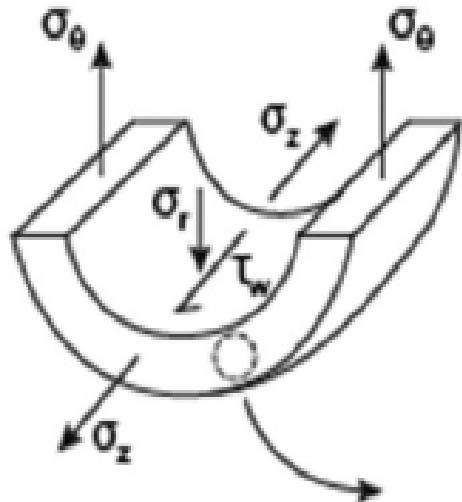




Mechanical characterization of  
arterial wall

**Prof. Stéphane AVRIL**

# Basics of arterial mechanics

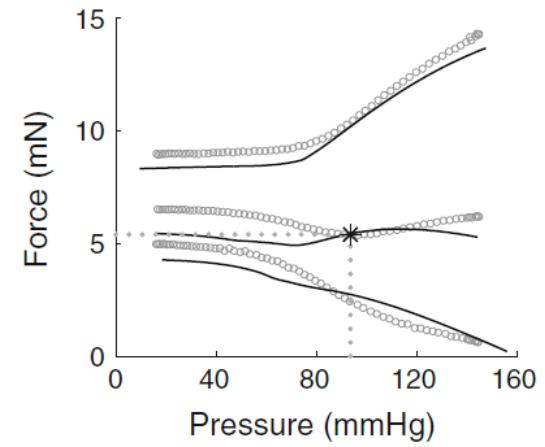
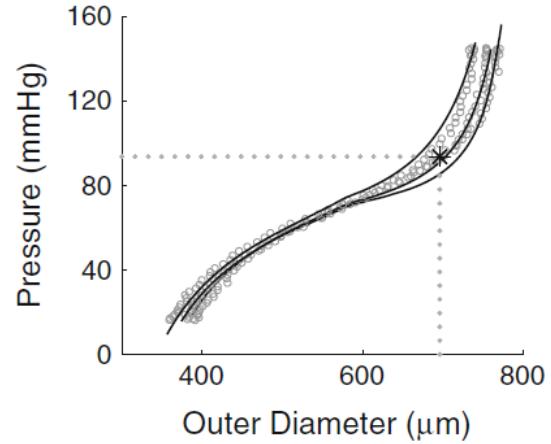
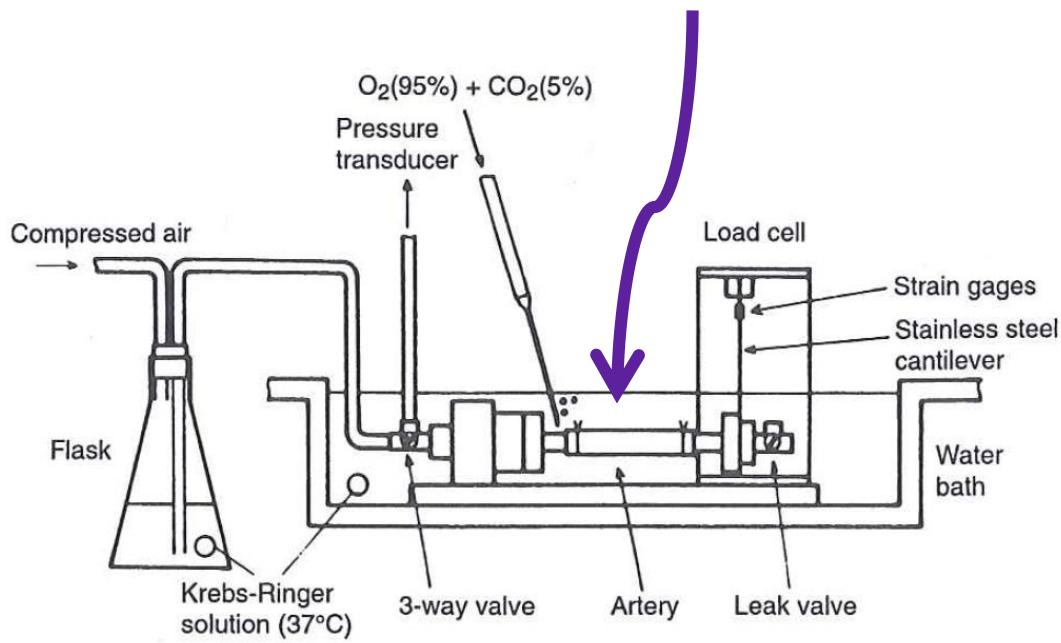


$$\tau_w = \frac{4\mu Q}{\pi a^3}, \quad \sigma_\theta = \frac{Pa}{h}$$

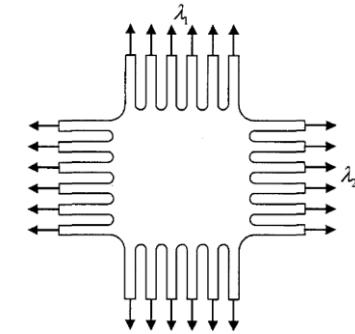
$$\sigma_z = \frac{f_z}{\pi(b^2 - a^2)} = \frac{f_z}{\pi h(2a - h)}$$

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

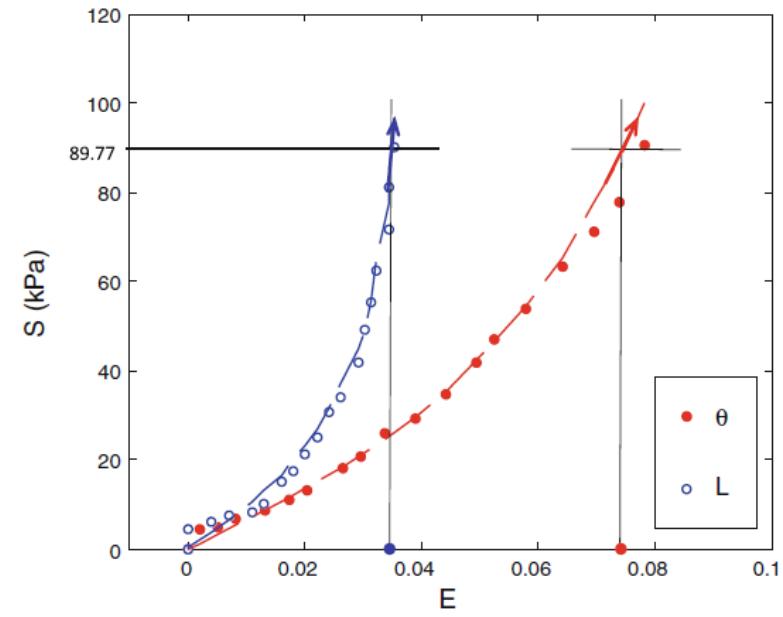
# Functional biomechanical behavior



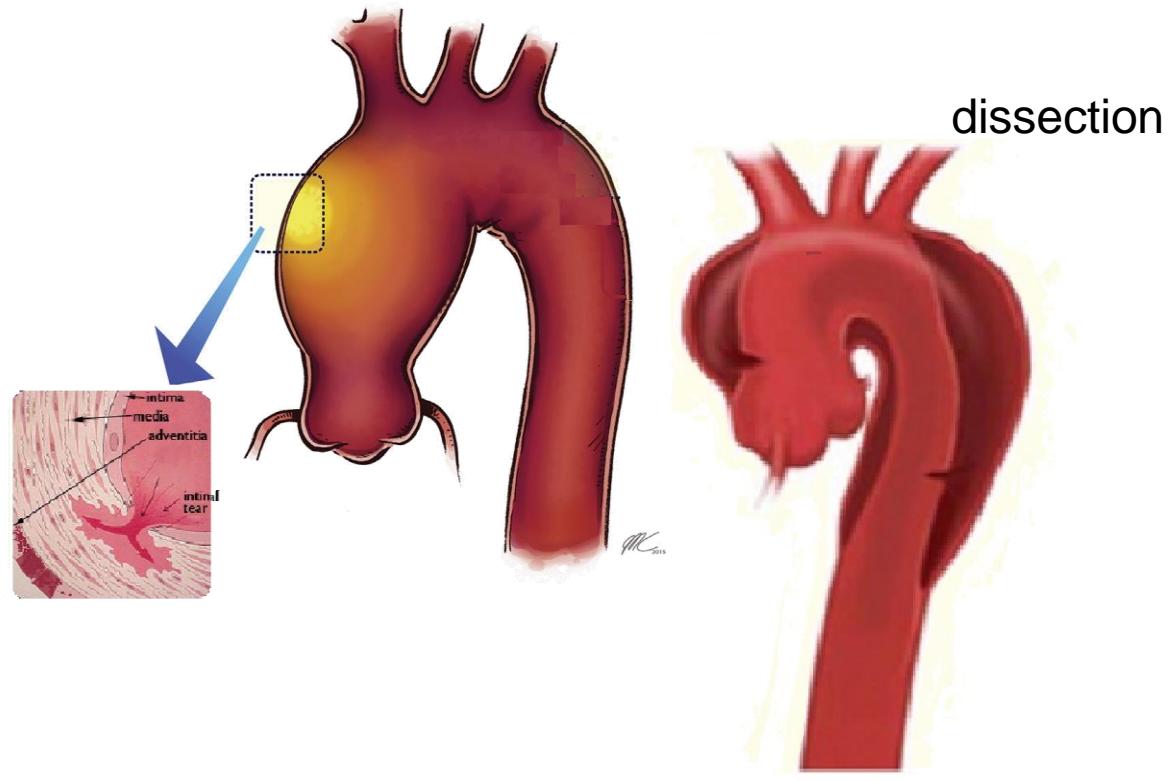
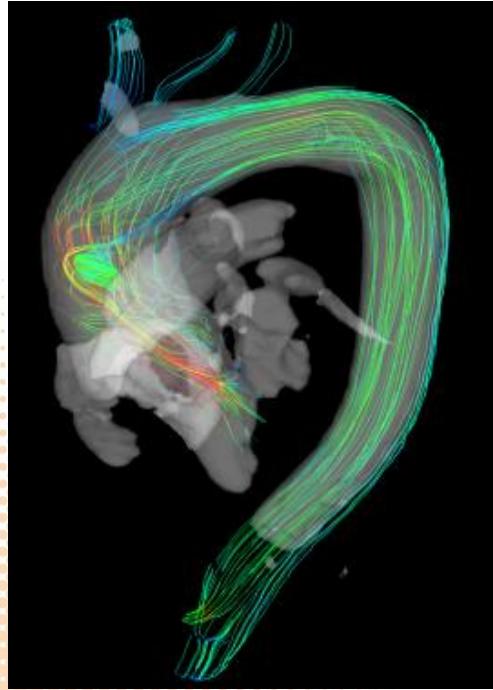
# Material characterization and constitutive modeling



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



# Application to the prediction of AA index of rupture?



## 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  $\geq 5.5$  cm Is Not a Good Predictor of Type A Aortic Dissection Observations From the International Registry of Acute Aortic Dissection (IRAD)*, Circulation, 2007

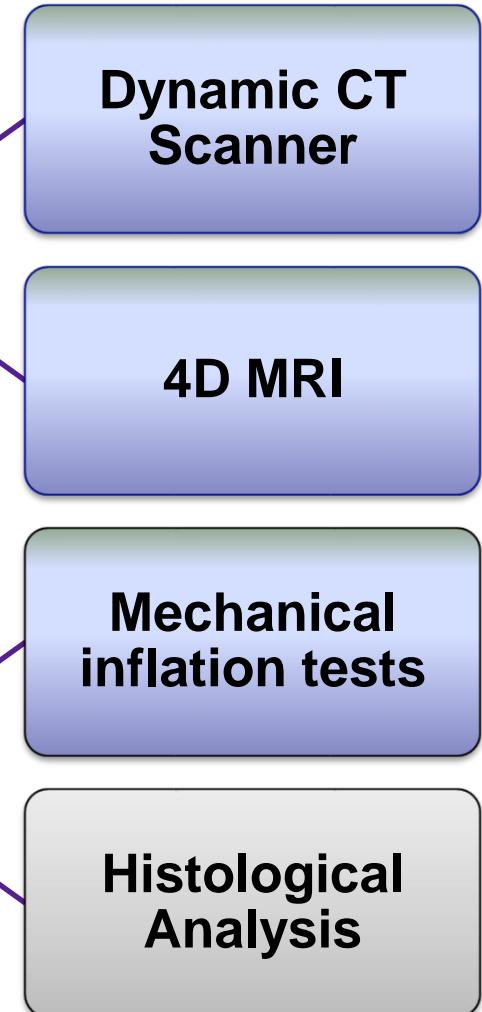
# Methodology

2014 ↑  
|  
|  
|  
|  
↓ 2017

**40 Patients  
with ATAA**

**Preoperative  
dynamic imaging**

**Collection of  
intraoperative  
aortic segment**



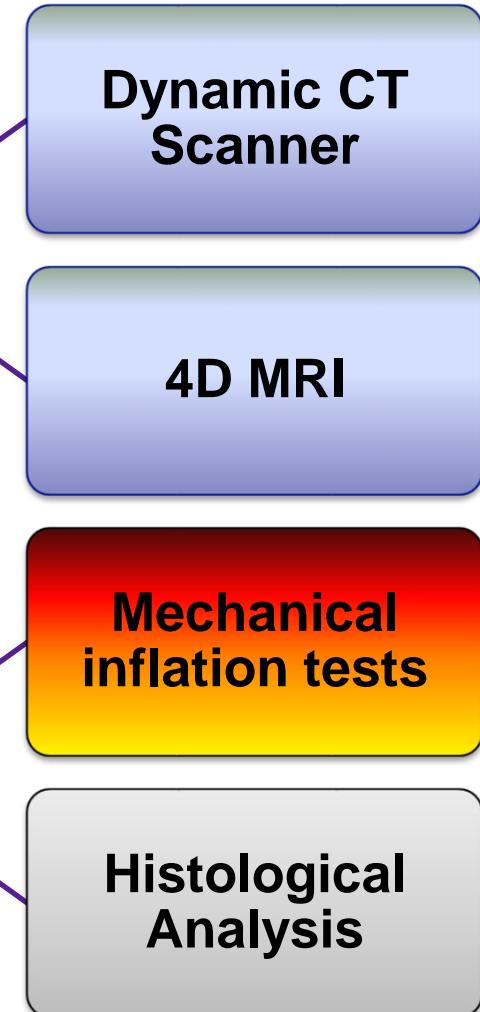
# Methodology

2014  
↑  
|  
|  
|  
↓  
2017

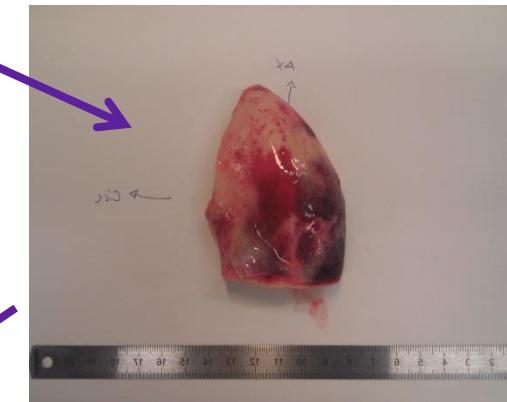
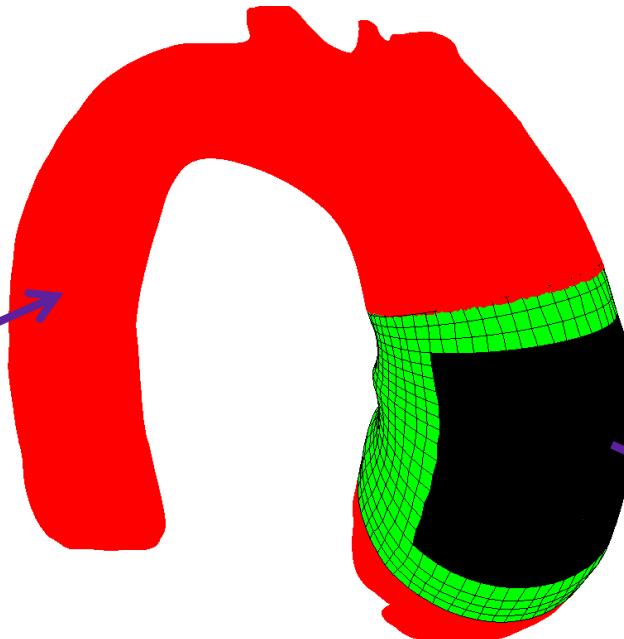
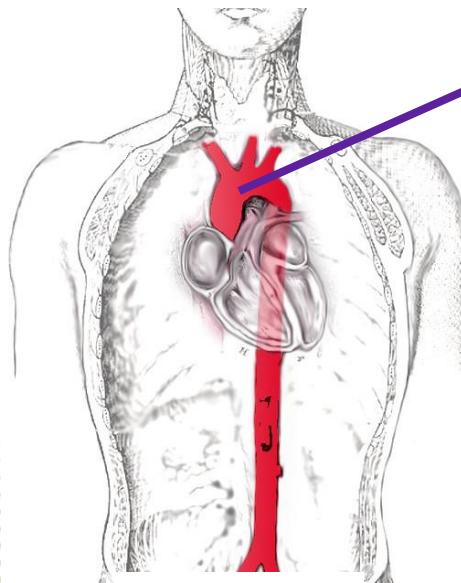
40 Patients with ATAA

Preoperative dynamic imaging

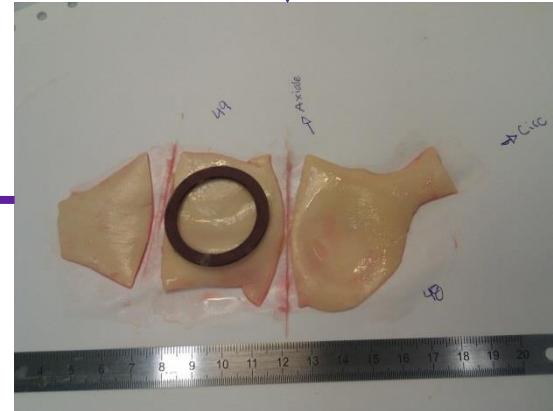
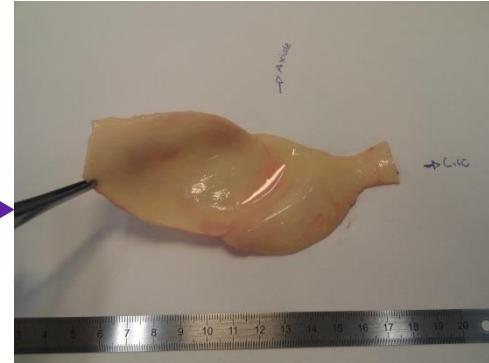
Collection of intraoperative aortic segment



# Collection of the samples

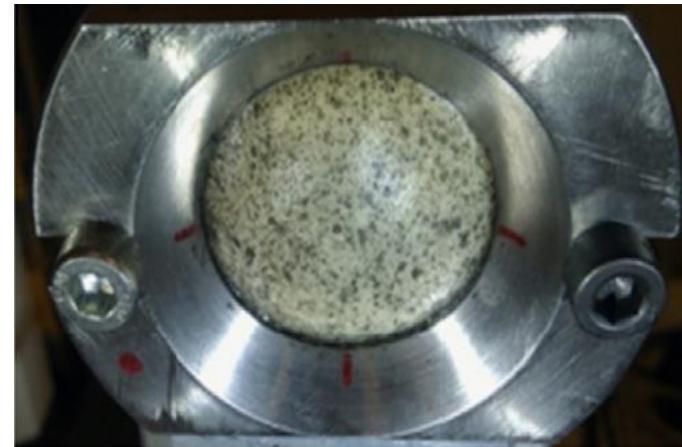
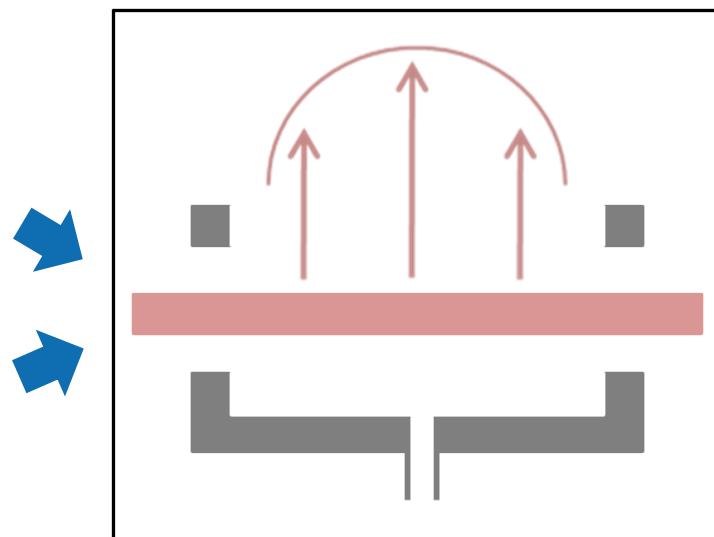


# PREPARATION

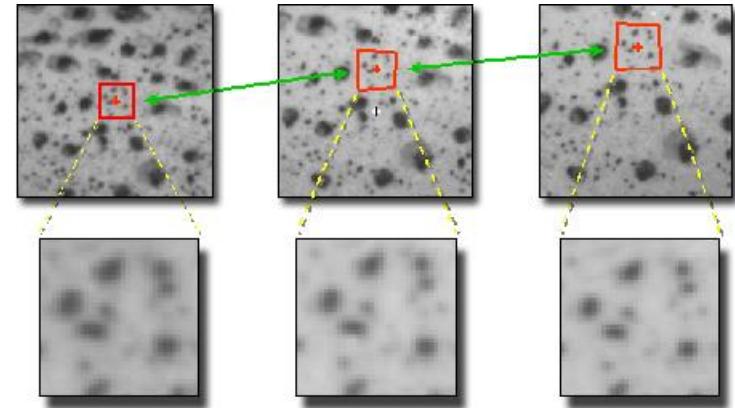


# Bulge inflation test

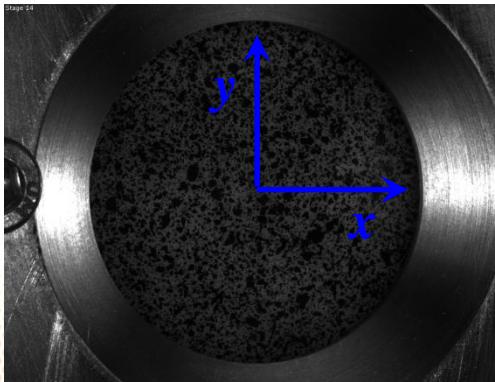
Romo et al. Journal of Biomechanics -2014.



# Full-field measurements using sDIC



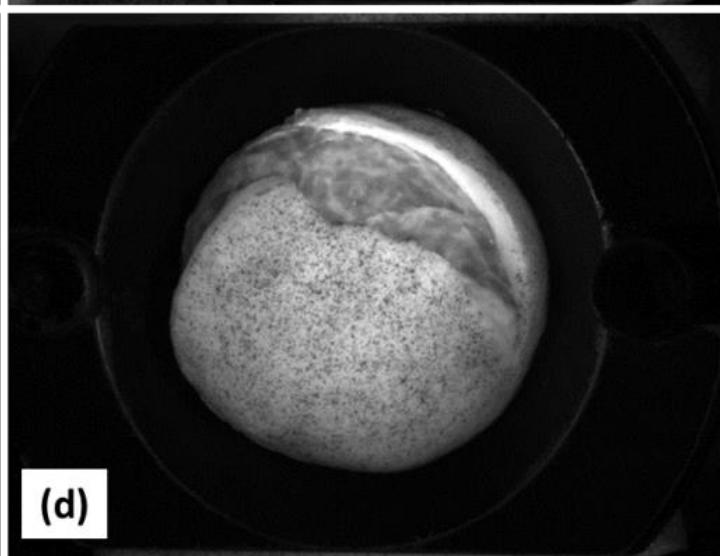
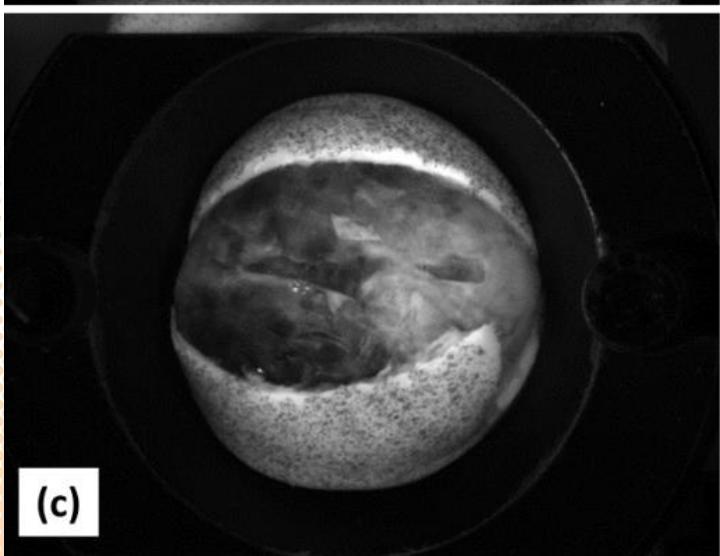
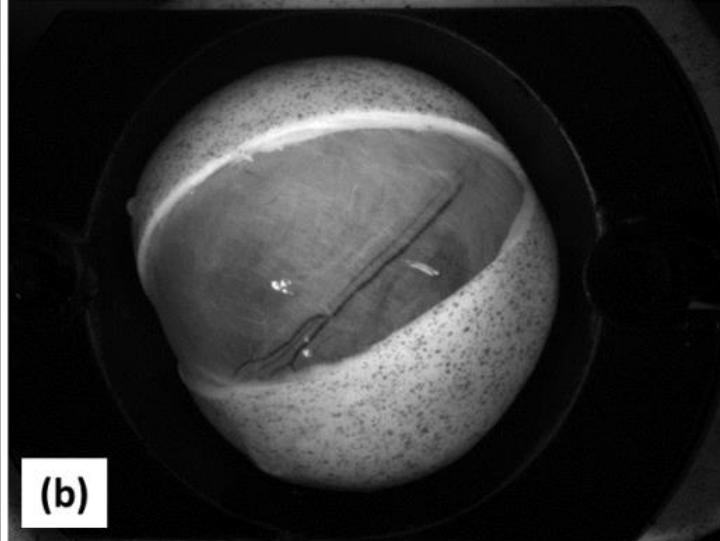
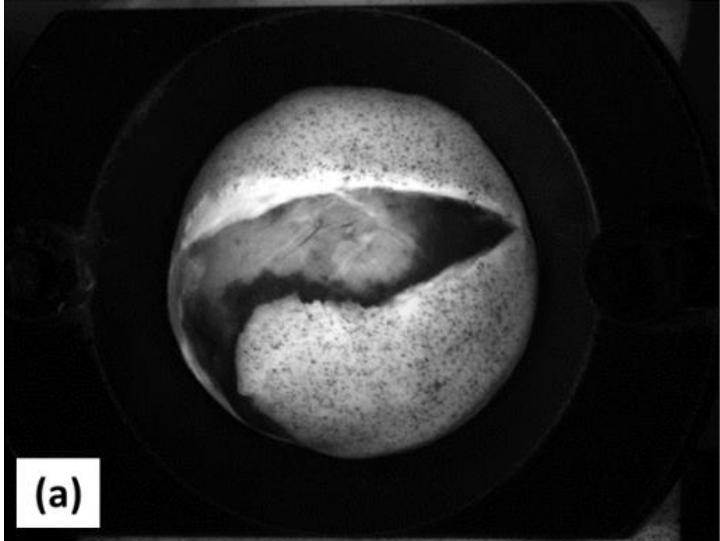
Undeformed



Deformed



# Rupture profiles

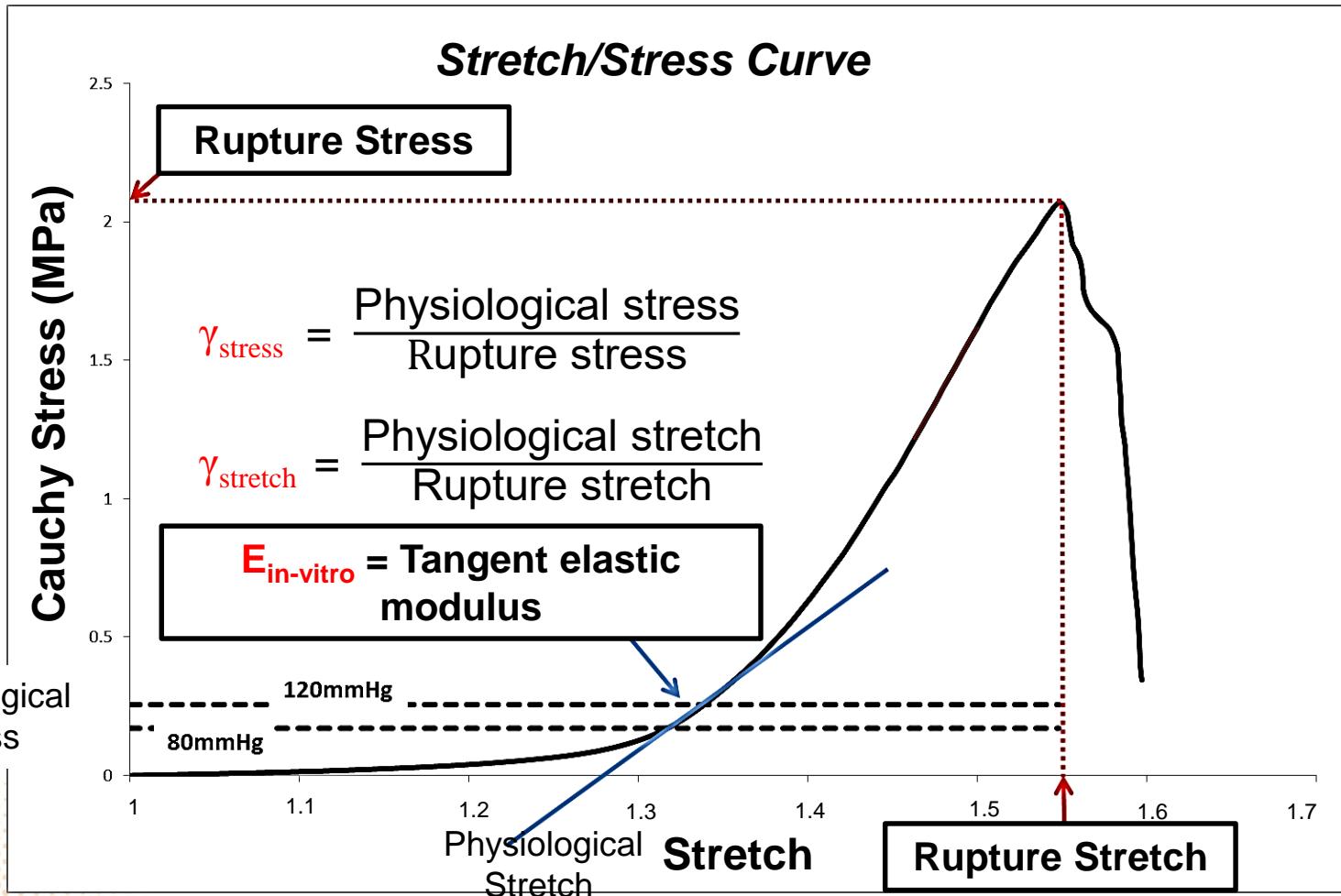


Blood flow

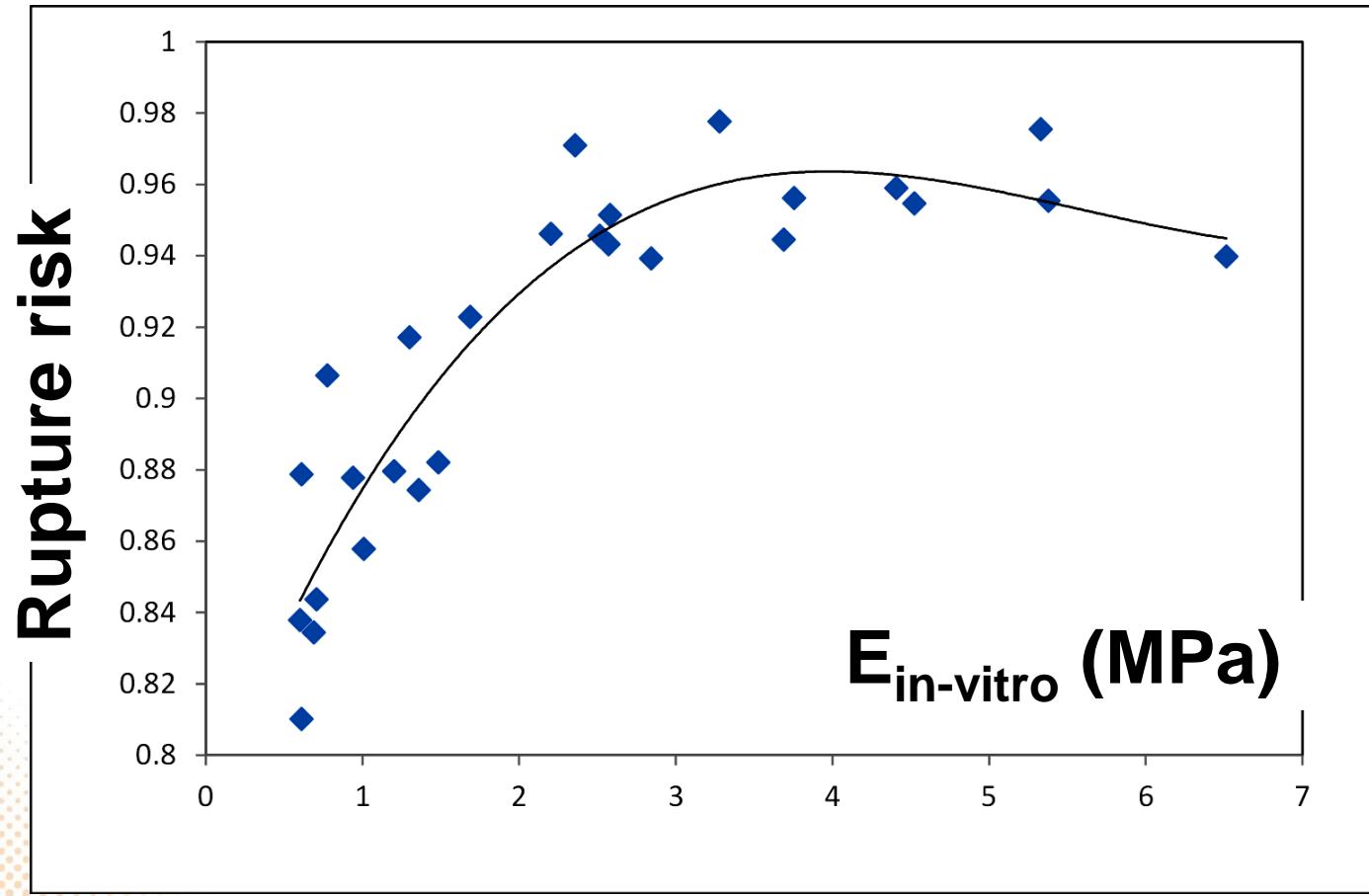


50% of aortas ruptured with an  
angle  $\theta$  equal to 90 °

# 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.

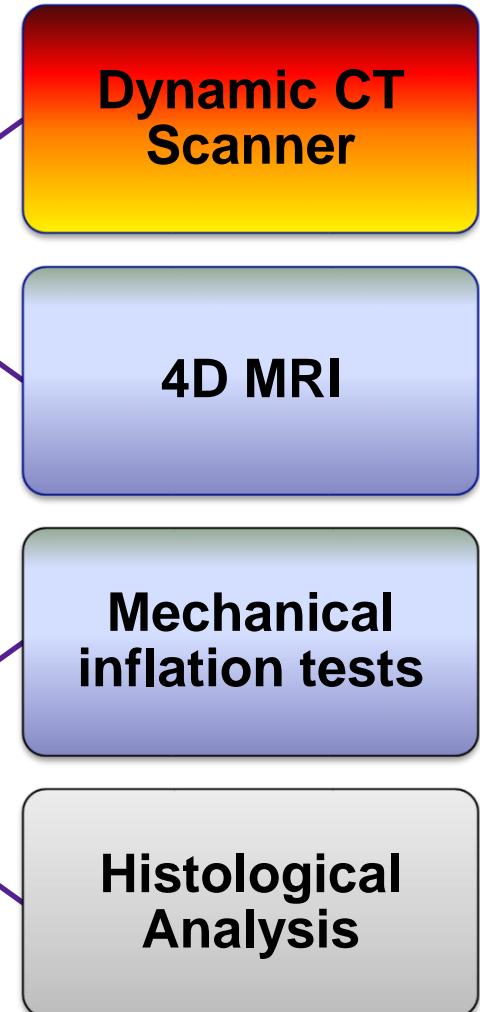
# SAINT-ETIENNE PROTOCOL

2014  
↑  
|  
|  
|  
|  
↓  
2017

40 Patients  
with ATAA

Preoperative  
dynamic imaging

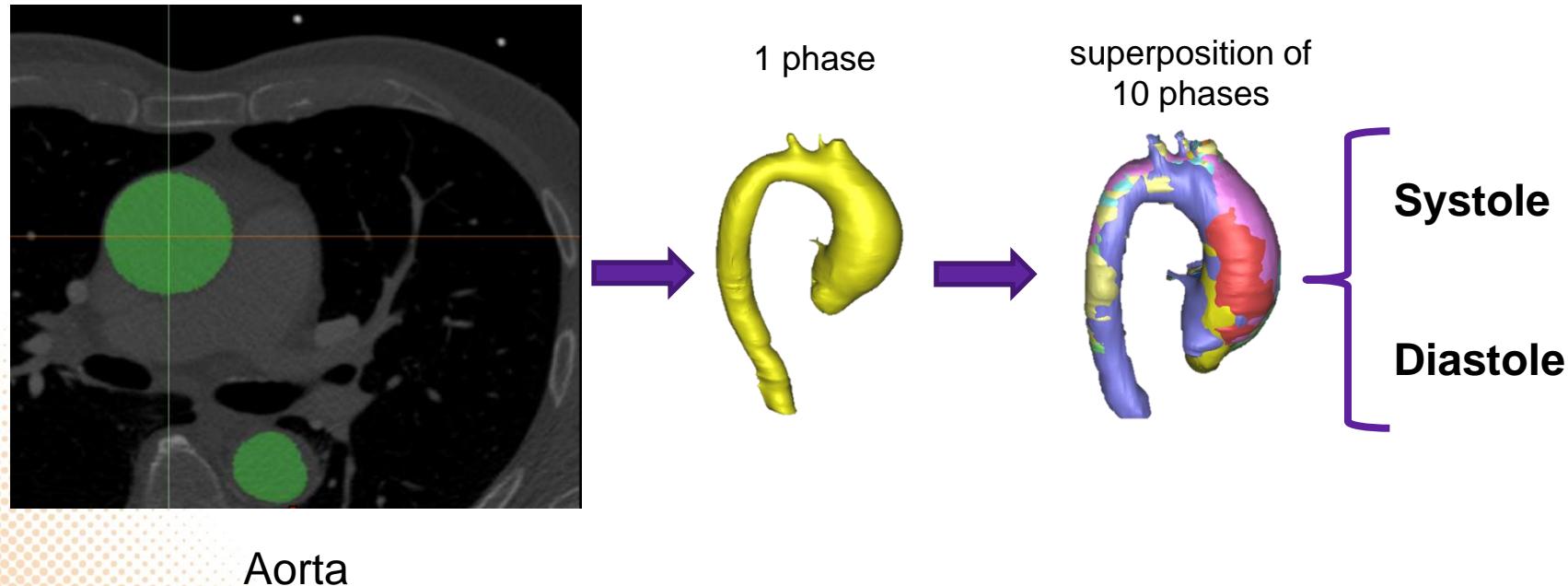
Collection of  
intraoperative  
aortic segment



# Measurement of aortic DISTENSIBILITY

## ■ *Gated CT – acquisition and segmentation*

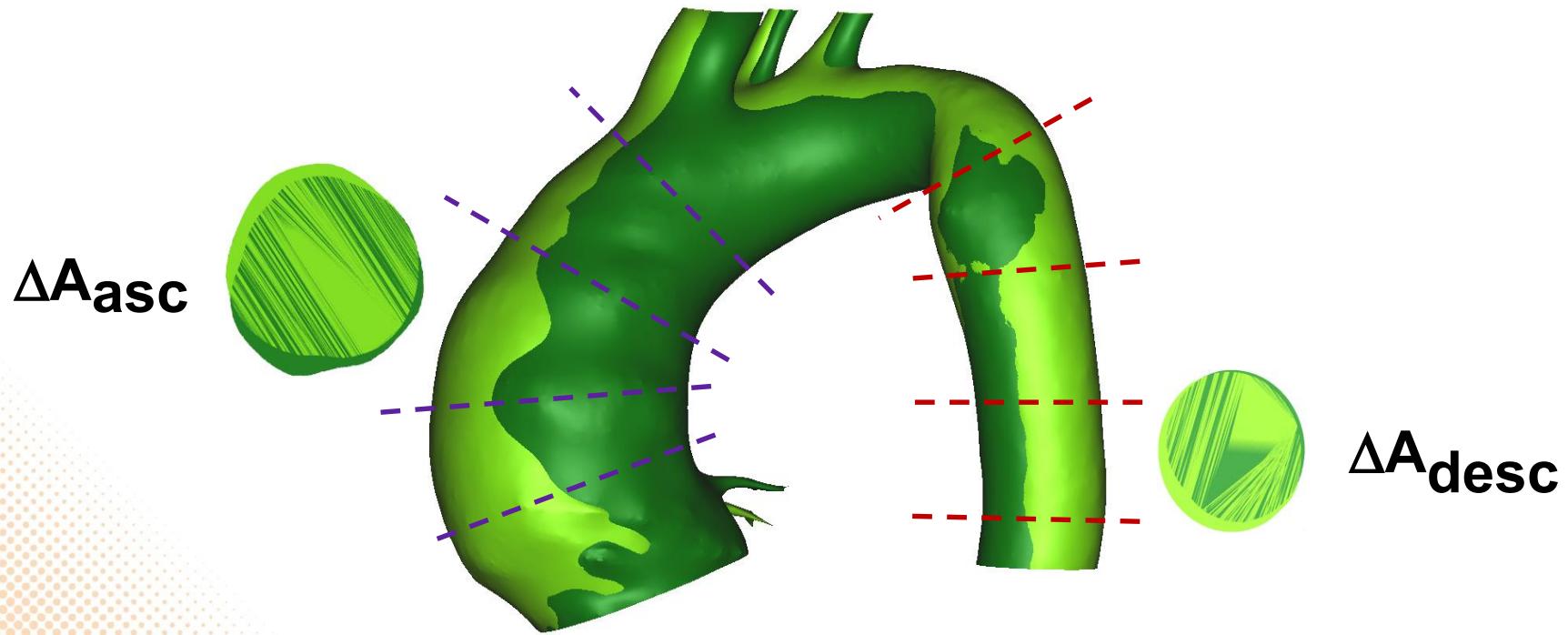
13 patients: Dynamic preoperative scanners during cardiac cycle ( $\sim 0.92$  s) = 10 phases.  
CT: (resolution 512x512, slice thickness of 0.5 mm)



# Measurement of aortic DISTENSIBILITY

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

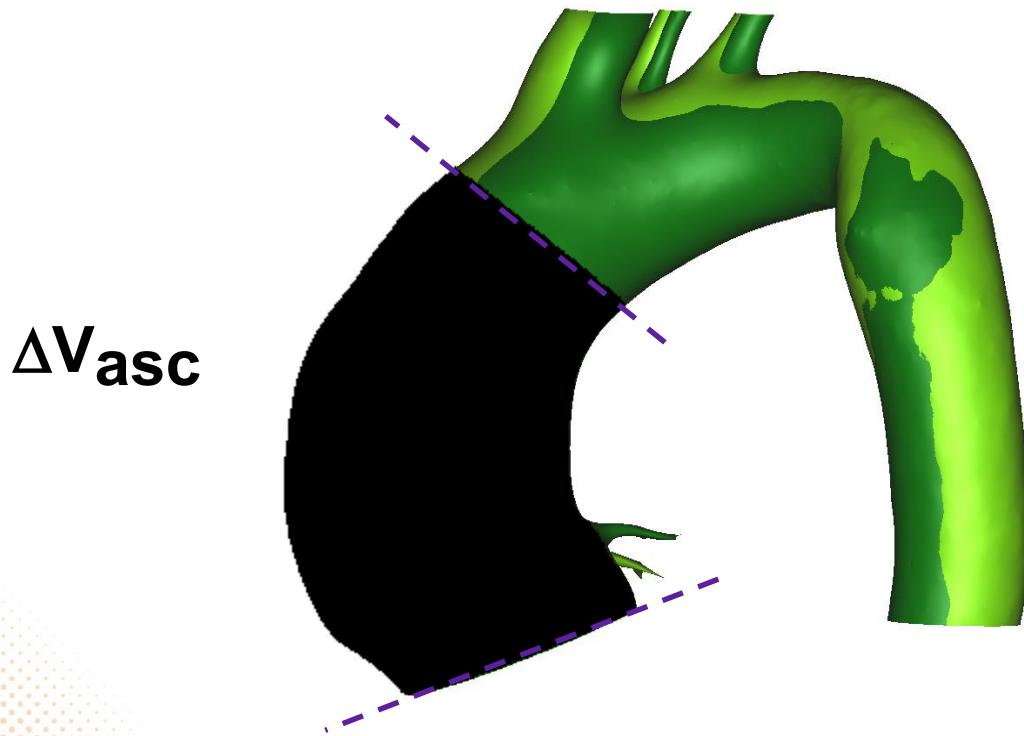
13 patients: Dynamic preoperative scanners during cardiac cycle ( $\sim 0.92$  s) = 10 phases.  
CT: (resolution 512x512, slice thickness of 0.5 mm)



# Measurement of aortic DISTENSIBILITY

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

13 patients: Dynamic preoperative scanners during cardiac cycle ( $\sim 0.92$  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.

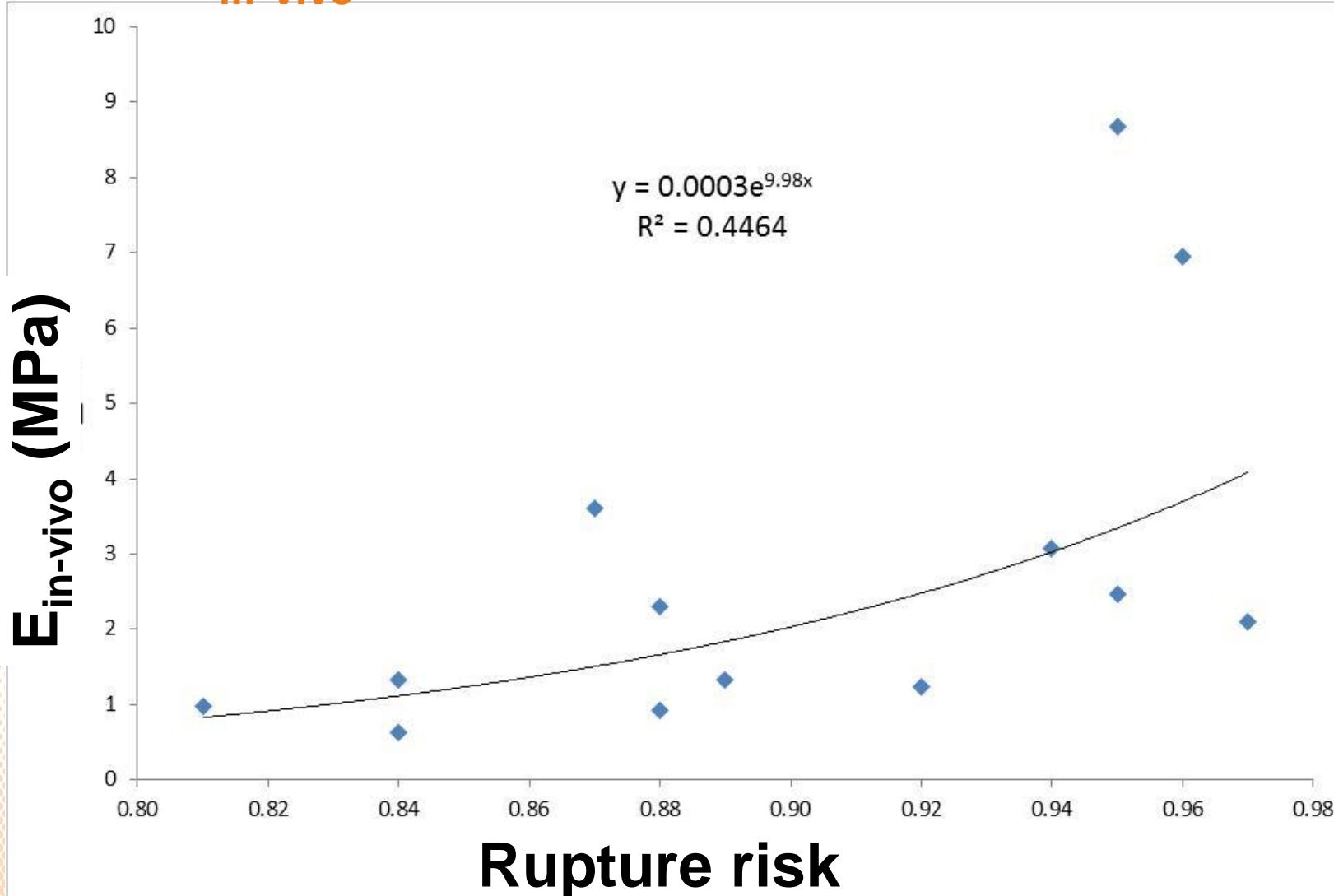
**$\emptyset$** : Maximal diameter of aneurysm.

**D**: Distensibility.

- Access the in vivo thickness?

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

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



## Summary

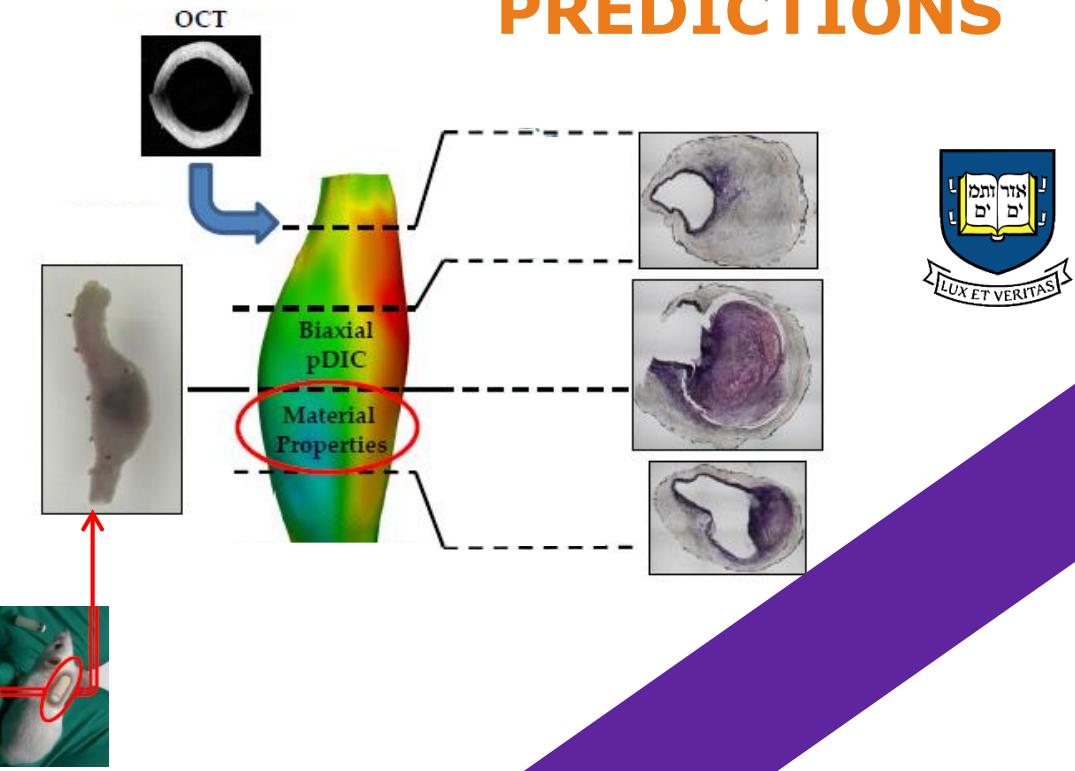
- 2 ways of defining rupture:
- PWS – but unknown patient-specific strength
- $\gamma_{\text{stretch}}$  correlated with in vivo circumferential stiffness

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



C. Martin et al., Acta Biomater. 9 (2013) 9392–9400

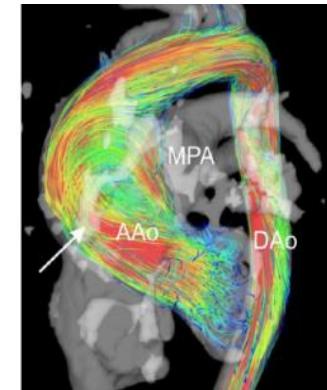
# TOWARDS ATAA GROWTH PREDICTIONS



Development of  
mechanobiological models



Clinical  
applications



European Research Council  
Established by the European Commission  
erc

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