Master thesis in Biomedical Engineering

Hydraulic Losses In Fontan Procedure For The Treatment Of The Univentricular Heart In Infants. A Numeric Study.

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OUTLINE

- Physiology: functioning of cardiovascular system
- Pathology: single ventricle heart defect
- Treatment: surgical steps

- Case of Study
  - Aim
  - Geometry
  - CFD Method

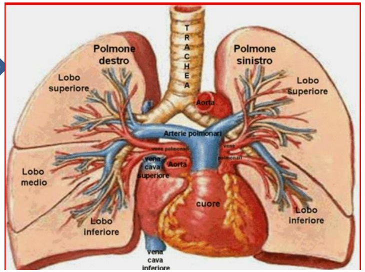
- Pre-processing Steps

- Sensitivity analysis

- Fluid dynamic simulation
  - Assumptions and Boundary Conditions
  - Hemodynamic Descriptors

- Post-processing results

- Conclusions and Future Work



Pulmonary arteries

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Right ventricle

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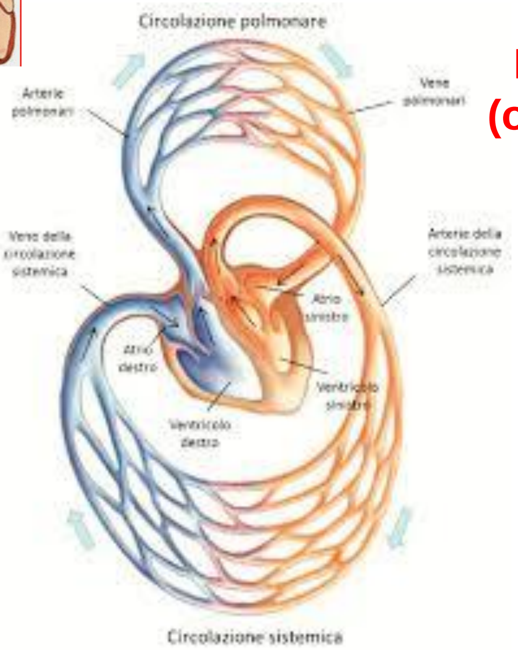
Right atrium (deoxygenated blood)

↗ ↖

SVC **IVC**



http://sistemacardiovascolare.blogspot.it/2015_05_01_archive.html

Pulmonary veins (oxygenated blood)

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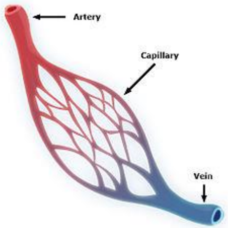
Left atrium

↑

Left ventricle

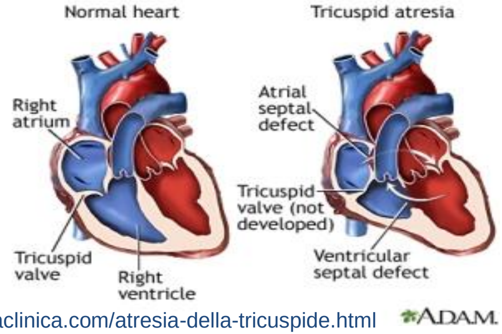
↑

Aorta



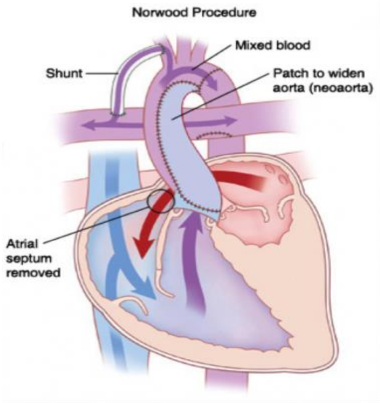
PATHOLOGY: Single Ventricle Heart Defect (SVHD)

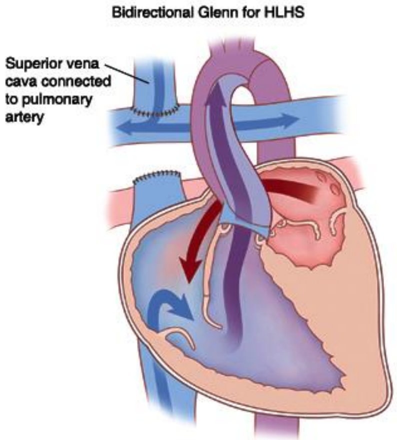
Congenital cardiovascular defect presents in 2% of infants.

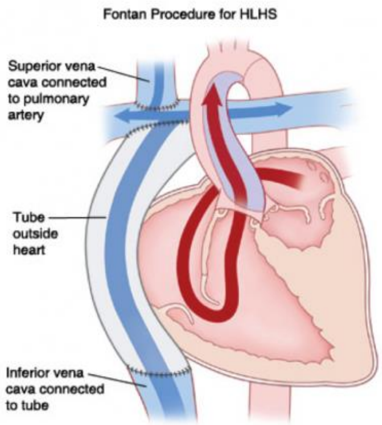


http://malattiaclinica.com/atresia-della-tricuspide.html

3 surgical steps







https://sites.psu.edu/rclwilliamspassion/2015/10/21/say-goodbye-to-open-heart-surgery

TREATMENT: Single Ventricle Heart Defect (SVHD)

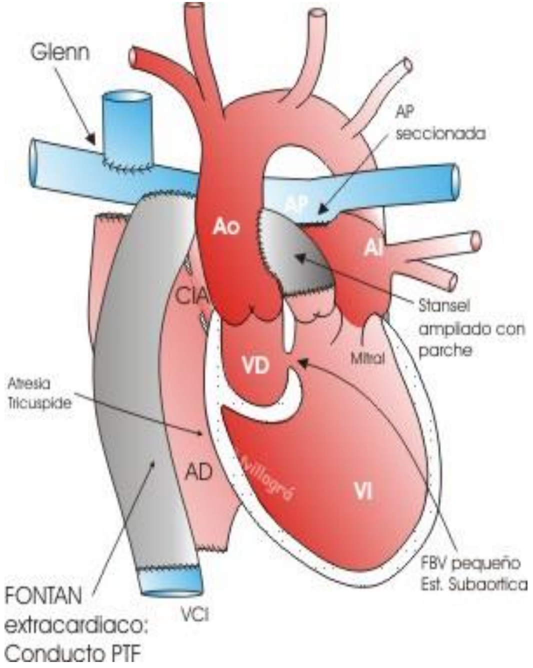
There are three variation of the ***Fontan procedure***:

1.Atriopulmonary connection (APA)

2.Intracardiac later tunnel total cavopulmonary connection (TCPC)

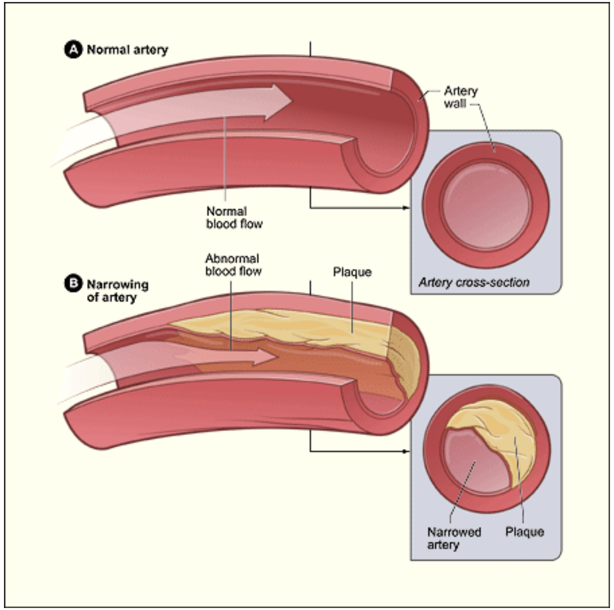
3.Extracardiac total cavopulmonary connection (TECPC)

TECPC model



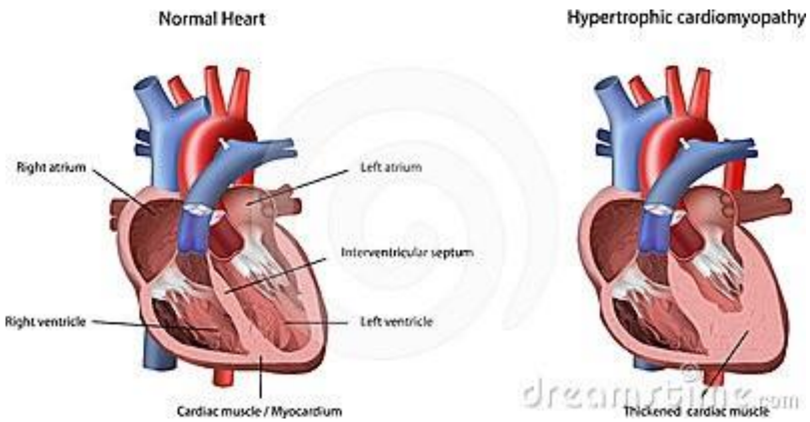
http://www.cardiopatiascongenitas.net/tipos_cc_n_vutxt.htm

Cardiovascular complication in the TECPC model



http://gattiforestenorvegesi.myblog.it/2012/11/03/test-cardiomiopatia-ipert

Endothelial cells, when subjected to low shear stresses, assume a rounded shape that leads to formation of gaps and therefore of atherosclerotic plaques.



http://gattiforestenorvegesi.myblog.it/2012/11/03/test-cardiomiopatia-ipert

If the energy dissipation exceeds tolerable levels, it has a huge impact on the functioning, that working more atrophies or dilates compromising irreversibly its function.

CASE OF STUDY

AIM

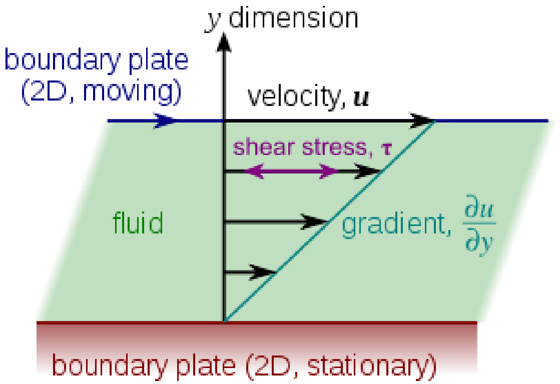
Evaluation of the local hemodynamics **WSS**

↓

To predict sites prone to cardiovascular complication

- The WSS, which has influence on vessels physiology, is defined as :

$$\tau = \mu \frac{\partial u}{\partial y}$$



https://en.wikipedia.org/wiki/Viscosity

It has influence on the blood behaviour; μ is the dynamic viscosity, u is the velocity parallel to the wall and y is the normal coordinate to the wall.

CASE OF STUDY

AIM

Calculation of **Hydraulic losses** in a TECPC model

⇓

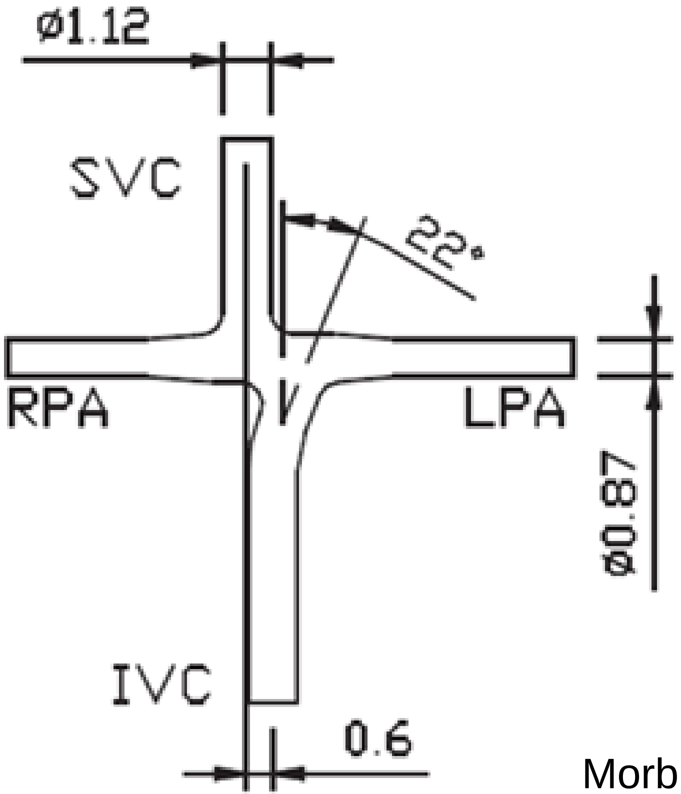
to preserve the functioning of the heart

- The **Energy loss**, which has influence on vessels physiology, is defined as :

$$E_{loss} = \left(\frac{1}{2}\rho v_{SVC}^2 + p_{SVC}\right) + \left(\frac{1}{2}\rho v_{IVC}^2 + p_{IVC}\right) - \left(\frac{1}{2}\rho v_{RPA}^2 + p_{RPA}\right) - \left(\frac{1}{2}\rho v_{LPA}^2 + p_{LPA}\right)$$

CASE OF STUDY

GEOMETRIC MODEL



Morbiducci et al. (2003)

CASE OF STUDY

CFD METHOD

Our computational fluid dynamic (**CFD**) analysis is based on the finite volume methods (**FVM**):

- ✓ **High spatial** and temporal resolution
- ✓ **robust tool** support the study of fluid dynamics

Fluid motion is overall governed by:

- ➢ the conservation of mass equation

$$\frac{\partial P}{\partial t} \nabla (\rho v) = 0$$

- ➢ the conservation of momentum equation

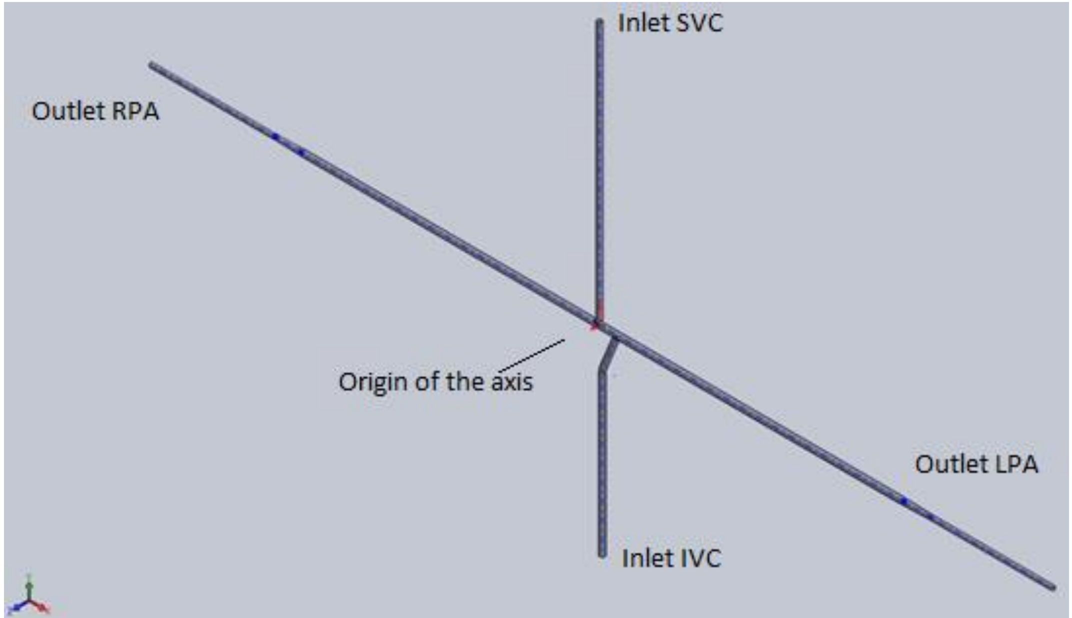
$$\frac{\partial v}{\partial t} + v \cdot \nabla v = -\frac{1}{\rho}\nabla p + \upsilon \nabla^2 v$$

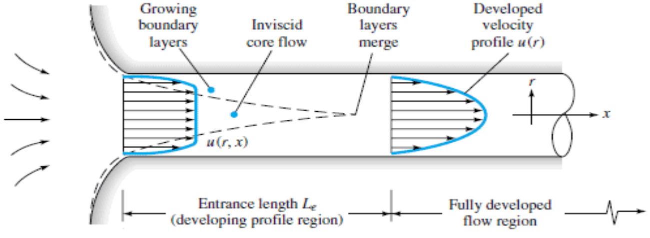
PRE-PROCESSING STEPS

CAD of geometrical model

$$Re = \frac{inertial\ forces}{viscous\ forces} = \frac{\rho v L}{\mu} < 2000$$ → **Laminar flow regime**

$$L_{e,laminare} = 0.05 * Re * D$$





Velocity Profile of Fluid in a Pipe (laminar Flow)

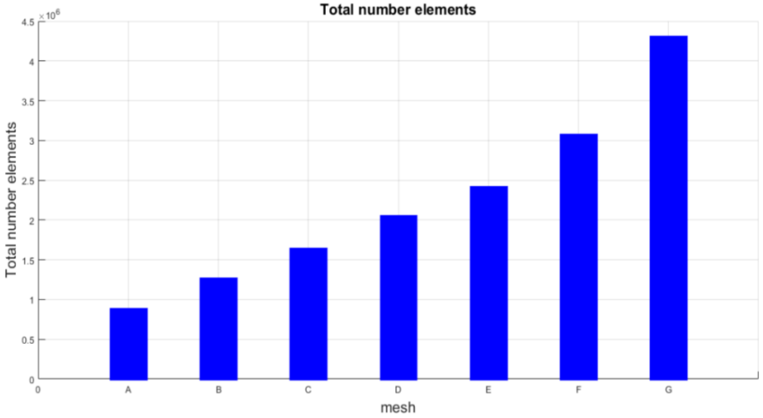
http://pcfarina.eng.unipr.it/dispense98/Aleotti106334/aleotti106334.htm

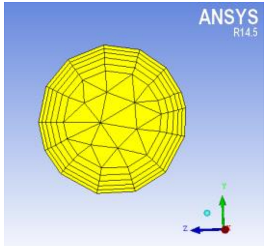
Total Flow rate	3 *l/min*
Flow rate SVC	1,2 *l/min*
Flow rate IVC	*1,8 l/min*
Flow rate RPA	*1,5 l/min*
Flow rate LPA	*1,5 l/min*

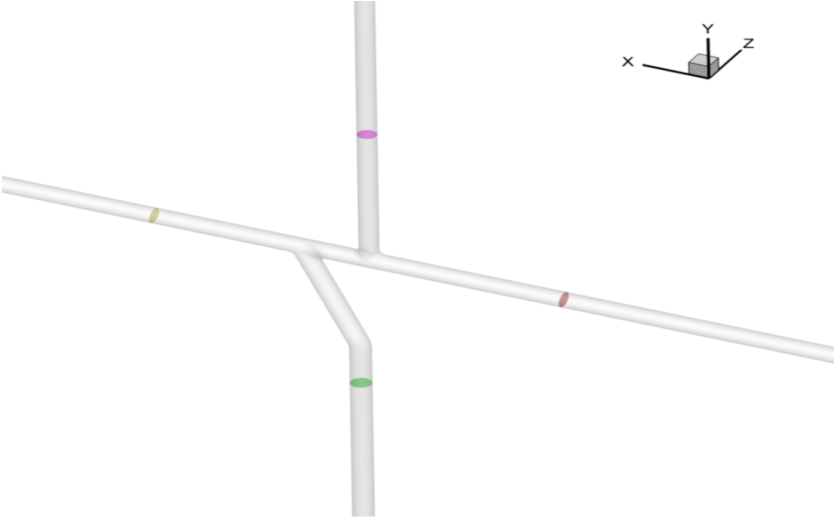
SENSITIVITY ANALYSIS

Sensitivity study : grid spatial resolution for this kind of fluid dynamic analysis

Seven meshes : creating with ANSYS ICEM® 14.5 testing through steady-state simulations comparing by evaluating hemodynamic variables (velocity and WSS).



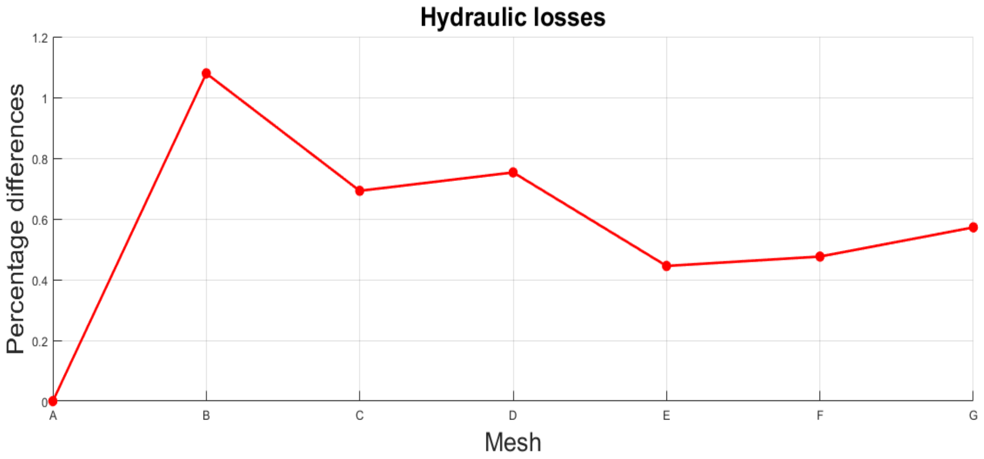




To analyse the results of the sensitivity analysis, all values obtained for each mesh were compared to their percentage differences.

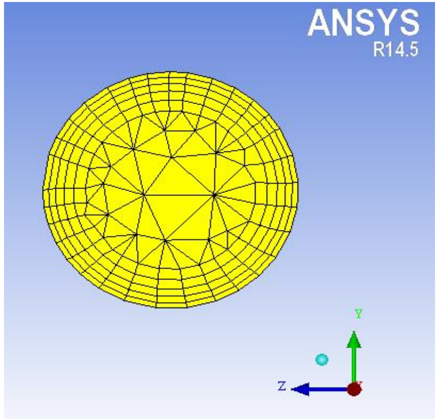
SENSITIVITY ANALYSIS

- **Calculation of hydraulic losses**



Low percentage difference between mesh G and F

The **mesh F** with **3.076.423** total elements is considered the 'best' because it allows to achieve the right balance between ***accuracy solution*** **and** ***computational costs***.



METHODS

Assumptions and boundary conditions

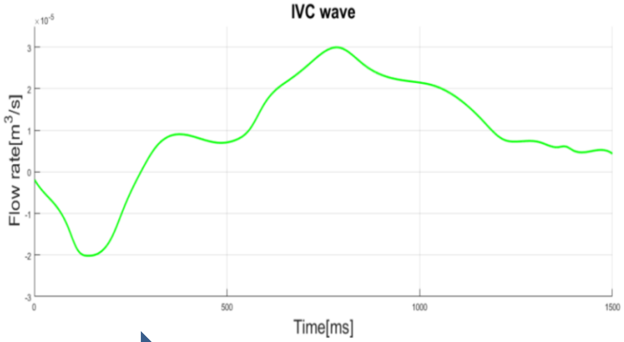
UNSTEADY SIMULATIONS are useful in order to simulate blood pulsating behaviour

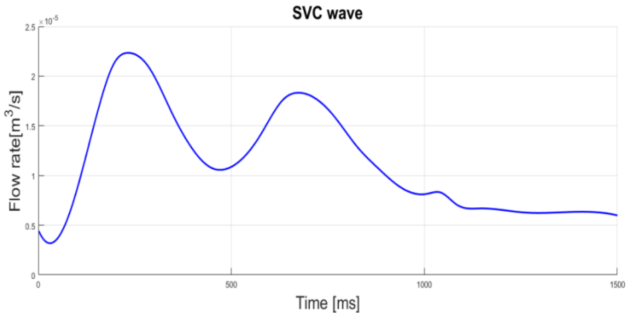
BLOOD rheological behaviour → Newtonian Fluid

WALL → rigid behaviour, no-slip condition

INLETS → a time dependent flow rate profile, given by a Fourier series interpolation of velocity samples, obtained by a article in literature

Yoganathan (2002)





OUTLETS → a 50/50 flow rate repartition in right and left pulmonary artery

- The cardiac cycle, having a period of **1500 *ms*,** was divided into **time-steps (t-s= 2 *ms*).** Computational costs: 22 hours to perform 1 single cardiac cycle

METHODS

HEMODYNAMIC DESCRIPTOR

WSS-based hemodynamic descriptors **localize** specific sites, as regards the development of cardiovascular complications.

The evaluated hemodynamic wall parameters (HWPs) are:

Time Averaged WSS

$$TAWSS = \frac{1}{T}\int_0^T |\boldsymbol{WSS}(\boldsymbol{s},t)| \cdot dt$$

TAWSS < 0.4 $^{N}/_{m^2}$ leads to plaque formation

Oscillatory Shear Index

$$OSI = \frac{1}{2}\left(1 - \left(\frac{|\int_0^T WSSdt|}{\int_0^T |WSS|}\right)\right)$$

high OSI values are related to intimal thickening

Relative Residence Time

$$RRT = \frac{1}{(1-2OSI)TAWSS} = \frac{T}{|\int_0^T |\boldsymbol{WSS}(\boldsymbol{s},t)| \cdot dt|}$$

high RRT values shows sites of thrombogenic risk

METHODS

HEMODYNAMIC DESCRIPTOR

Hemodynamic descriptors provide a description of the bulk flow structures, such as helical and vortical patterns, which influence the inflammatory response of the endothelial layer, because they create alterations in blood components residence time.

Local Normalized Helicity:

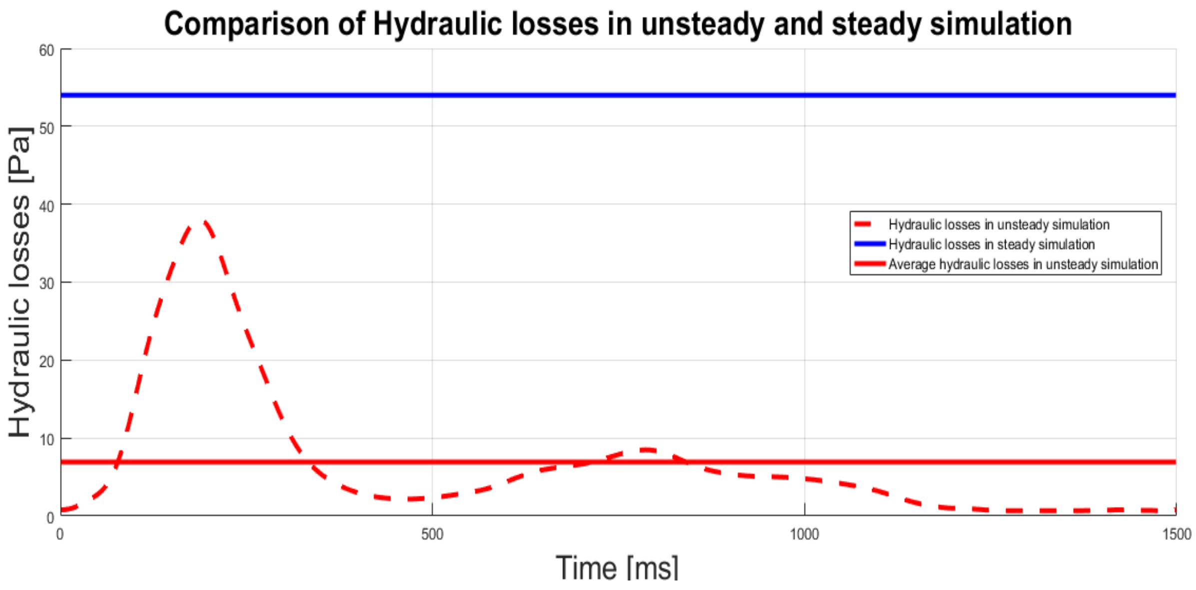
$$\boldsymbol{LNH}(\boldsymbol{x},t)=\frac{\boldsymbol{v}(\boldsymbol{x},t)\cdot\boldsymbol{w}(\boldsymbol{x},t)}{|\boldsymbol{v}(\boldsymbol{x},t)||\boldsymbol{w}(\boldsymbol{x},t)|}=\cos\varphi(\boldsymbol{x},t)$$

$$-1\leq LNH\leq 1$$

POST-PROCESSING RESULT

HYDRAULIC LOSSES

Comparison between hydraulic losses in steady simulation with the average flow rate of the unsteady simulation and unsteady model



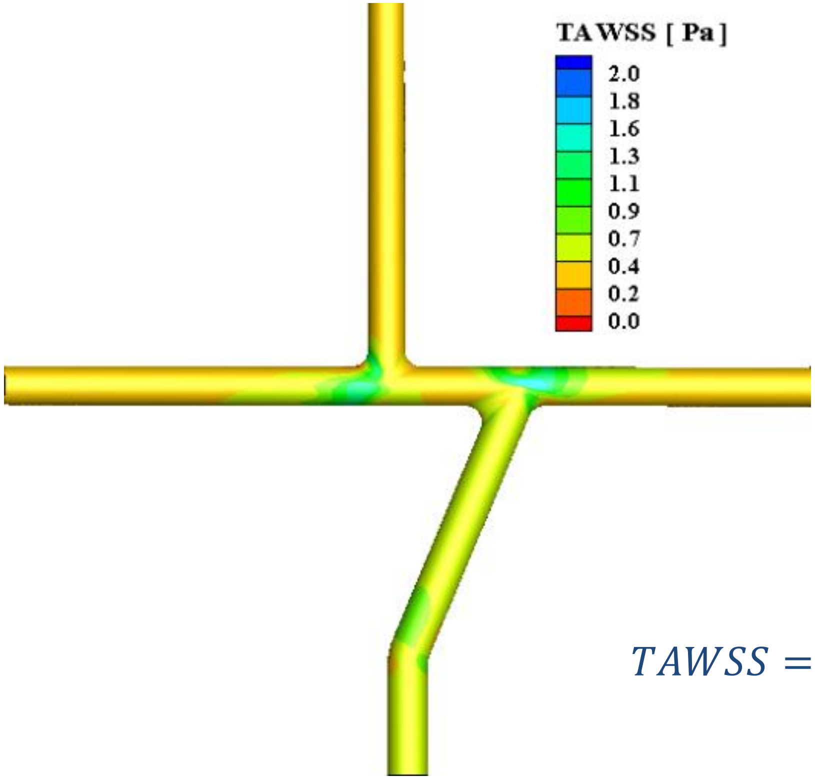
Hydraulic losses in steady simulation

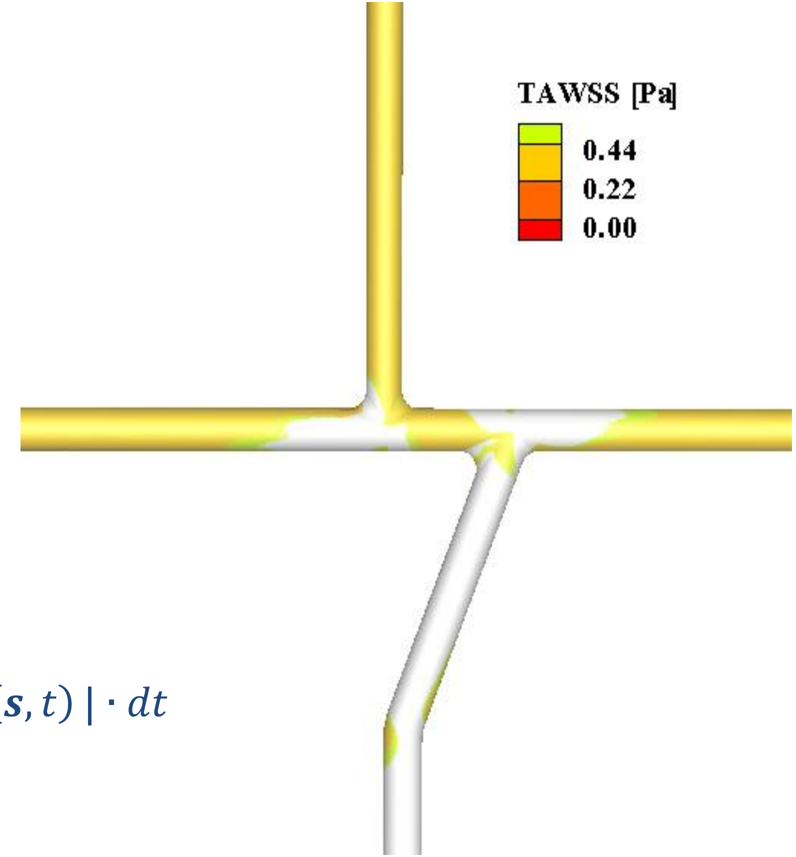
Hydraulic losses in unsteady simulation

Difference ≅48 Pa

POST-PROCESSING RESULT

TAWSS

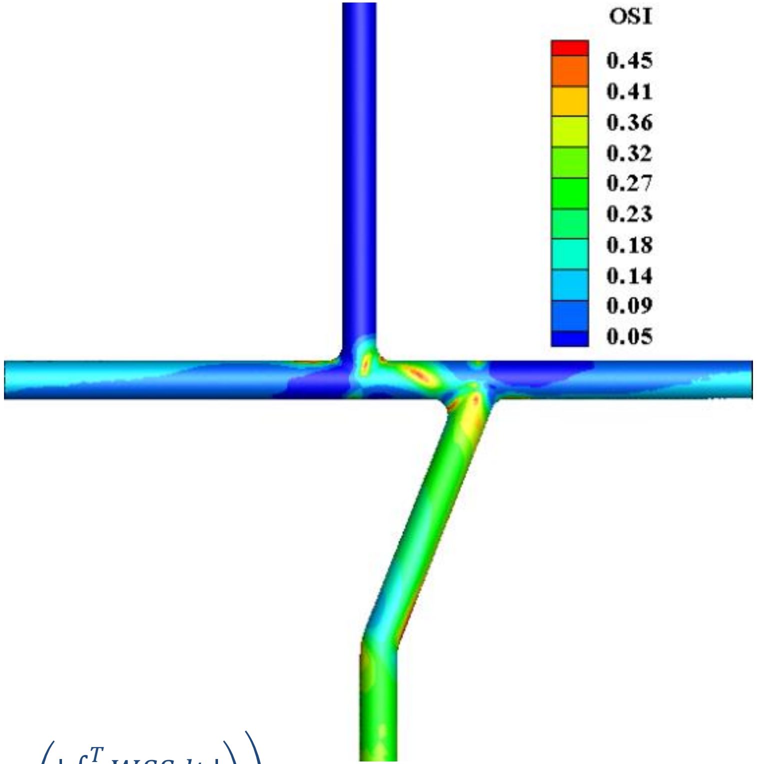




$$TAWSS = \frac{1}{T}\int_0^T |\boldsymbol{WSS}(\boldsymbol{s},t)| \cdot dt$$

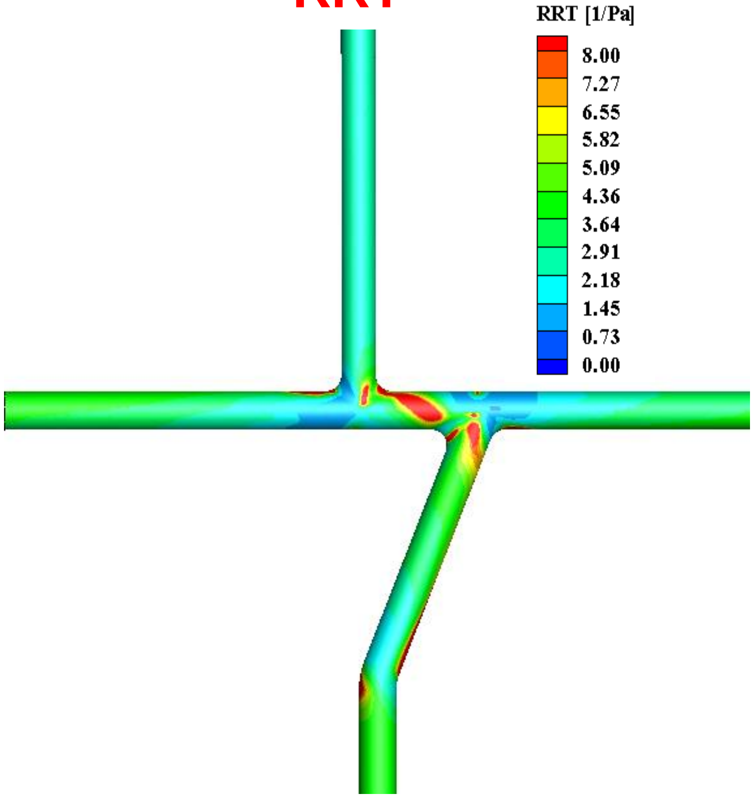
POST-PROCESSING RESULT

OSI



$$OSI = \frac{1}{2}\left(1 - \left(\frac{\left| \int_0^T WSSdt \right|}{\int_0^T |WSS|}\right)\right)$$

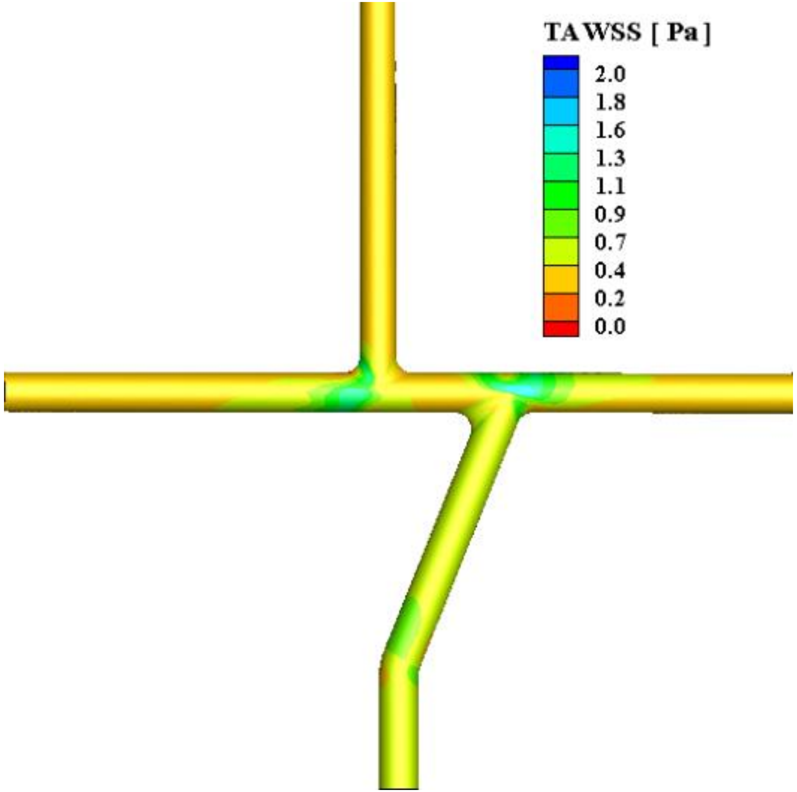
RRT



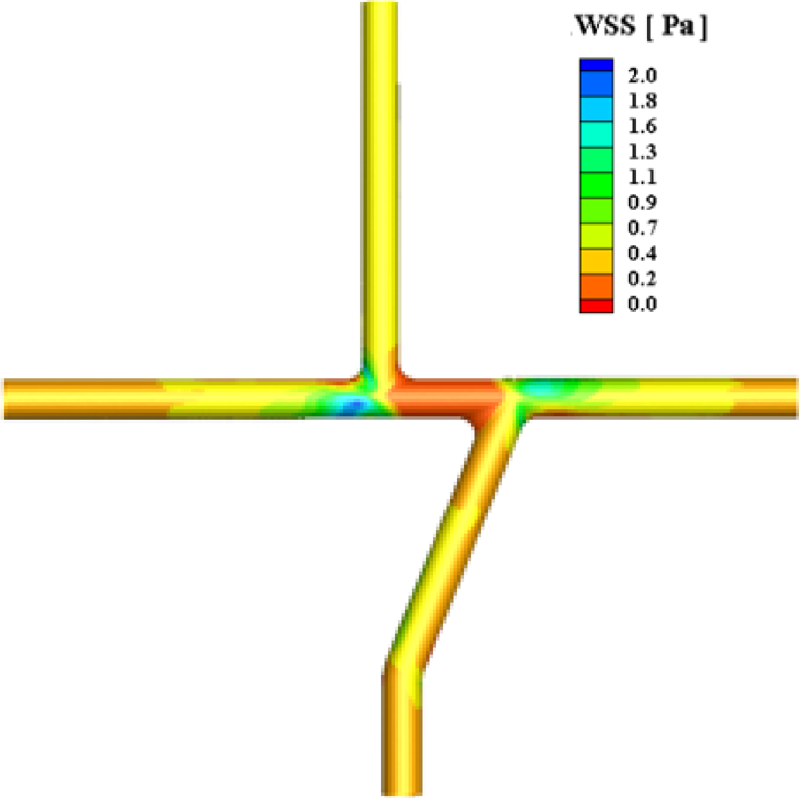
$$RRT = \frac{1}{(1 - 2OSI)TAWSS} = \frac{T}{\left| \int_0^T |\boldsymbol{WSS}(\boldsymbol{s}, t)| \cdot dt \right|}$$

POST-PROCESSING RESULT

TAWSS

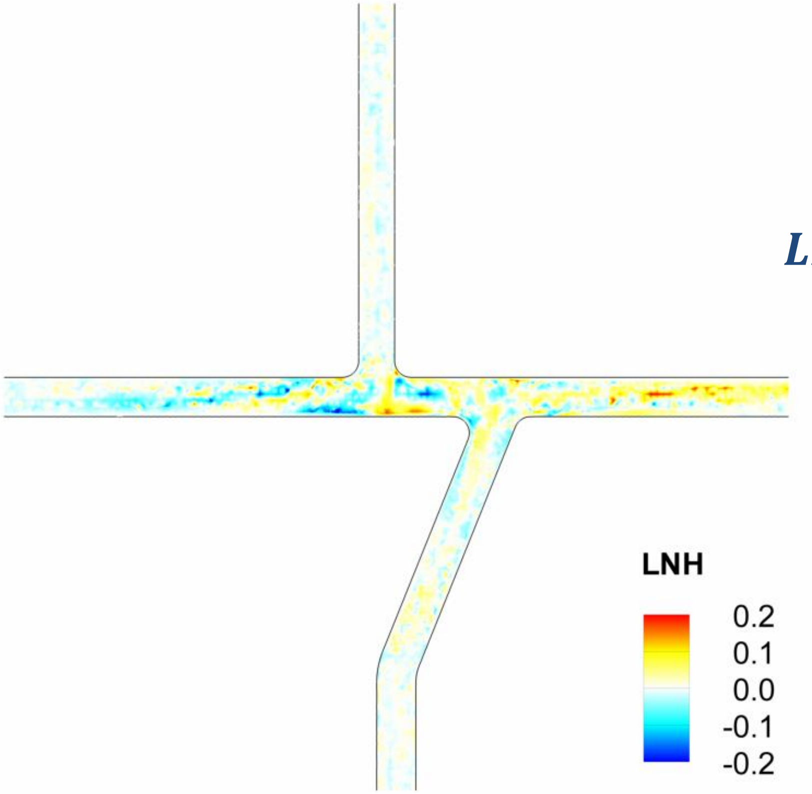


WSS in steady simulation



POST-PROCESSING RESULT

LNH



$$\boldsymbol{LNH}(\boldsymbol{x},t)=\frac{\boldsymbol{v}(\boldsymbol{x},t)\cdot\boldsymbol{w}(\boldsymbol{x},t)}{|\boldsymbol{v}(\boldsymbol{x},t)||\boldsymbol{w}(\boldsymbol{x},t)|}=\cos\varphi(\boldsymbol{x},t)$$

CONCLUSION

Hydraulic losses in unsteady & Steady model →	It is better used **UNSTEADY MODEL** for study hydraulic losses
WSS in unsteady & Steady model →	Same behaviour of WSS on the vessel wall
WSS-based approach →	the area of artery included between the venas cava, are subject to pro-atherogenetic behaviour
Bulk flow approach →	in the pulmonary artery the particles in the flow experience complete rotations in both the clock-wise and the counter clock-wise, identifying the present of sites in which there is a '**disturbed flow**', that is the sites prone to fibrointimal thickening and atherosclerotic plaque formation.

FUTURE WORK

- apply a fenestration to the model
- Realization of a model obtained directly from the patient's clinical images, using also values at the inlet obtained from the patient, in order to analyze a model that gives us the more reliable results.

Thank You for Your attention