Rupture risk estimation in thoracic aortic aneurysms

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Prof. Stéphane AVRIL

Where do I come from?

Demanget et al., Perrin et al.

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

MINES Saint-Étienne

CHU Saint-Étienne

UNIVERSITÉ DE LYON

MINES Saint-Étienne

SAINBIOSE
SAnté INgéniérie BIOlogie Saint-Etienne
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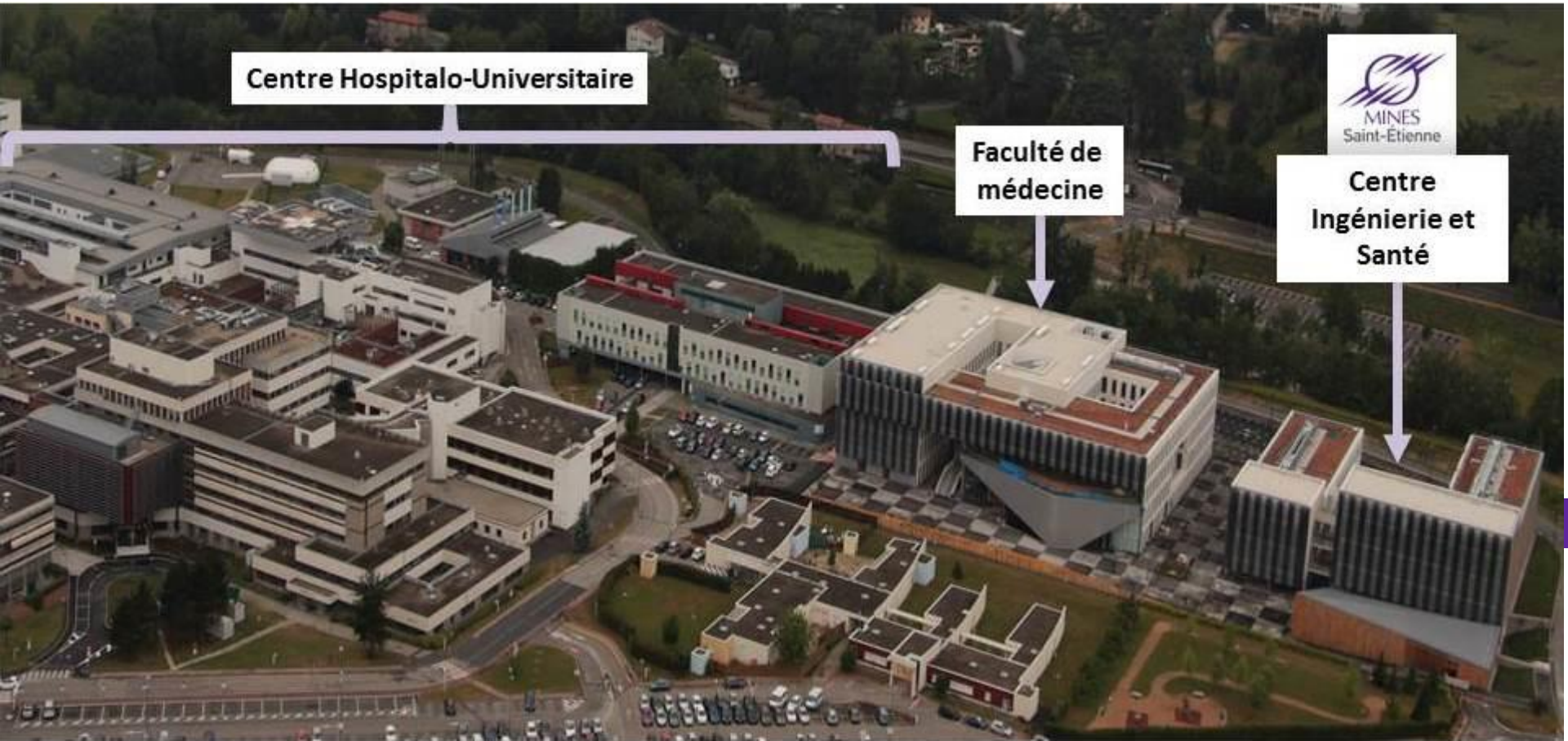
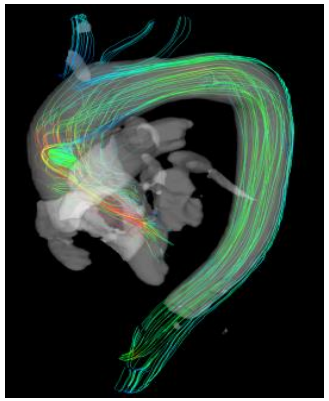
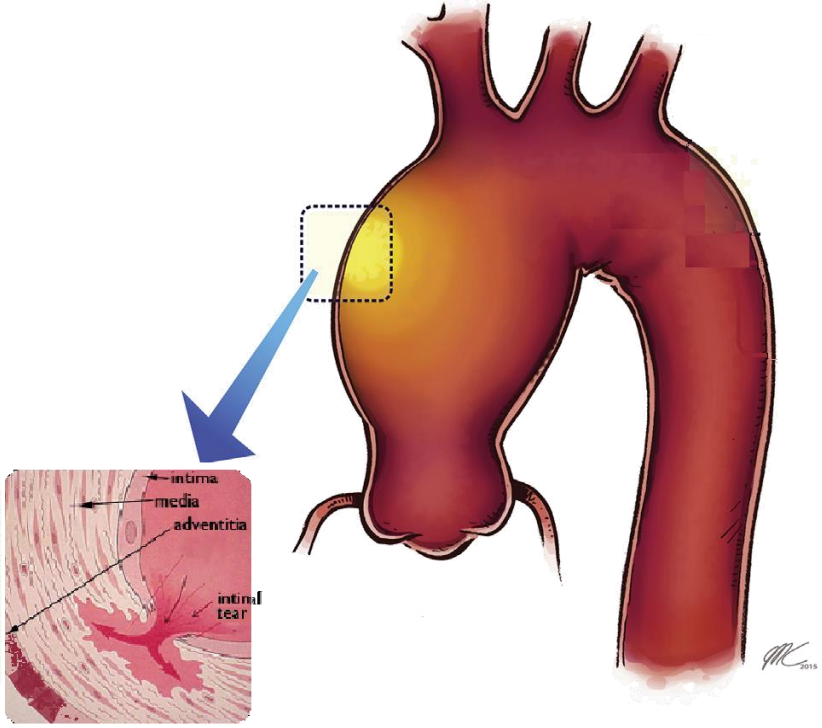
Inserm
Institut national de la santé et de la recherche médicale



Introduction of ATAA





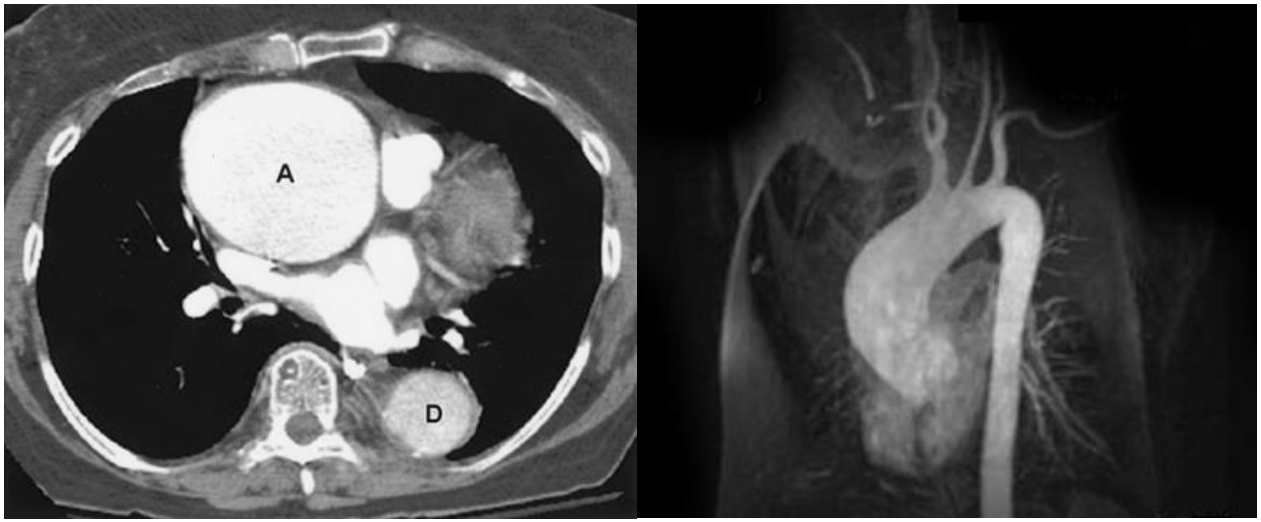
dissection

Epidemiology statistics

Incidence : 10.4 per 100 000 persons

Elevated mortality without treatment for acute aortic dissection:
50% in 48 hours / 90% in 3 months

BAV patients: ½ develop an ATAA



Risk management

Decision of surgical repair based on a measure if the Maximal Diameter

- **The International Registry of Acute Aortic Dissection (IRAD): among 591 type A aortic dissection, 59% had a diameter <5.5 cm (Pape, 2007)**

5.5 cm

Possible stability	Possible complication

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

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Context

- **More and more aneurysms are detected at an early stage (incidence >8% for males >65 years old).**

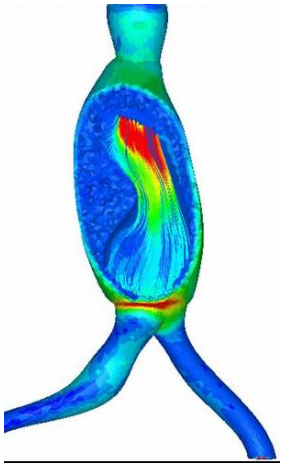
- **An intervention is recommended if the aneurysm grows more >1cm/year or it is >5.5cm. This represents >90000 interventions per year in Europe and USA**

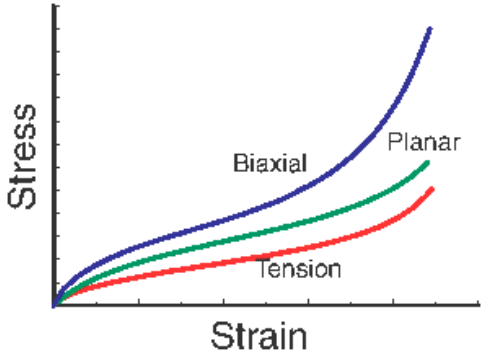
- **<u>BUT</u>:**
  - 25% aneurysms <5.5cm rupture : 15000 deaths!
  - 60% of aneurysms >5.5 cm never experience rupture!

- **In summary: very high rate of inappropriate decisions and misprogramed surgical interventions!!**

Added value of biomechanics

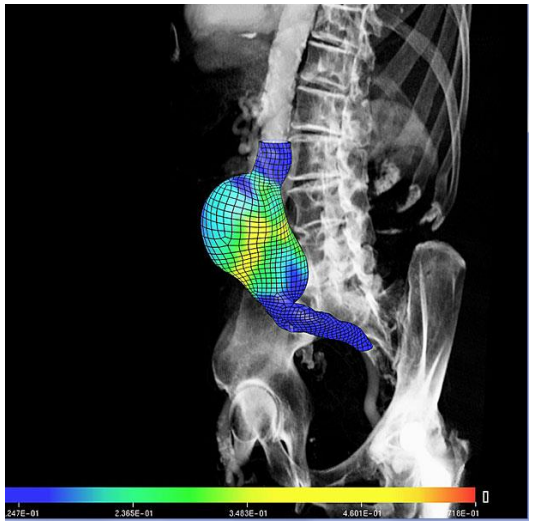
- **New insights on aneurysm rupture mechanisms**
  - Arterial wall mechanics
  - How does it rupture ?
  - When ?





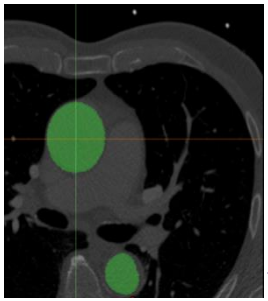
Scotti, 2007

- **New patient-specific decision making tool**
  - Patient-specific
  - From medical images

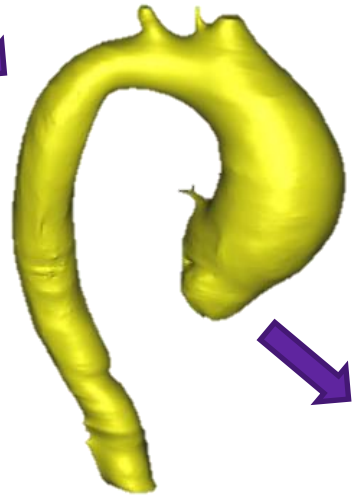


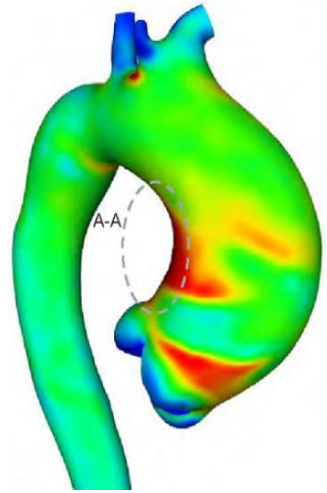
Vascops

Recent developments in computational modeling and challenges

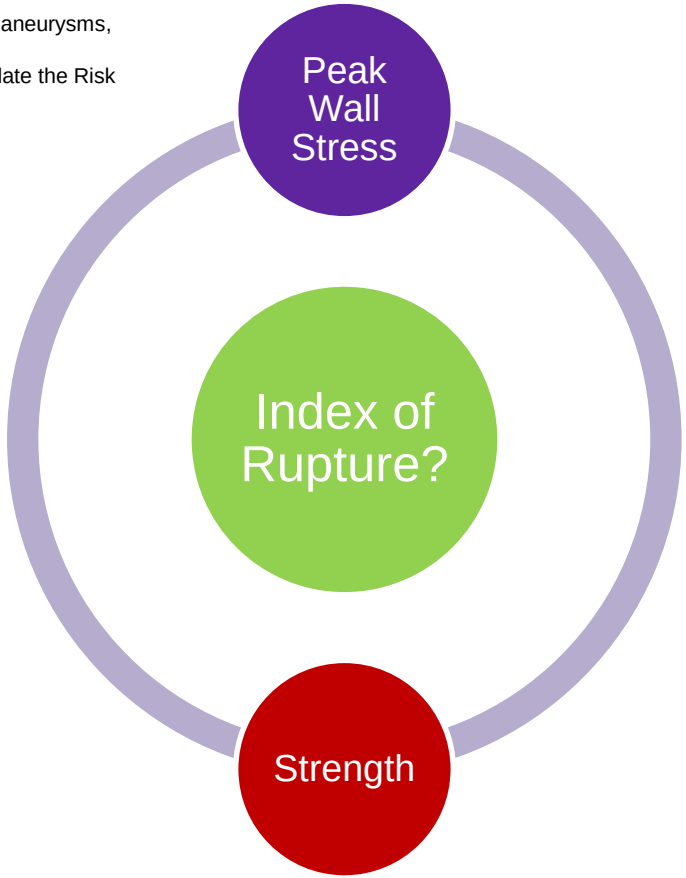


O. Trabelsi, et al, Patient specific stress and rupture analysis of ascending thoracic aneurysms, J. Biomech. (2015).
G. Martufi, et al, Is There a Role for Biomechanical Engineering in Helping to Elucidate the Risk Profile of the Thoracic Aorta?, Ann. Thorac. Surg. 101 (2016) 390–398.
S. Pasta et al., Constitutive modeling of ascending thoracic aortic aneurysms using microstructural parameters, Med. Eng. Phys. 38 (2016) 121–130.

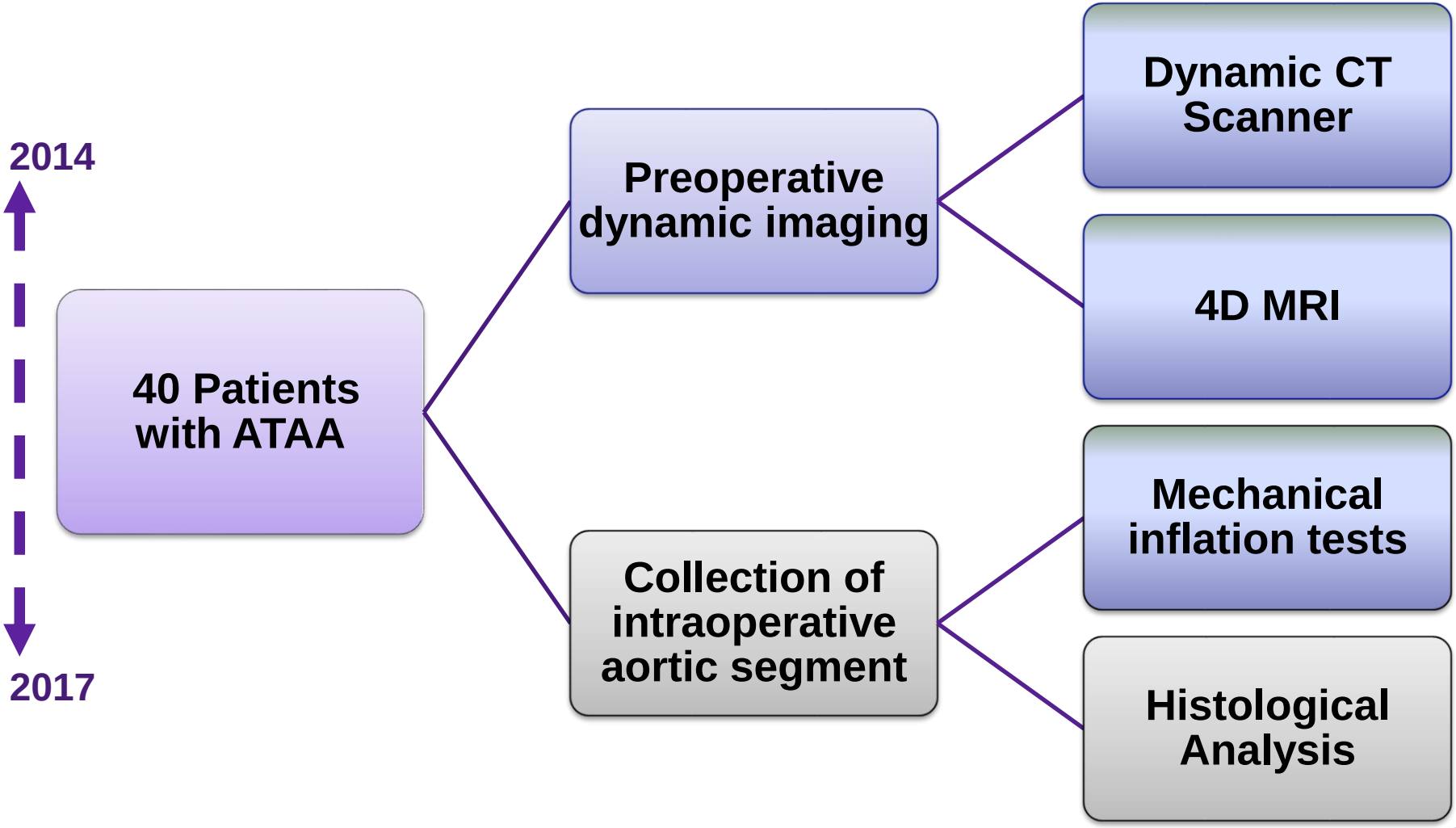




Finite-element modeling



SAINT-ETIENNE PROTOCOL



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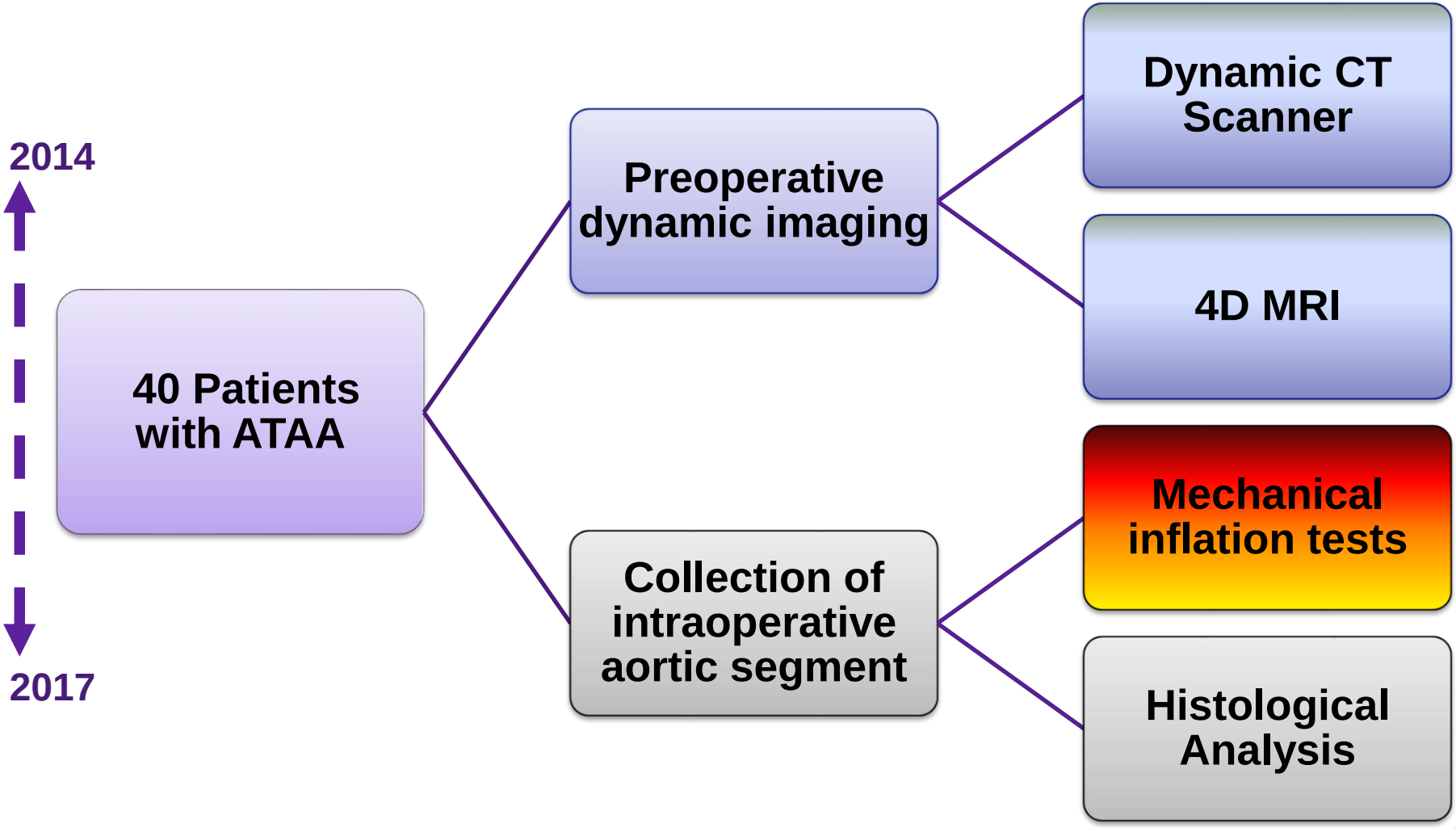
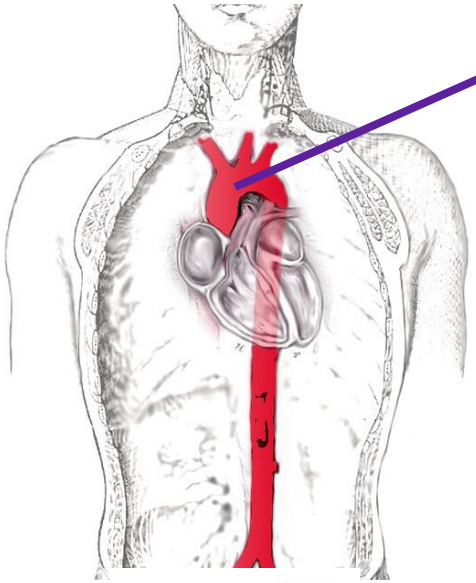
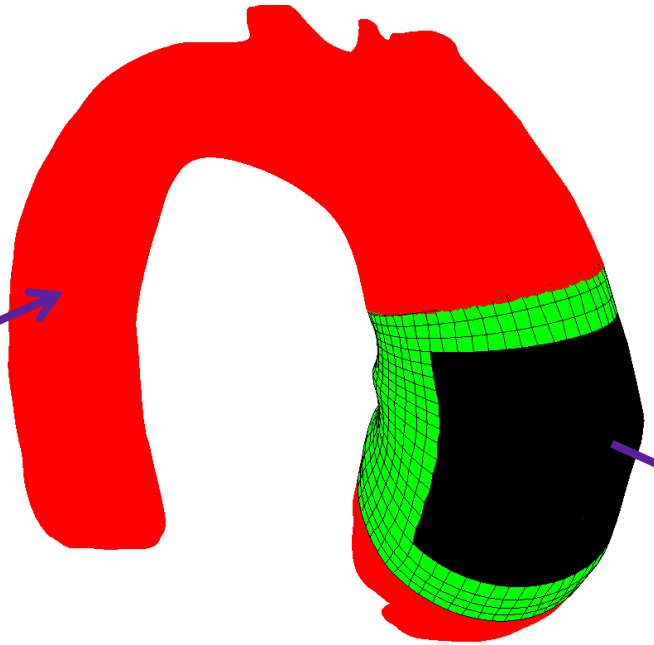
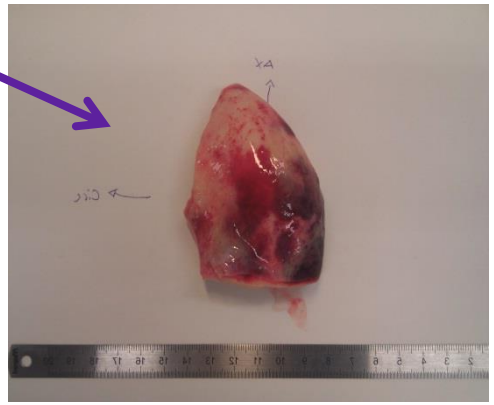
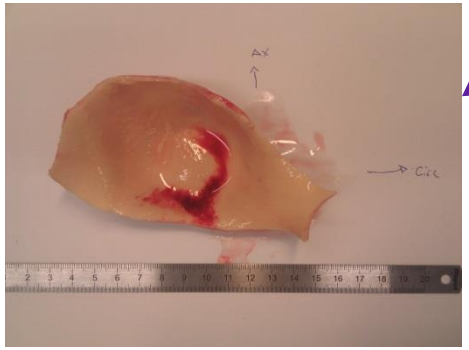


Collection of the samples

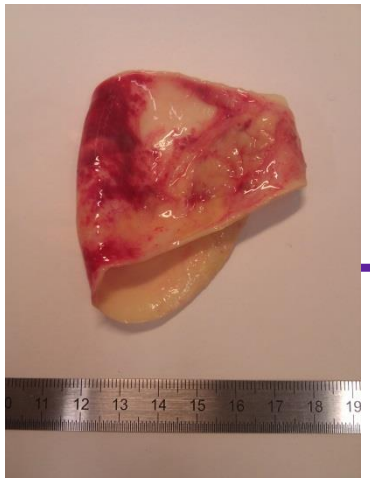


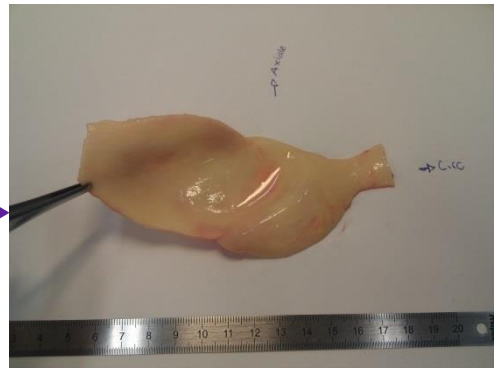


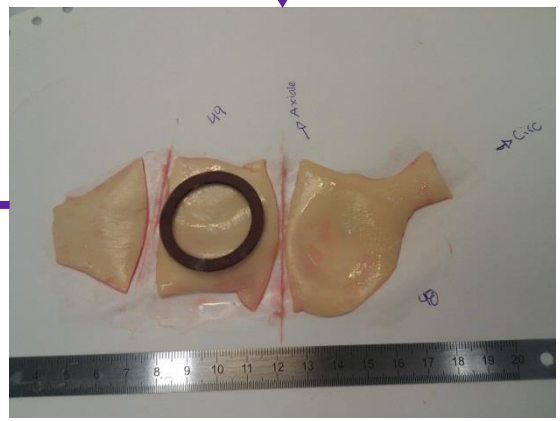




PREPARATION

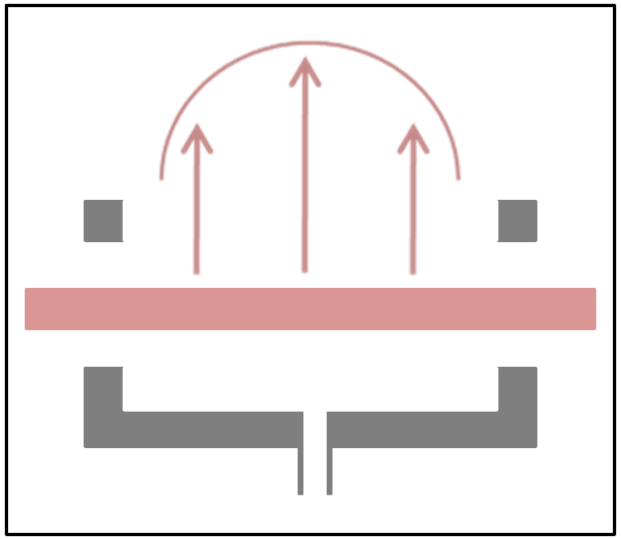


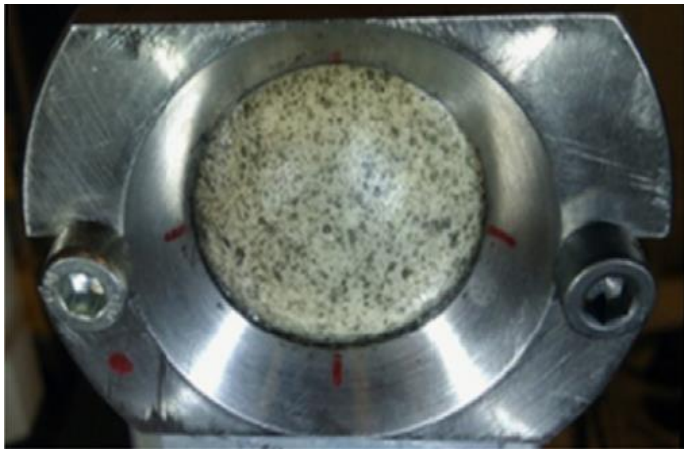




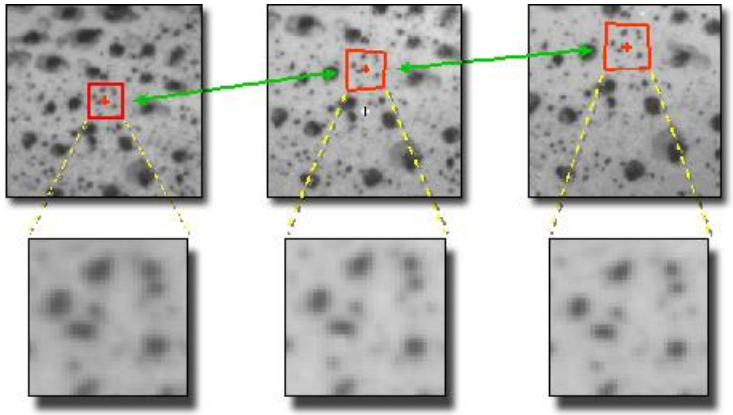
Bulge inflation test

Romo et al. Journal of Biomechanics -2014.

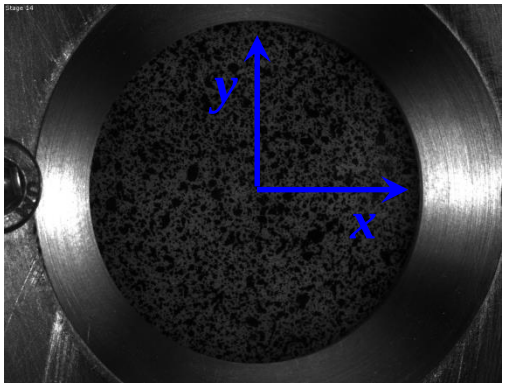




Full-field measurements using sDIC



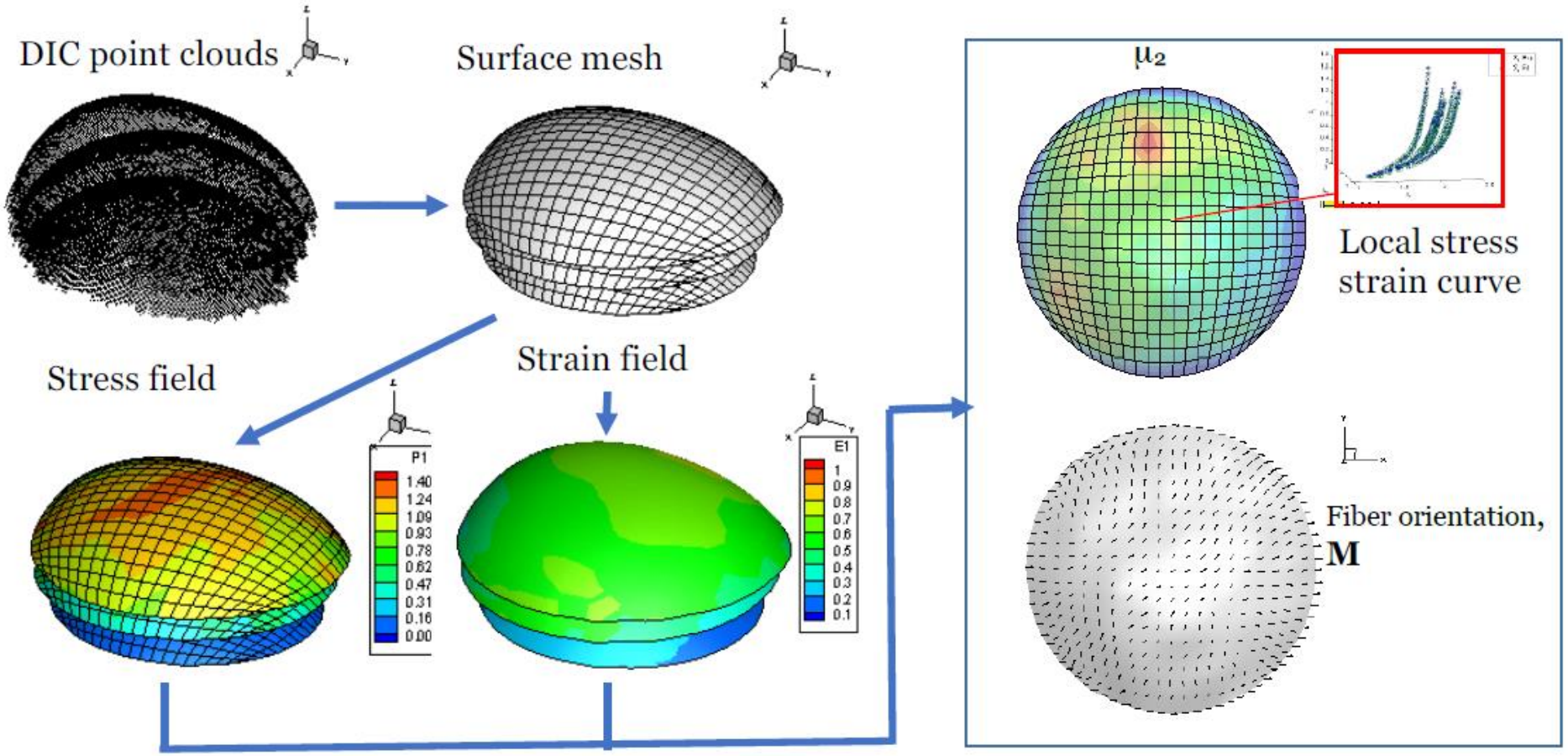
Undeformed



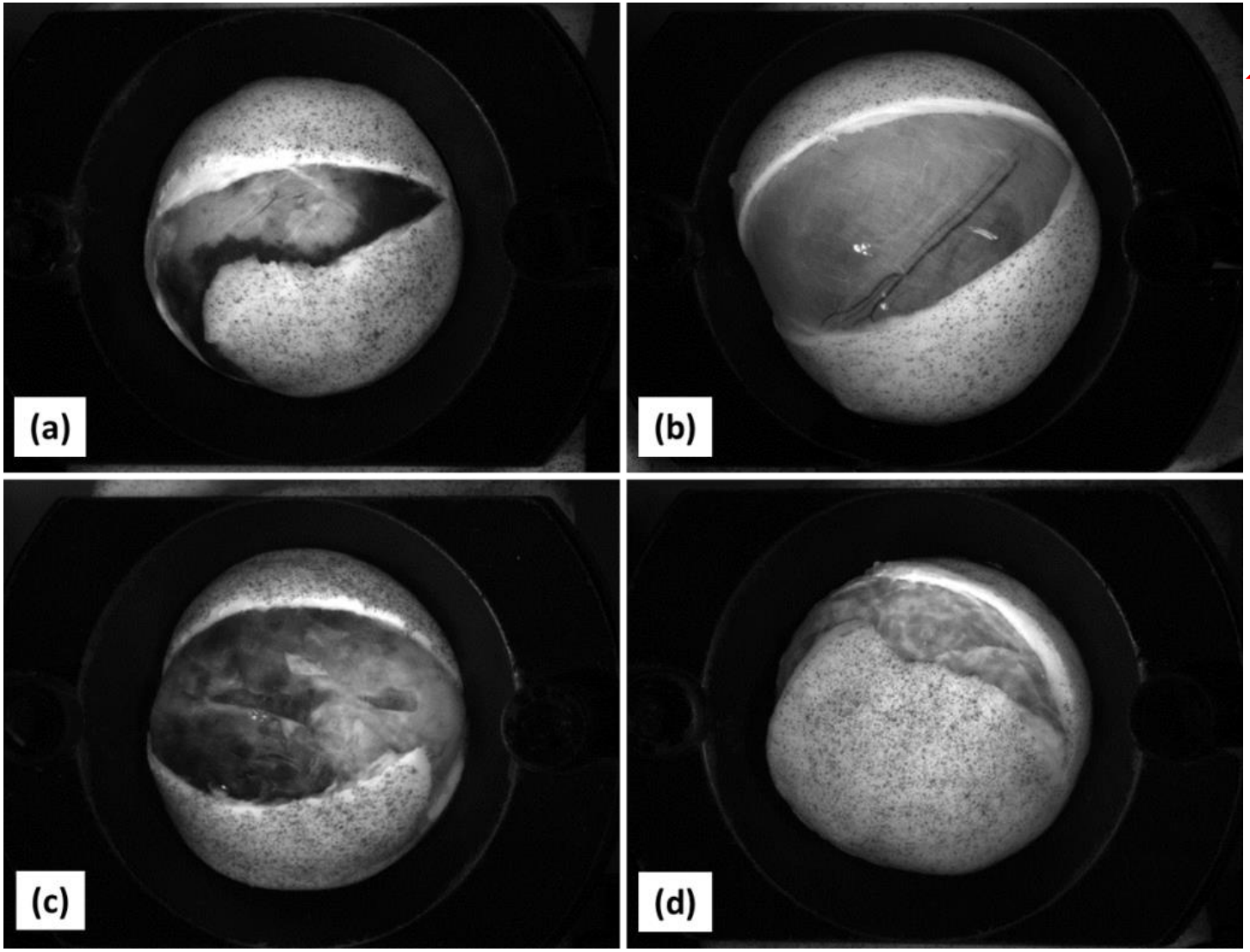
Deformed

Identification of local material properties

Davis et al. BMMB – 2015.
Davis et al. JMBBM – 2016
Zhao et al. Acta Biomaterialia - 2016



Rupture profiles



Blood flow

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

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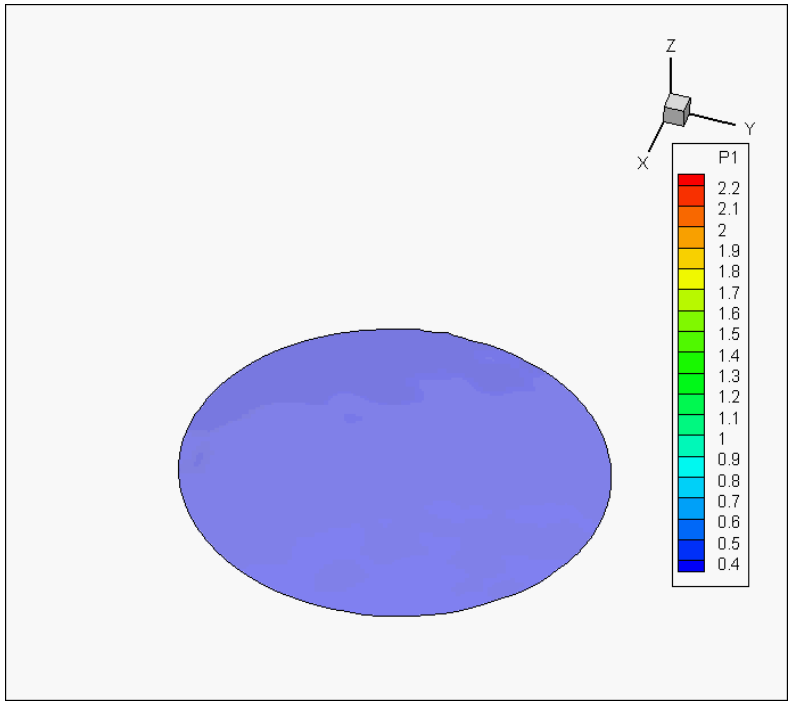
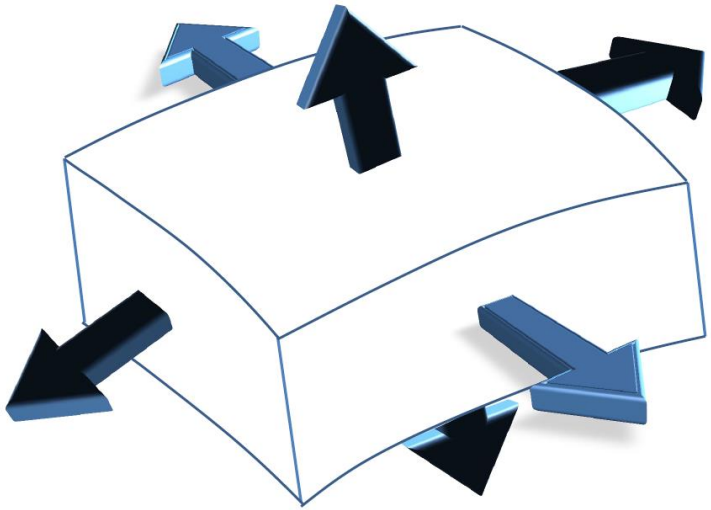
Local stress reconstruction



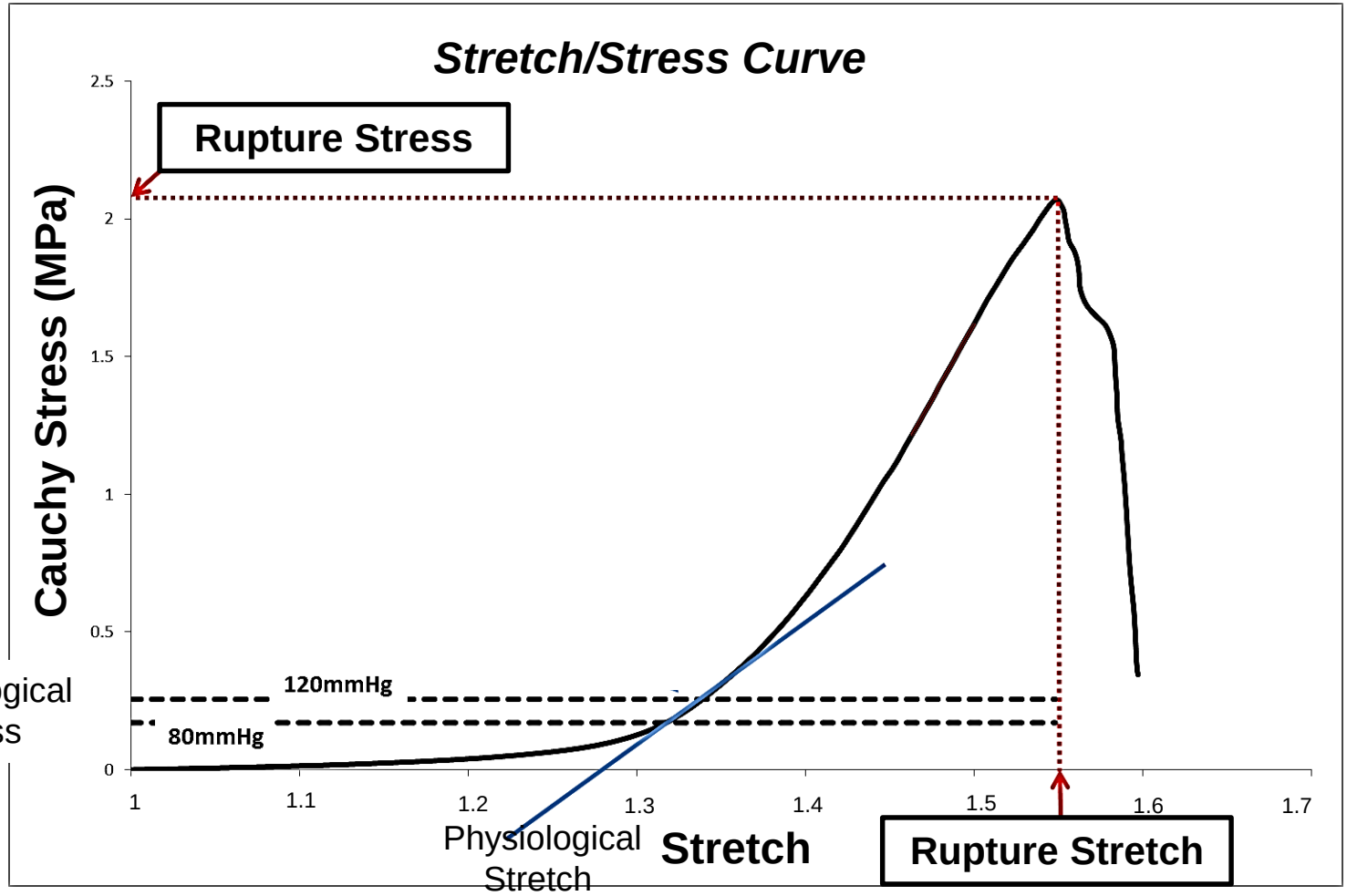


$$div(\boldsymbol{\sigma}) + f = 0$$

$$[A] \cdot [\boldsymbol{\sigma}] = [B]$$

Stress-stretch analysis in the bulge inflation test

σ_{rup} : Rupture stress, λ_{rup} : Rupture stretch,



Stress-stretch analysis in the bulge inflation test

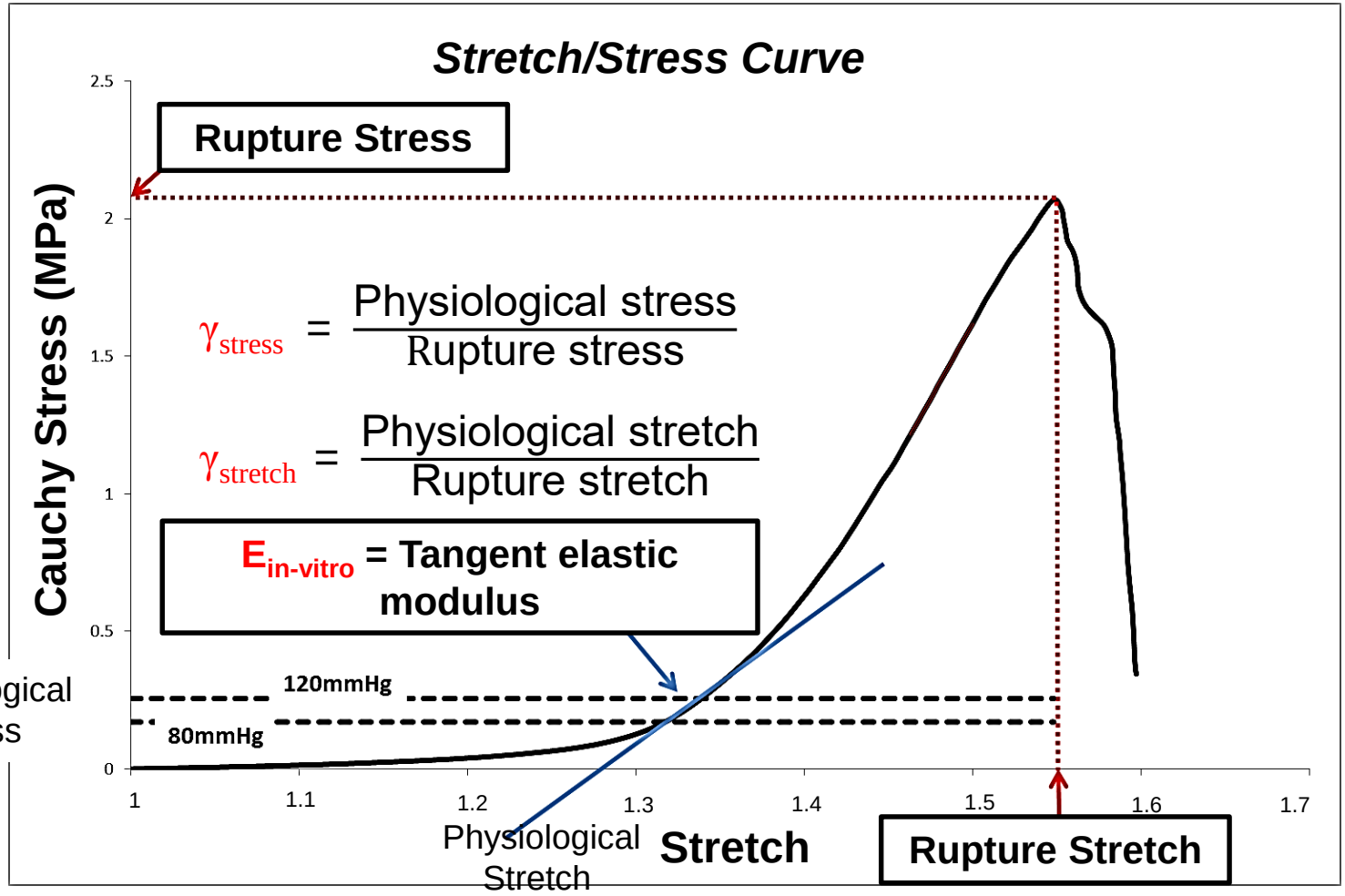
- **Laplace law:**

$$\sigma_{dias/sys} = \frac{P_{dias/sys} * \phi}{2h}$$

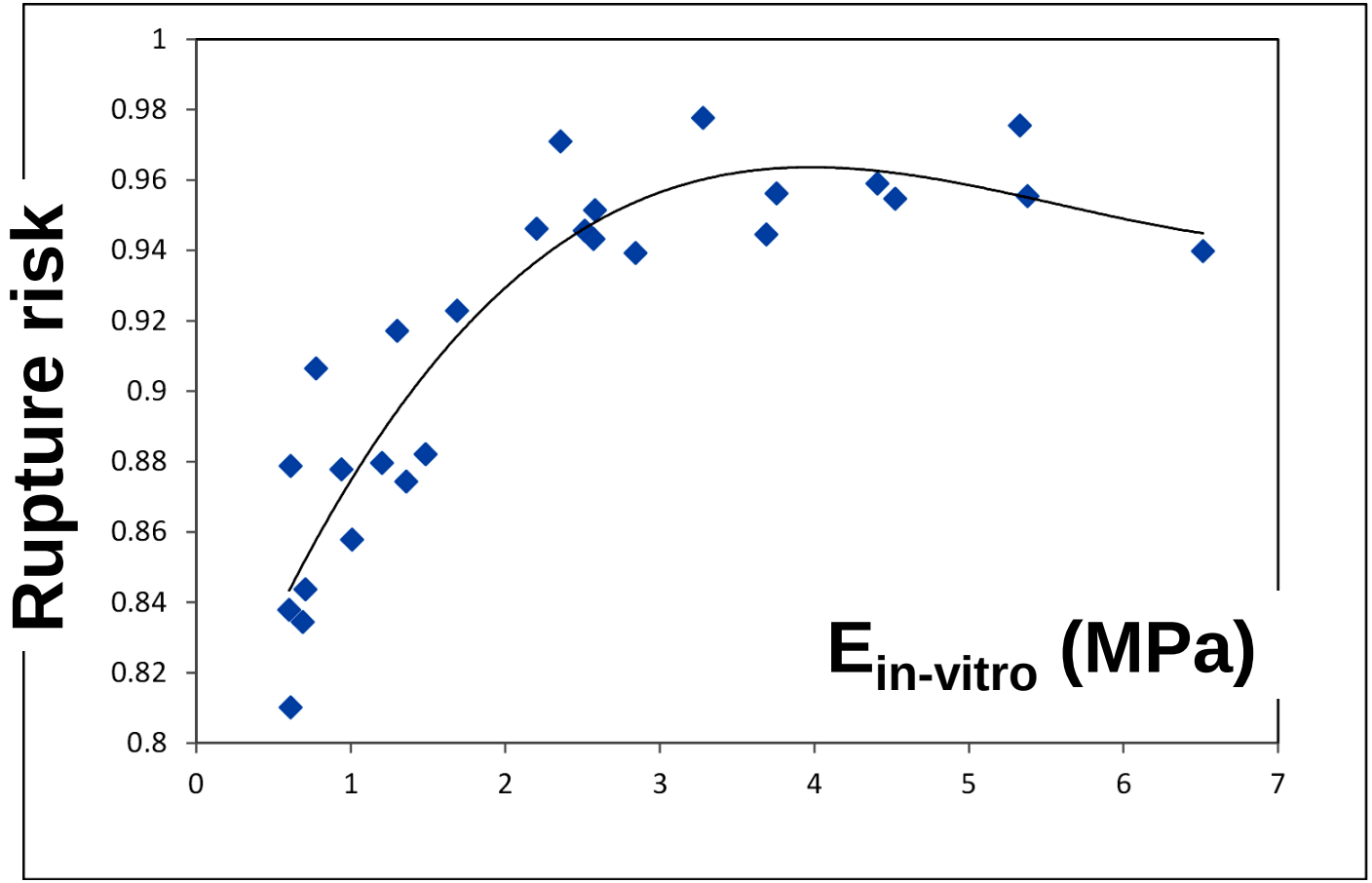
- **Tangent physiological elastic modulus**

$$E_{in-vitro} = \lambda_{1,physio} \frac{d\sigma_{1,physio}}{d\lambda_{1,physio}}$$

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.***

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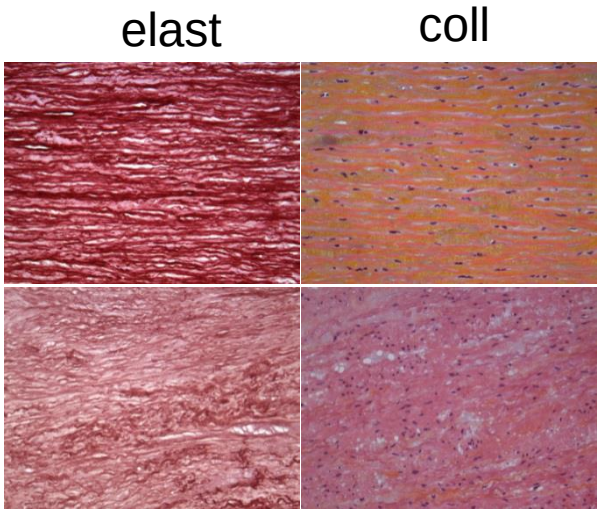
Histological interpretation

- **ATAA always manifests with elastin damage**
- **More and more collagen tends to be recruited in the physiological range**

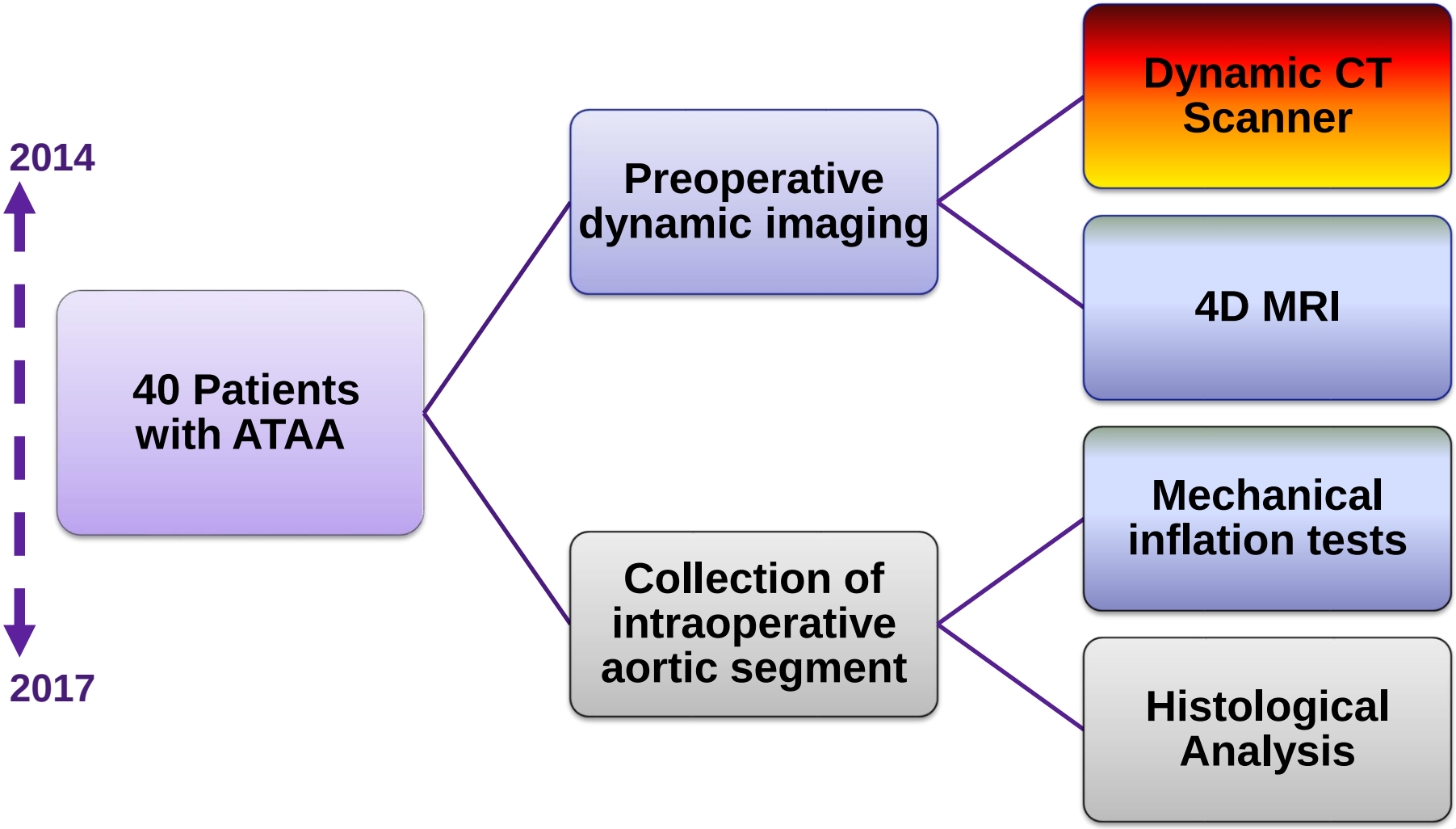
Patient with largest $\gamma_{stretch}$

Patient with smallest $\gamma_{stretch}$



M.R. Hill et al,, J. Biomech. 45 (2012) 762–771

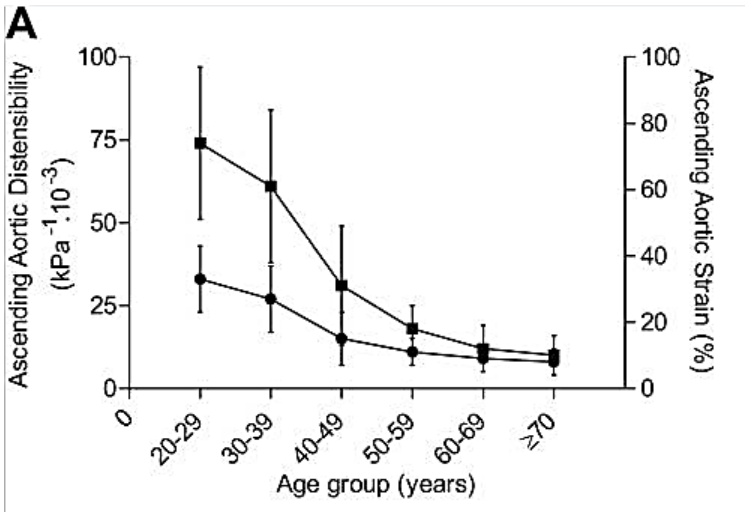
SAINT-ETIENNE PROTOCOL

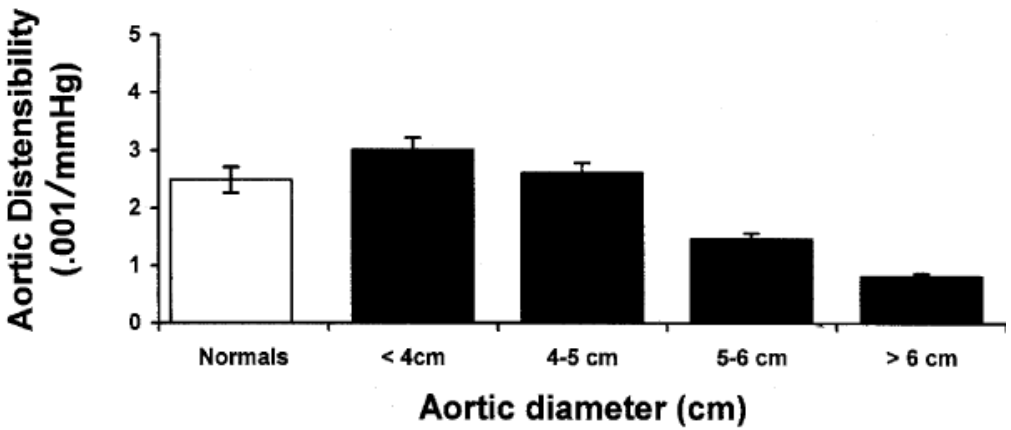


Measurement of aortic DISTENSIBILITY

- **D: Distensibility (mmHg^{-1}), $\Delta A/\Delta V$: cross sectional areas/volume variation between systole and diastole, ΔP: luminal pressure variation between systole and diastole**

$$D = \frac{\Delta A}{A_{sys}\Delta P} = \frac{\Delta V}{V_{sys}\Delta P}$$





I. Voges et al. Normal values of aortic dimensions, distensibility, and pulse wave velocity in children and young adults: a cross-section study. J. of cardiovacsular magnetic resonance. 2012.

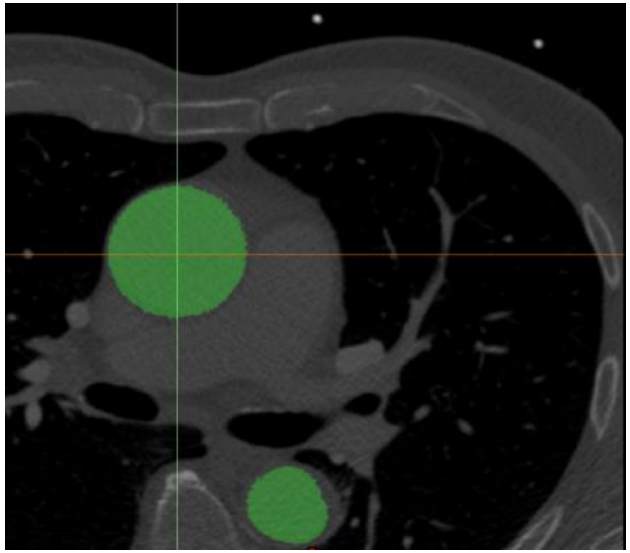
G. Koullias et al. Mechanical deterioration underlies malignant behavior of aneurysmal human ascending aorta. J. of thoracic and cardiovacsular surgery. 2005.

A. Redheuil, et al. Reduced ascending aortic strain and distensibility earliest manifestations of vascular aging in humans. Hypertension. 2010.

Measurement of aortic DISTENSIBILITY

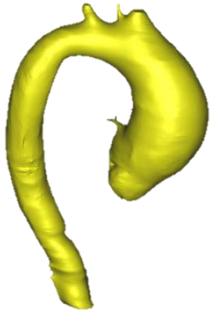
- ***Gated CT – acquisition and segmentation***

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

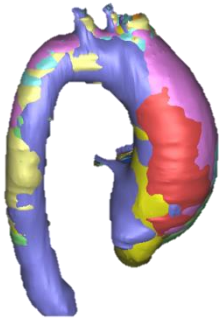


Aorta

1 phase



superposition of
10 phases



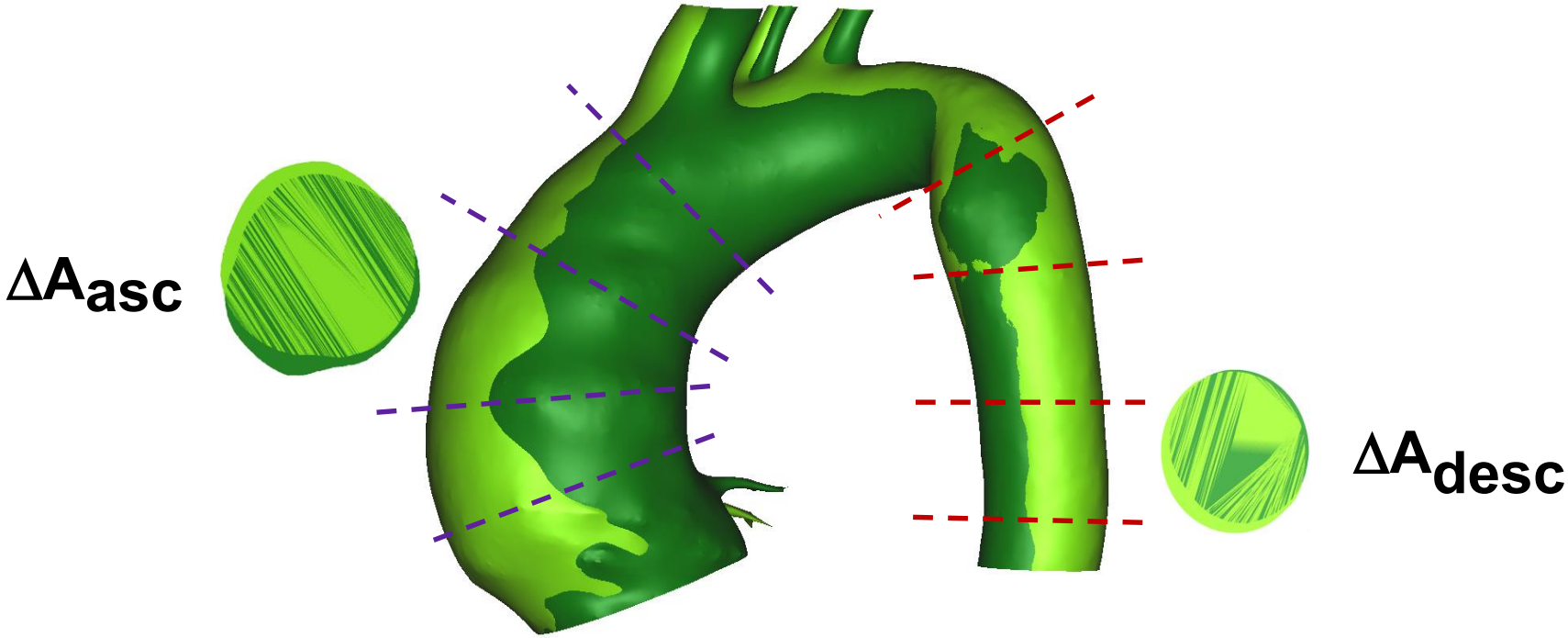
Systole

Diastole

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)

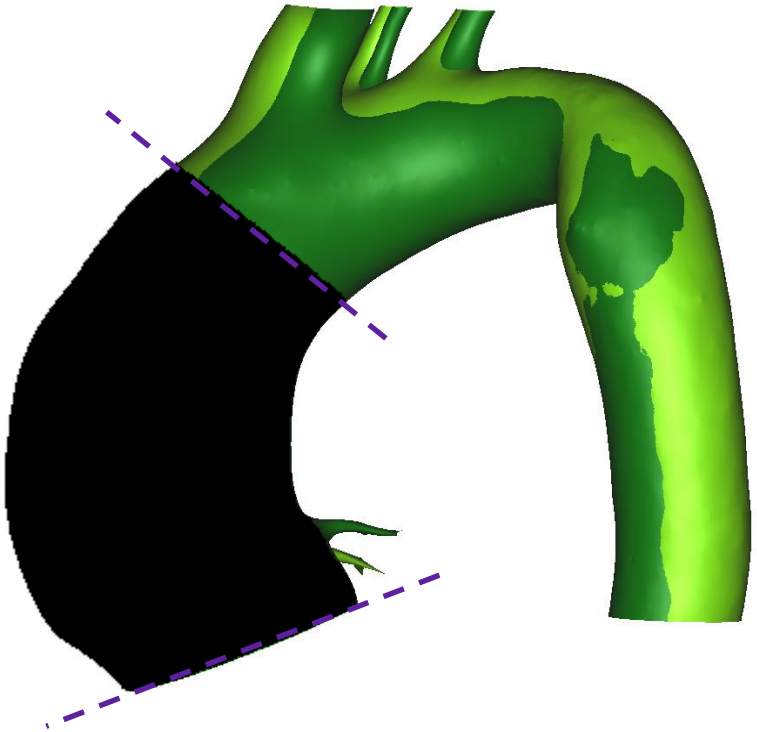


Measurement of aortic DISTENSIBILITY

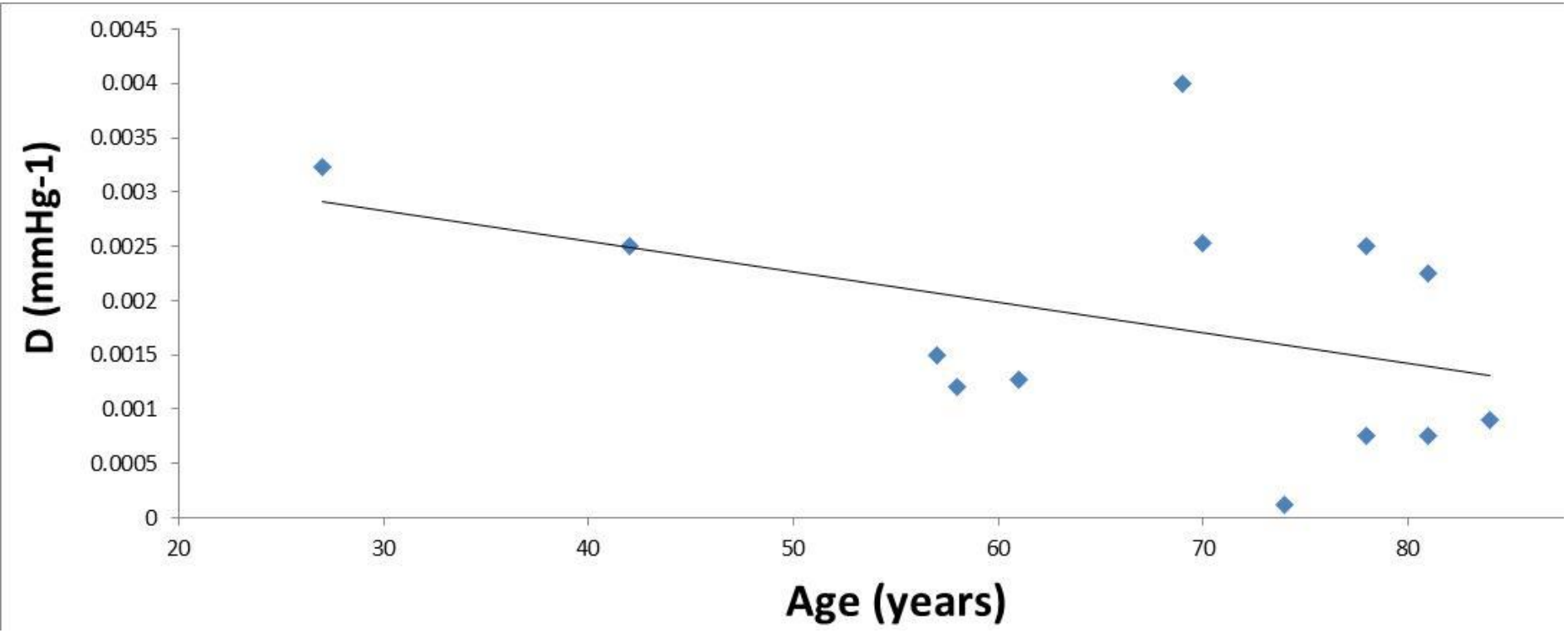
- ***Aortic wall - 3D reconstruction from gated CT***

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

ΔV_{asc}



Trend of distensibility with age



Distensibility of ATA decreases with age in ATAA patients

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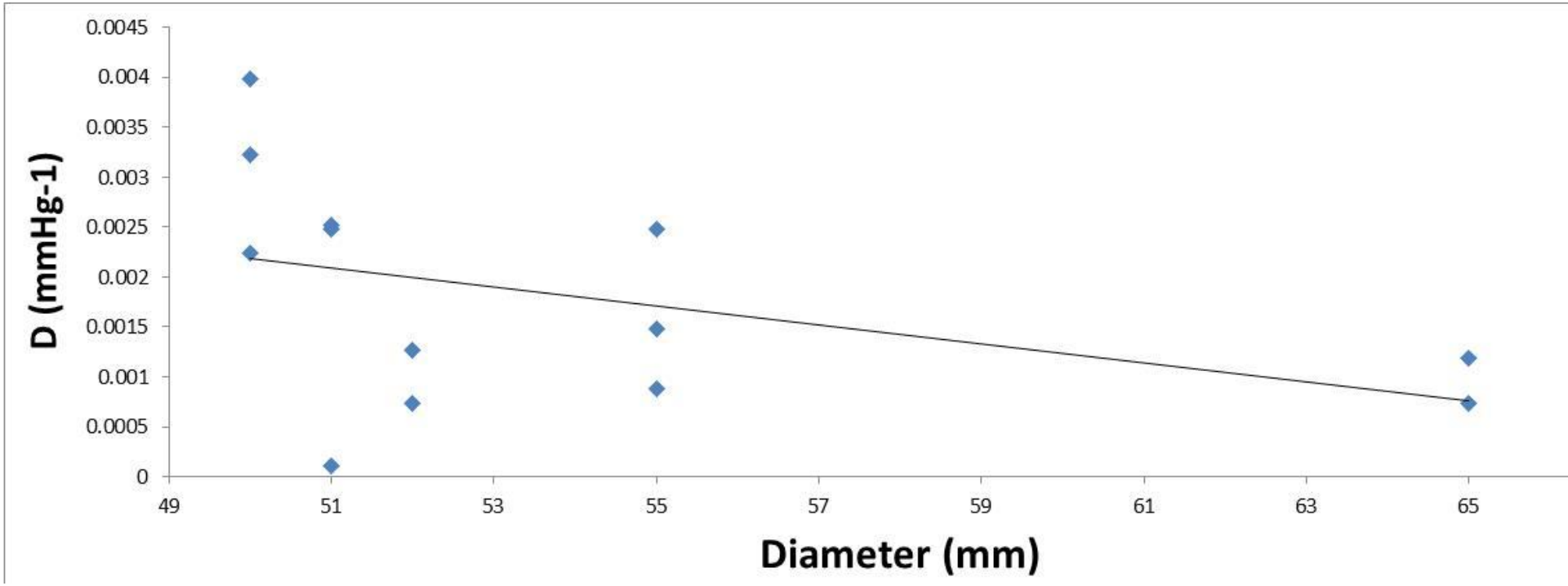
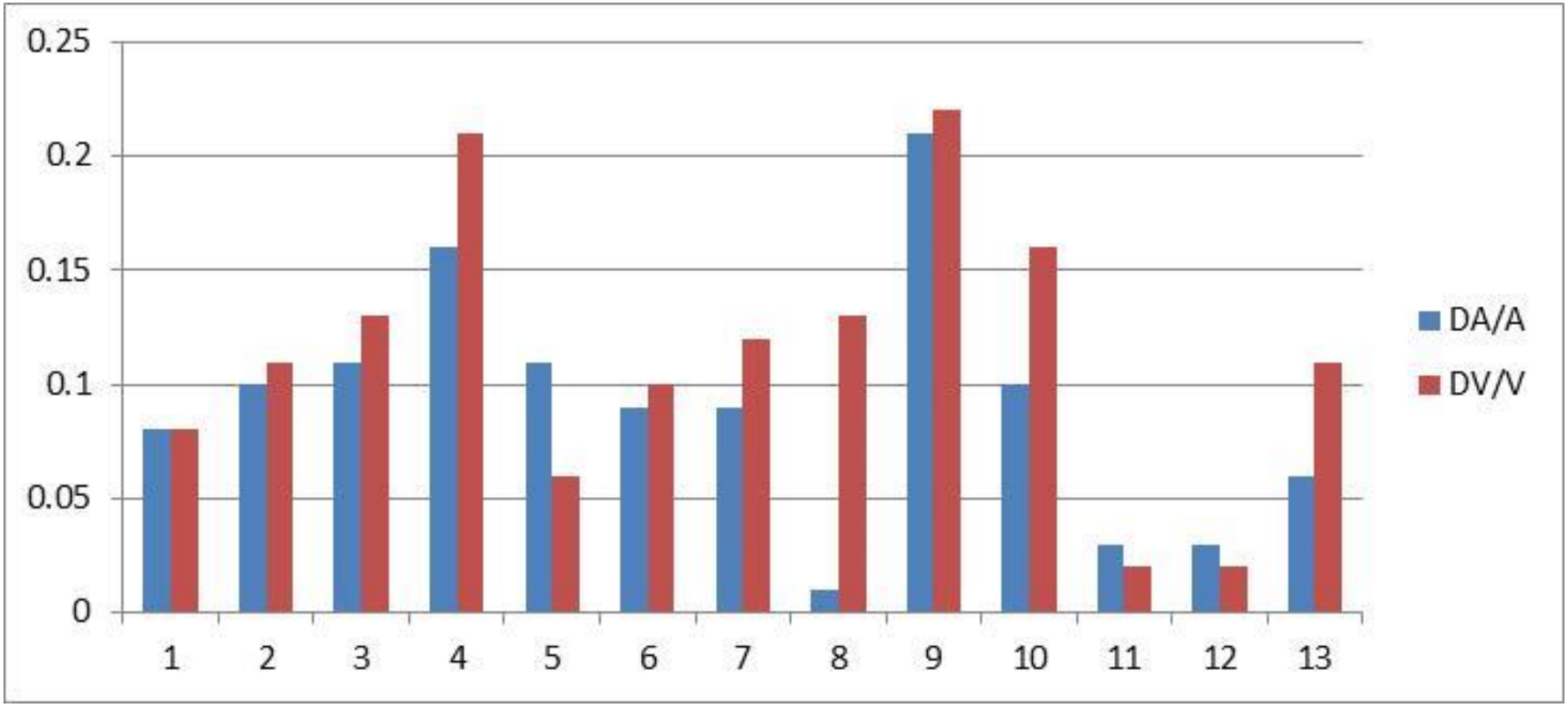
Trend of distensibility with ATAA diameter



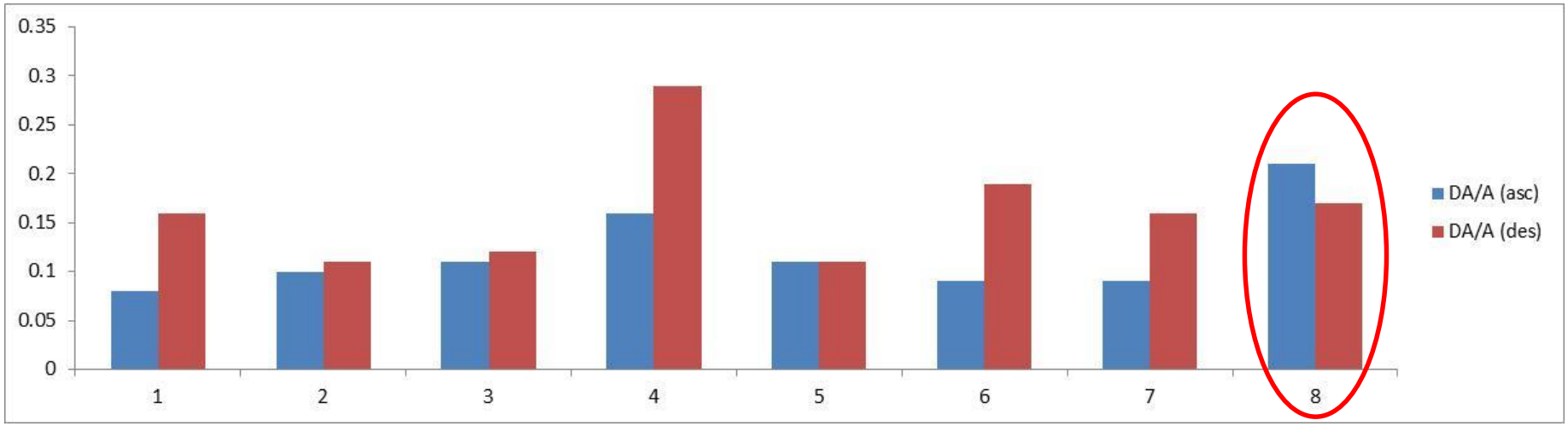
ATA distensibility decreases when diameter increases

Volume vs cross-sectional distensibility

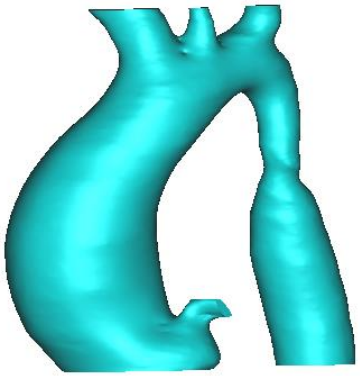


$$\frac{\Delta A_{asc}}{A_{sys}} \leq \frac{\Delta V_{asc}}{V_{sys}}$$

ATA vs DTA distensibility



$$\frac{\Delta A_{asc}}{A_{sys}} \leq \frac{\Delta A_{desc}}{A_{sys}}$$



M/27/BAV

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Measurement of aortic circumferential STIFFNESS

- **The tangent elastic modulus can be derived using:**
  $E_{in-vivo} = \frac{\emptyset}{hD}$ **where**

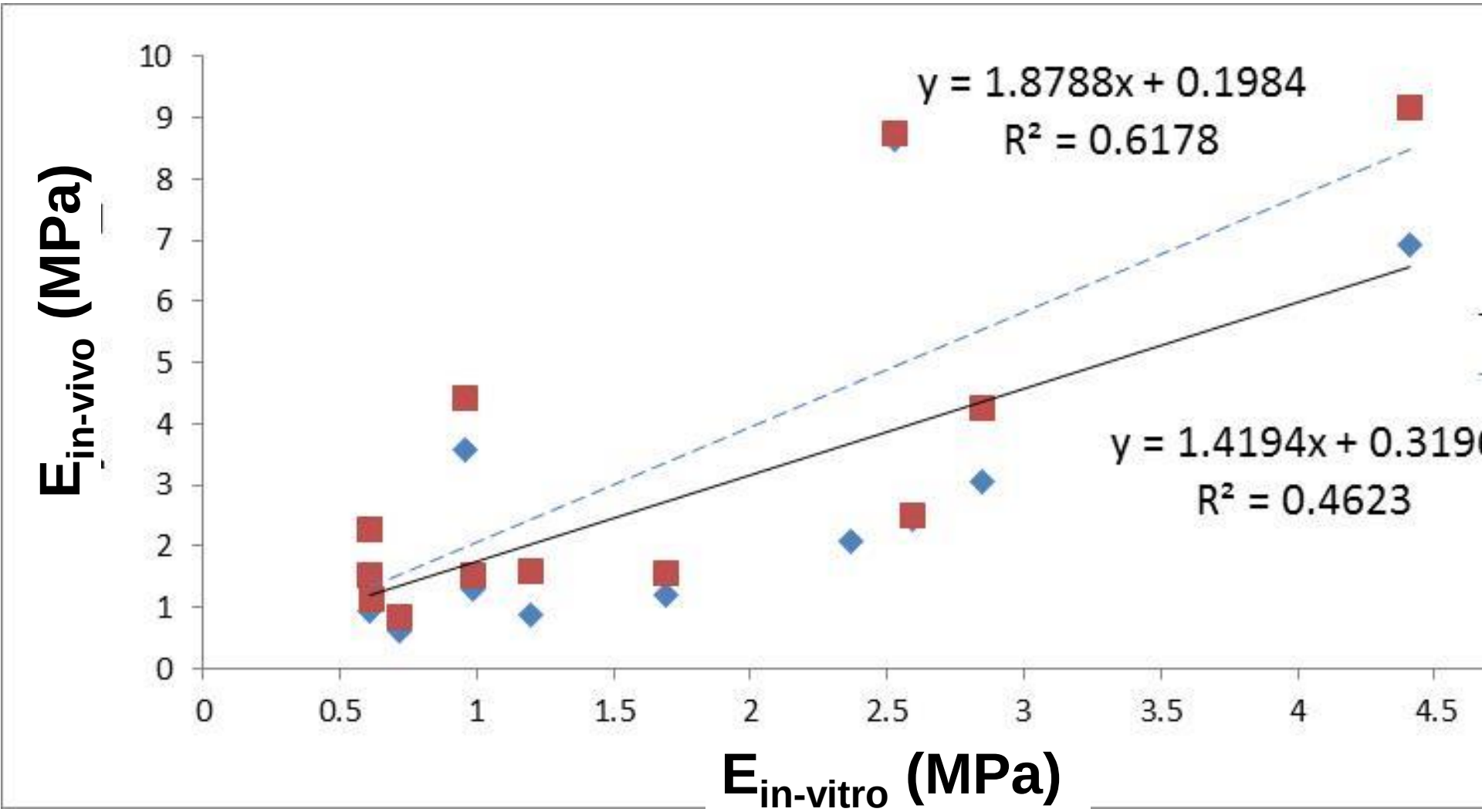
  h **: thickness of the aortic wall.**
  $\emptyset$**: Maximal diameter of aneurysm.**
  D: Distensibility.

- **Access the in vivo thickness?**

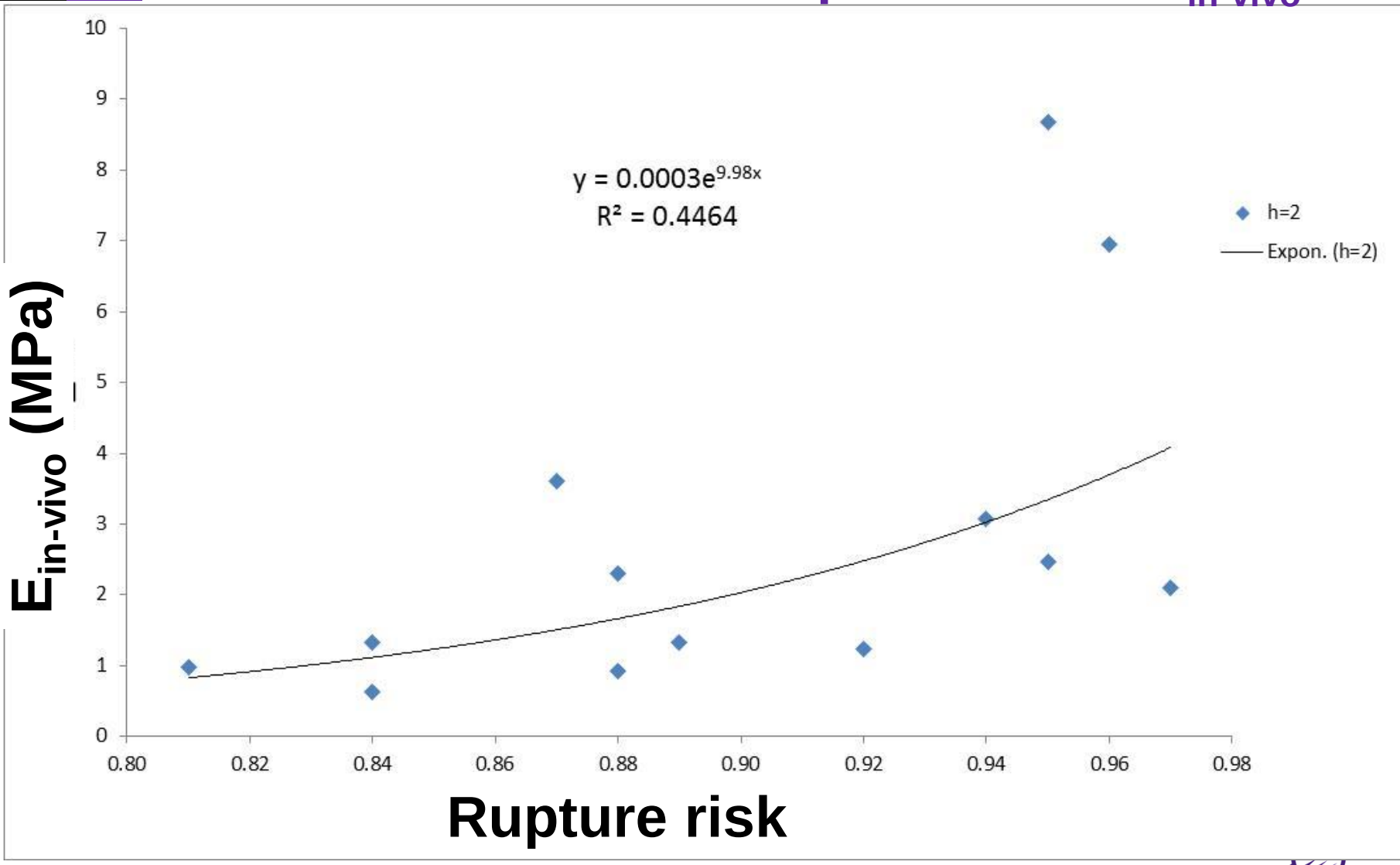
$$h = \frac{h_0}{\lambda_1 * \lambda_2} \cong \frac{h_0}{\lambda_{in\ vivo}}$$

$$h \approx 2\ mm$$

Results: $E_{in\text{-}vivo}$ vs $E_{in\text{-}vitro}$



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



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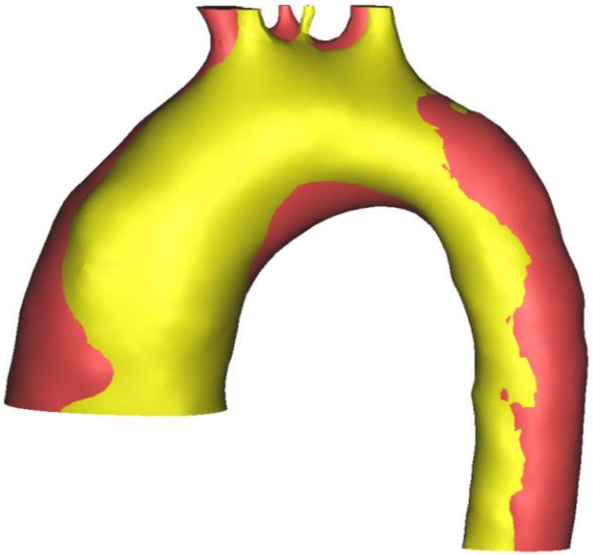
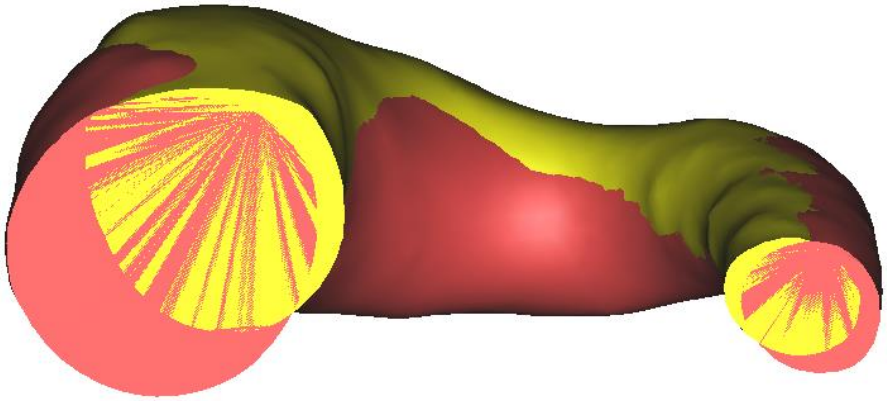
Comparison with a Healthy volunteer

- Healthy Female volunteer, 30 years old
- 4D MRI Segmentation (less resolution than CT scans)

$\Rightarrow E_{in\text{-}vivo}$ (ATA) ≈ $E_{in\text{-}vivo}$ (DTA) (0.134 MPa and 0.139 MPa)





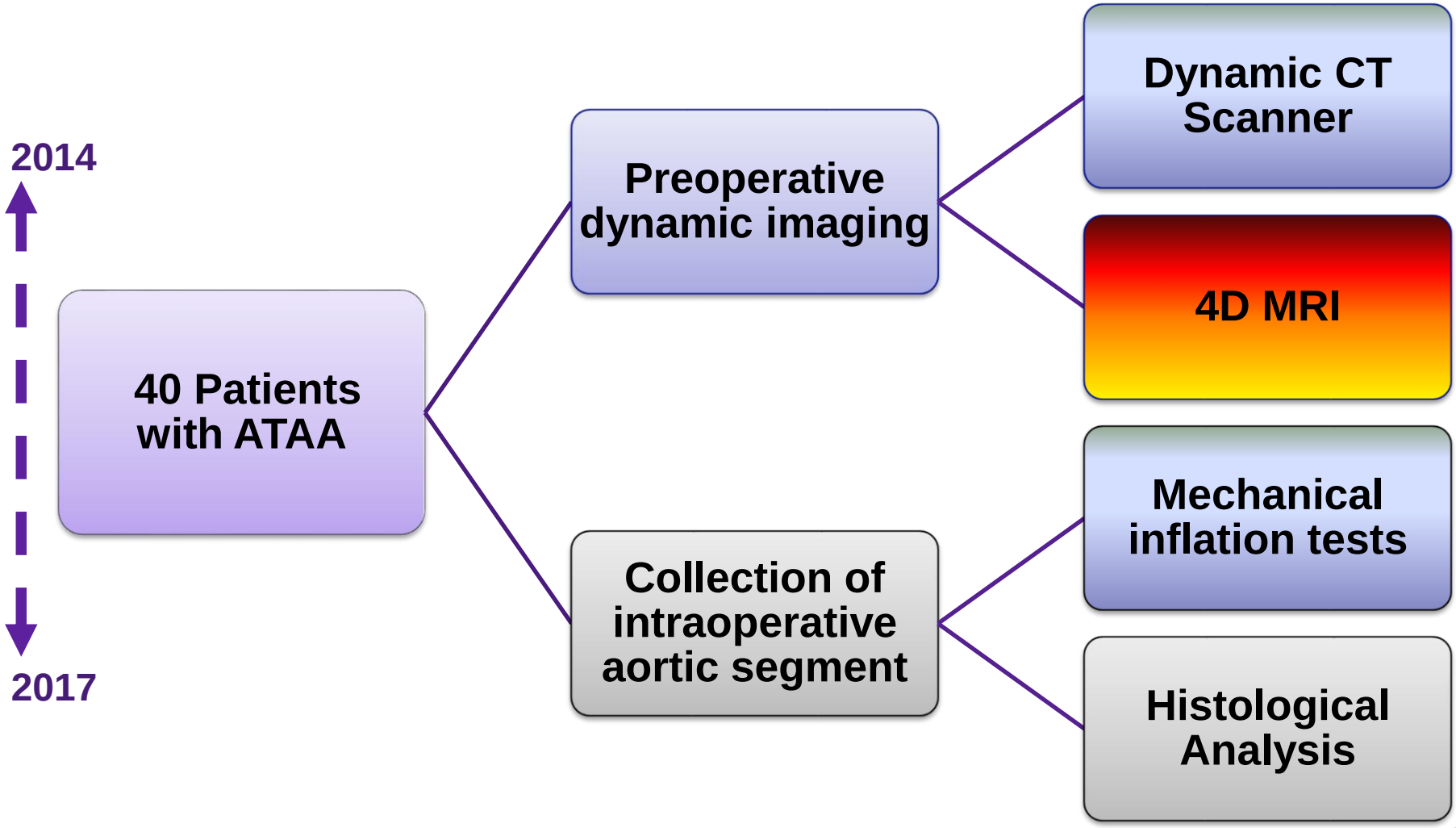
Summary

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

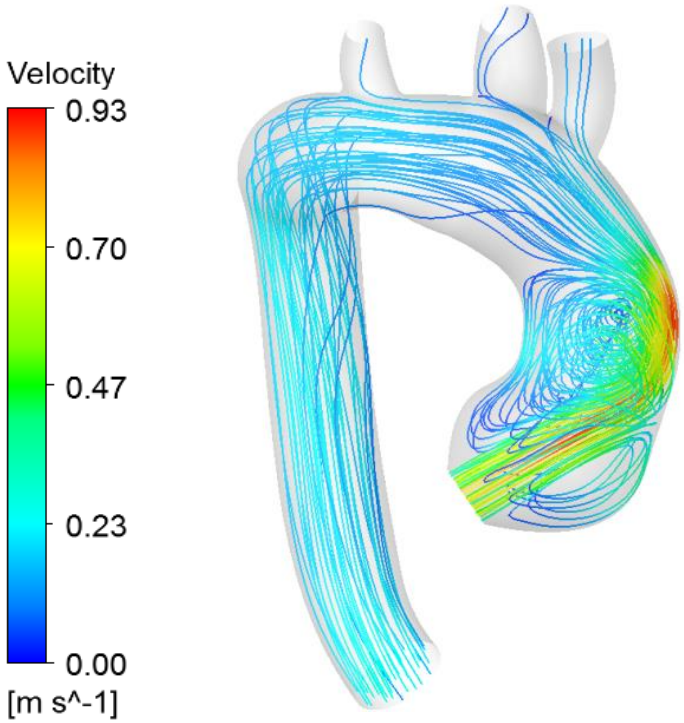
Higher distensibility $\Rightarrow$ less risk because the aneurysm can more easily withstand volume variation

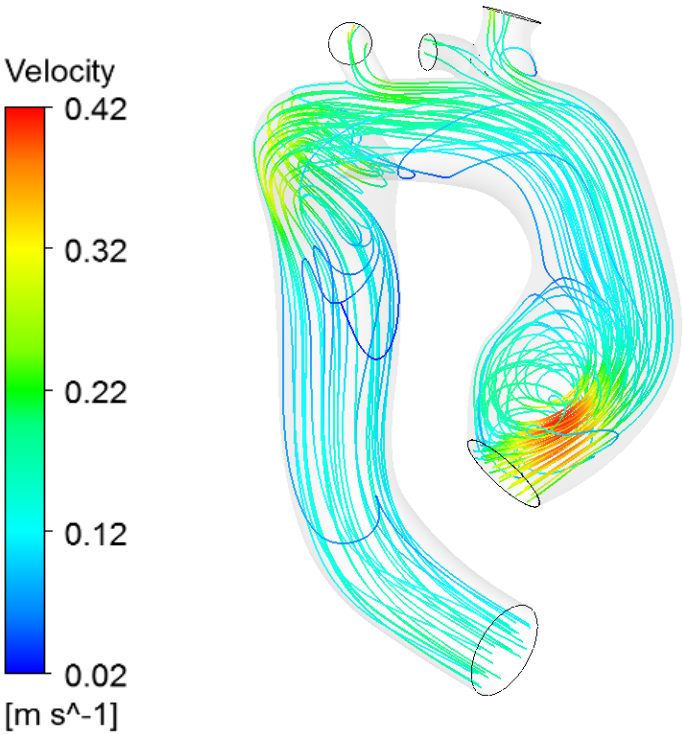
C. Martin et al., Acta Biomater. 9 (2013) 9392–9400

SAINT-ETIENNE PROTOCOL

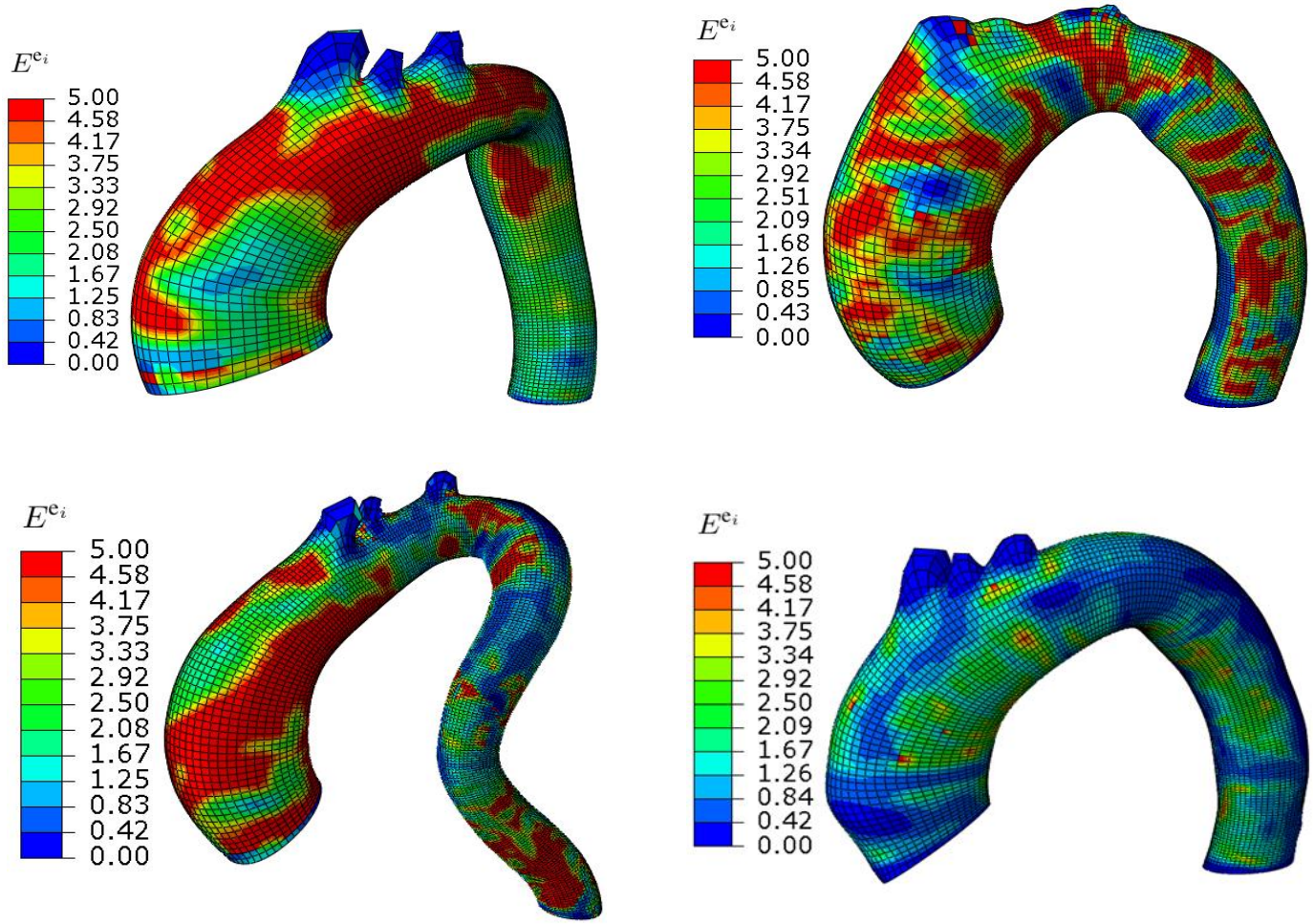


Computer fluid dynamics combined with 4D MRI



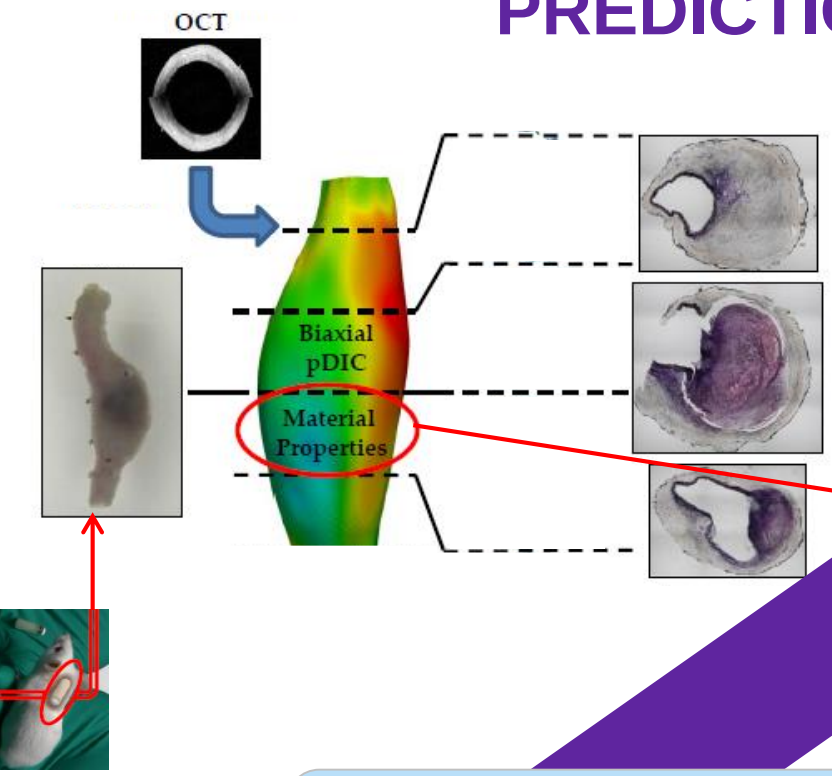


Future work: regional reconstruction of the linearized in vivo stiffness



MR Bersi, C Bellini, P Di Achille, JD Humphrey, K Genovese, S Avril, Novel Methodology for Characterizing Regional Variations in the Material Properties of Murine Aortas, ASME Journal of Biomechanical Engineering, 2016, 138(7), 071005

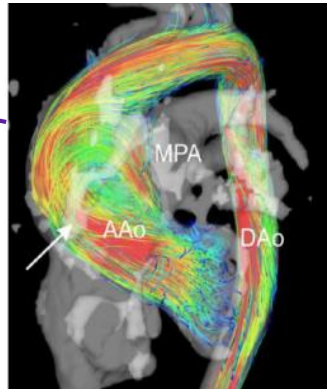
TOWARDS ATAA GROWTH PREDICTIONS



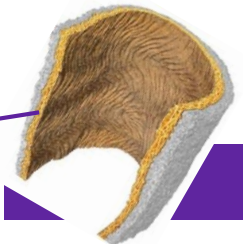
Clinical applications

Application to mice models of aortic aneurysms

Identification of regional variations of material properties in aortas



Development of mechanobiological models



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Invitation

Advanced School on
Material parameter identification and inverse problems in soft tissue biomechanics
Udine (Italy), October 16 - 20, 2017
Contact: avril@emse.fr

Lecturers:
- **Hazel Screen, Queen Mary University of London**
- **Sam Evans, Cardiff University**
- **Christian Gasser, KTH**
- **Amit Gefen, Tel Aviv University**
- **Cees Oomens. TU Eindhoven**