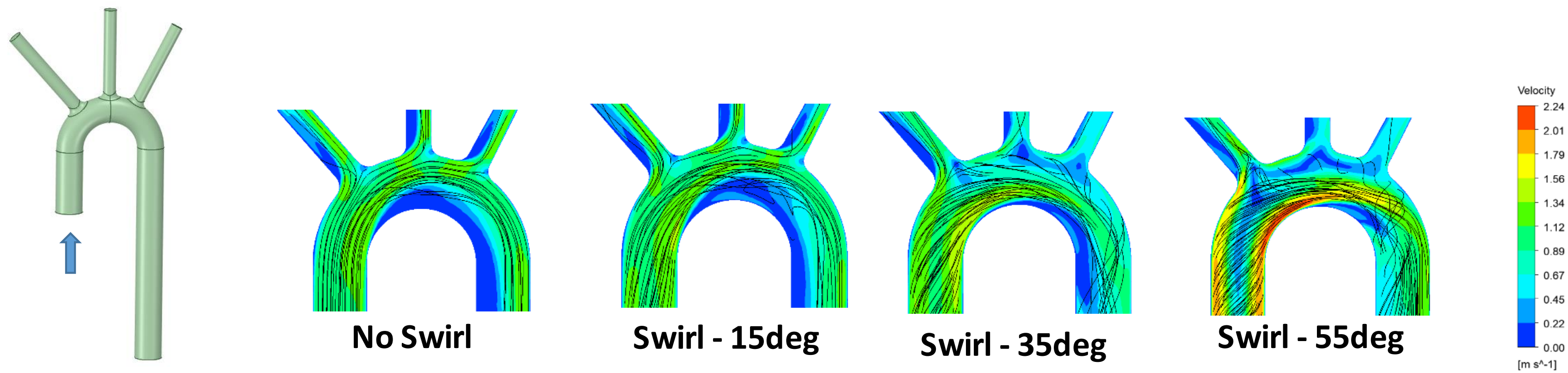
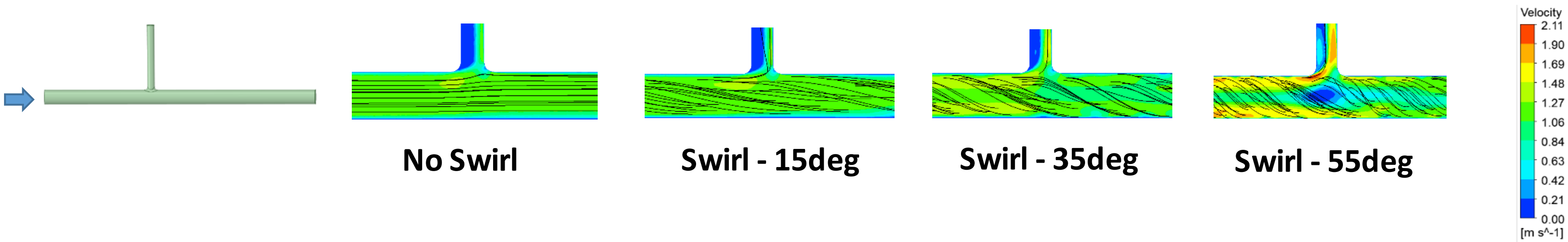
INFLUENCE OF SWIRL ON BRANCH FLOW DISTRIBUTION





Swirl increases the flow near boundaries. So, side branch flow increases in T-pipe. But , in a bent pipe, swirl decreases side branch flows on outer curve by dragging flow away from them. So, if the side branches are on inner curve, swirl increases the side flows even in bent pipe.

KEY FINDINGS

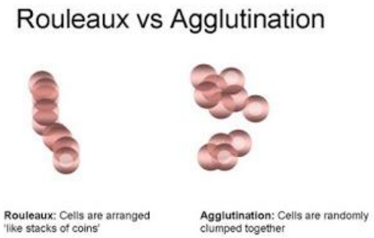
- <u>OBSERVATION</u> : Asymmetry in the leaflet structures of BAVs and TAVs
  <u>IMPACT</u> : Considerable differences in vorticity

- <u>OBSERVATION</u> : Curvature of the aorta subdues the vorticity in the flow
  <u>IMPACT</u> : Similar stress values for BAV and TAV in DAo.

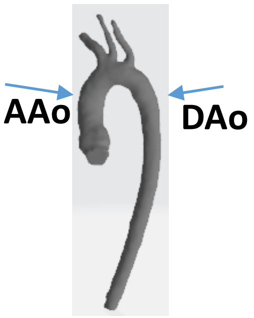
- <u>OBSERVATION</u> : Size of *flow structures vary along the aorta and based on the valve type*
  <u>IMPACT</u> : Does this affect the clumping nature of RBCs and make BAVs more Non- Newtonian ?

- <u>OBSERVATION</u> : Descending aorta can have higher stress than ascending aorta sections in the later half of systole
  <u>IMPACT</u> : Descending section of aorta is also susceptible to tissue damage

- <u>OBSERVATION</u> : Swirl decreases the flow into aorta branches because of its curvature.
  <u>IMPACT</u> : Does this affect the blood flow going into brain significant enough to cause dementia or other neuro cognitive disorders ?
  <u>IMPACT</u> : Oil & Gas Industry, Water transportation



SOURCE : Rexchimex.com



Publications :

- First author manuscript (under review at Journal of Biomechanics)

Influence of aortic valve morphology on vortical structures and flow distribution in the proximal thoracic aorta
Contribution : MRI processing, Modelling, Simulation, Post-processing, Manuscript preparation

- Co-authored publications

Sundström E, Jonnagiri R, Gutmark-Little I, et al. Effects of Normal Variation in the Rotational Position of the Aortic Root on Hemodynamics and Tissue Biomechanics of the Thoracic Aorta. Cardiovasc Eng Technol. 2020;11(1):47-58. doi:10.1007/s13239-019-00441-2
Contribution : MRI processing

Sundström, E., Jonnagiri, R., Gutmark-Little, I., Gutmark, E., Critser, P., Taylor, M. D., & Tretter, J. T. (2020). Hemodynamics and tissue biomechanics of the thoracic aorta with a trileaflet aortic valve at different phases of valve opening. International Journal for Numerical Methods in Biomedical Engineering, 36(7). http://doi.org/10.1002/cnm.3345
Contribution : MRI processing

Presentations :

- *Clinical and Engineering Frontiers in Pediatric and Congenital Heart Disease, Philadelphia, May 2019*
- *Dayton Symposium (DCASS), March 2019 & March 2020*

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CURRENT WORK : VALVE MODELLING & FSI

- Pulsatile flow with windkessel model
- Moving valve
- Compliant aorta

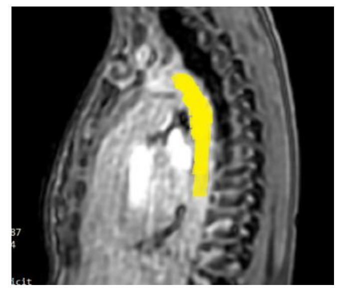
THANK YOU !

BACK UP SLIDES

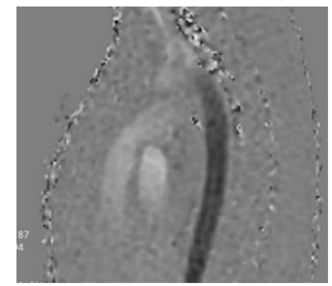
METHODOLOGY – MRI PROCESSING

Regular MRI

Phase Contrast MRI



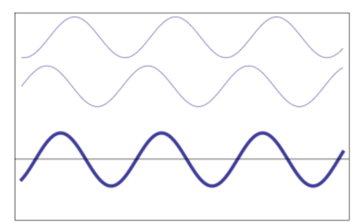
Magnitude



Direction

Magnetic Resonance Imaging (MRI) : protons in water nuclei of tissue are aligned in magnetic field, excited with radio waves and relaxed. Emitted radiation is proportional to protons i.e., water content

Phase Contrast MRI (PCMRI) : phase of emitted radiation depends on speed of moving protons in a gradient field, which can also be obtained as intensity.



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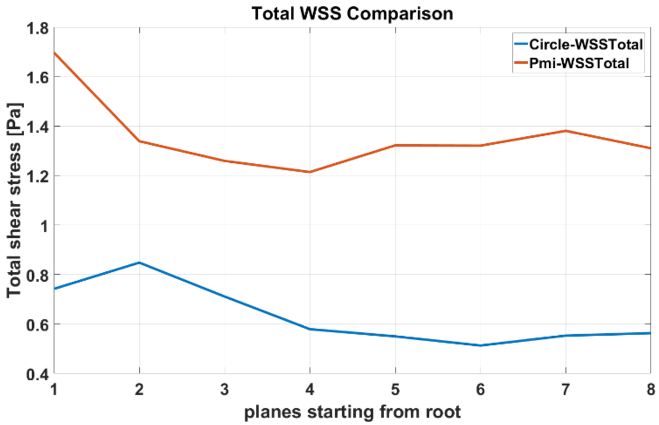
PROBLEMS WITH MRI PROCESSING SOFTWARE

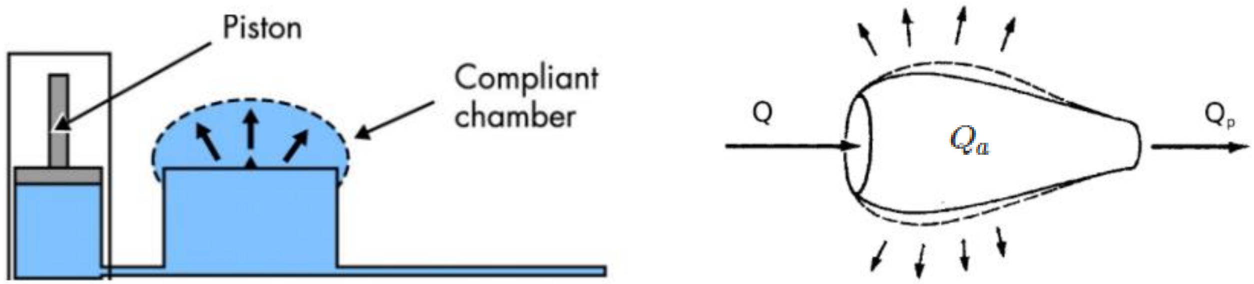
- Flow analysis limited to shear stress and pressure
- Restrictions on exporting data for further analysis
- No transparency in mathematical models used
- Different results from different software



VELOCITY CORRECTIONS IN MRI

- Remove pixels with low magnitudes
- Eddy current offset errors reduced based on static tissue

WINDKESSEL MODEL



$$Q = Q_a + Q_p = \frac{\partial V}{\partial p}\frac{\partial p}{\partial t} + \frac{p}{R}$$

$$\frac{\partial p}{\partial t} + \frac{1}{RC}p = \frac{Q(t)}{C}$$

R – peripheral resistance, C – arterial compliance, P – pressure

- SOURCE : Hellevik@NTNU, 2018

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