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Santé INgénierie  
BIOlogie Saint-Etienne

U1059 • INSERM • SAINT-ETIENNE



Institut national  
de la santé et de la recherche médicale



VIII International Conference on  
Computational Bioengineering  
4-6 September 2019, Belgrade, Serbia

# Inverse problems in cardiovascular continuum mechanics and medical applications

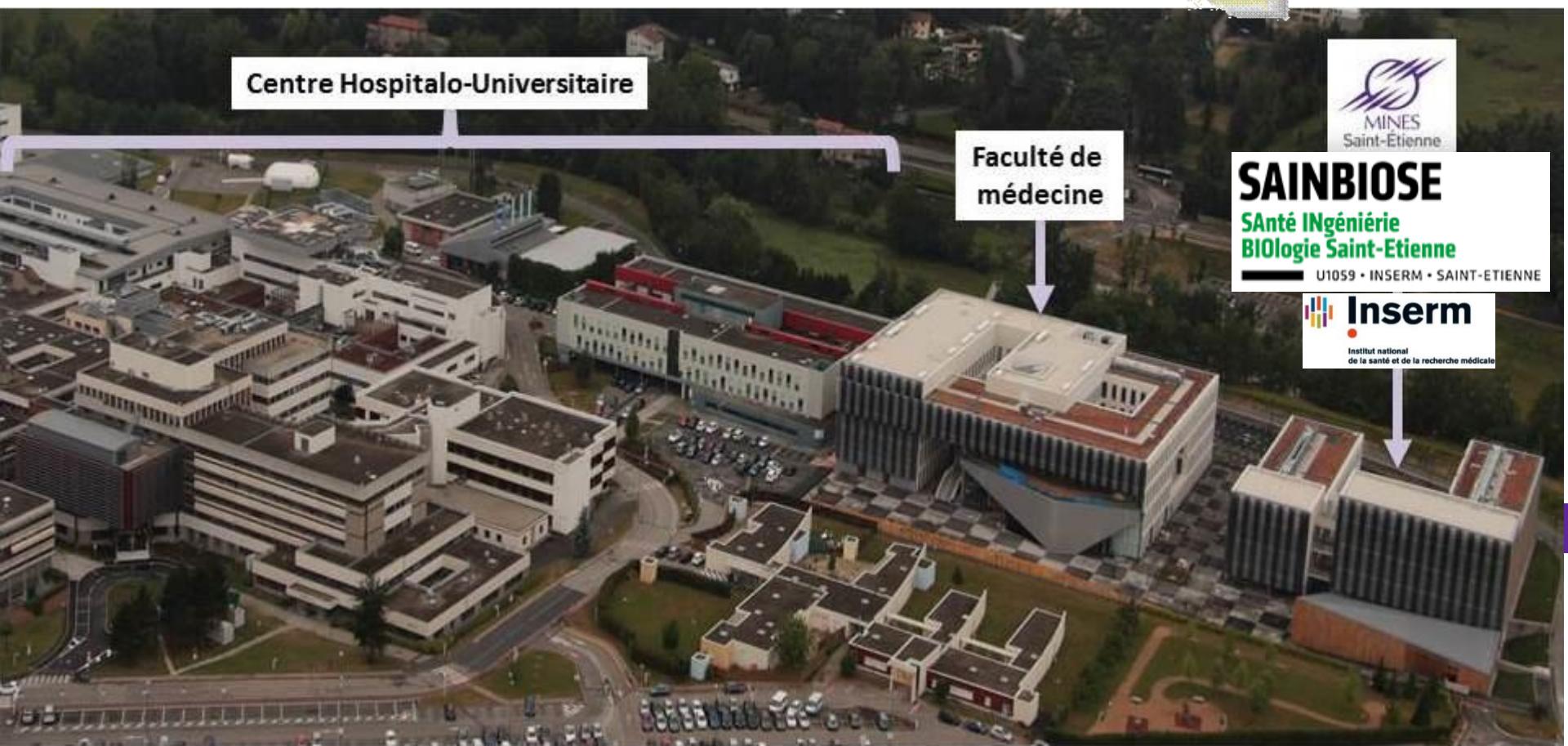
Prof. Stéphane AVRIL



**MINES SAINT-ETIENNE**  
First Grande Ecole  
outside Paris  
Founded in 1816

PARIS

AUVERGNE  
RHONE-ALPES

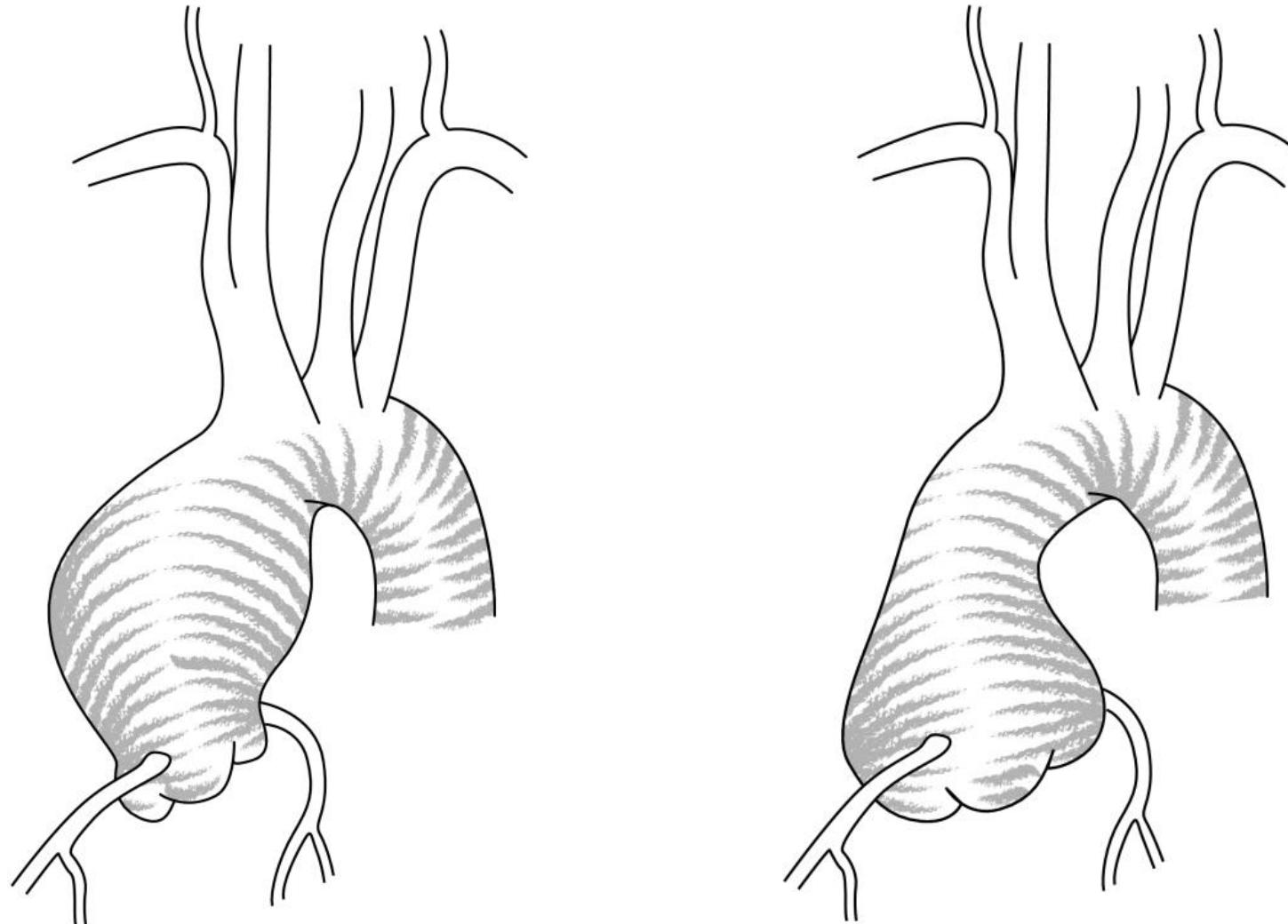


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# Aortic root dilatations and ascending thoracic aortic aneurysms (ATAA)



# Risks: Aortic dissections



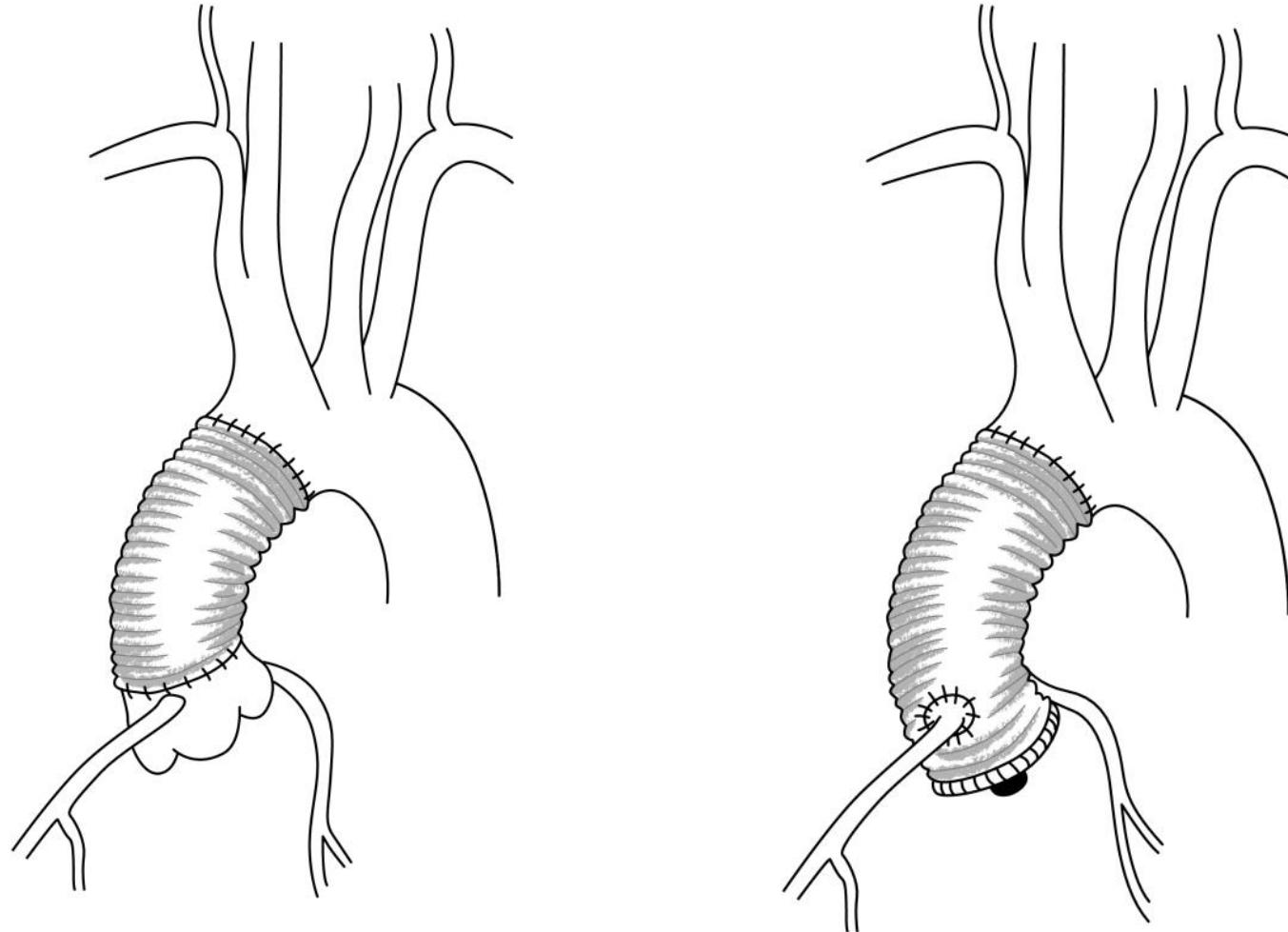
# Surgical elective repair of ATAA

## ■ Indications:

- Aortic insufficiency requiring surgical correction
- Size  $\geq 55$  mm
- Size  $\geq 50$  mm in patients with Marfan syndrome or bicuspid valves
- Growth rate  $\geq 1$  cm/year

- More and more aneurysms are detected at an early stage (incidence >8% for males >65 years old).
- >90000 interventions per year in Europe and USA

# Surgical techniques for ATAA repair

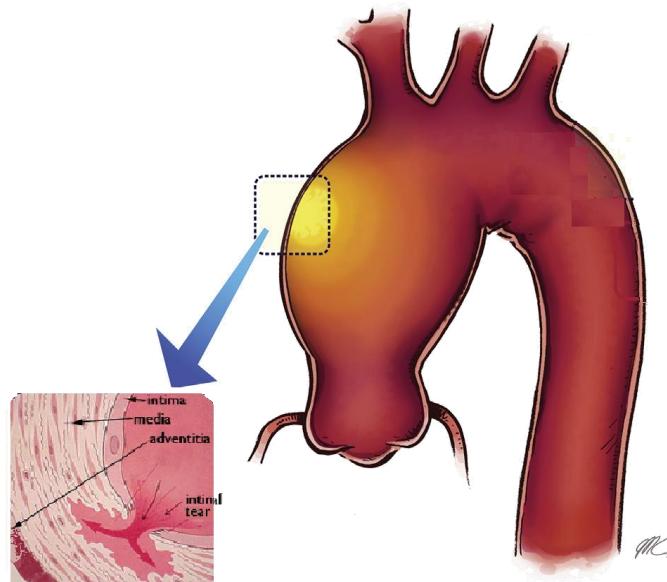
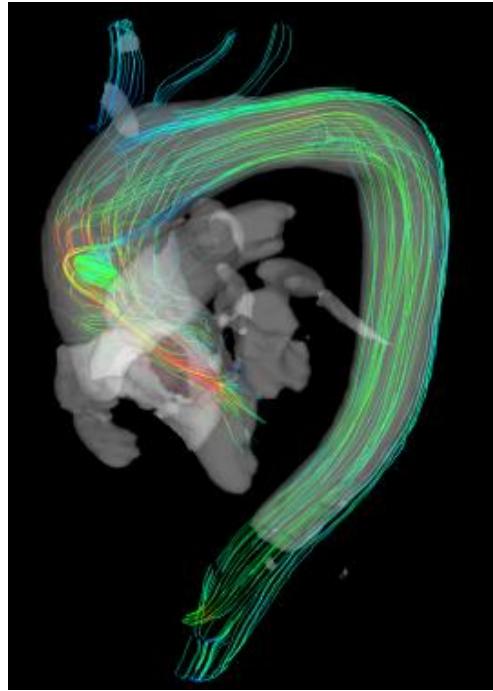


# Current situation

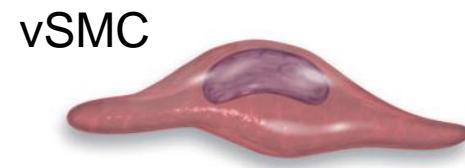
- **Current indications:**
  - 25% ATAA < 5.5cm rupture : 15000 deaths\*\*!
  - 60% of ATAA > 5.5 cm never experience rupture!
  - 9% mortality and morbidity after ATAA repair
- **In summary: inappropriate decisions and misprogrammed surgical interventions have major consequences!!**
- **Need insightful assistance from biomechanics ☺☺☺**

\*\* Pape et al, *Aortic Diameter ≥5.5 cm Is Not a Good Predictor of Type A Aortic Dissection Observations From the International Registry of Acute Aortic Dissection (IRAD)*, Circulation, 2007

# Background on Aneurysms and Dissections of the ascending thoracic aorta

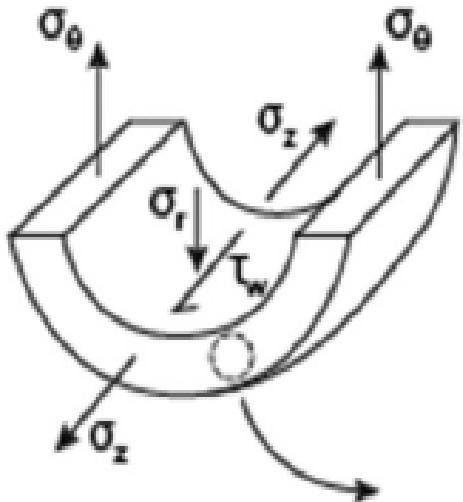


dissection



Humphrey et al, Science, 2014

# Basics of arterial mechanics

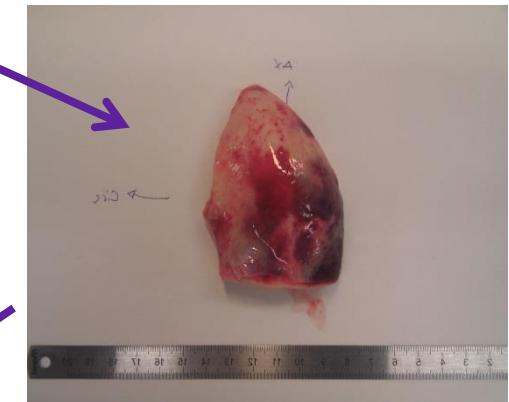
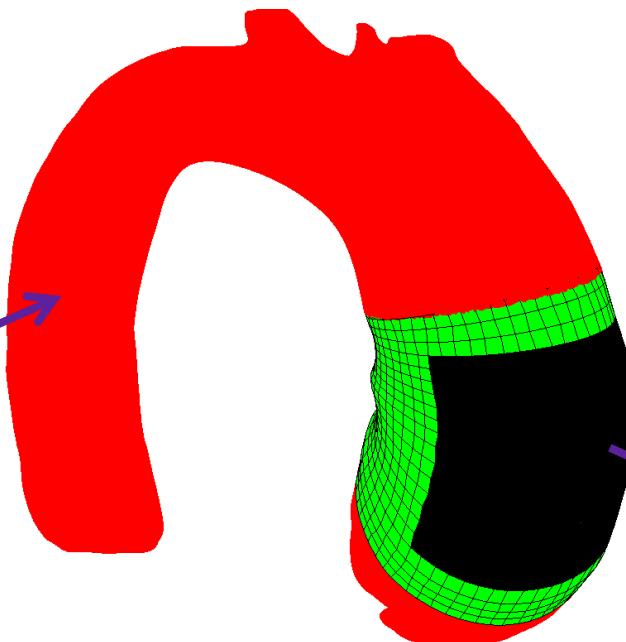
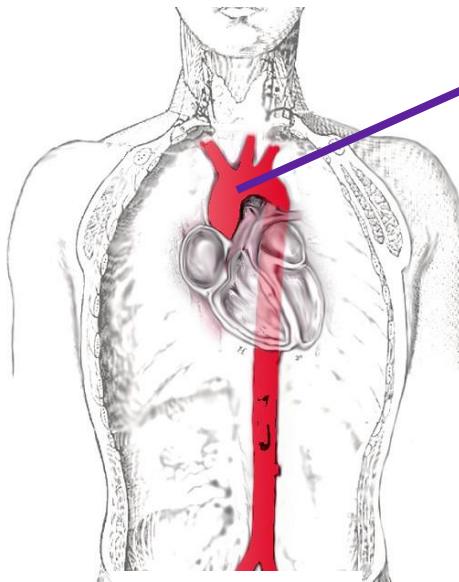


$$\tau_w = \frac{4\mu Q}{\pi a^3},$$

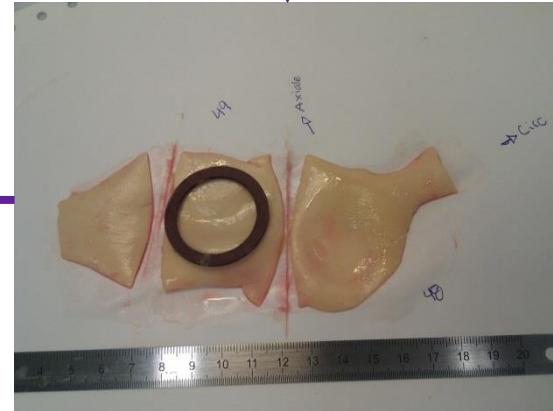
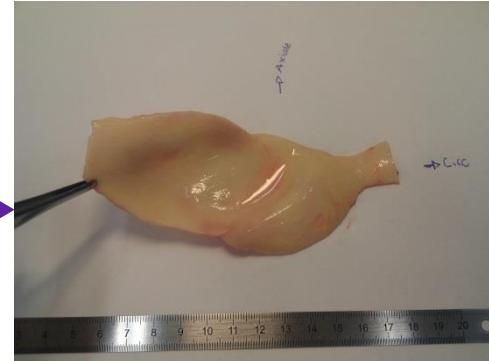
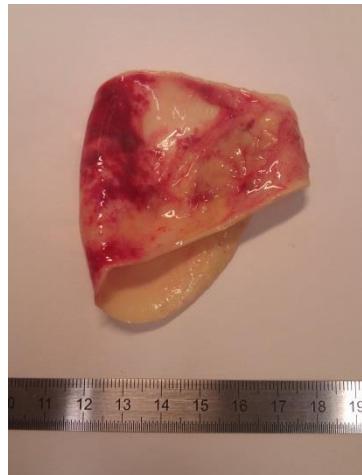
$$\sigma_\theta = \frac{P a}{h}$$

Humphrey JD (2002) *Cardiovascular Solid Mechanics: Cells, Tissues, and Organs*, Springer-Verlag, NY

# Collection of the samples

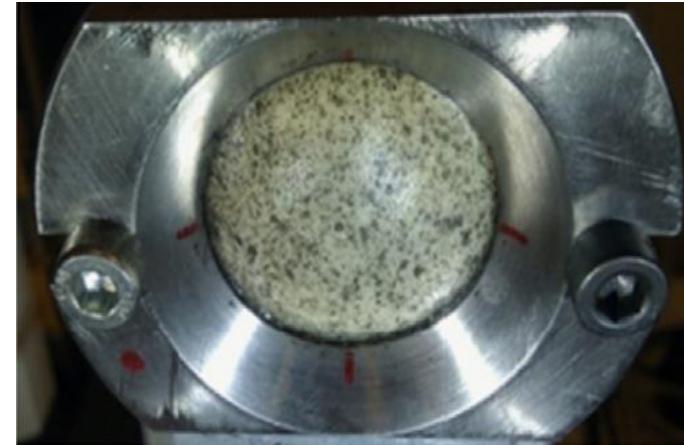
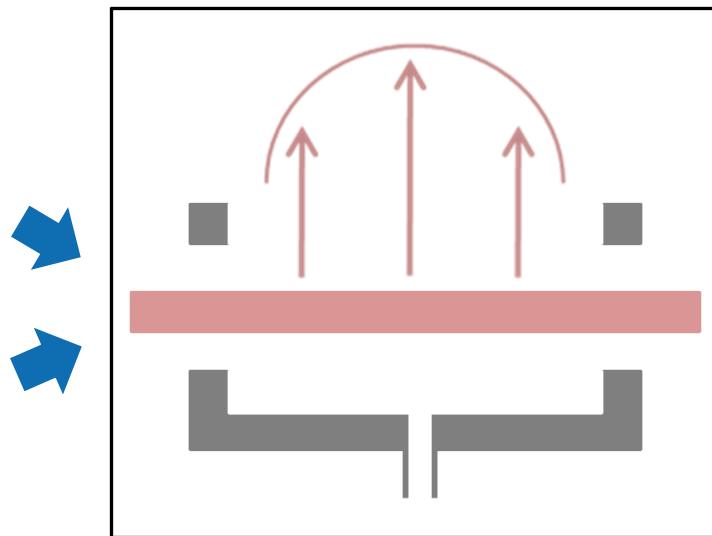


# Preparation

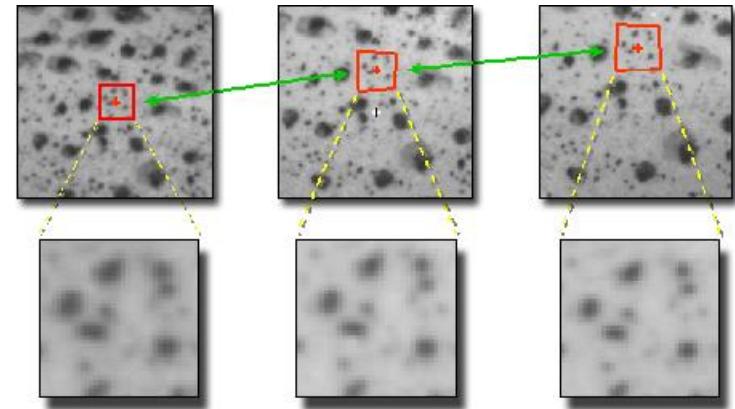


# Bulge inflation test

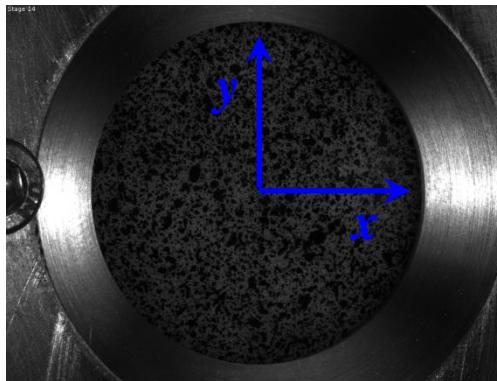
Romo et al. Journal of Biomechanics -2014.



# Full-field measurements using sDIC



Undeformed

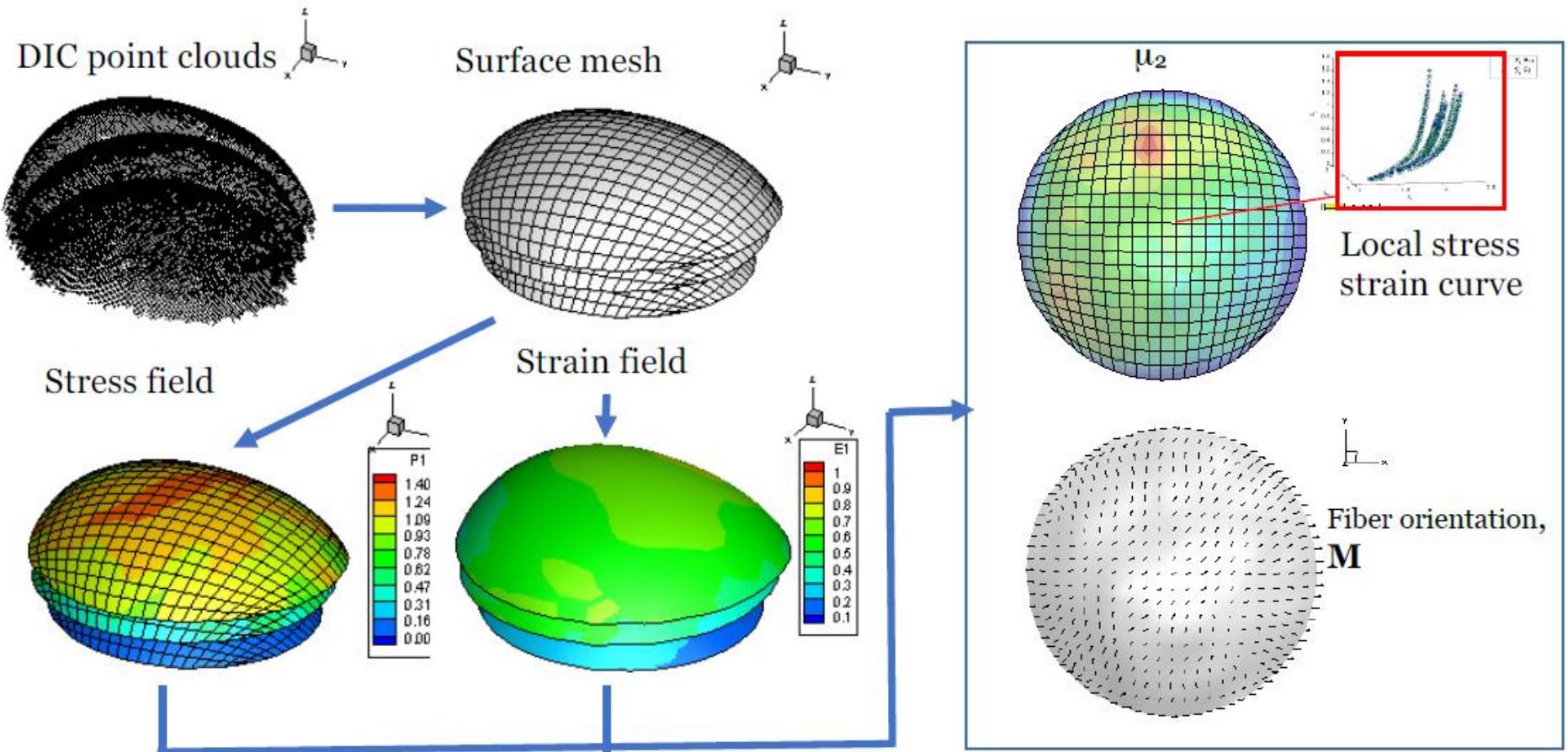


Deformed



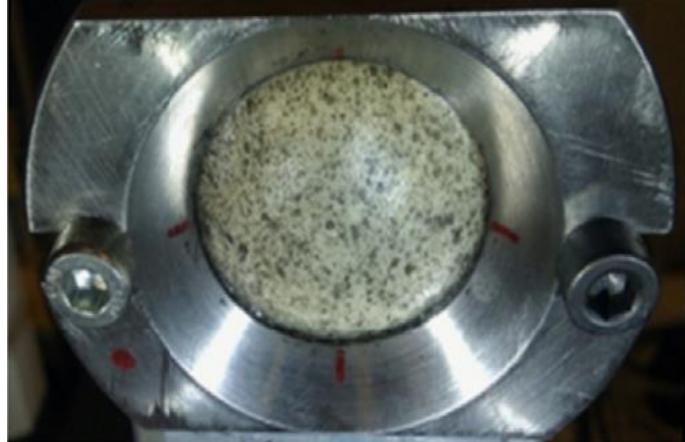
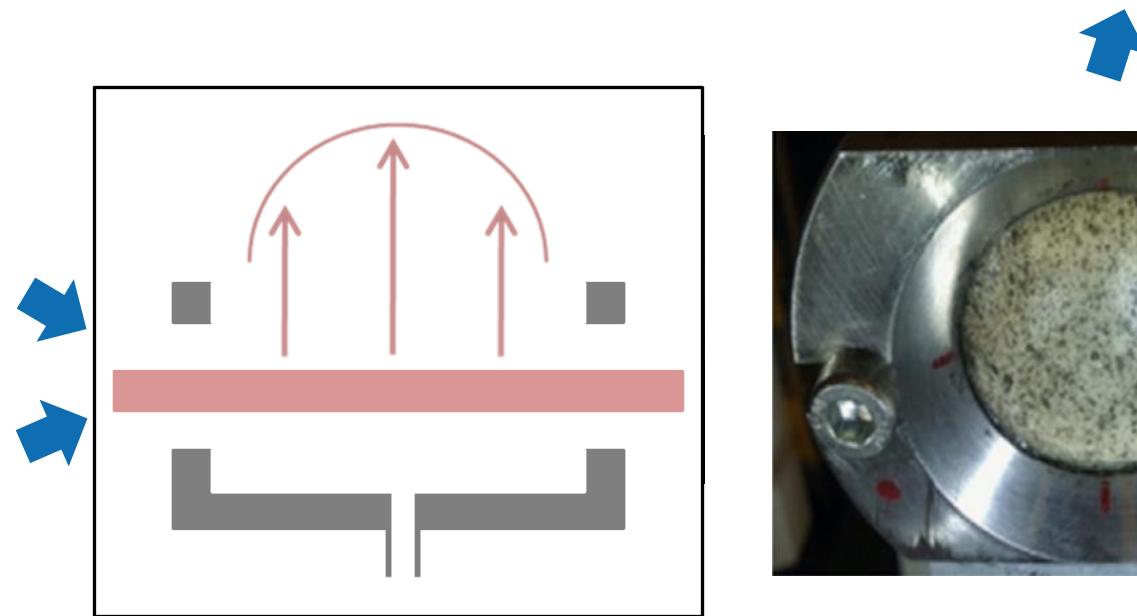
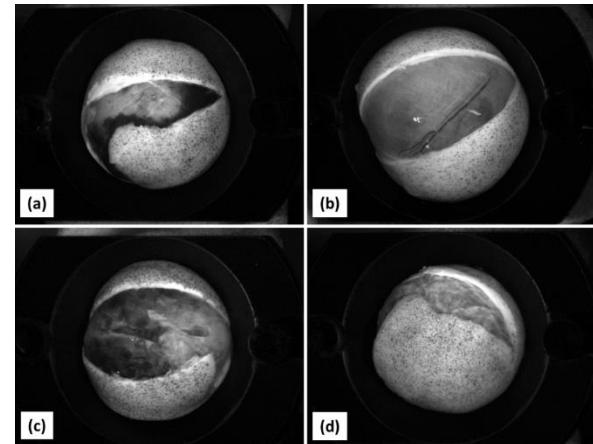
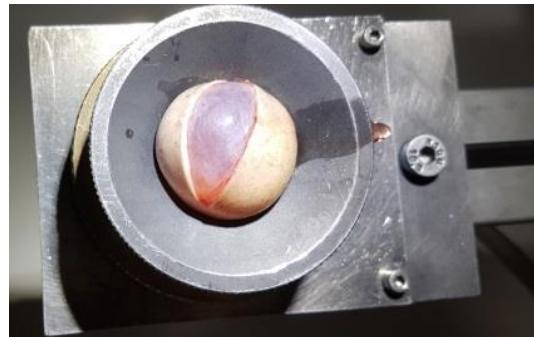


# Identification of local material properties

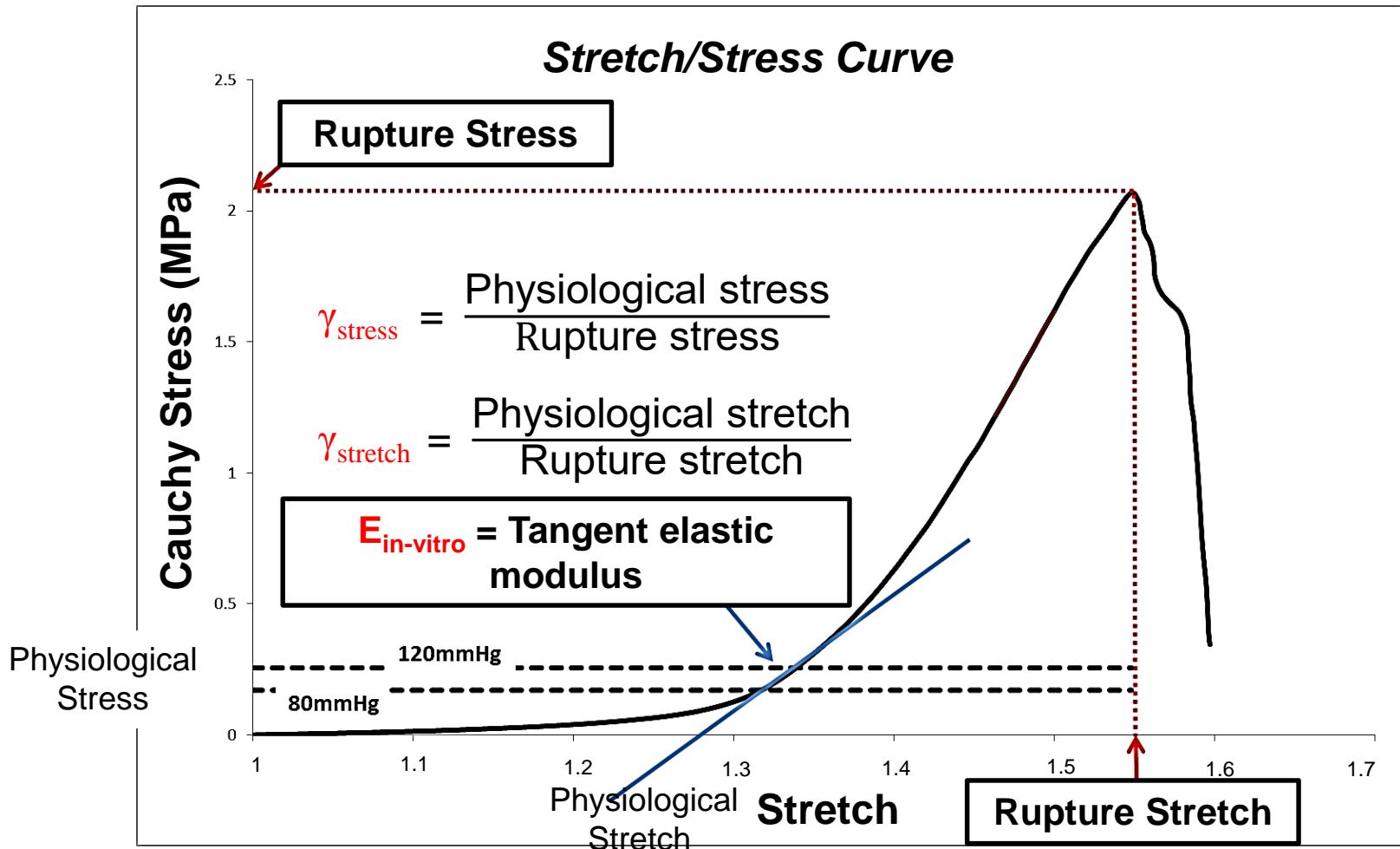


# Bulge inflation test

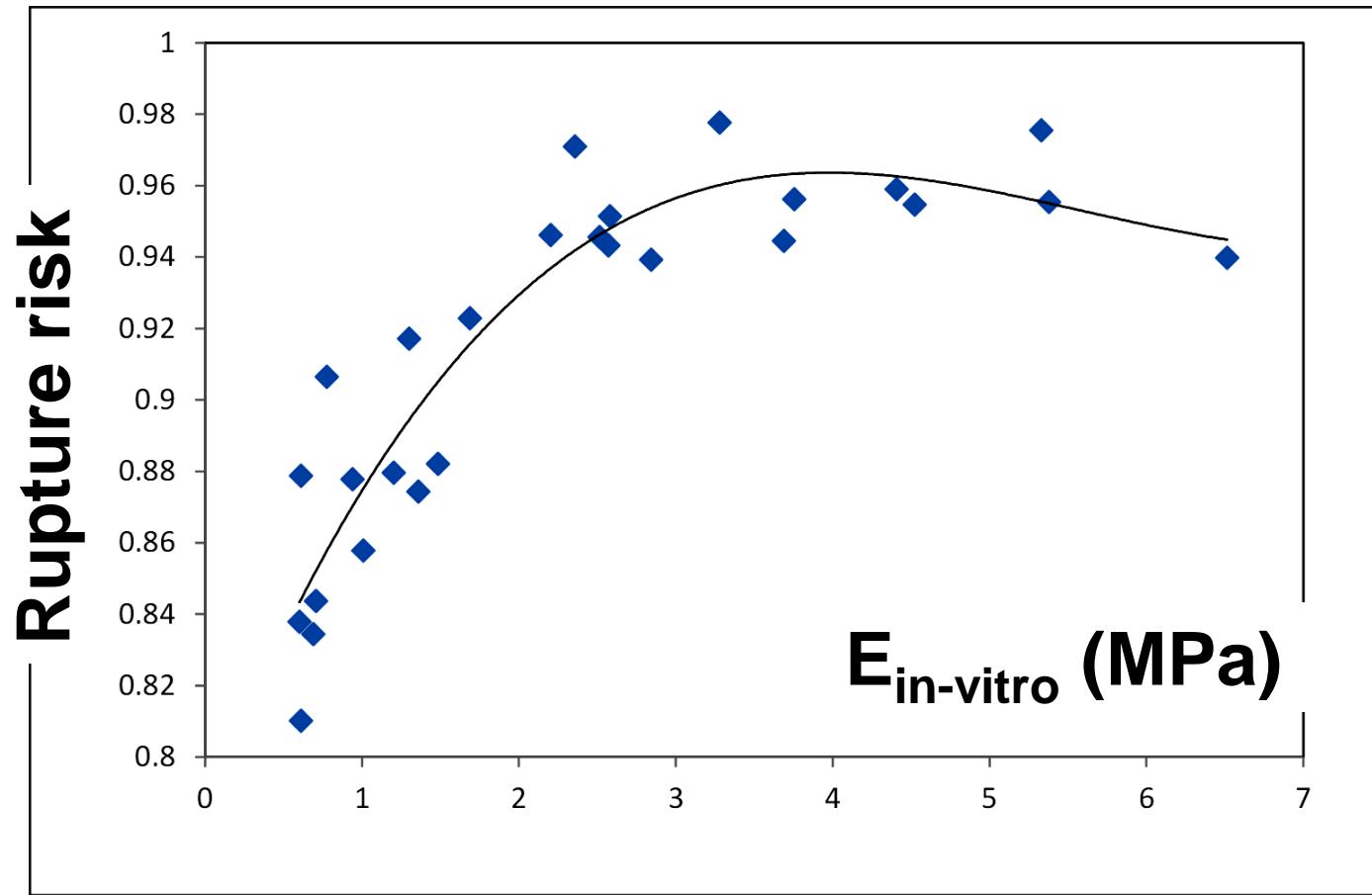
Romo et al. Journal of Biomechanics -  
2014



# Rupture risk estimation



# Correlation between the stretch-based rupture risk and the tangent elastic modulus

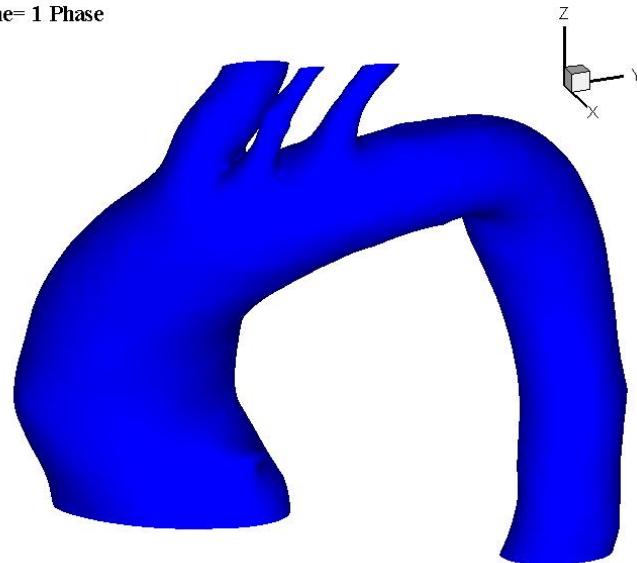


Duprey A, et al. Biaxial rupture properties of ascending thoracic aortic aneurysms. *Acta Biomaterialia* 2016.

# Relationship with aortic stiffness?

Is the stretch based rupture risk criterion correlated to the aortic stiffness which could be measured by elastography techniques?

Time= 1 Phase



Olfa Trabelsi, Miguel A Gutierrez Cambron, Solmaz Farzaneh, Ambroise Duprey, Stéphane Avril. A non-invasive methodology for ATAA rupture risk estimation. *Journal of Biomechanics* 2017.

avril@emse.fr

# Methodology

## Cohort of 10 patients with:

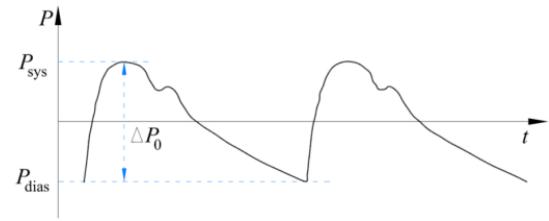
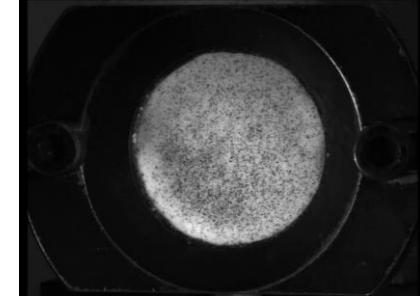
- Postoperative rupture properties of ATAA from bulge inflation test
- Preoperative Dynamic gated CT scans
- Segmentation of images to obtain STL files
- Patient specific blood pressure (Systole & diastole)



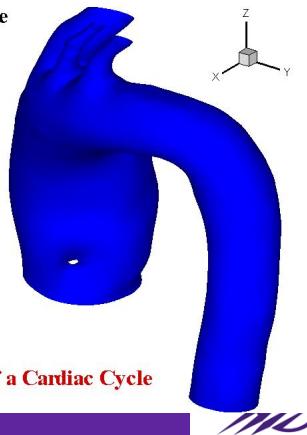
avril@emse.fr



Ten Phases of a Cardiac Cycle



Time= 1<sup>th</sup>Phase



# Methodology

<b>Patients</b>	<b>Age</b>	<b>Aortic Valve Morphology</b>	<b>Valvulopathy</b>	<b>d (mm)</b>
1	58	BAV	AI grade 4+	53
2	68	TAV	AI grade 4+	49
3	77	BAV	AI grade 4+	55
4	70	TAV	AI grade 4+	41
5	58	TAV	Physiologic	55
6	83	TAV	AI grade 2+	57
7	73	TAV	Physiologic	70
8	45	BAV	AS	56
9	76	TAV	AI grade 4+	45
10	82	TAV	AI grade 2+	43

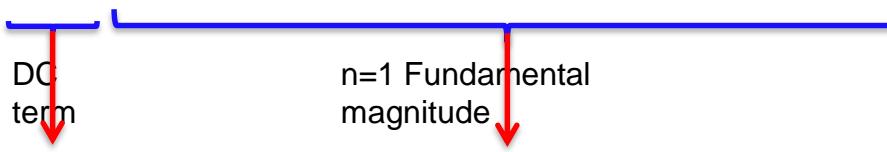
BAV= bicuspid aortic valve; TAV=tricuspid aortic valve; AI grade 4+= severe aortic insufficiency; AI grade 2+= moderate aortic insufficiency; AS= aortic stenosis; d= diameter in the region of the bulge.

# Methodology

## Discrete Fourier transform of the aortic deformation at every position

- STL files of 10 Phases for each patient
- Structural mesh for all phases
- Mesh morphing function between the geometries of each phase
- Writing the coordinates of all phases

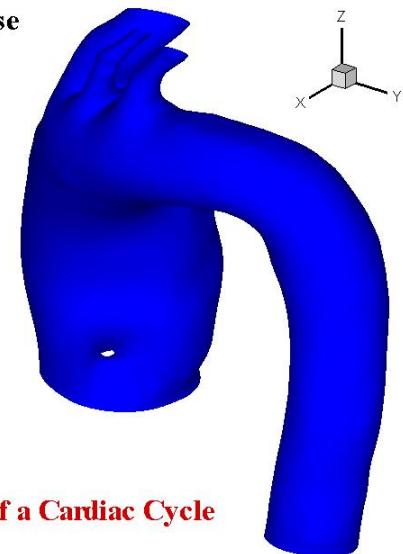
$$x(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(nft) + \sum_{n=1}^{\infty} b_n \sin(nft)$$



Average geometry

Displacements over a cardiac cycle

Time= 1<sup>th</sup>Phase



Ten Phases of a Cardiac Cycle

# Equation of local membrane stiffness

$$Q = \frac{\Delta P + \frac{\tau_1^0 \Delta r_1}{(r_1^0)^2} + \frac{\tau_2^0 \Delta r_2}{(r_2^0)^2}}{\frac{\varepsilon_1(t) + \nu \varepsilon_2(t)}{r_1^0} + \frac{\nu \varepsilon_1(t) + \varepsilon_2(t)}{r_2^0}}$$

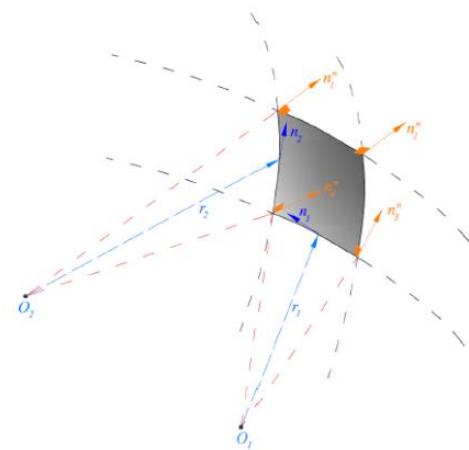
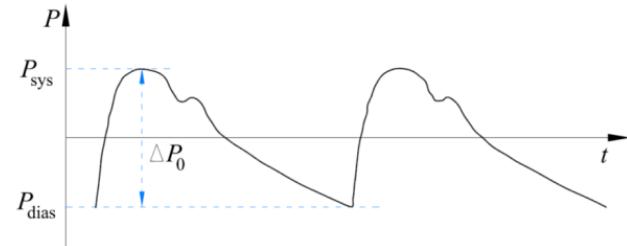
$$\Delta P = \frac{\Delta P_0}{2} = \frac{P_{sys} - P_{dia}}{2}$$

$r_1^0, r_2^0$ : Circumferential and longitudinal radii of curvature in average geometry

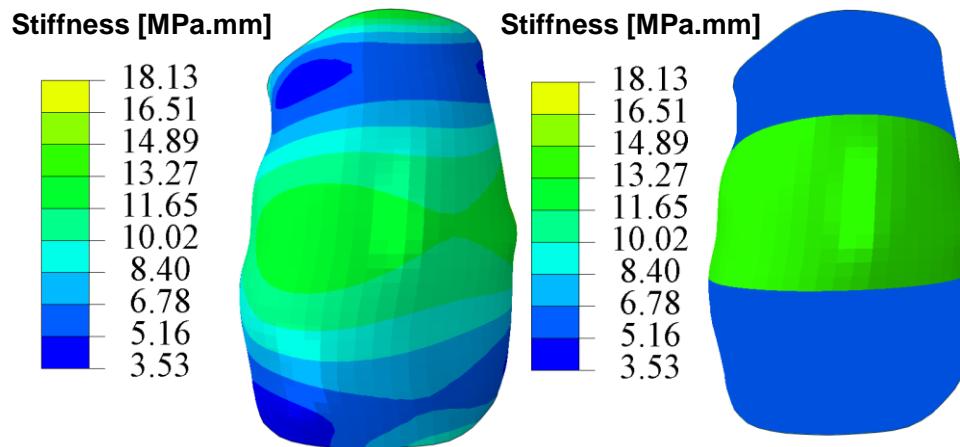
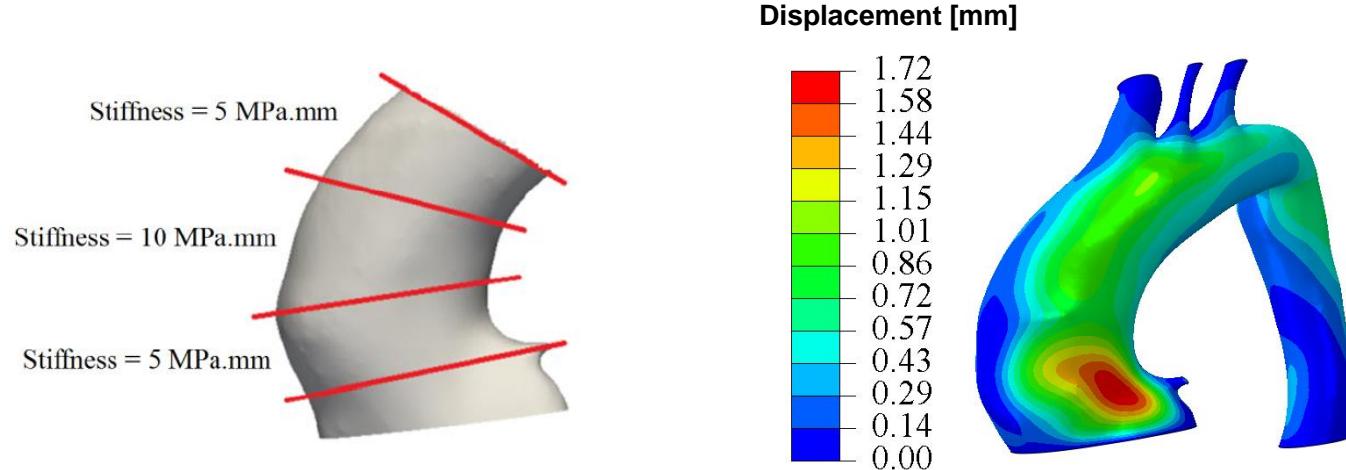
$\Delta r_1, \Delta r_2$ : Fundamental circumferential and longitudinal radii of curvature

$\varepsilon_1, \varepsilon_2$ : Circumferential and longitudinal strains

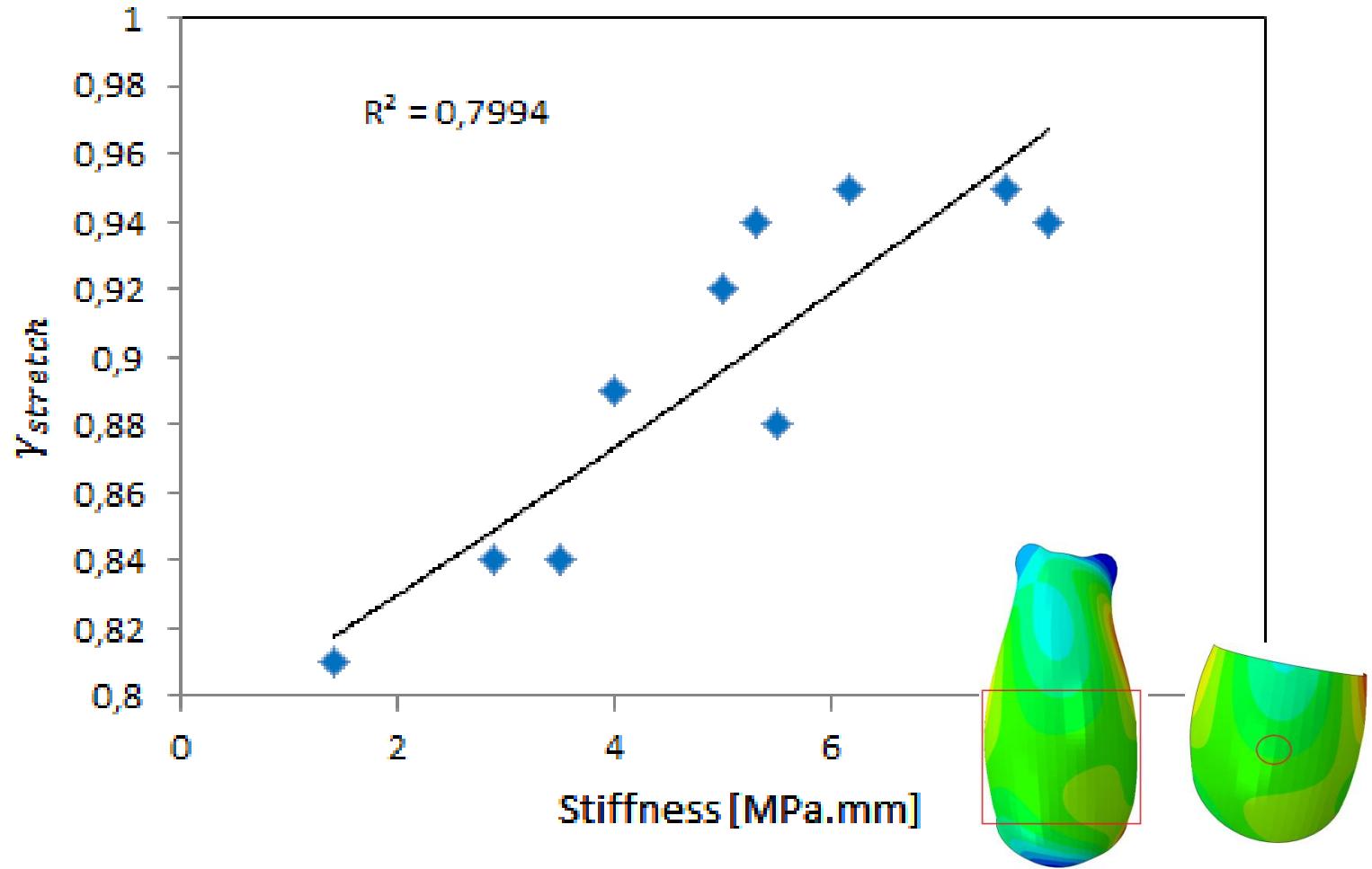
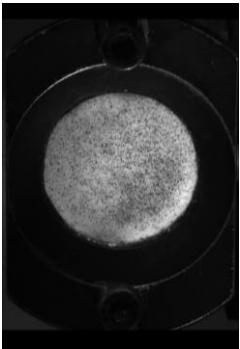
$\tau_1^0, \tau_2^0$ : Pretensions in circumferential and longitudinal directions



# Validation



# Results



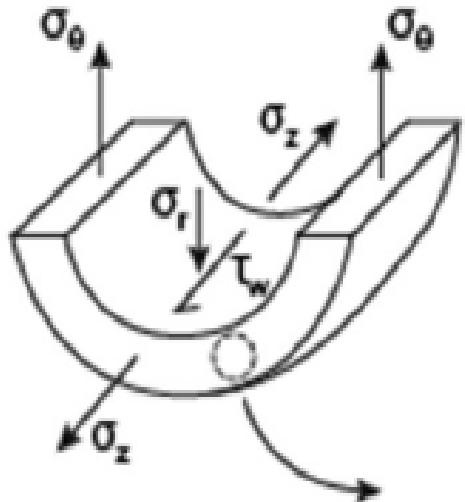
# Summary

- 2 ways of defining rupture:
- PWS – but unknown patient-specific strength
- $\gamma_{\text{stretch}}$  correlated with in vivo circumferential stiffness

Higher stiffness  $\Rightarrow$  less risk because the aneurysm can more easily withstand volume variation



# Basics of arterial mechanics

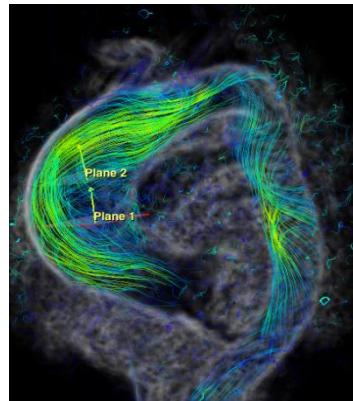


$$\tau_w = \frac{4\mu Q}{\pi a^3}$$

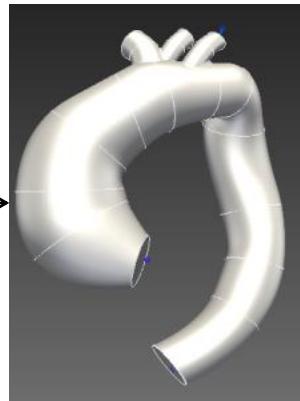
$$\sigma_\theta = \frac{P a}{h}$$

Humphrey JD (2002) *Cardiovascular Solid Mechanics: Cells, Tissues, and Organs*, Springer-Verlag, NY

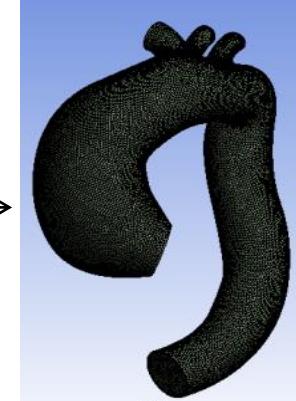
# RELATIONSHIP WITH HEMODYNAMICS?



Preoperative dynamic imaging  
4D MRI

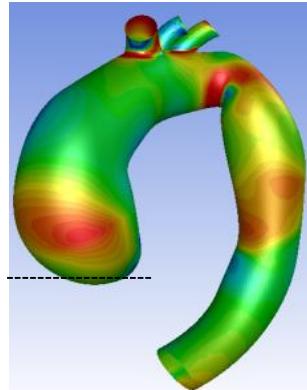


CAD

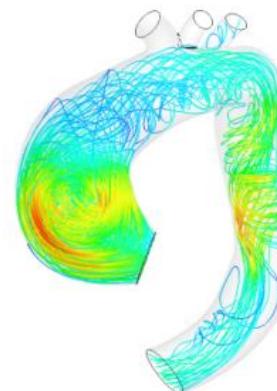


Mesh

Numerical  
Solution



TAWSS

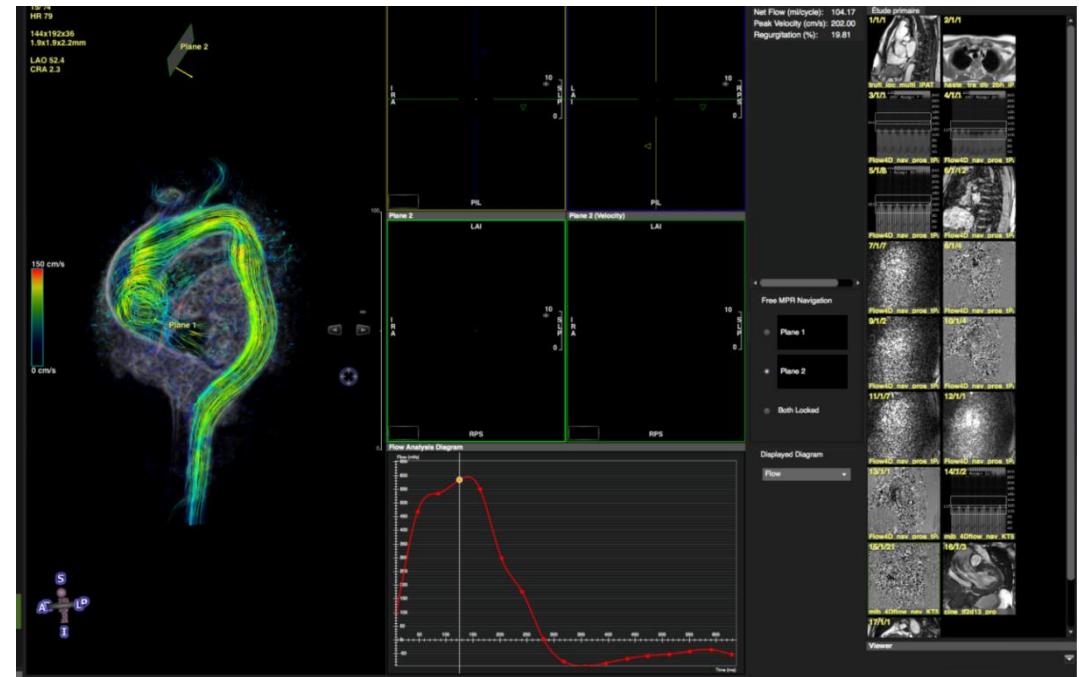


Streamlines, velocity

# Material and Methods- 4D MRI images Pre-processing



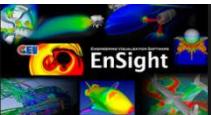
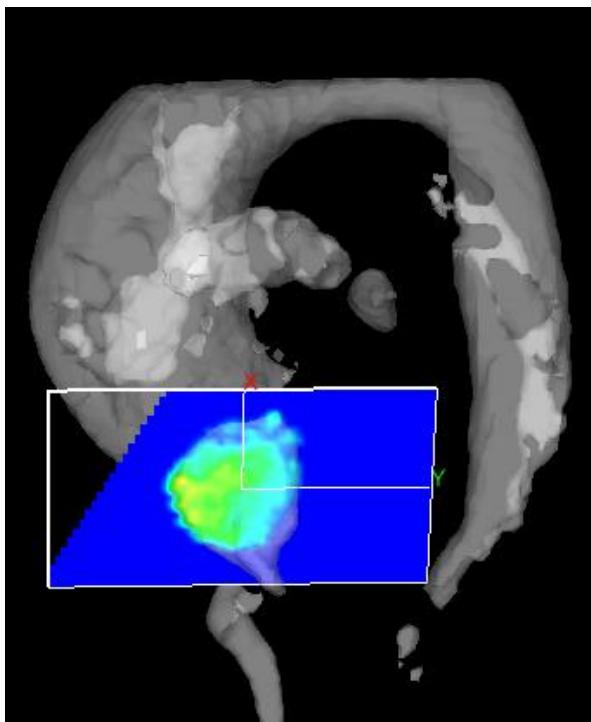
Siemens 3T Prisma



# MATERIAL AND METHODS- Patient Specific BCs

## Velocity profile mapping

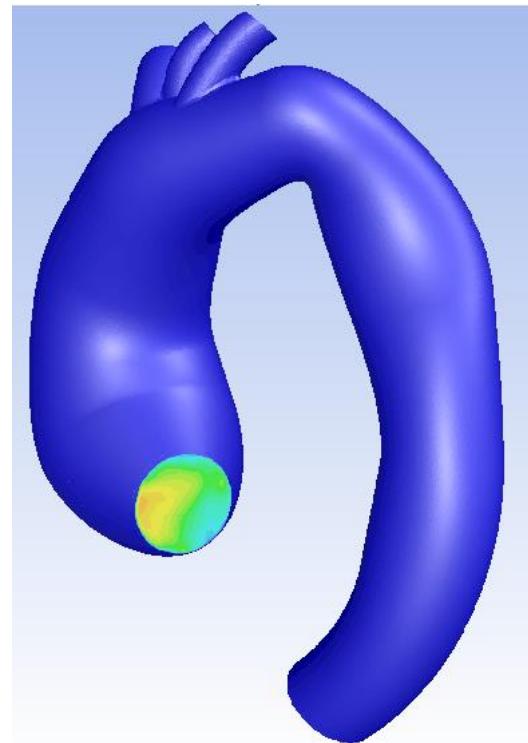
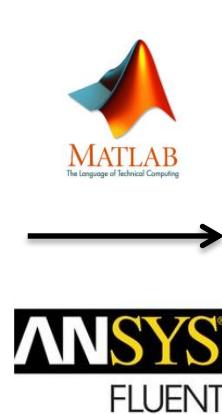
4D MRI data Velocity Profile



[29] m/s

avril@emse.fr

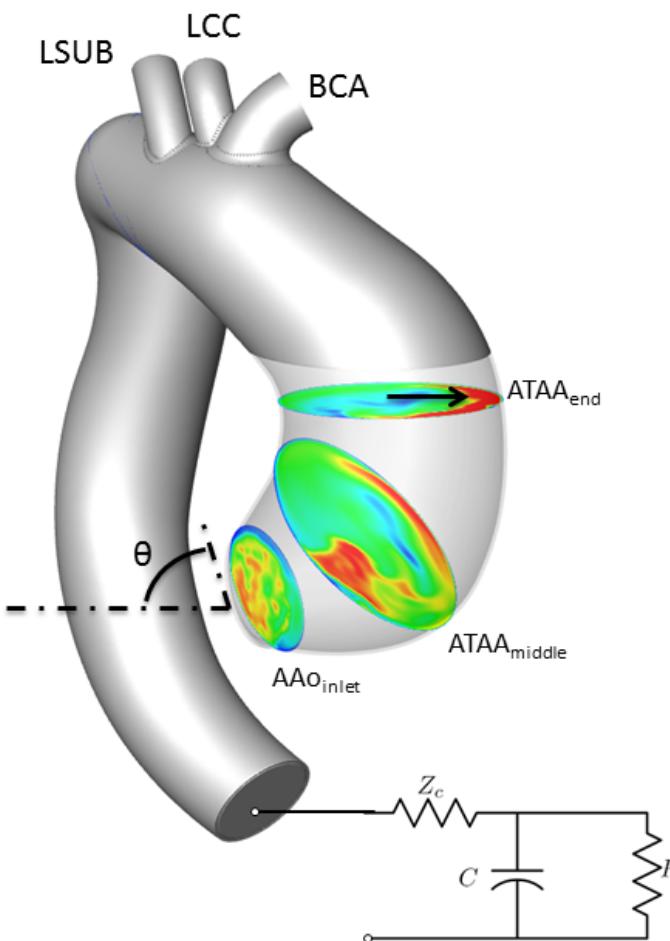
CFD Velocity Profile



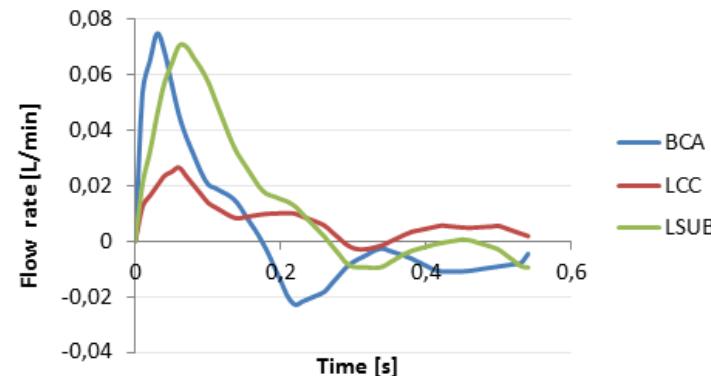
Stéphane Avril - 2019 Sept 5 - ICCB Belgrade

# CFD - Numerical resolution

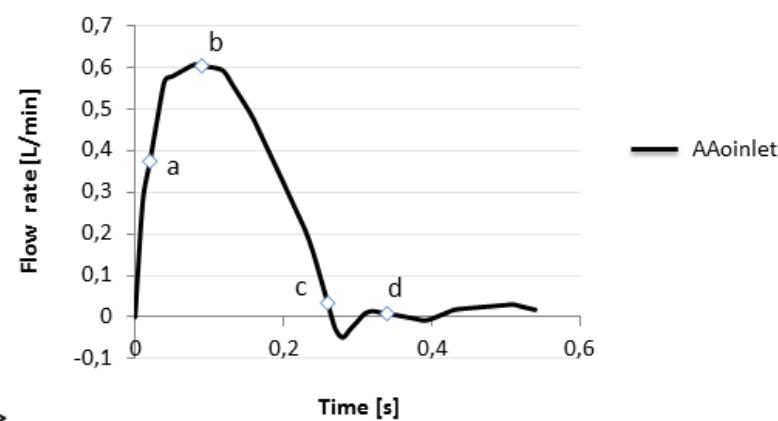
A



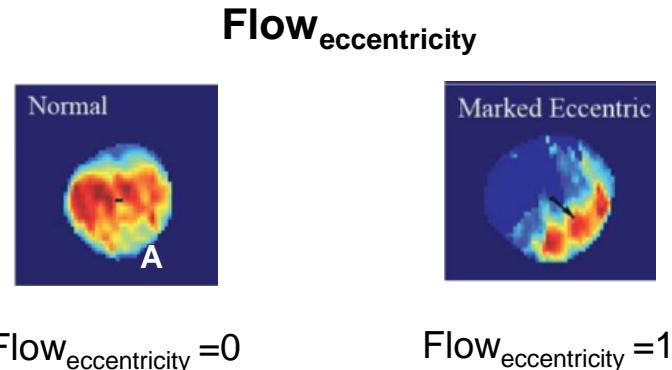
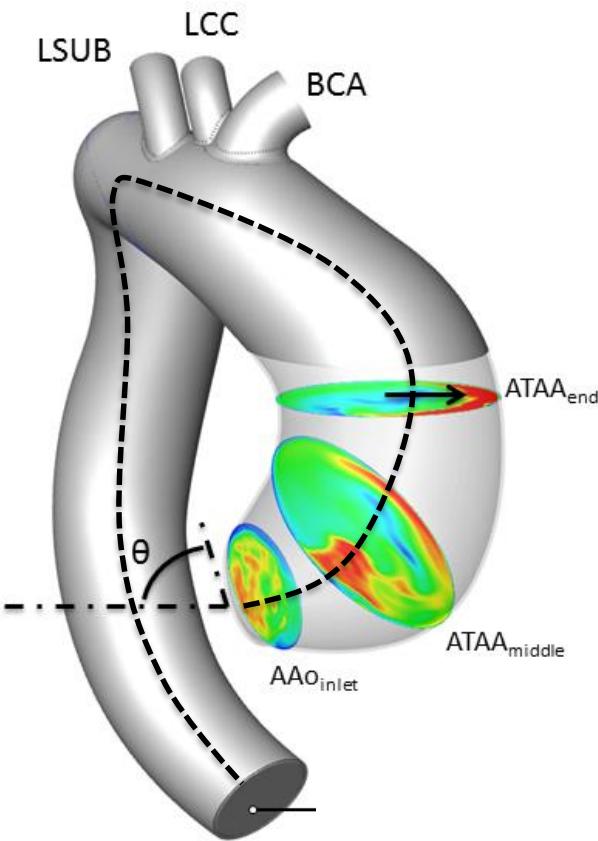
B



C



# Validation of the computational model



Sigovan, M., M.D. Hope, P. Dyverfeldt, D. Saloner. Comparison of four-dimensional flow parameters for quantification of flow eccentricity in the ascending aorta. J Magn Reson Imaging. 34(5):1226-30, 2011.

# Quantitative analysis of hemodynamics indices



Localized Normalized Helicity

$$LNH(s; t) = \frac{V(s; t) \cdot \omega(s; t)}{|V(s; t)| |\omega(s; t)|}$$

$V$ = velocity;  $\omega$ = vorticity

$h_2$  = helicity intensity

Morbiducci, U., R. Ponzini, G. Rizzo, M. Cadioli, A. Esposito, F.M. Montevercchi, A. Redaelli. Mechanistic insight into the physiological relevance of helical blood flow in the human aorta: an in vivo study. Biomech. Model. Mechanobiol. 10:339–355, 2011.

# Wall shear stress analysis

Time averaged wall shear stress (WSS):

$$TAWSS = \frac{1}{T} \int_0^T WSS \, dt$$

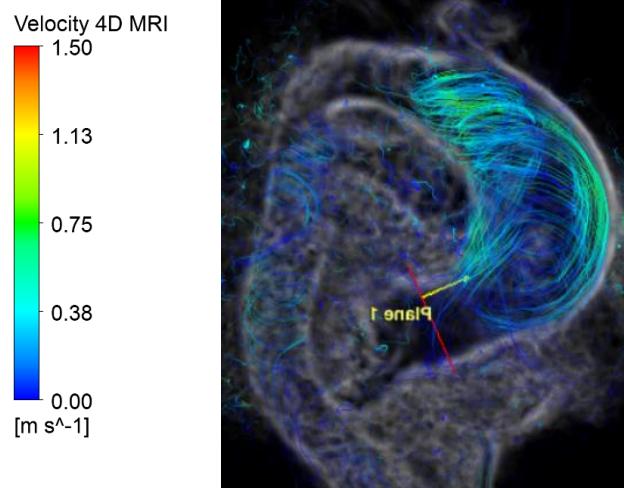
Oscillatory Shear Index:

$$OSI = 0.5 \left[ 1 - \left( \frac{\left| \int_0^T WSS(s, t) \cdot dt \right|}{\int_0^T |WSS(s, t)| \cdot dt} \right) \right]$$

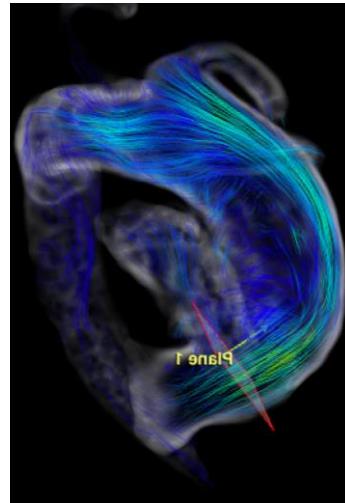
where T is the period of the cardiac cycle and WSS is the instantaneous wall shear stress.

# RESULTS

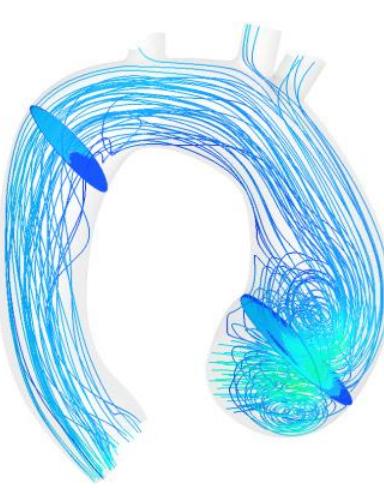
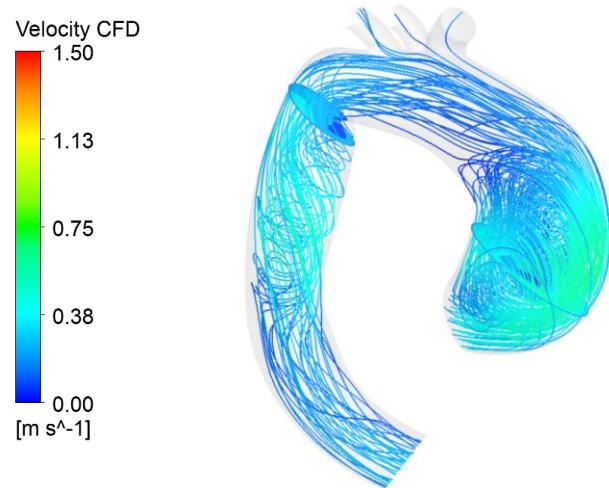
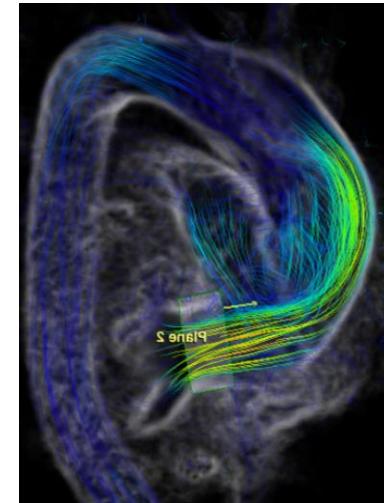
Patient 1 (BAV)



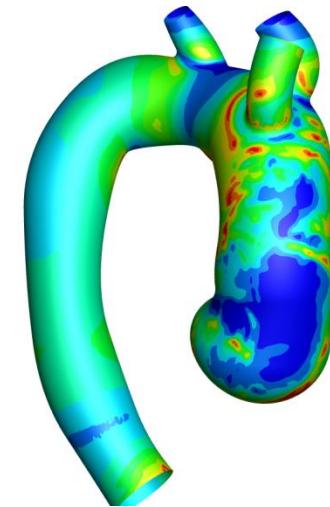
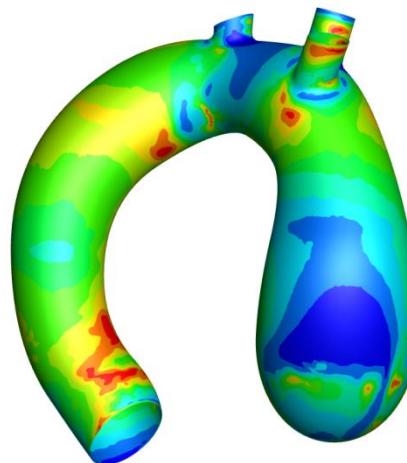
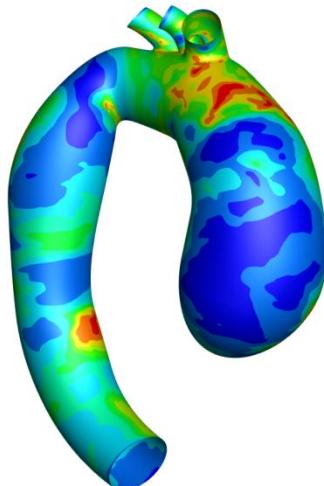
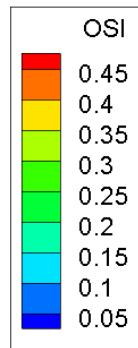
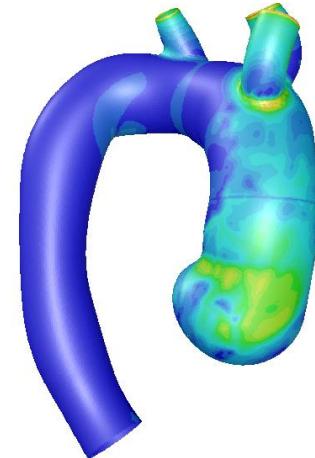
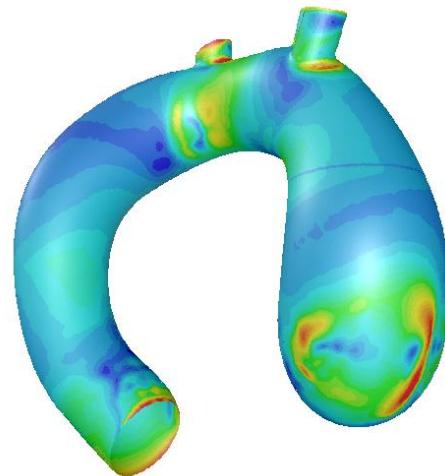
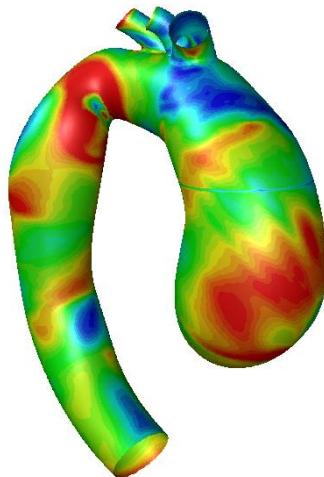
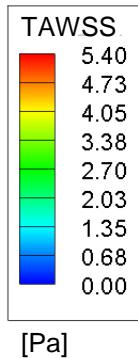
Patient 2 (TAV)



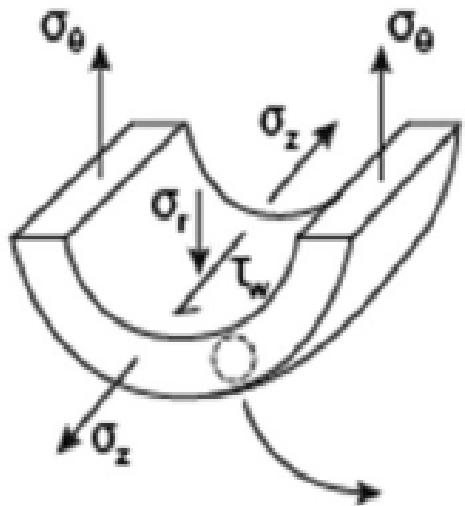
Patient 3 (BAV)



# RESULTS - OSI and TAWSS



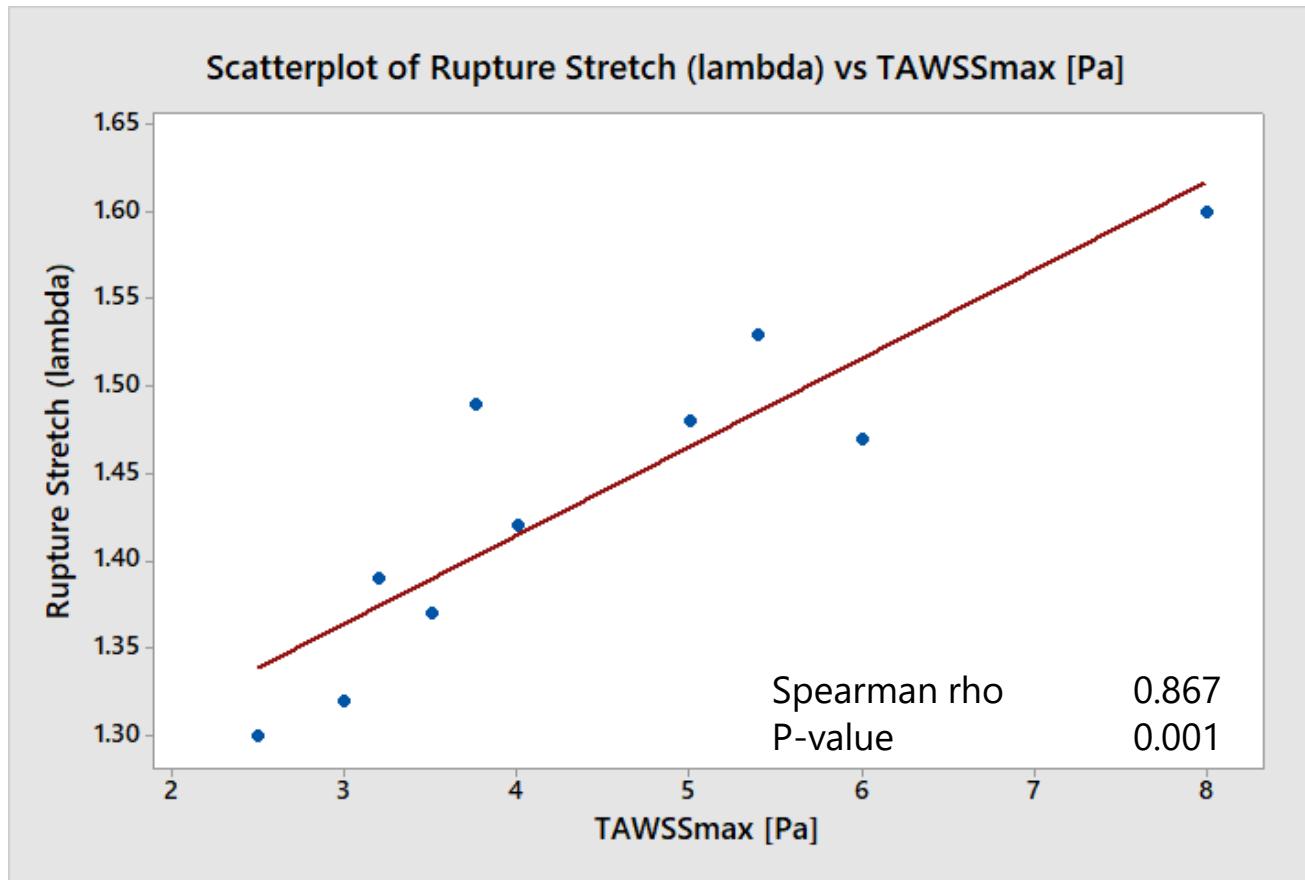
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Humphrey JD (2002) *Cardiovascular Solid Mechanics: Cells, Tissues, and Organs*, Springer-Verlag, NY

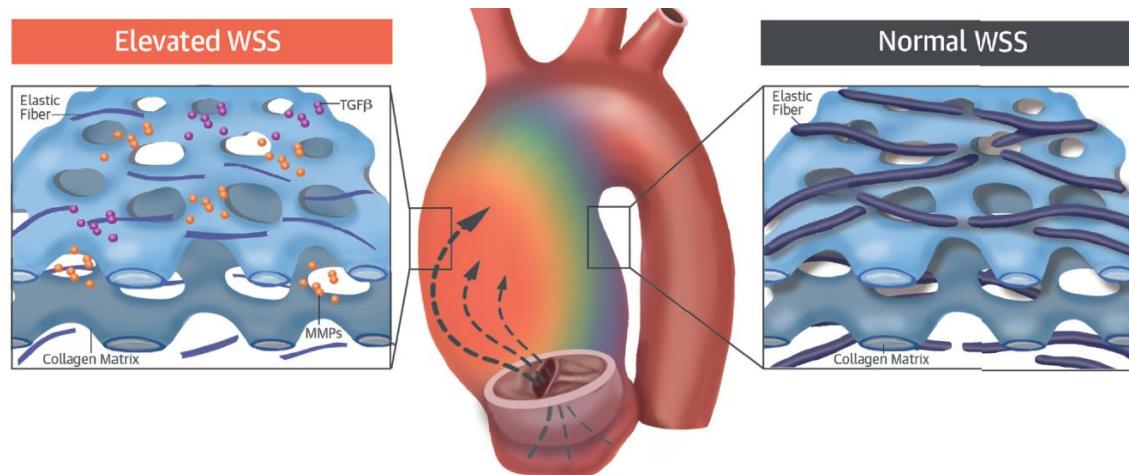
# Statistical Analysis-Spearman Rho: $\lambda_{\text{rupture}}$ vs. TAWSSmax [Pa]



Conde mi et al, IEEE Transactions on Biomedical Engineering, 2019

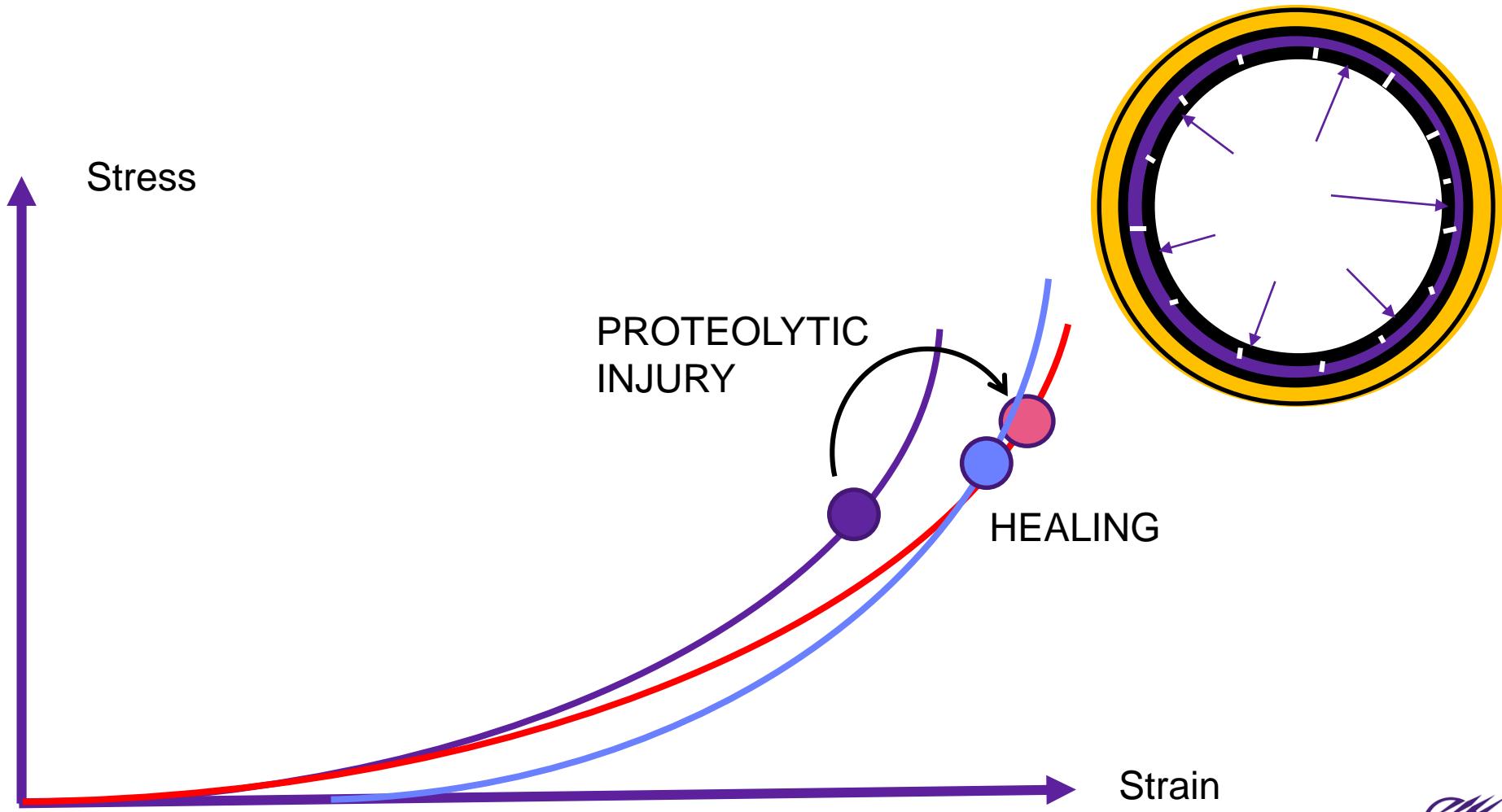
# DISCUSSION

- Protective role of larger TAWSS, associated with low oscillatory wall shear stress?
- Controversial effects

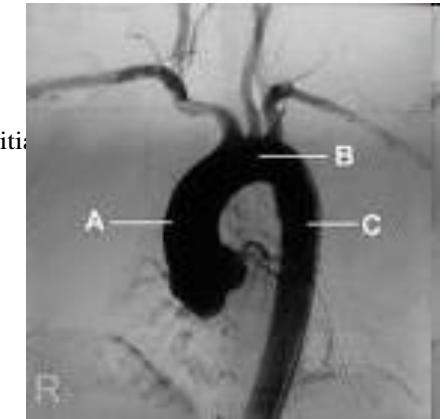
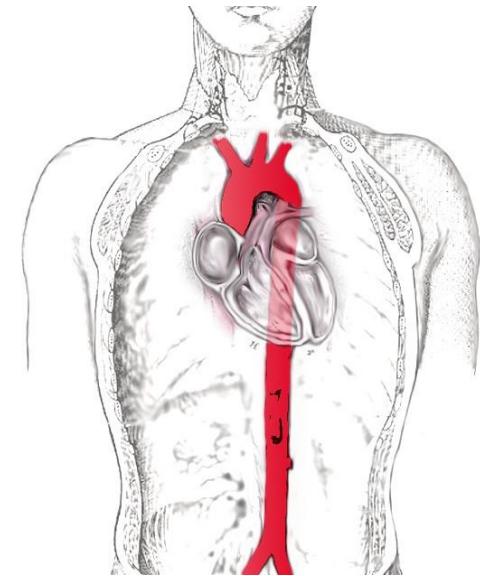
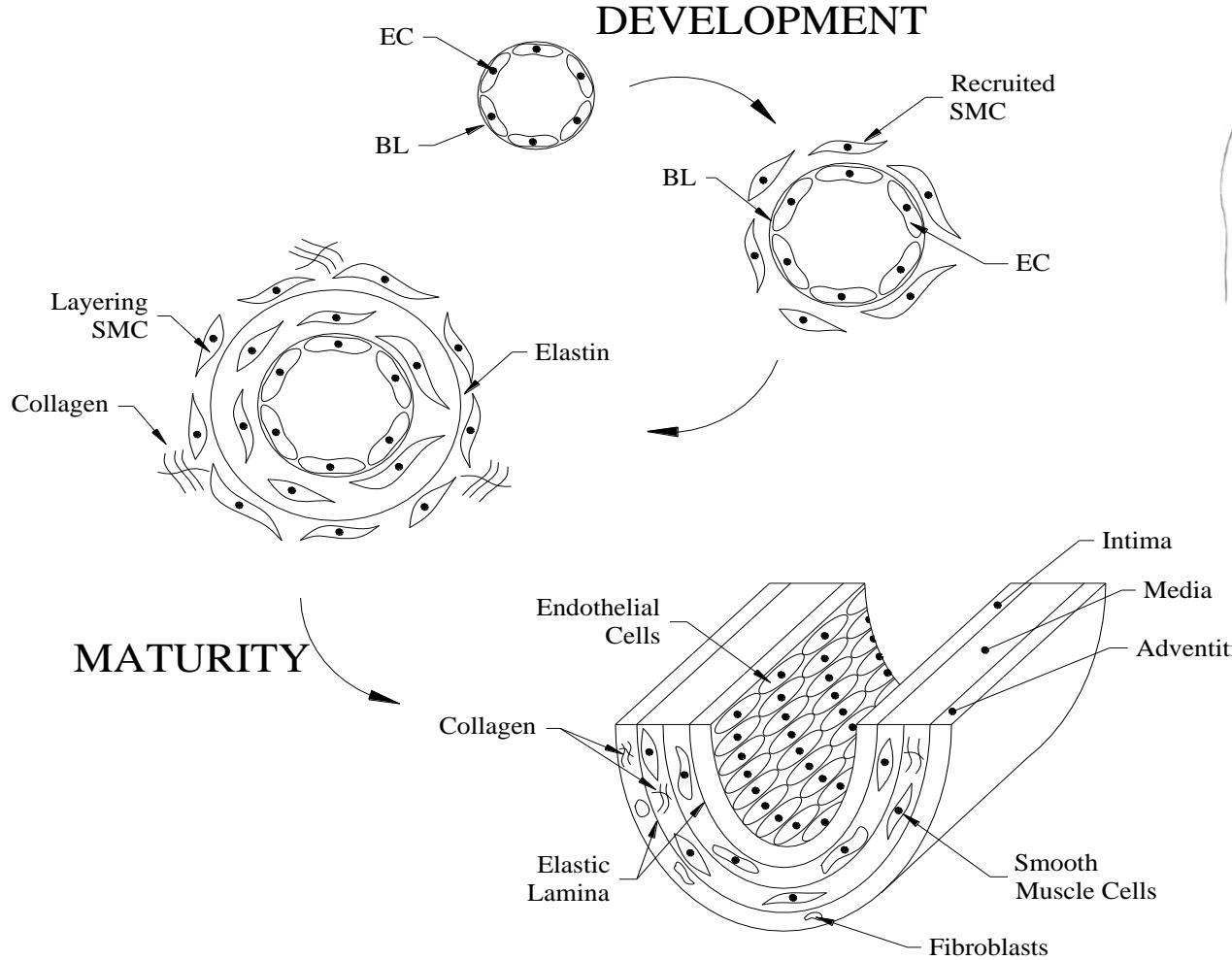


Guzzardi et al. JACC 2015

# Proteolytic injury and tissue adaptation

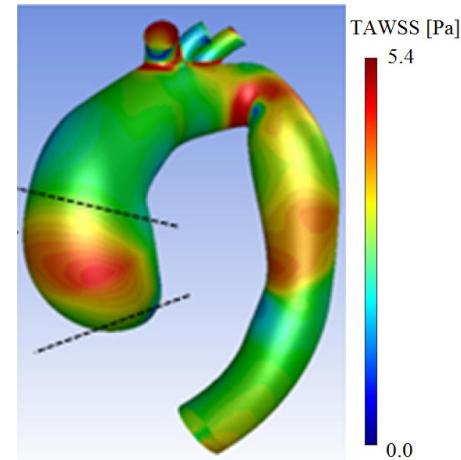


# Modeling of mechanobiological processes



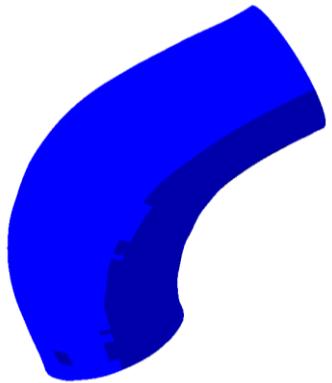
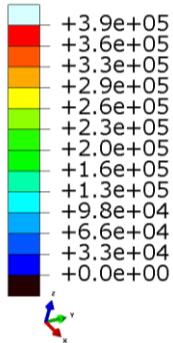
# Patient-specific predictions

Growth and remodeling of a two-layer patient-specific human ATAA due to elastin loss

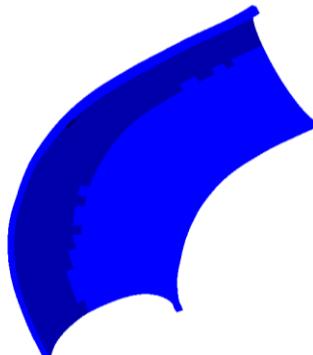
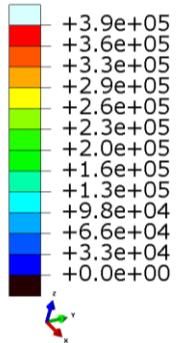


Small growth parameter

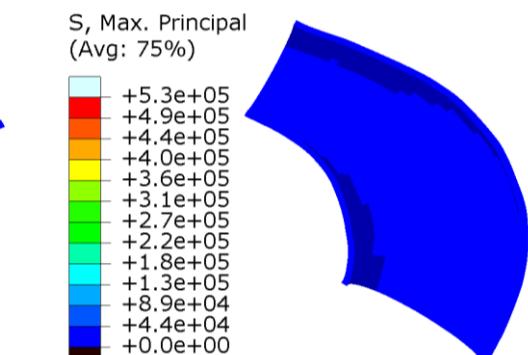
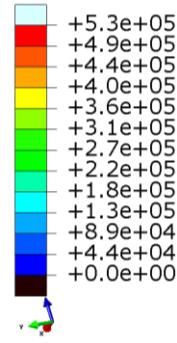
S, Max. Principal  
(Avg: 75%)



S, Max. Principal  
(Avg: 75%)



S, Max. Principal  
(Avg: 75%)



Maximum Principal stress

Mousavi et al, BMMB 2019

avril@emse.fr



## SUMMARY

- ATAA at higher “biomechanical” risk have an increased stiffness and a disturbed flow with reduced maximum TAWSS
  
- Our future work will focus on idiopathic ATAA and try to understand better what are the main triggers for the overstiffening.



# Computational mechanics in the OR for vascular surgery?

[www.predisurge.com](http://www.predisurge.com)



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