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BIOlogie Saint-Etienne
U1059 • INSERM • SAINT-ETIENNE

 **Inserm**
Institut national
de la santé et de la recherche médicale

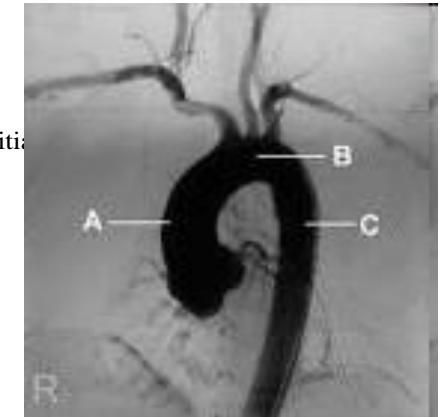
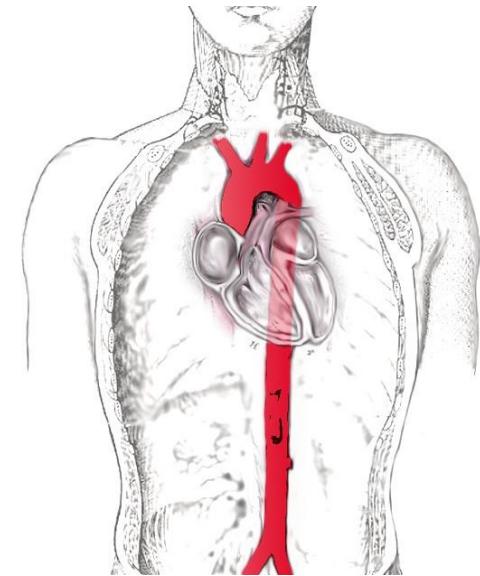
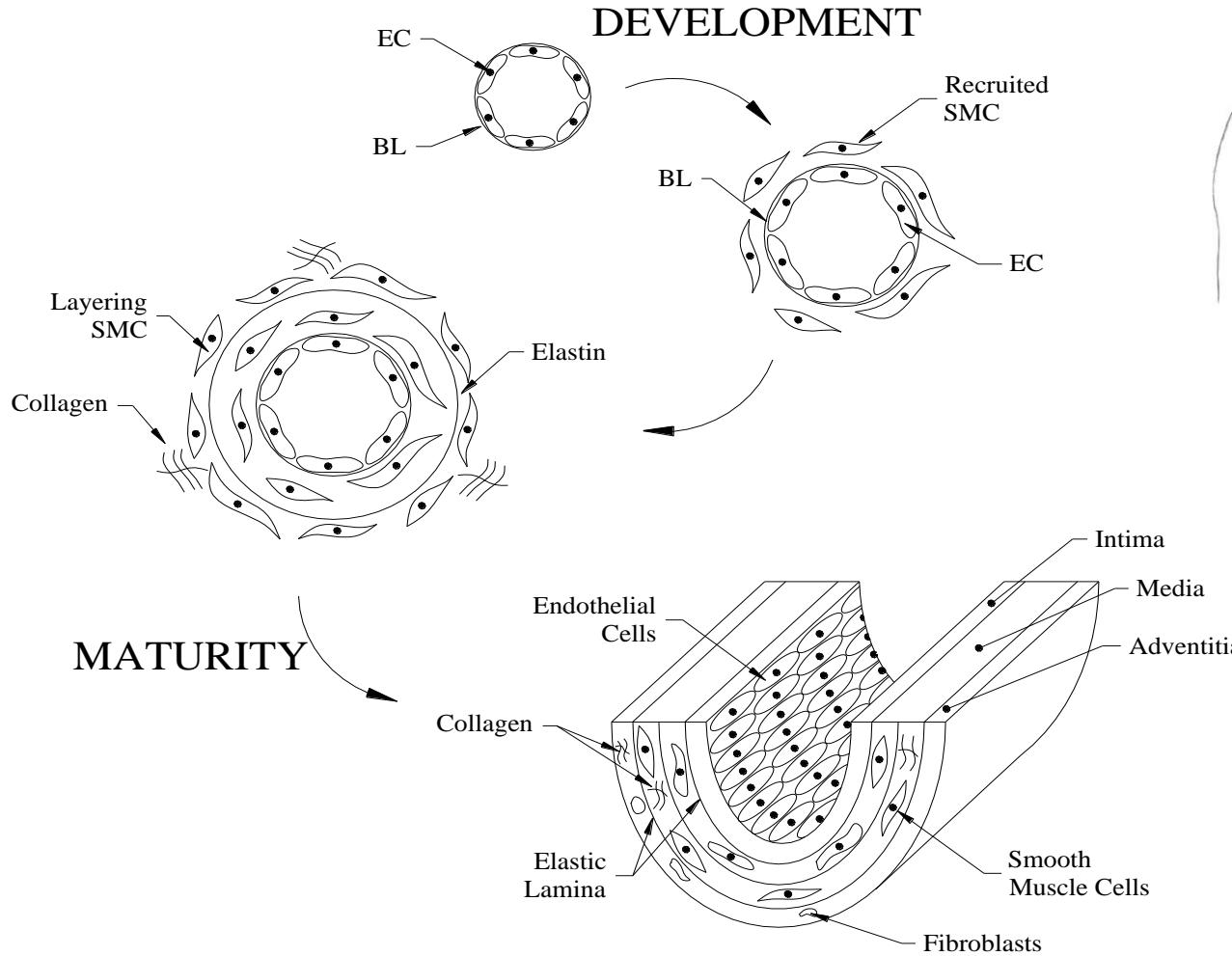


Biomechanics of the aorta

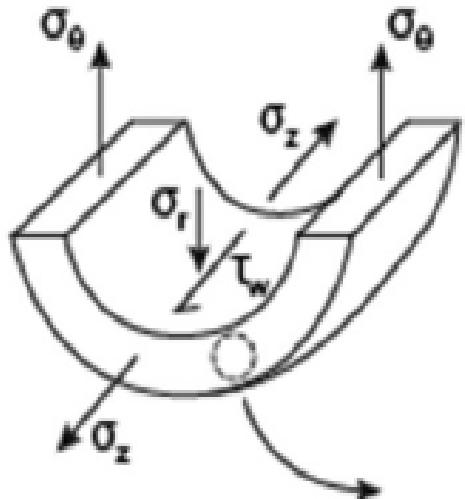
Prof. Stéphane AVRIL



Schematic representation of aortic structure



Basics of aortic mechanics

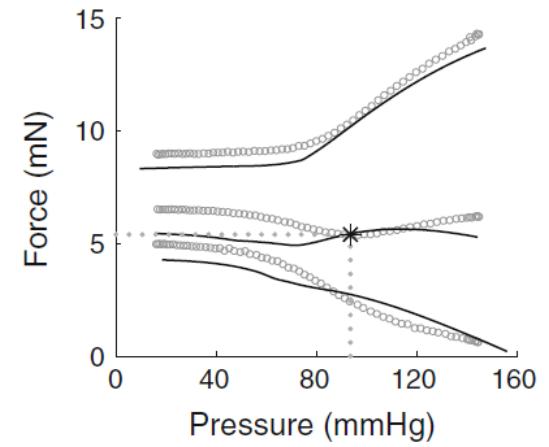
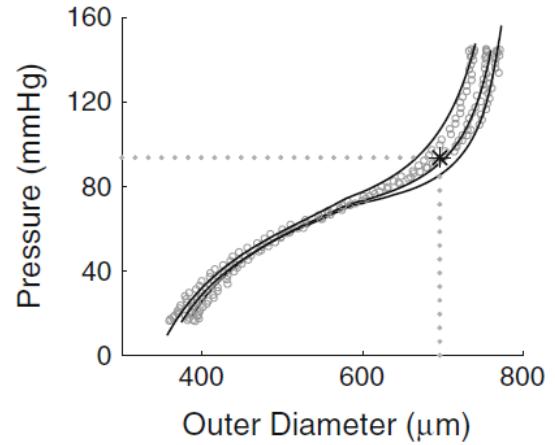
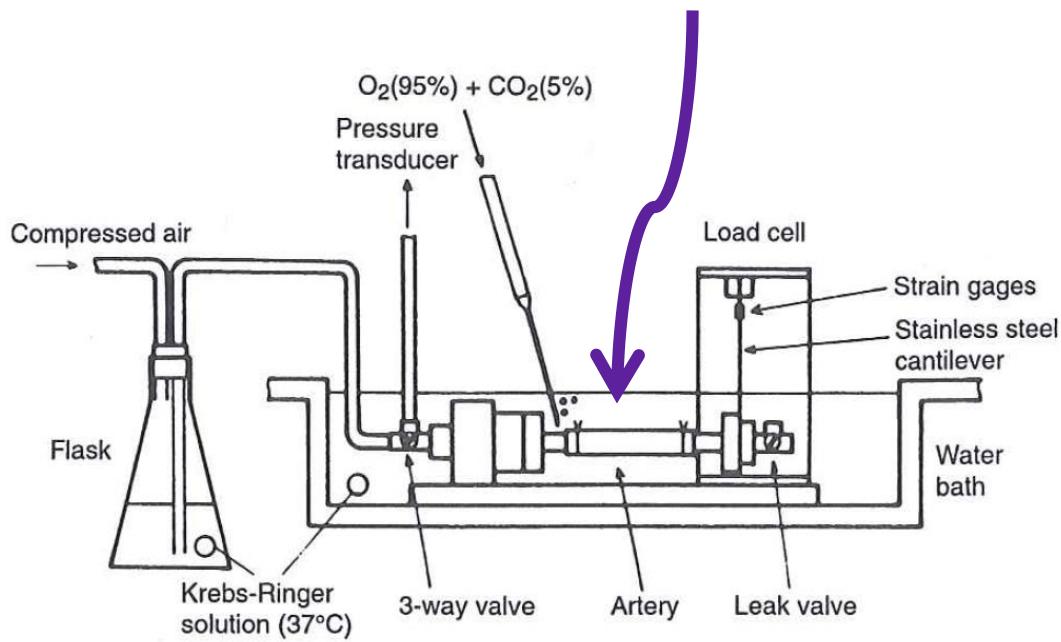


$$\tau_w = \frac{4\mu Q}{\pi a^3}, \quad \sigma_\theta = \frac{Pa}{h}$$

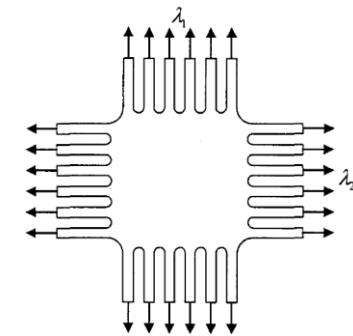
$$\sigma_z = \frac{f_z}{\pi(b^2 - a^2)} = \frac{f_z}{\pi h(2a - h)}$$

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

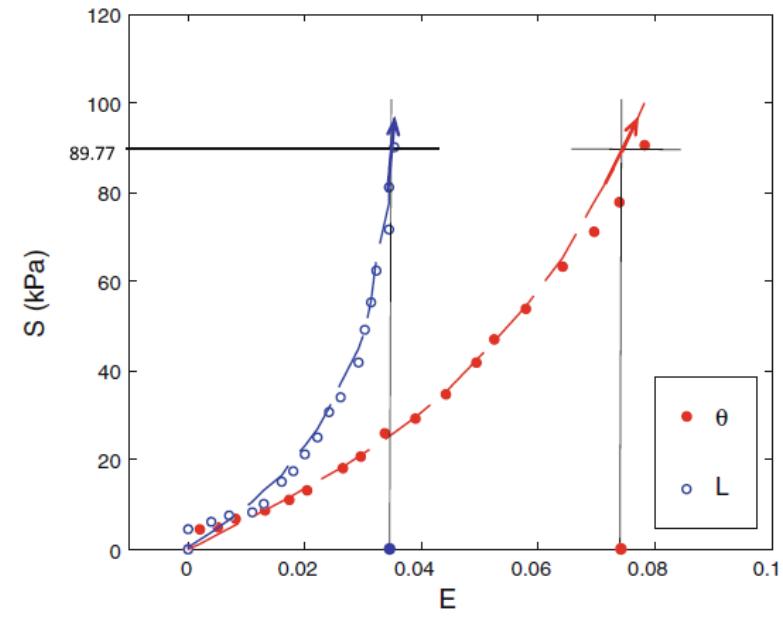
Functional biomechanical behavior



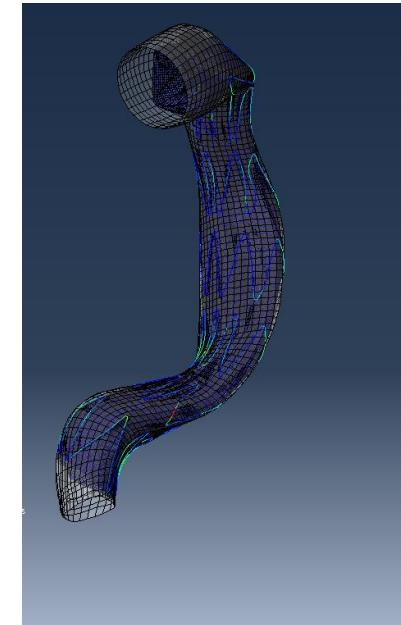
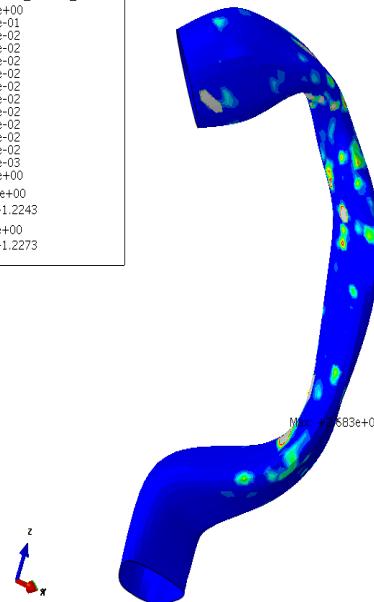
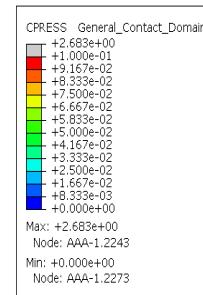
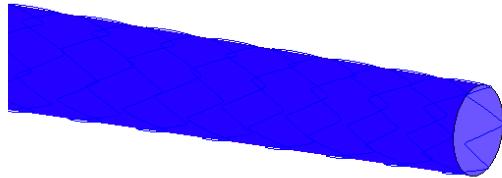
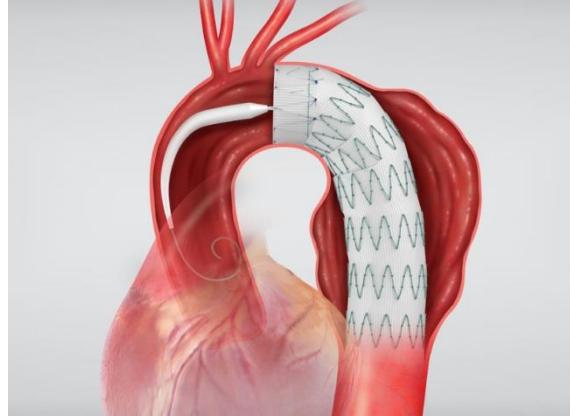
Material characterization and constitutive modeling



$$W = C_{10} (\bar{I}_1 - 3) + \frac{1}{D} \left(\frac{J^2 - 1}{2} - \ln J \right) + \frac{k_1}{2k_2} \sum_{\alpha=1}^N \left\{ \exp \left[k_2 \langle \bar{E}_\alpha \rangle^2 \right] - 1 \right\}$$



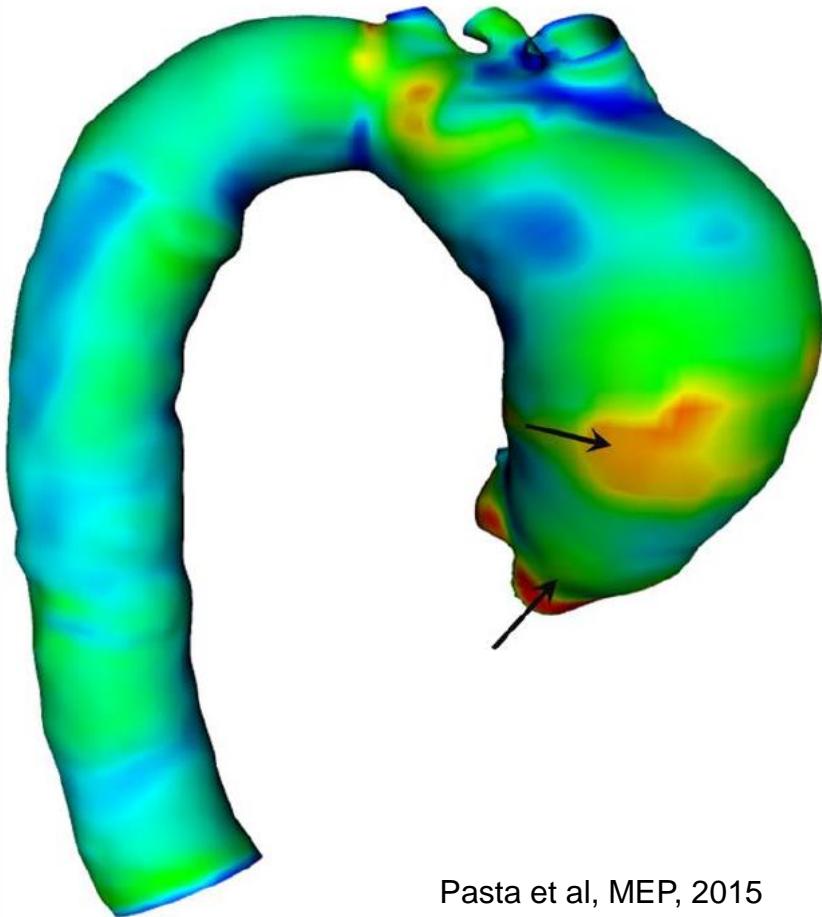
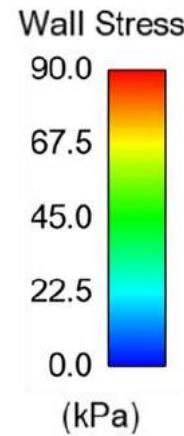
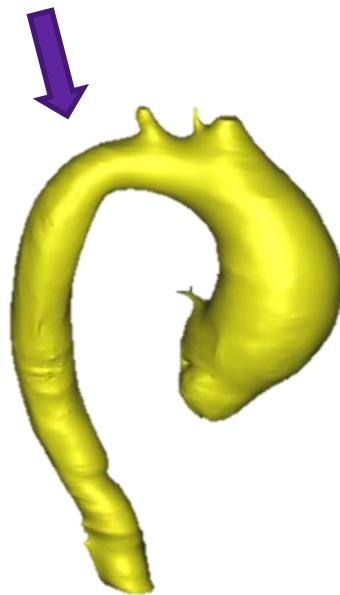
Predictions of interactions between the aorta and medical deviced



www.predisurge.com

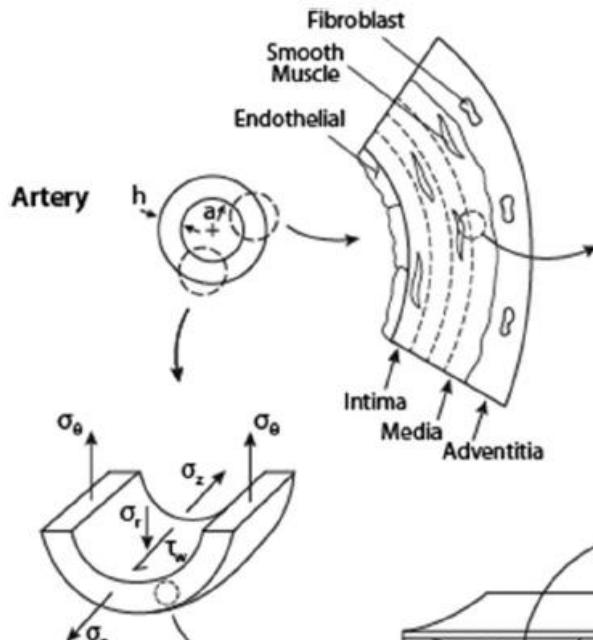


Finite-element modeling of fluid-structure interactions

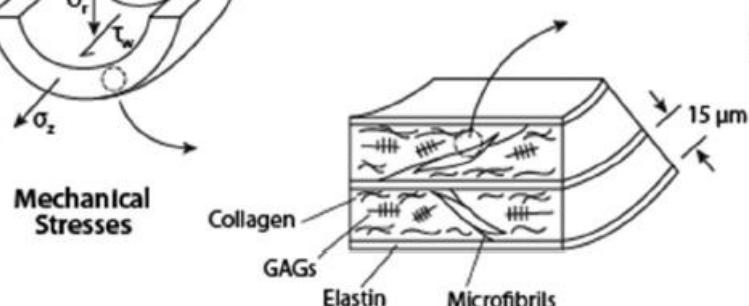
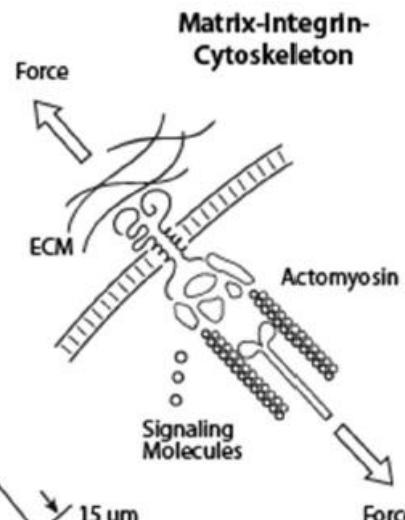


Pasta et al, MEP, 2015

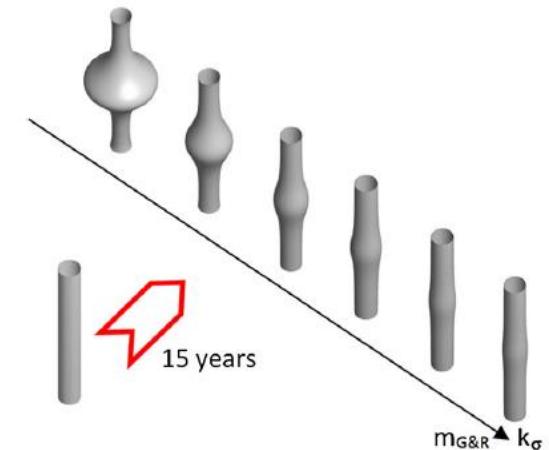
Predictions of vascular adaptation and disease development



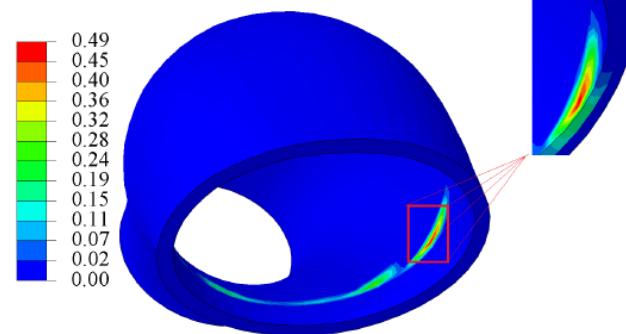
MECHANOBIOLOGY



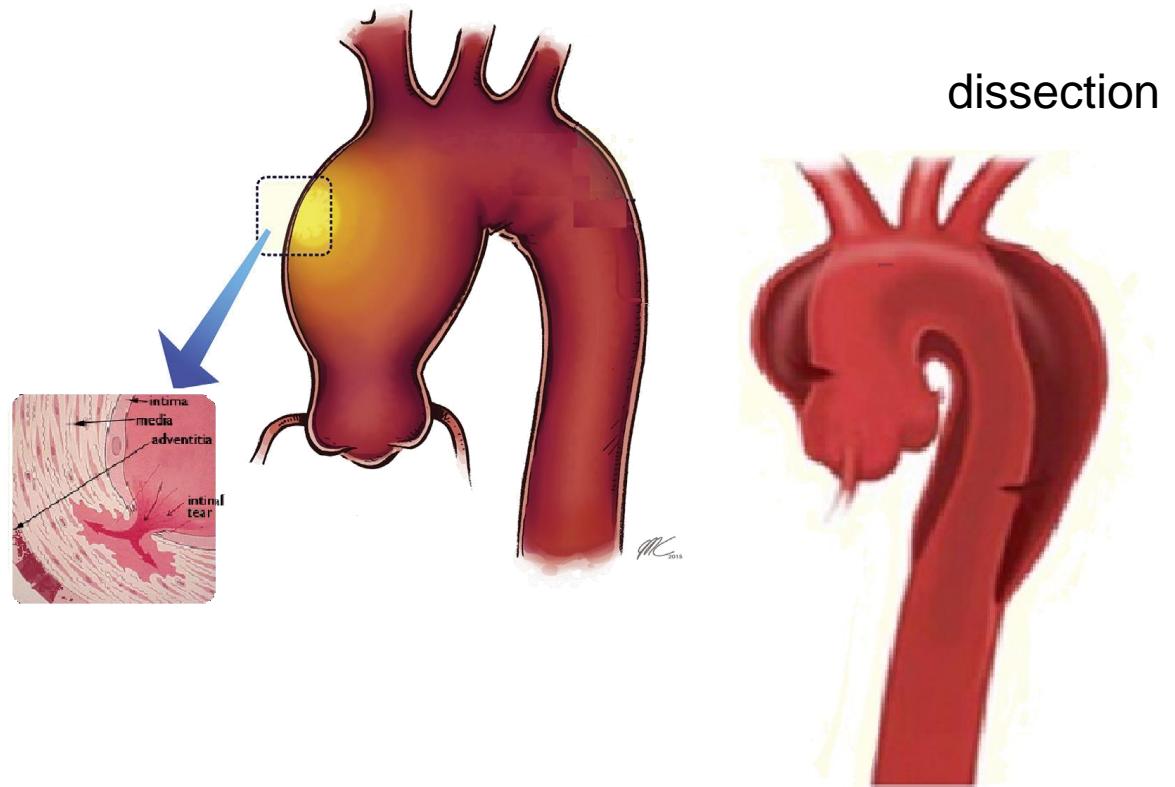
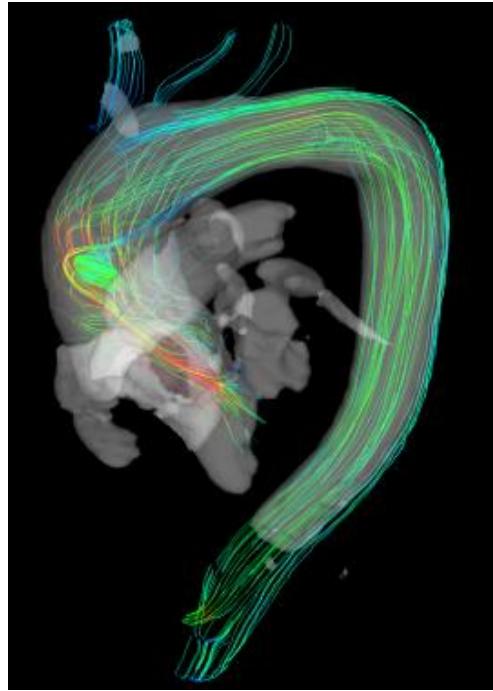
MECHANICS



Cyron et al, BMMB, 2016, Mousavi et al, IJNMBE, 2018



Prediction of risk of rupture and dissection

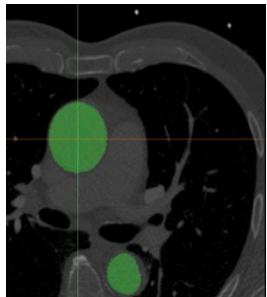


Context

- **More and more aneurysms are detected at an early stage (incidence >8% for males >65 years old).**
- **An intervention is recommended if the aneurysm grows more >1cm/year or it is >5.5cm. This represents >90000 interventions per year in Europe and USA**
- **BUT:**
 - 25% aneurysms <5.5cm rupture : 15000 deaths**!
 - 60% of aneurysms >5.5 cm never experience rupture!
- **In summary: very high rate of inappropriate decisions and misprogrammed surgical interventions!!**

** 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

Challenges raised by rupture prediction

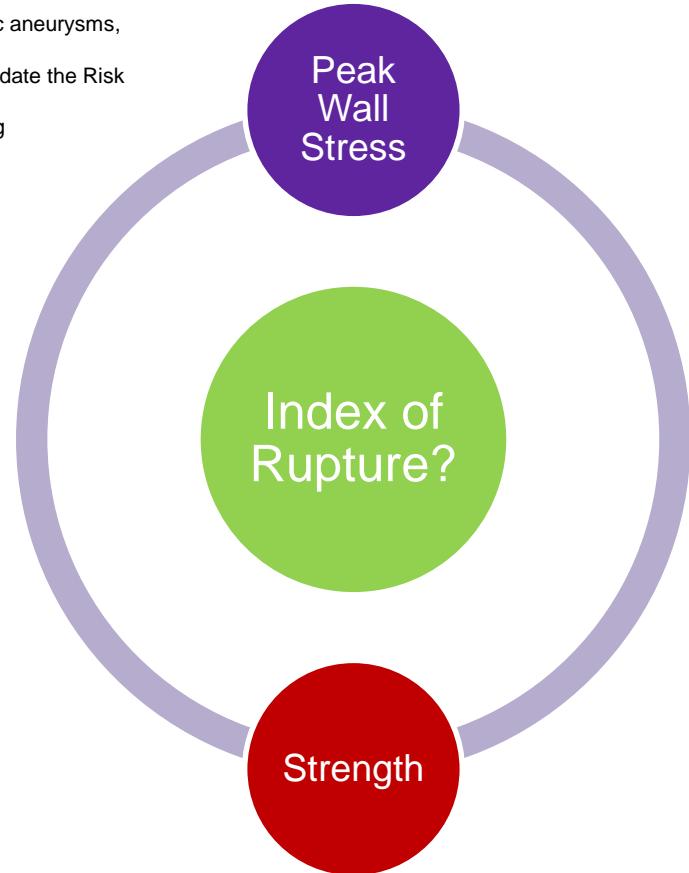
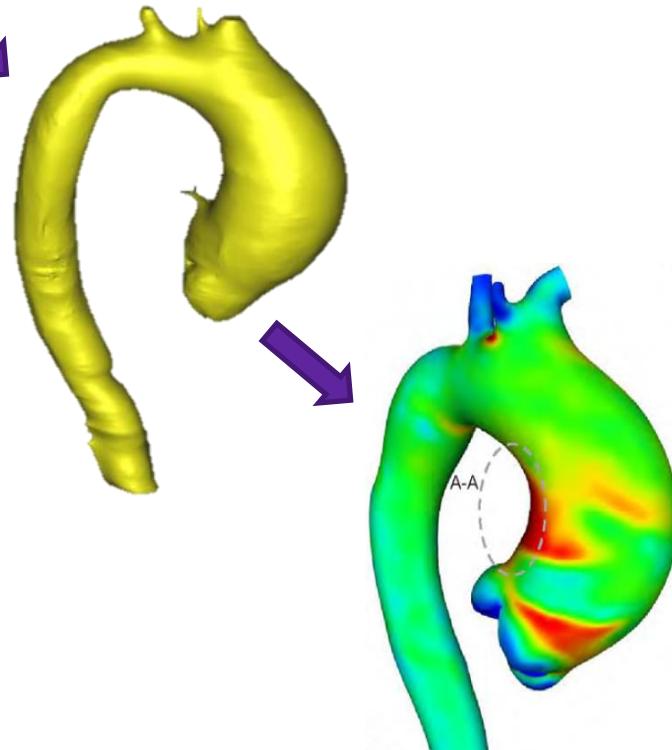


O. Trabelsi, et al, Patient specific stress and rupture analysis of ascending thoracic aneurysms, J. Biomech. (2015).

G. Martufi, et al, Is There a Role for Biomechanical Engineering in Helping to Elucidate the Risk Profile of the Thoracic Aorta?, Ann. Thorac. Surg. 101 (2016) 390–398.

S. Pasta et al., Constitutive modeling of ascending thoracic aortic aneurysms using microstructural parameters, Med. Eng. Phys. 38 (2016) 121–130.

Finite-element
modeling



Methodology

2014
↑
|
|
|
↓
2017



40 Patients
with ATAA

Preoperative
dynamic imaging

Dynamic CT
Scanner

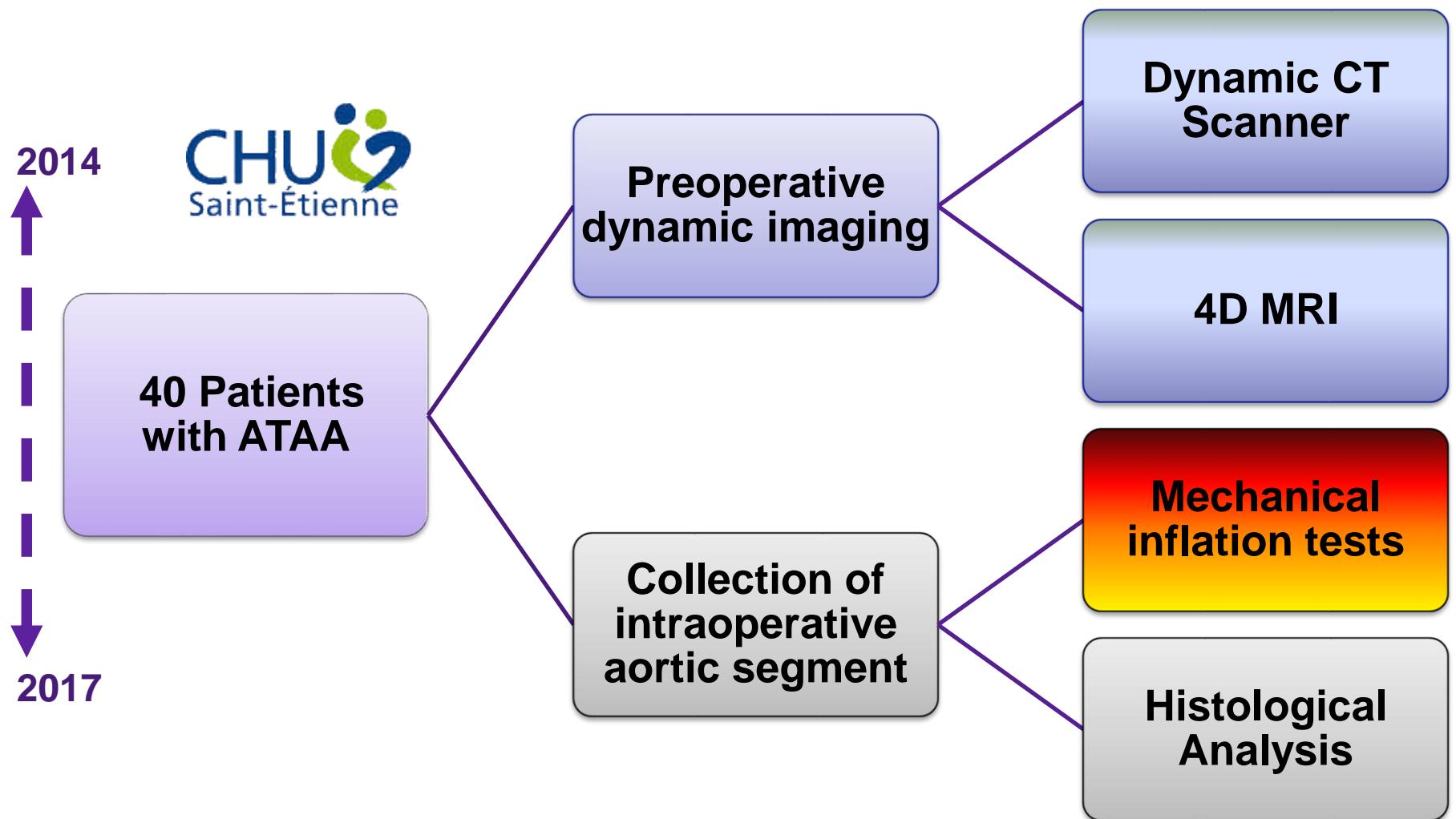
4D MRI

Collection of
intraoperative
aortic segment

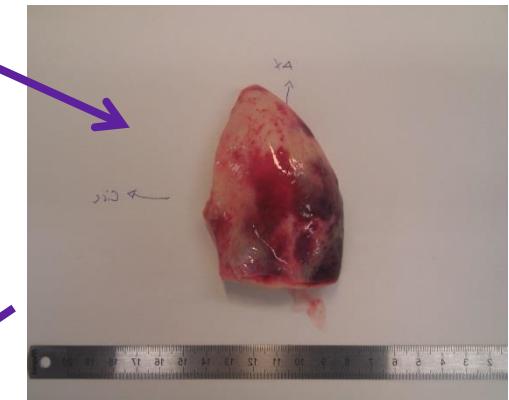
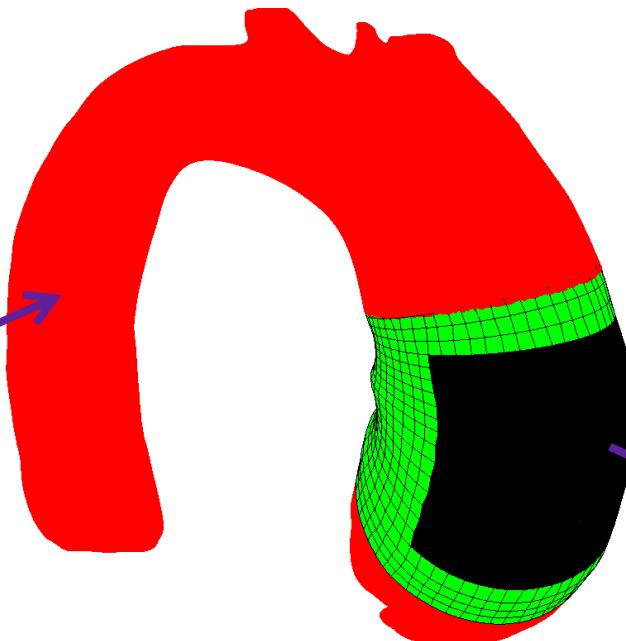
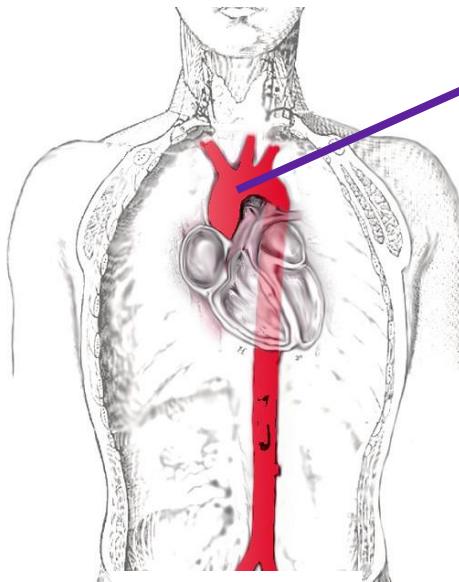
Mechanical
inflation tests

Histological
Analysis

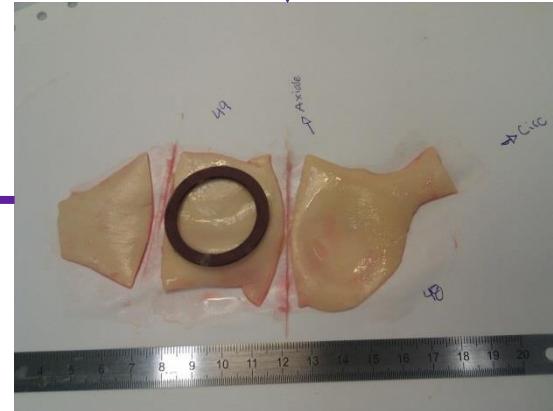
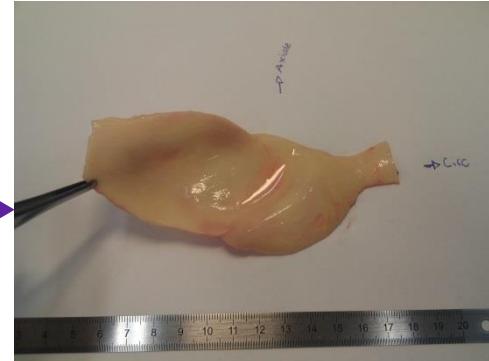
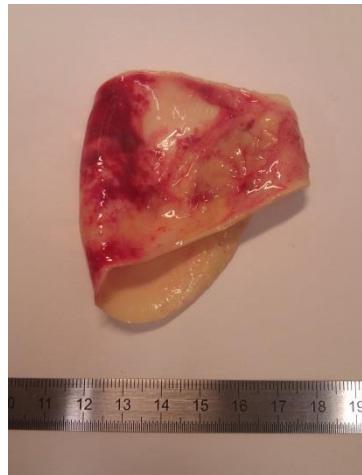
Methodology



Collection of the samples



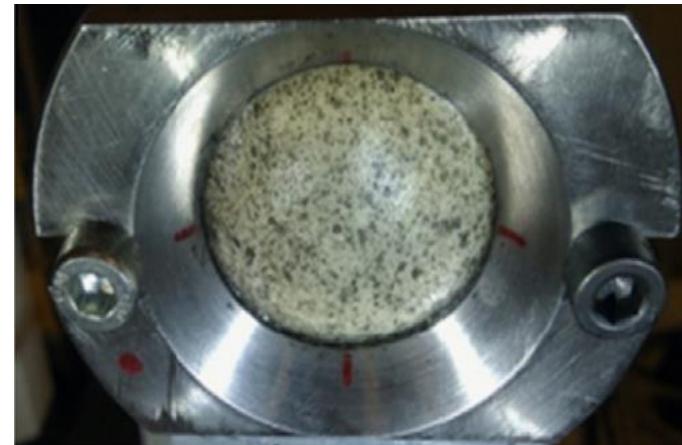
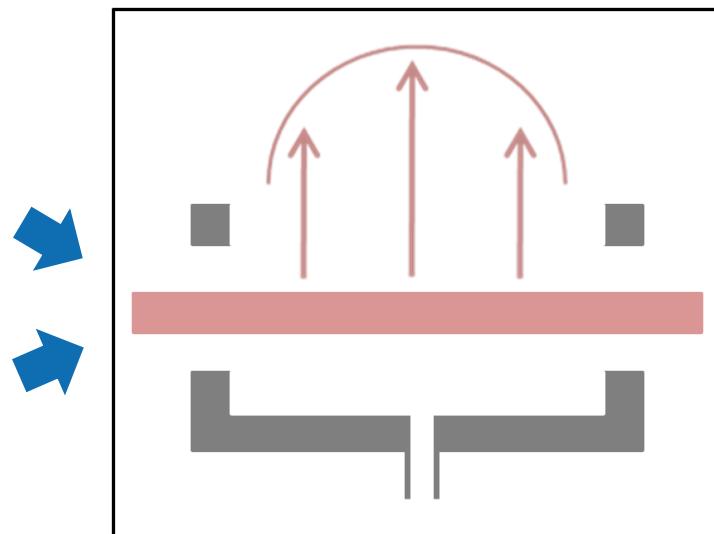
Preparation



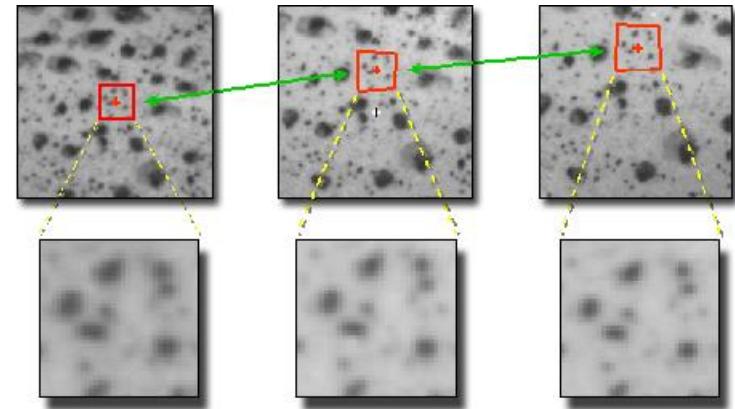


Bulge inflation test

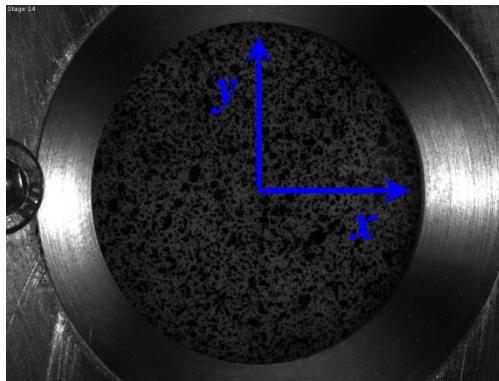
Romo et al. Journal of Biomechanics -2014.



Full-field measurements using sDIC



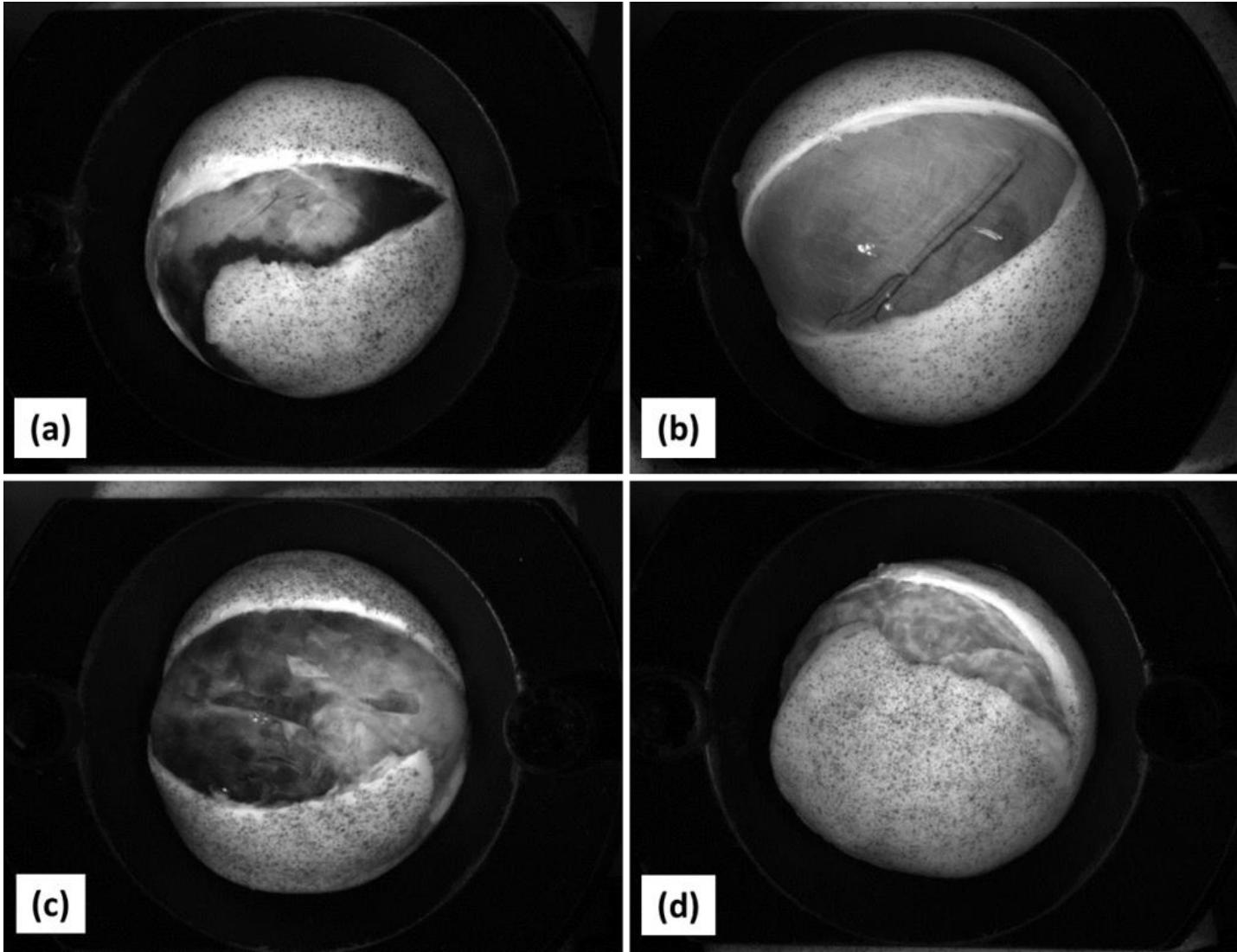
Undeformed



Deformed



Rupture profiles

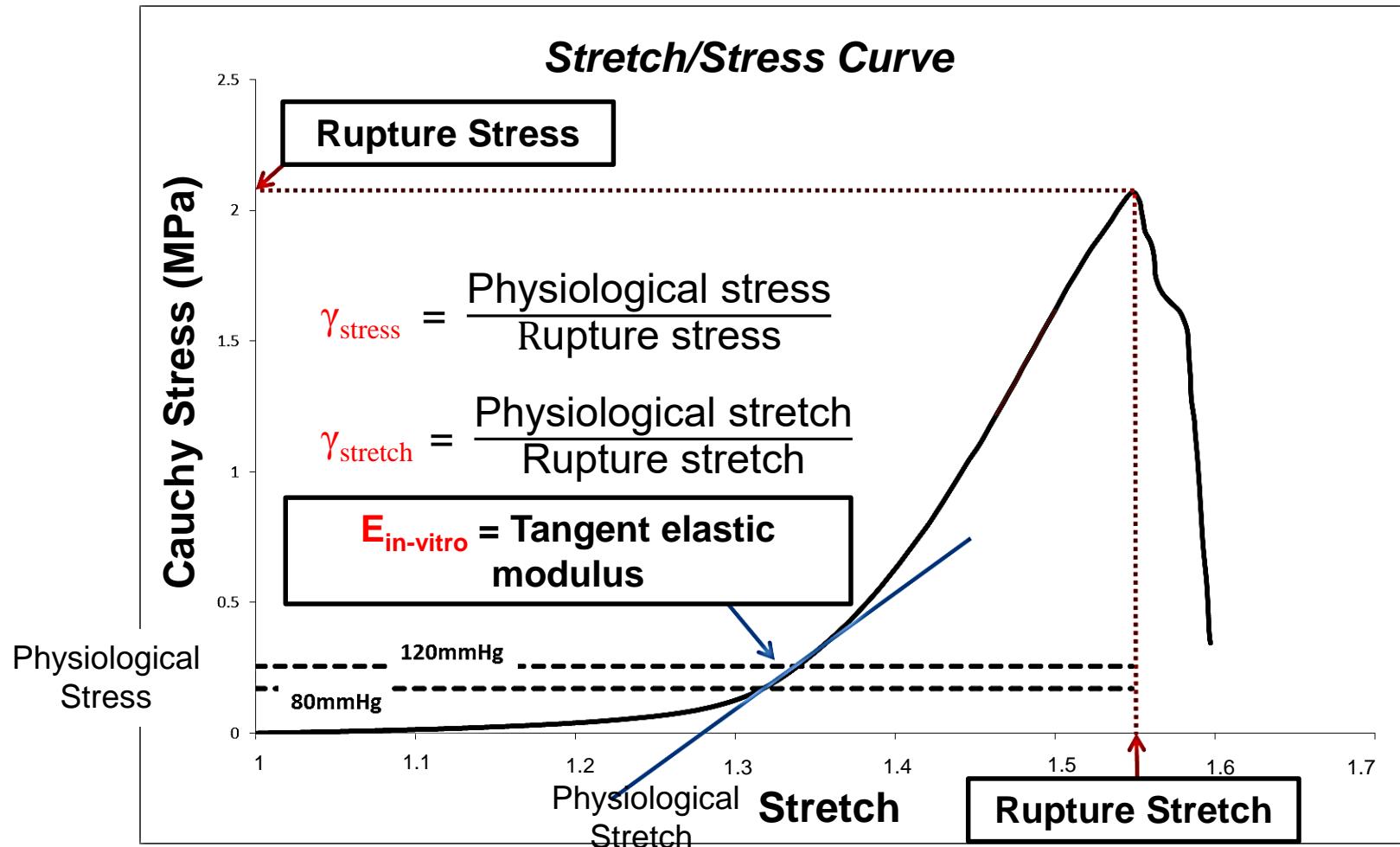


Blood flow

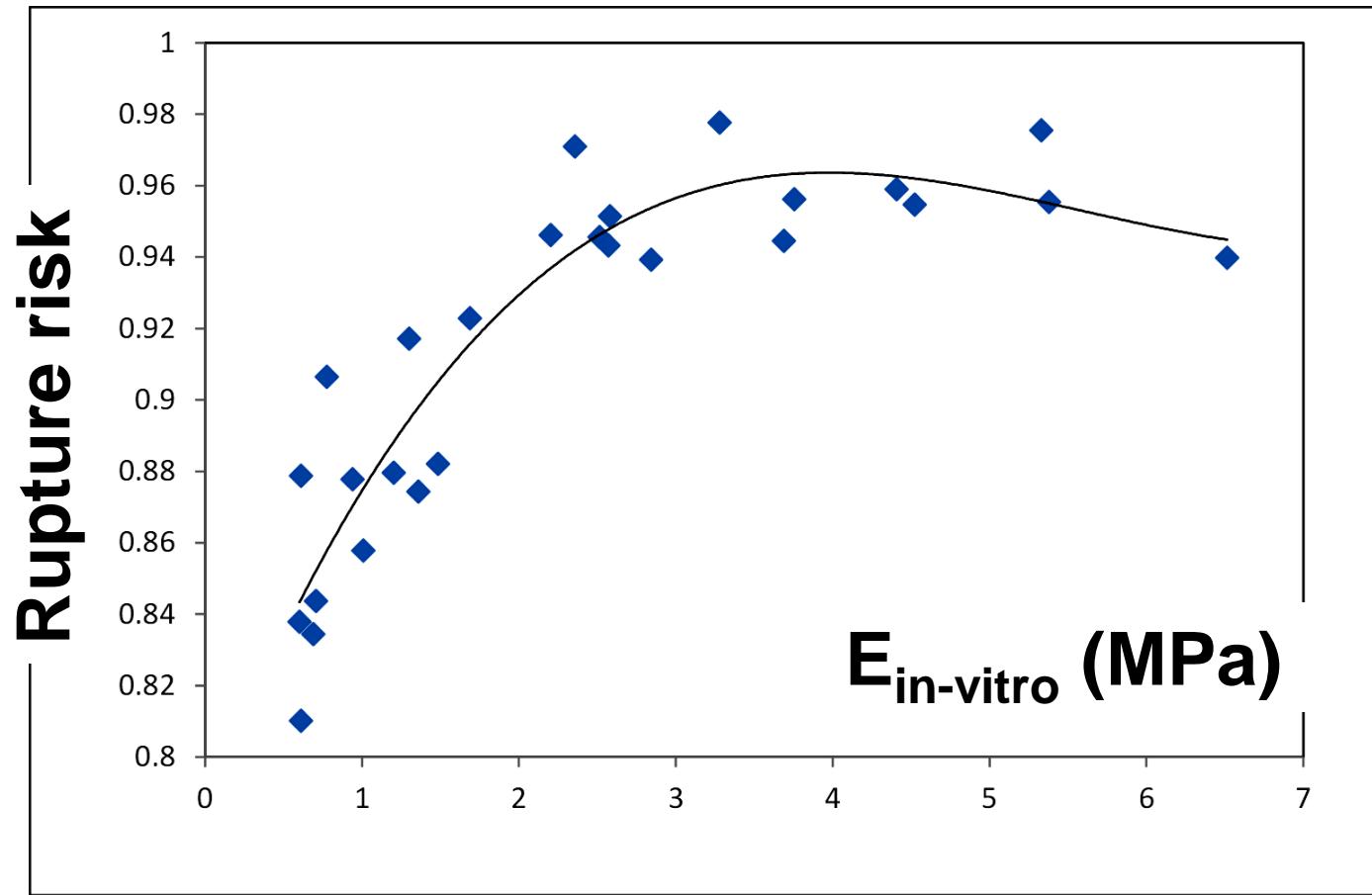


50% of aortas ruptured with an
angle θ equal to 90°

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.

Methodology

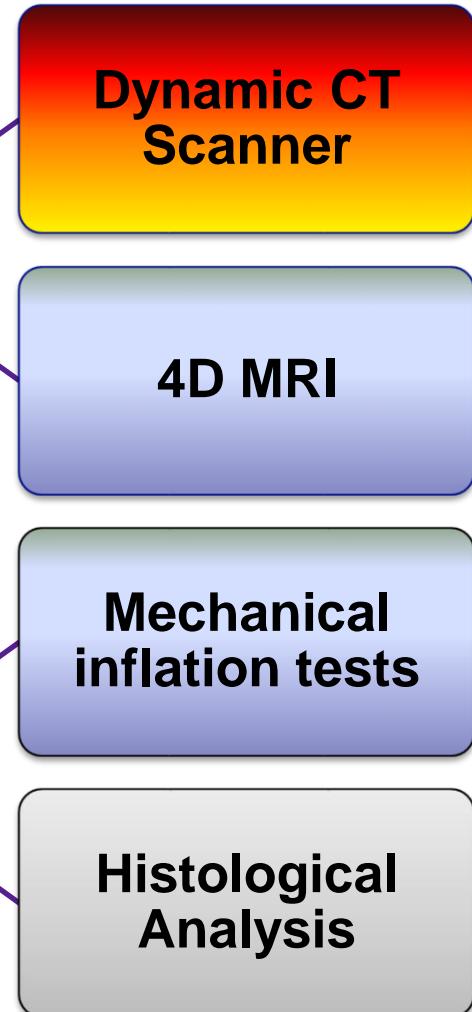
2014
↑
|
|
|
↓
2017



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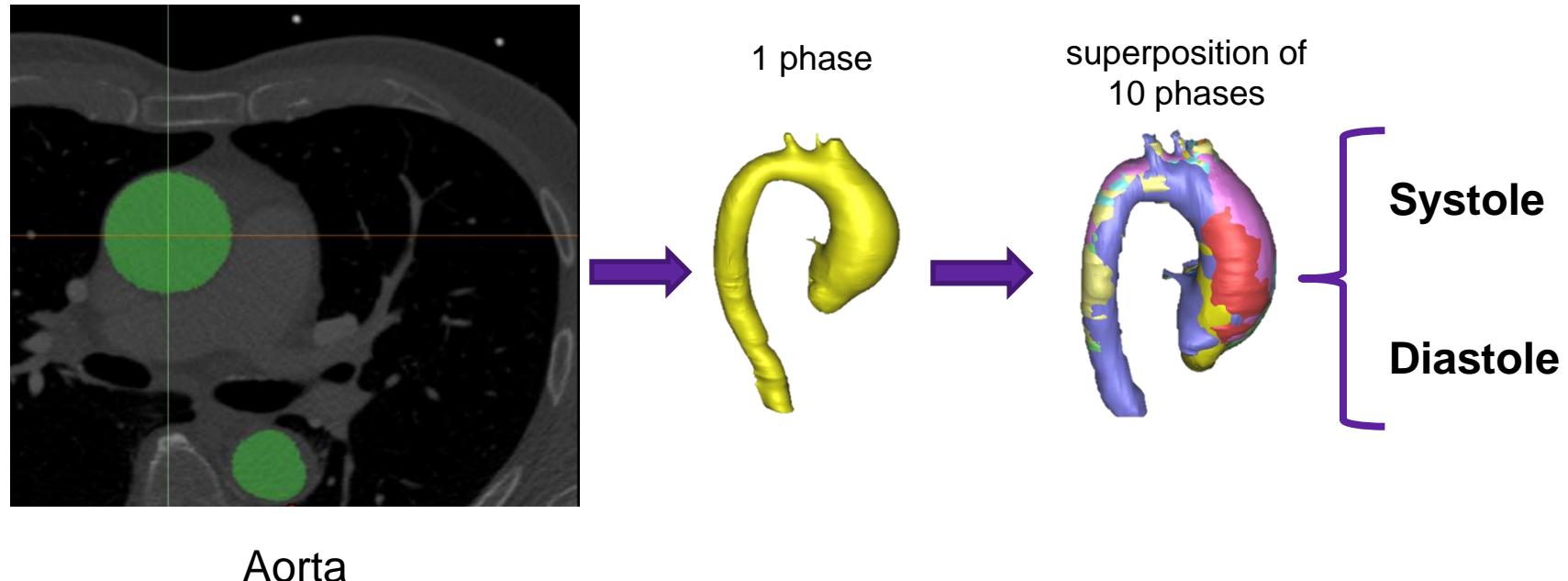
Collection of
intraoperative
aortic segment



Measurement of aortic DISTENSIBILITY

■ *Gated CT – acquisition and segmentation*

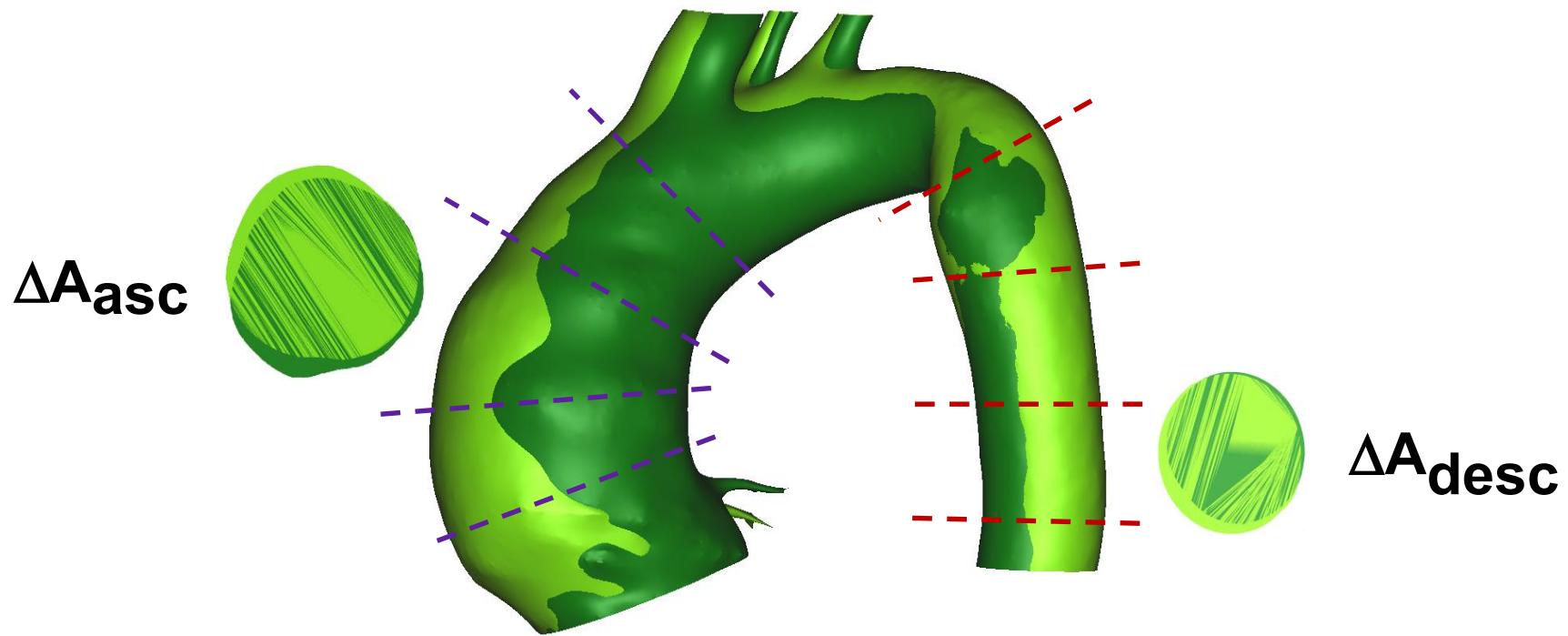
13 patients: Dynamic preoperative scanners during cardiac cycle (~ 0.92 s) = 10 phases.
CT: (resolution 512x512, slice thickness of 0.5 mm)



Measurement of aortic DISTENSIBILITY

Aortic wall - 3D reconstruction from gated CT

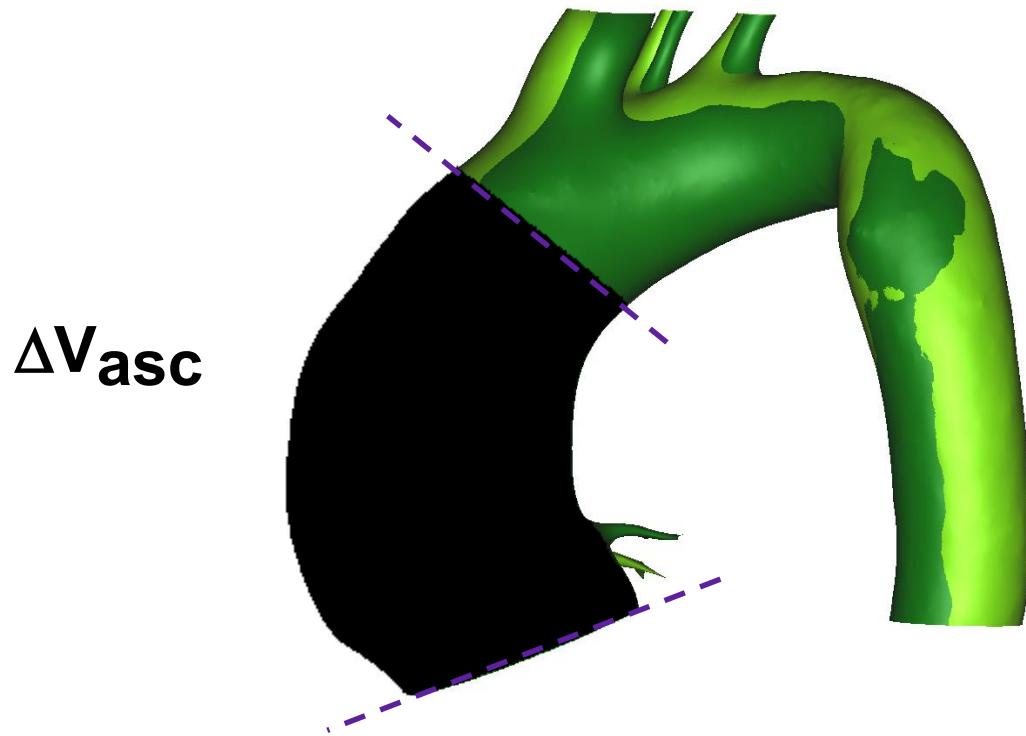
13 patients: Dynamic preoperative scanners during cardiac cycle (~ 0.92 s) = 10 phases.
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Measurement of aortic DISTENSIBILITY

■ *Aortic wall - 3D reconstruction from gated CT*

13 patients: Dynamic preoperative scanners during cardiac cycle (~ 0.92 s) = 10 phases.
CT: (resolution 512x512, slice thickness of 0.5 mm)



Measurement of aortic circumferential STIFFNESS

- The tangent elastic modulus can be derived using:

$$E_{in-vivo} = \frac{\emptyset}{hD} \quad \text{where}$$

h : thickness of the aortic wall.

\emptyset : Maximal diameter of aneurysm.

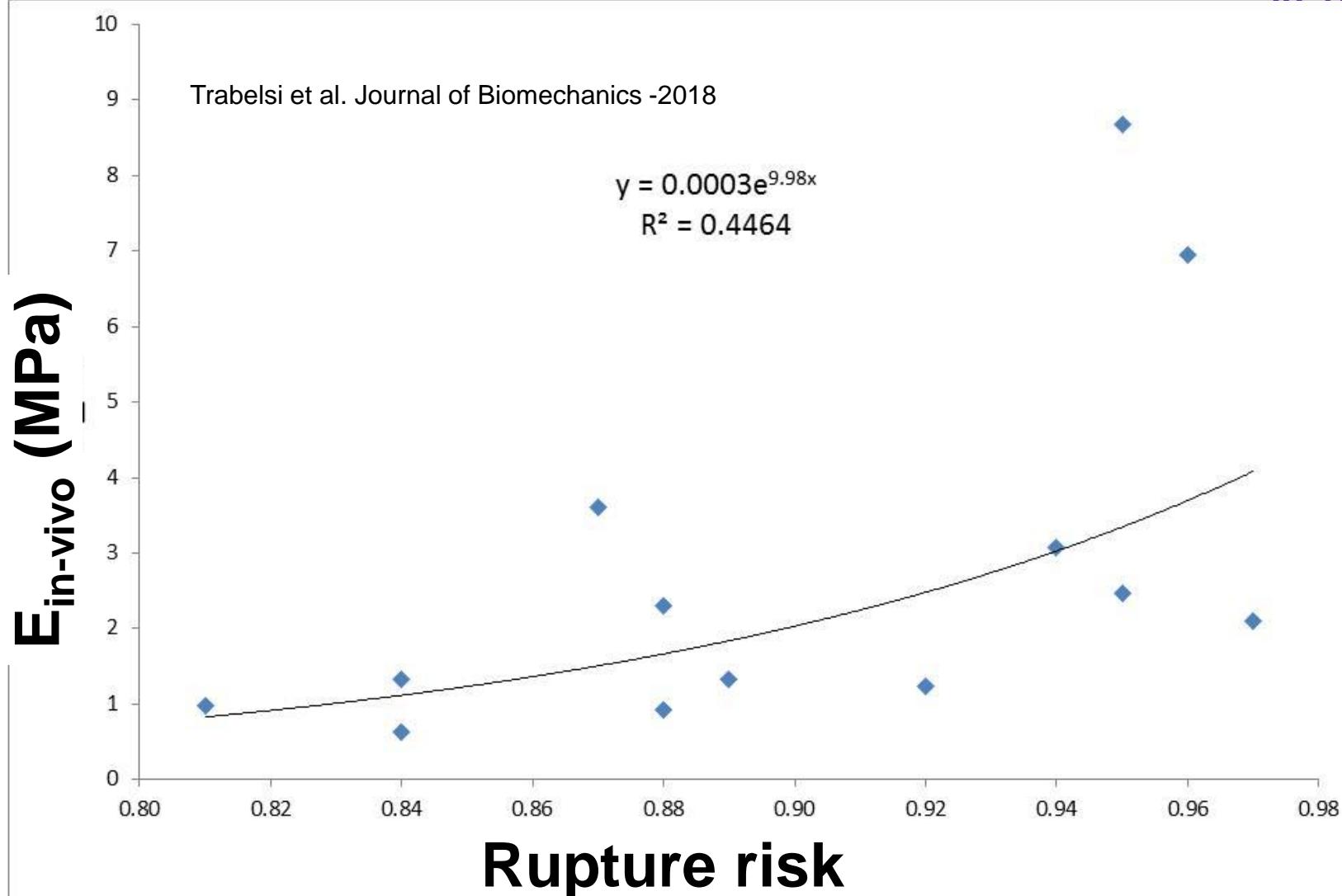
D: Distensibility.

- Access the in vivo thickness?

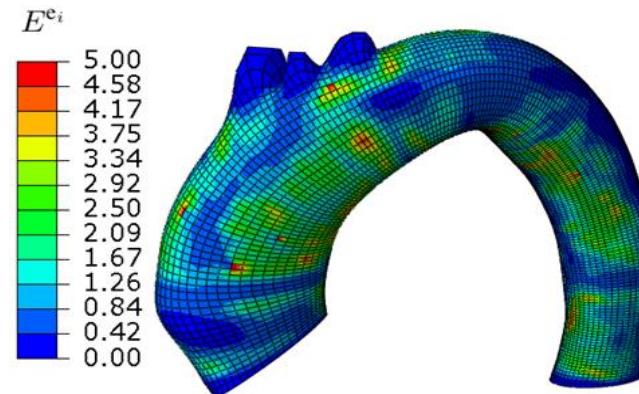
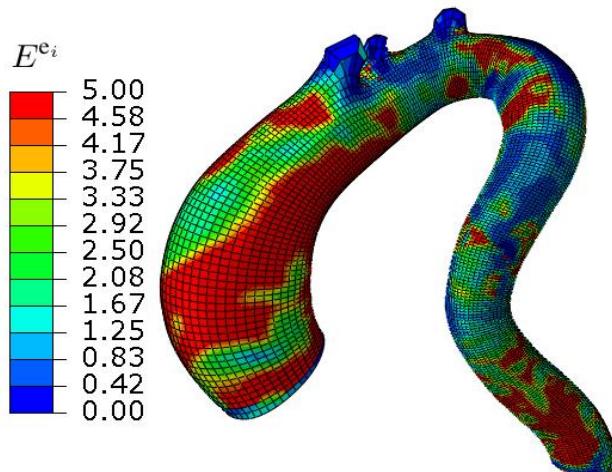
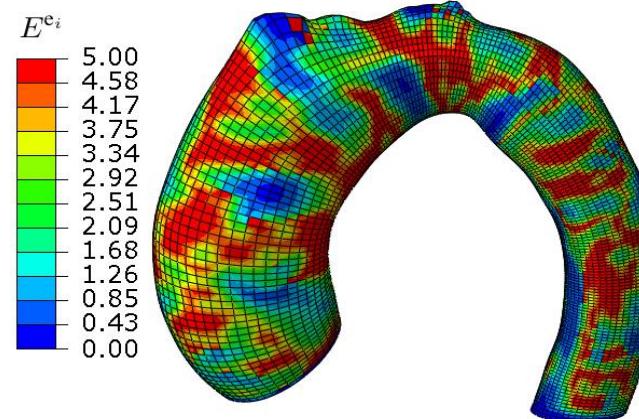
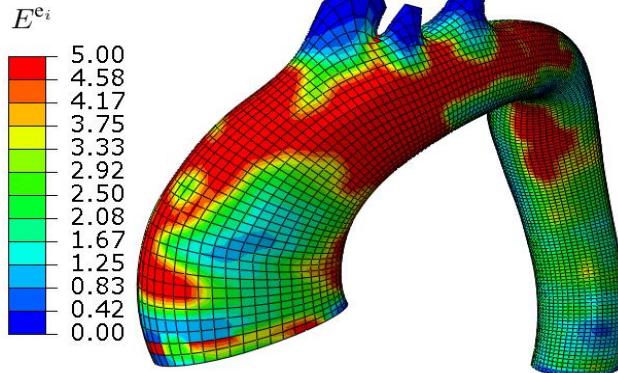
$$h = \frac{h_0}{\lambda_1 * \lambda_2} \approx \frac{h_0}{\lambda_{in vivo}}$$

$$h \approx 2 \text{ mm}$$

Results: stretch-based rupture risk vs $E_{in-vivo}$



Future work: regional reconstruction of the linearized in vivo stiffness



Bersi et al, ASME JBME, 2016, Farzaneh et al, IEEE TBME, 2018

Summary

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

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



Martin et al., Acta Biomater. 2013, Duprey et al., Acta Biomater. 2016.

Methodology

2014
↑
|
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2017



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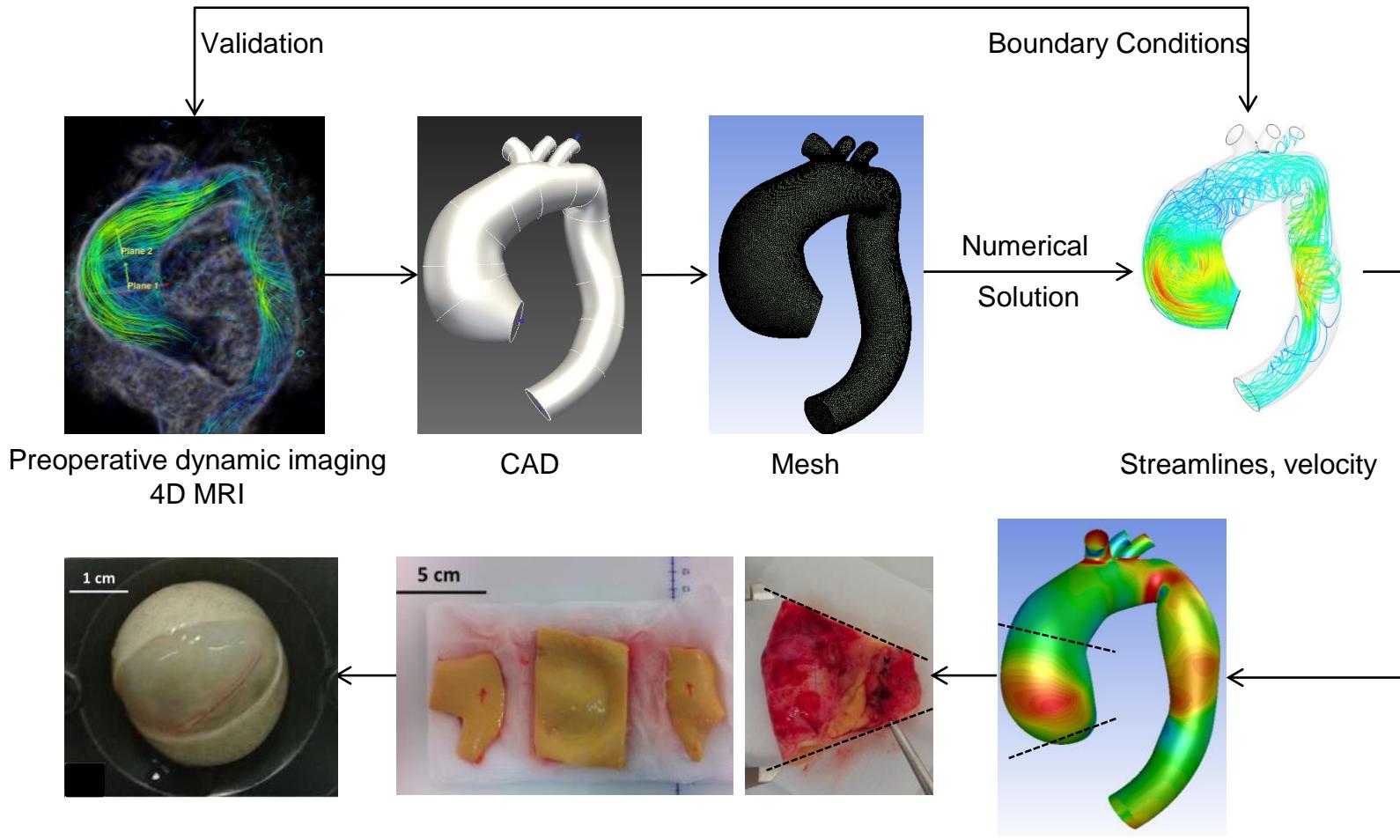
Dynamic CT
Scanner

4D MRI

Mechanical
inflation tests

Histological
Analysis

Role of hemodynamics in rupture risk

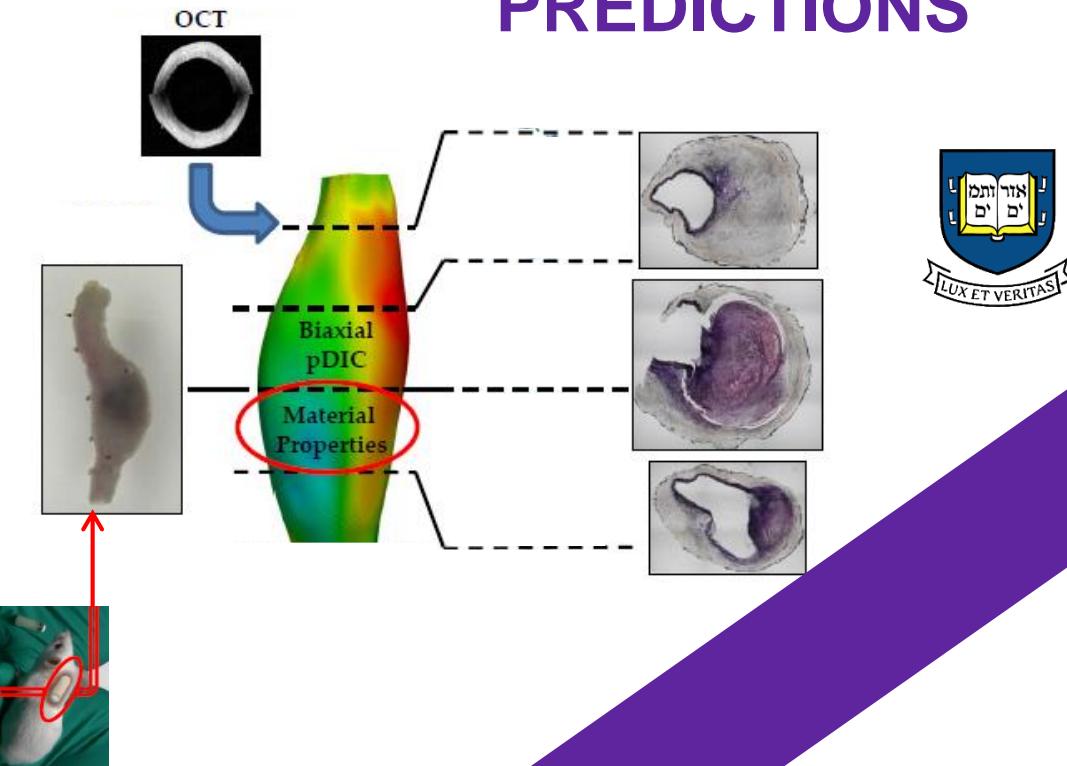


Condemi et al., ABME. 2017

Postoperative sample

TAWSS

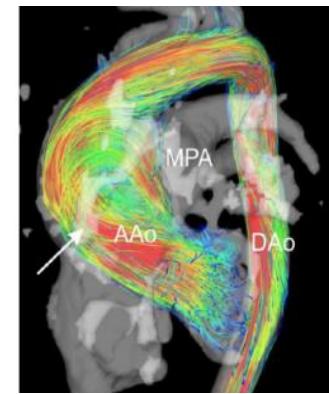
TOWARDS ATAA GROWTH PREDICTIONS



Development of
mechanobiological models



Clinical
applications



European Research Council
Established by the European Commission
erc

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