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SAnté INgénierie
BIOlogie Saint-Etienne
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**Inserm**
Institut national
de la santé et de la recherche médicale



**Finite-element predictions of
human aortic root dilatation
based on the homogenized
constrained mixture model**



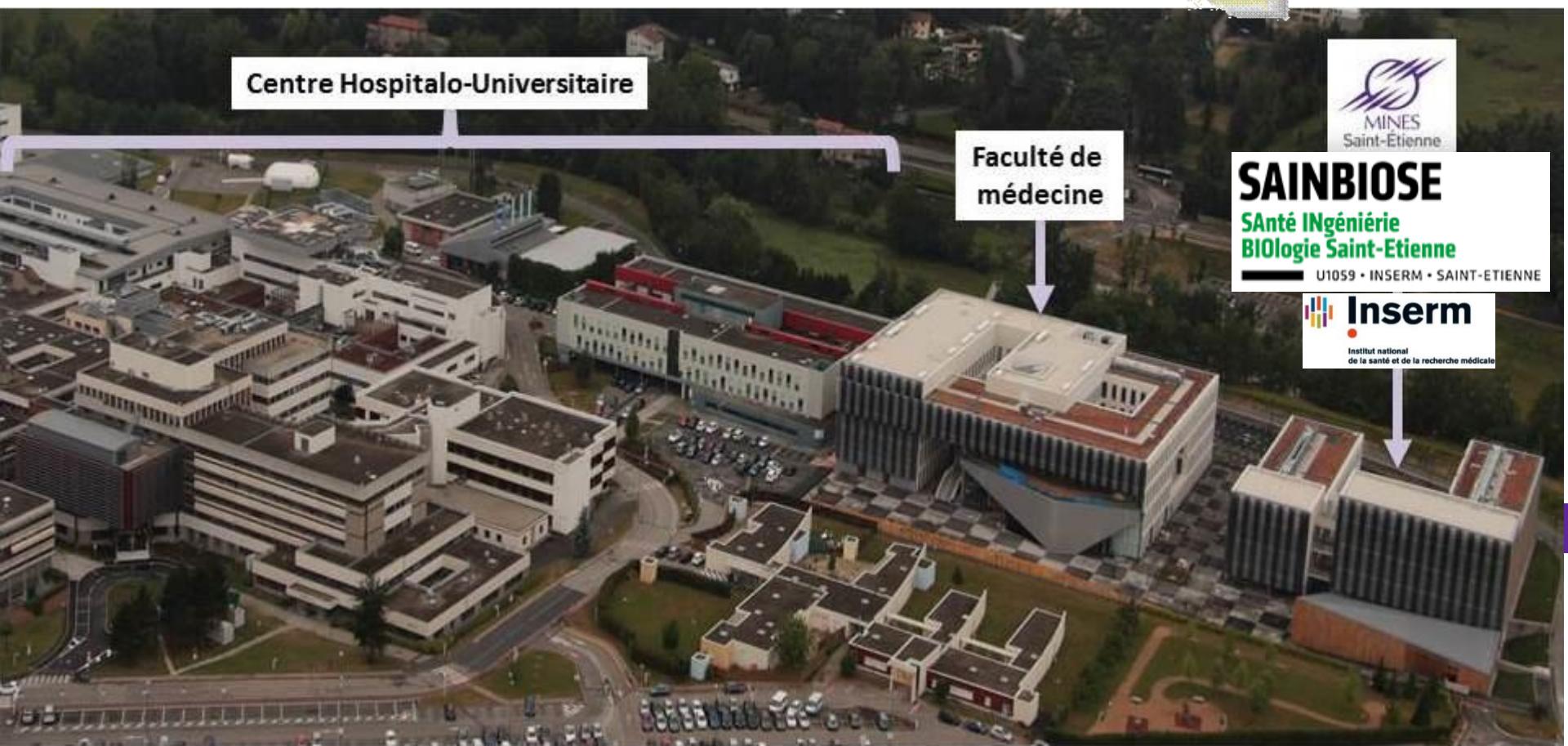
Prof. Stéphane AVRIL



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

PARIS

AUVERGNE
RHONE-ALPES

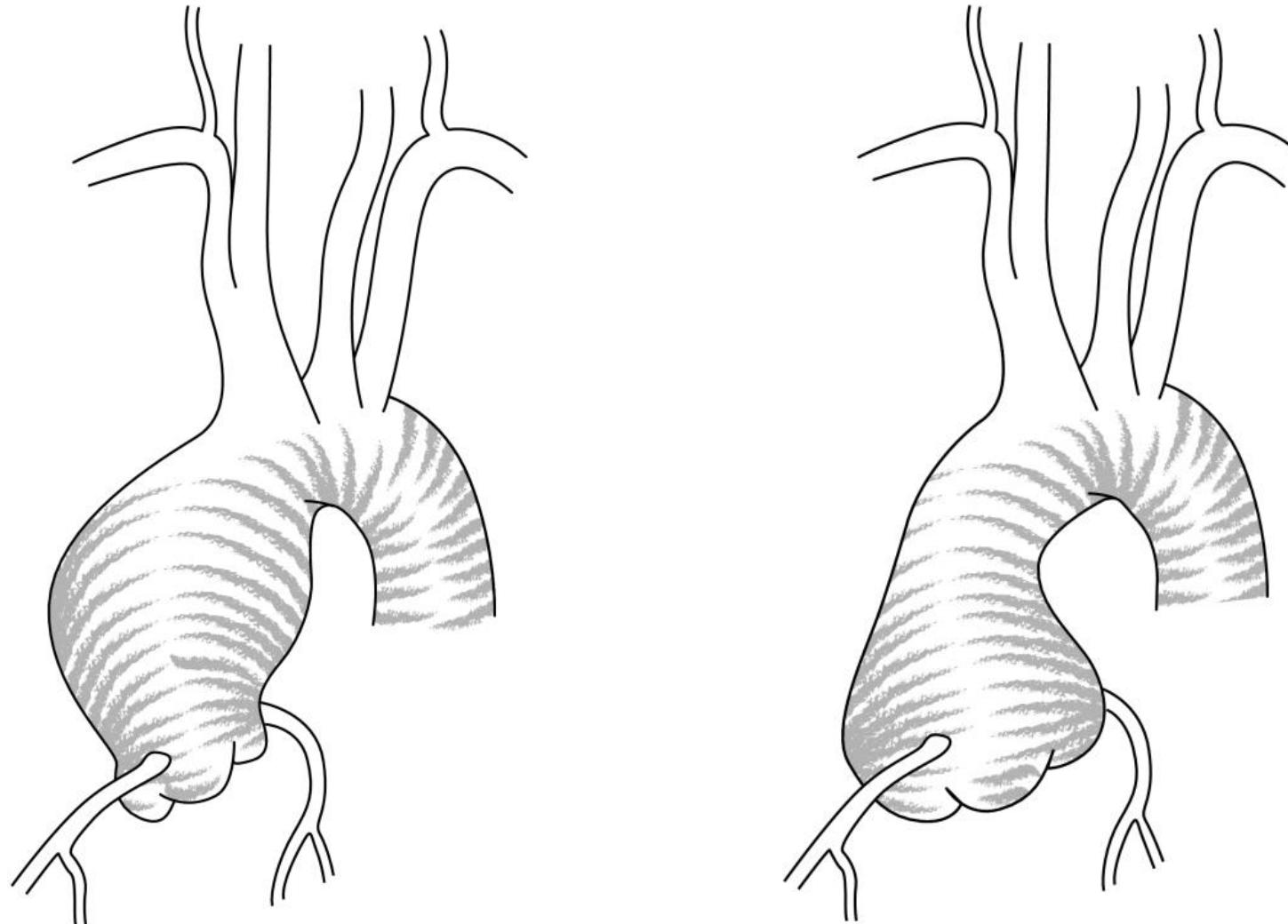


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Aortic root dilatations and ascending thoracic aortic aneurysms (ATAA)



Risks: Aortic dissections



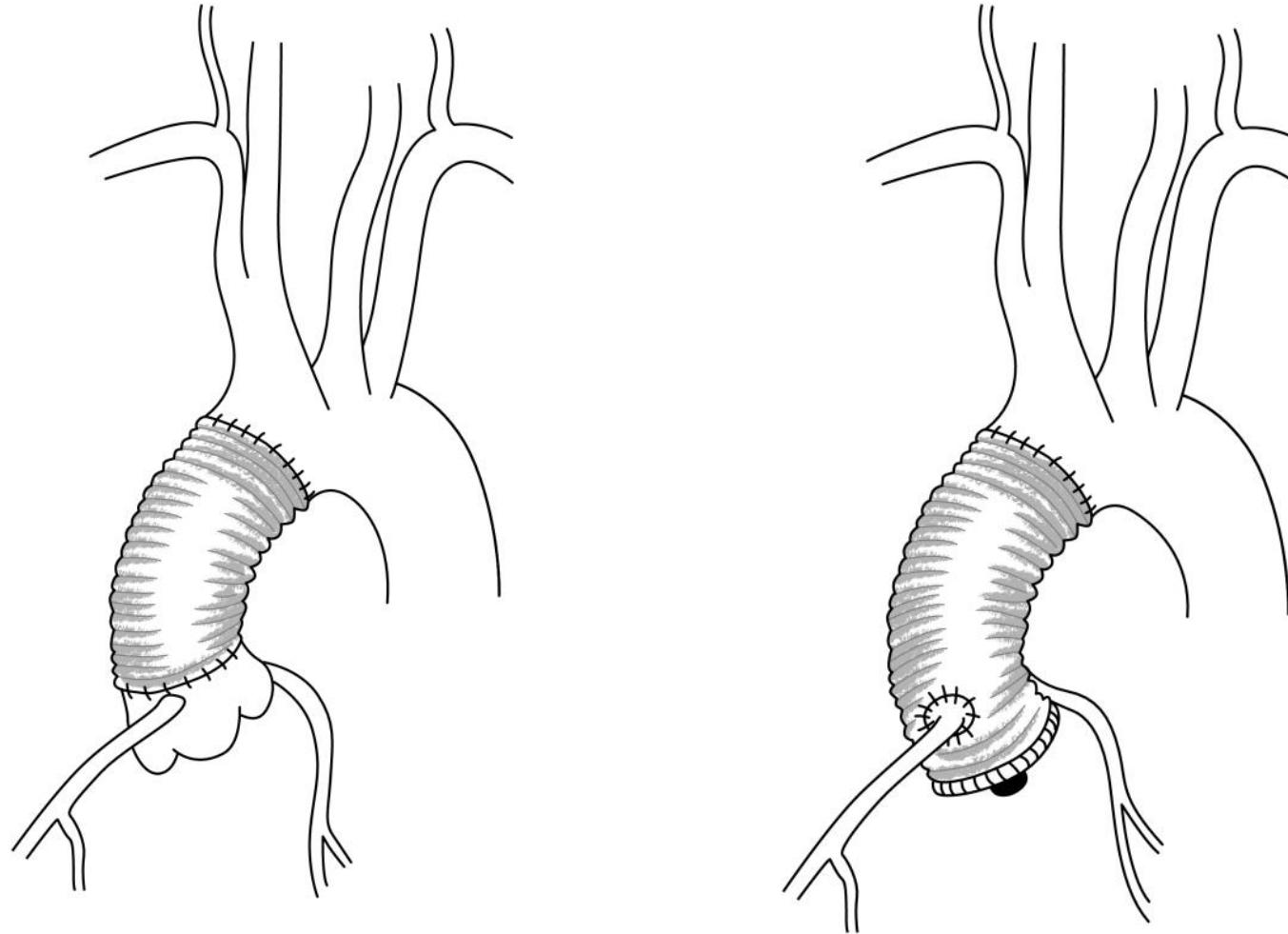
Surgical elective repair of ATAA

■ Indications:

- Aortic insufficiency requiring surgical correction
- Size ≥ 55 mm
- Size ≥ 50 mm in patients with Marfan syndrome or bicuspid valves
- Growth rate ≥ 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



Context

- **BUT:**
 - 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 ☺☺☺**

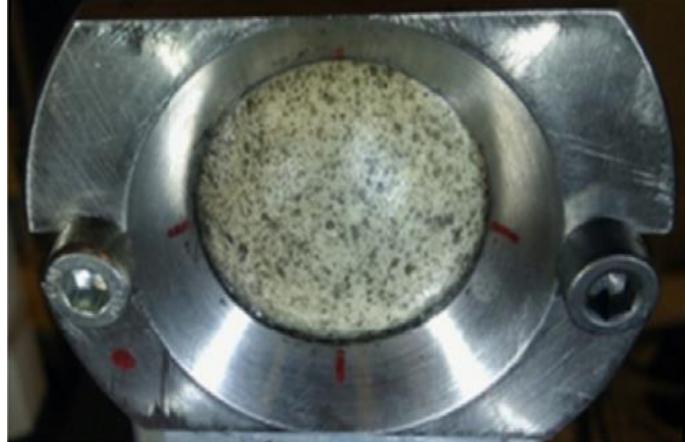
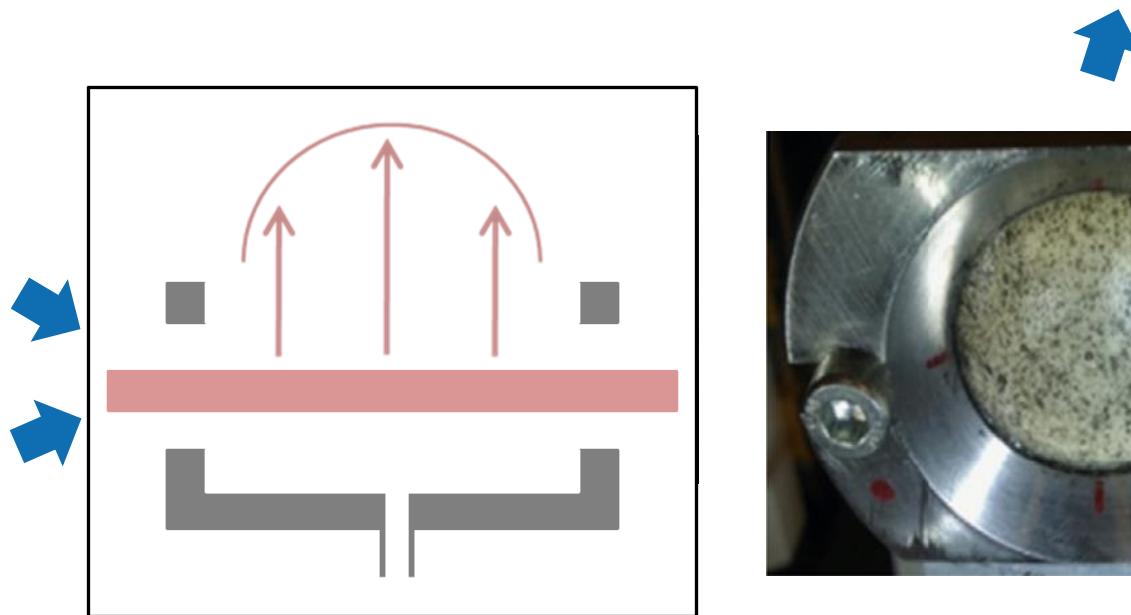
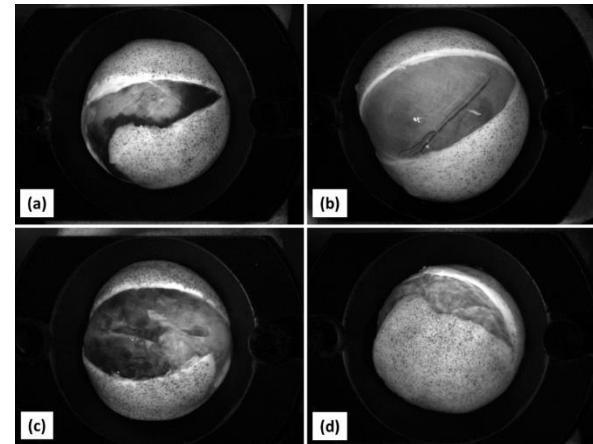
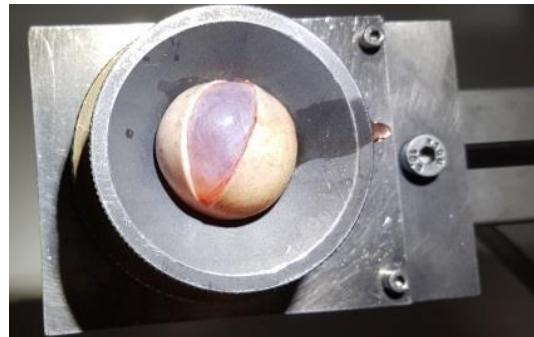
** Pape et al, *Aortic Diameter ≥ 5.5 cm Is Not a Good Predictor of Type A Aortic Dissection Observations From the International Registry of Acute Aortic Dissection (IRAD)*, Circulation, 2007



EXPERIMENTAL WORK

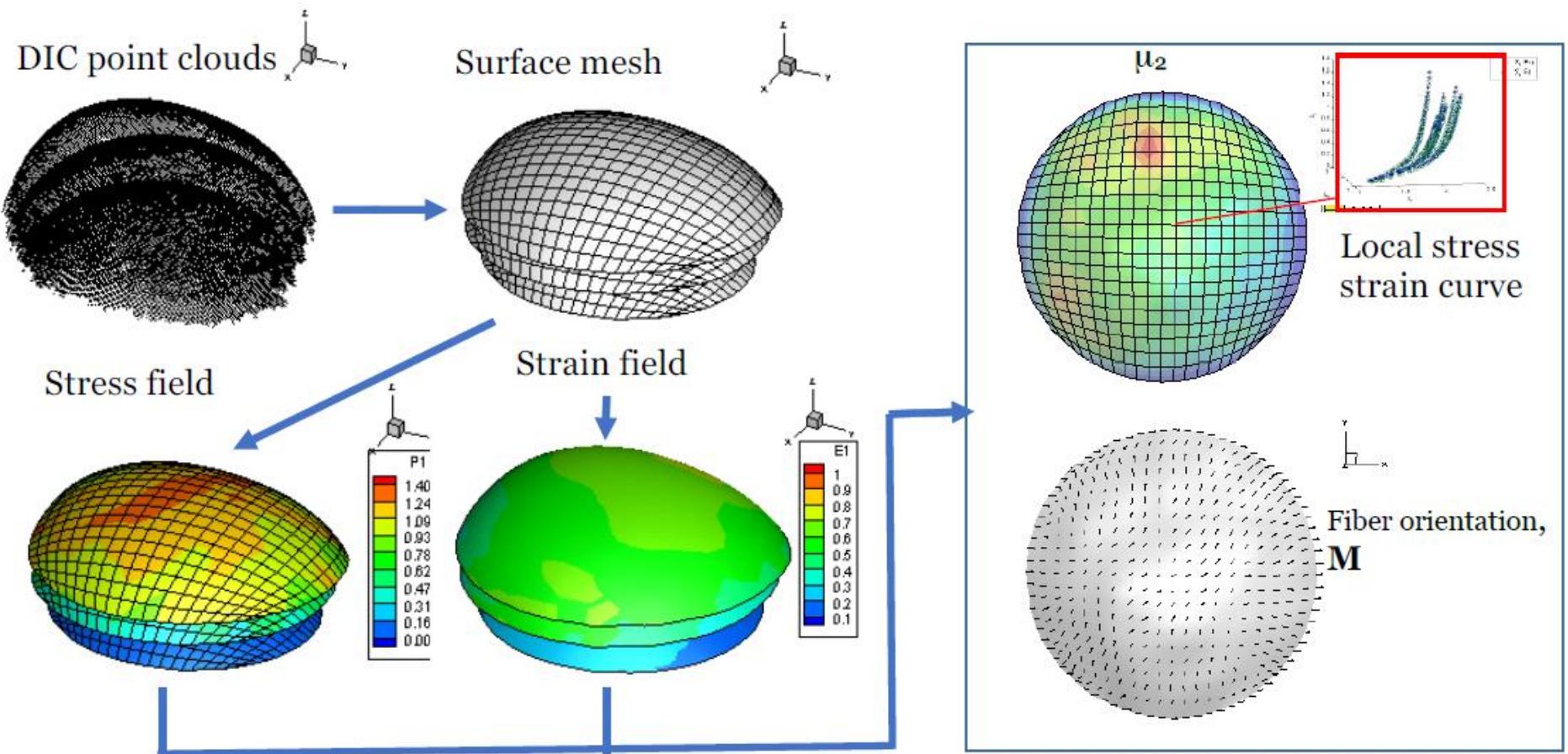
Bulge inflation test

Romo et al. Journal of Biomechanics -
2014

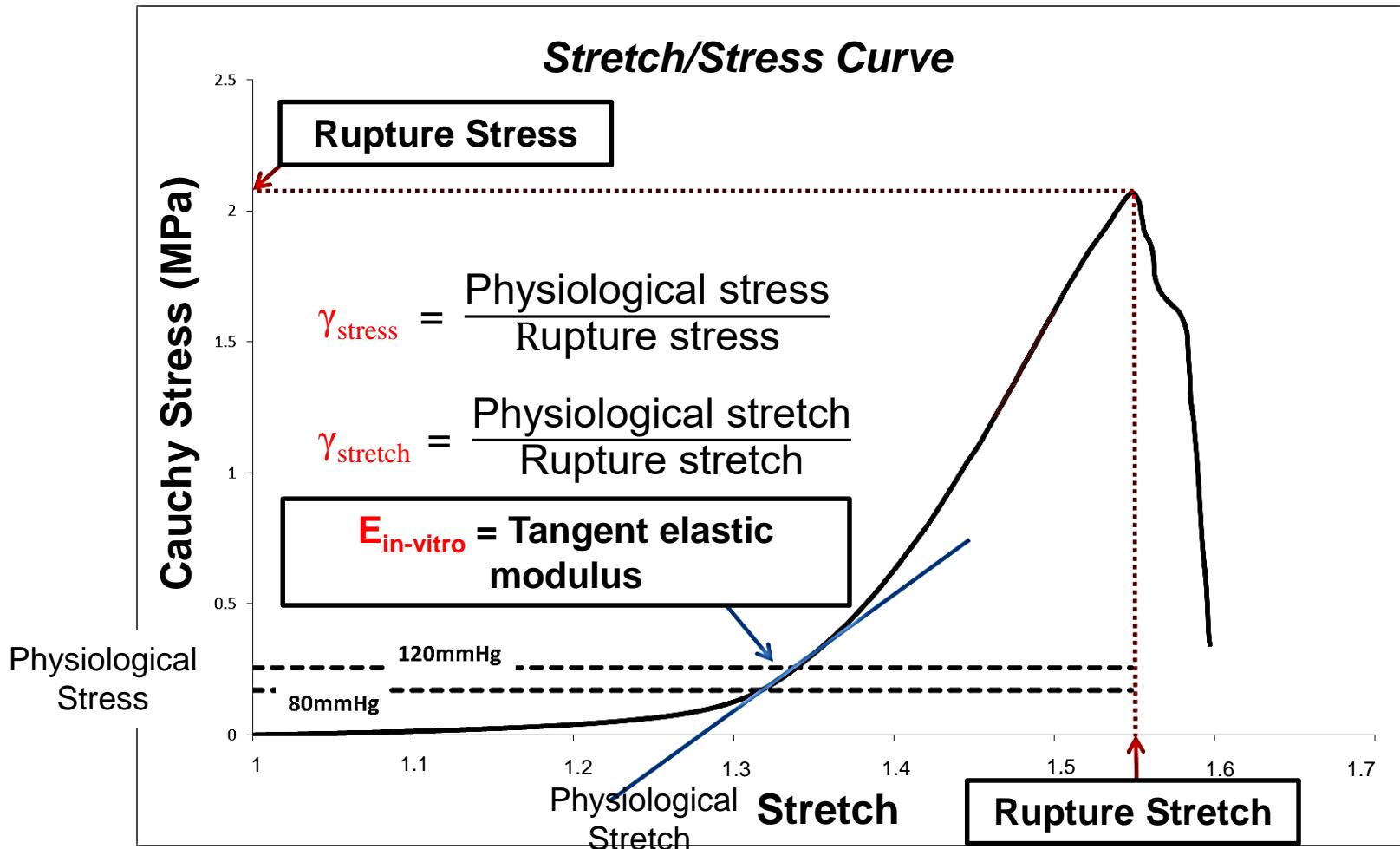




Identification of local material properties

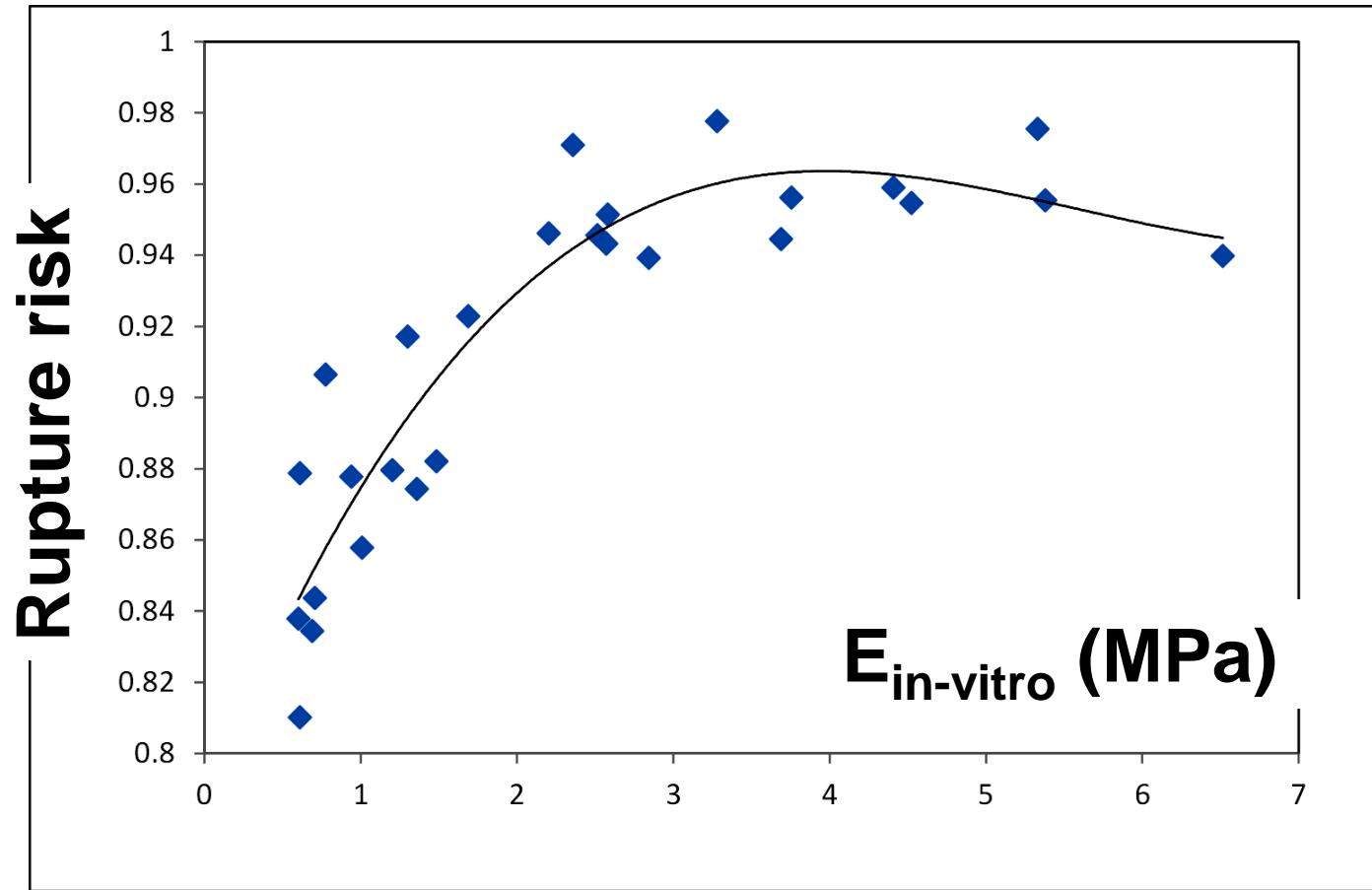


Rupture risk estimation





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



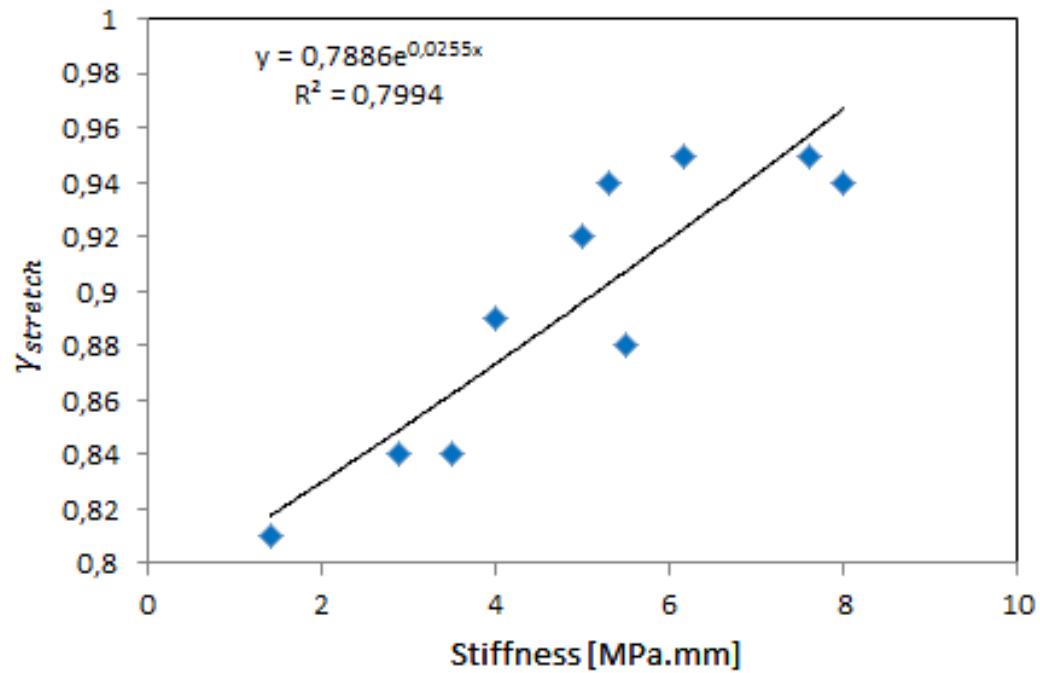
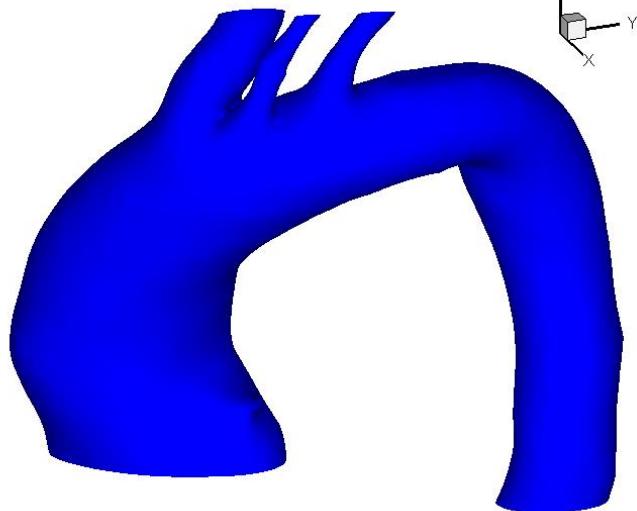
Duprey A, et al. Biaxial rupture properties of ascending thoracic aortic aneurysms. *Acta Biomaterialia* 2016.



Relationship with aortic stiffness

The stretch based rupture risk criterion correlates to the aortic stiffness measured by elastography techniques

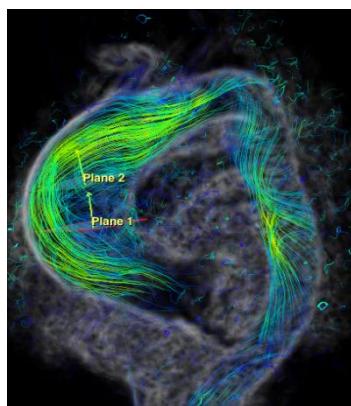
Time= 1 Phase



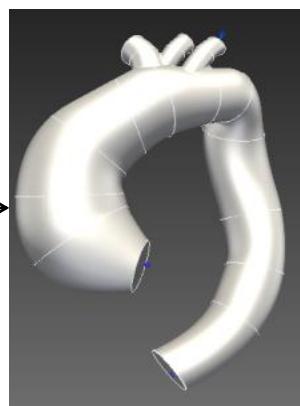
Olfa Trabelsi, Miguel A Gutierrez Cambron, Solmaz Farzaneh, Ambroise Duprey, Stéphane Avril. A non-invasive methodology for ATAA rupture risk estimation. *Journal of Biomechanics* 2017.



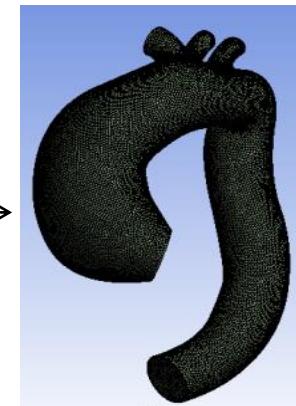
RELATIONSHIP WITH HEMODYNAMICS



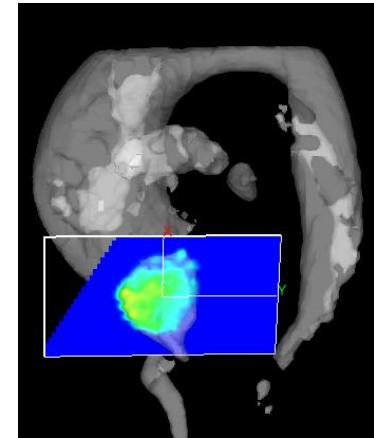
Preoperative dynamic imaging
4D MRI



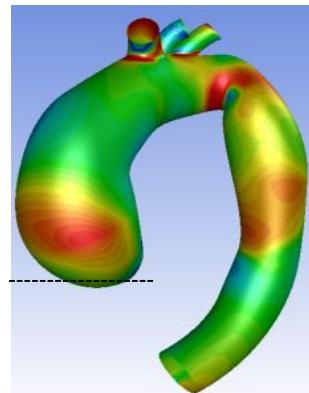
CAD



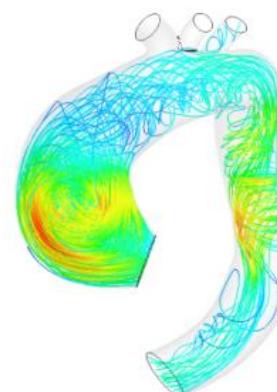
Mesh



BCs



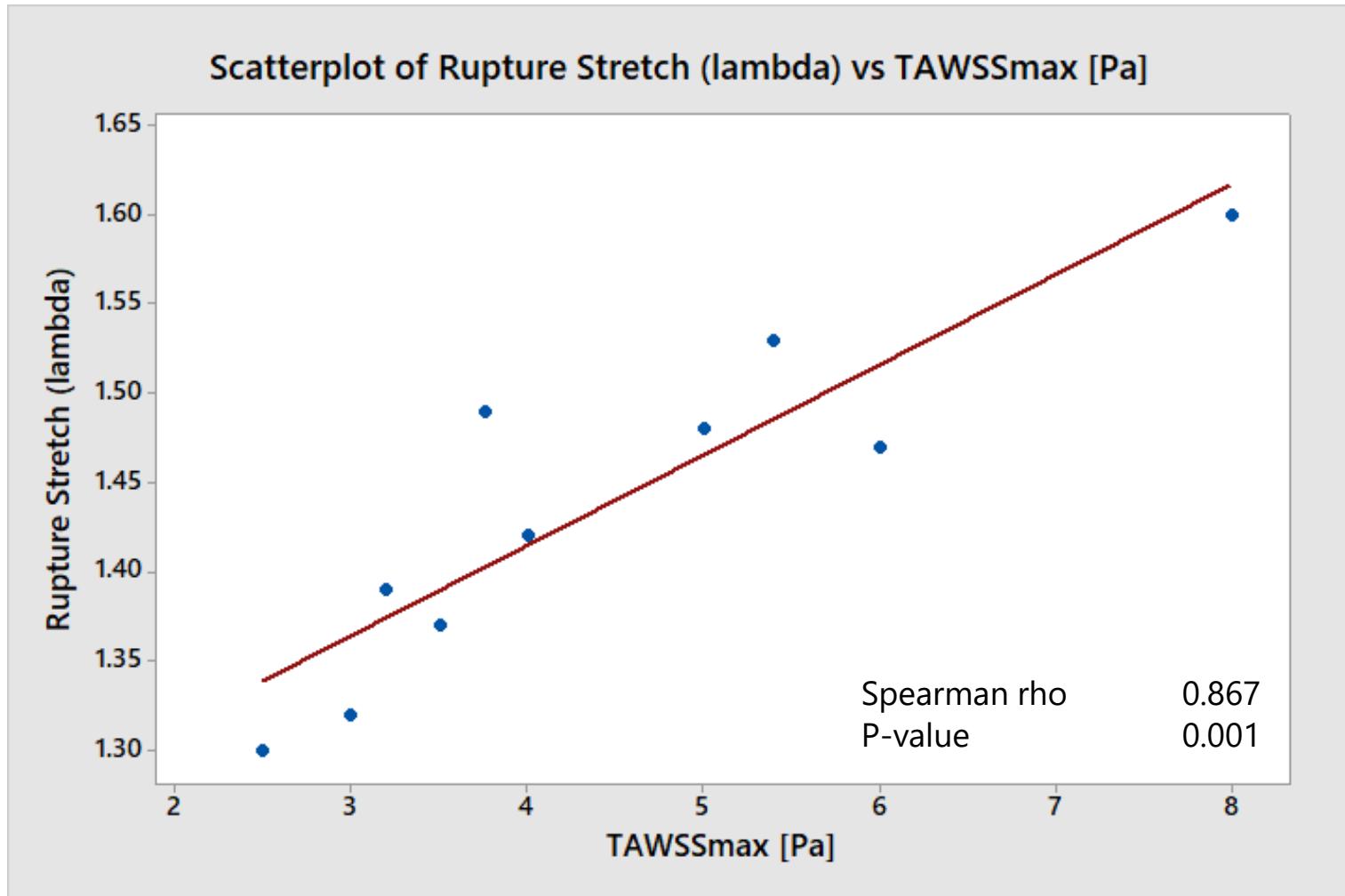
TAWSS



Streamlines, velocity

Numerical
resolution

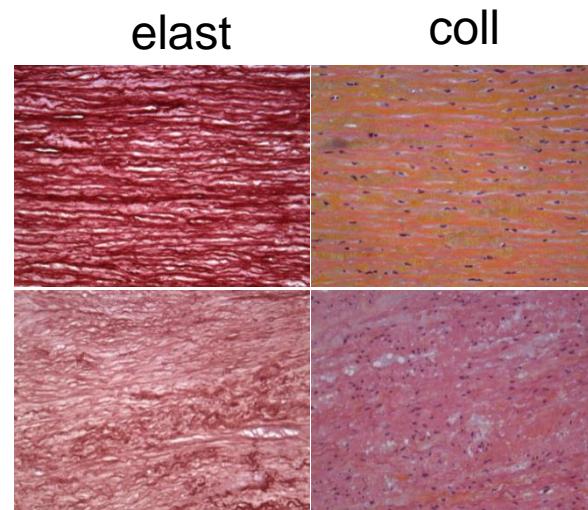
Relationship λ_{rupture} vs. TAWSSmax [Pa]



Histological interpretation

- ATAA always manifests with damaged elastic fibers
- More and more collagen tends to be recruited biomechanically in the physiological range

Patient with
largest γ_{stretch}



Patient with
smallest γ_{stretch}

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

Summary

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

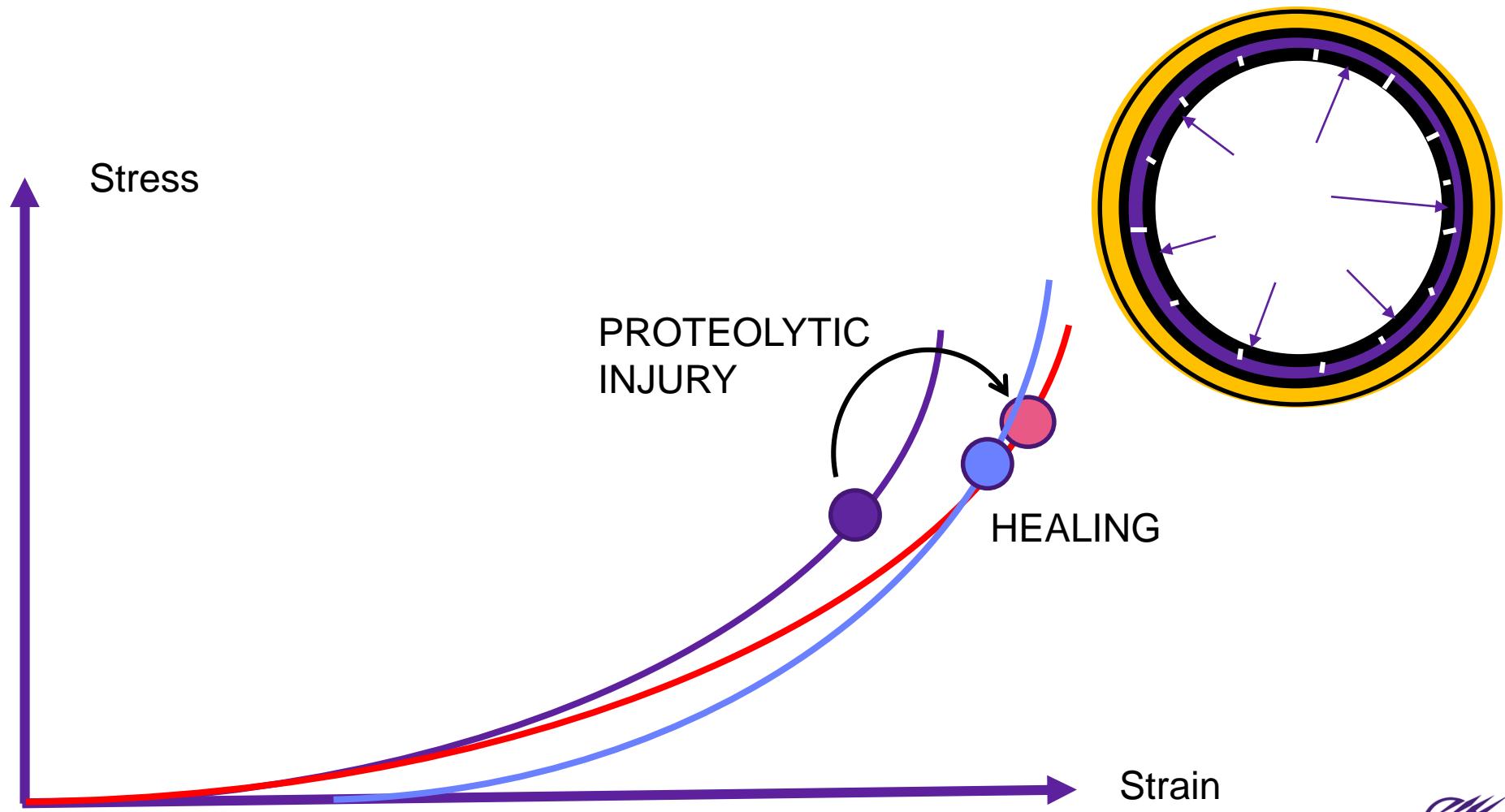
Higher stiffness \Rightarrow less risk because the aneurysm can more easily withstand volume variation



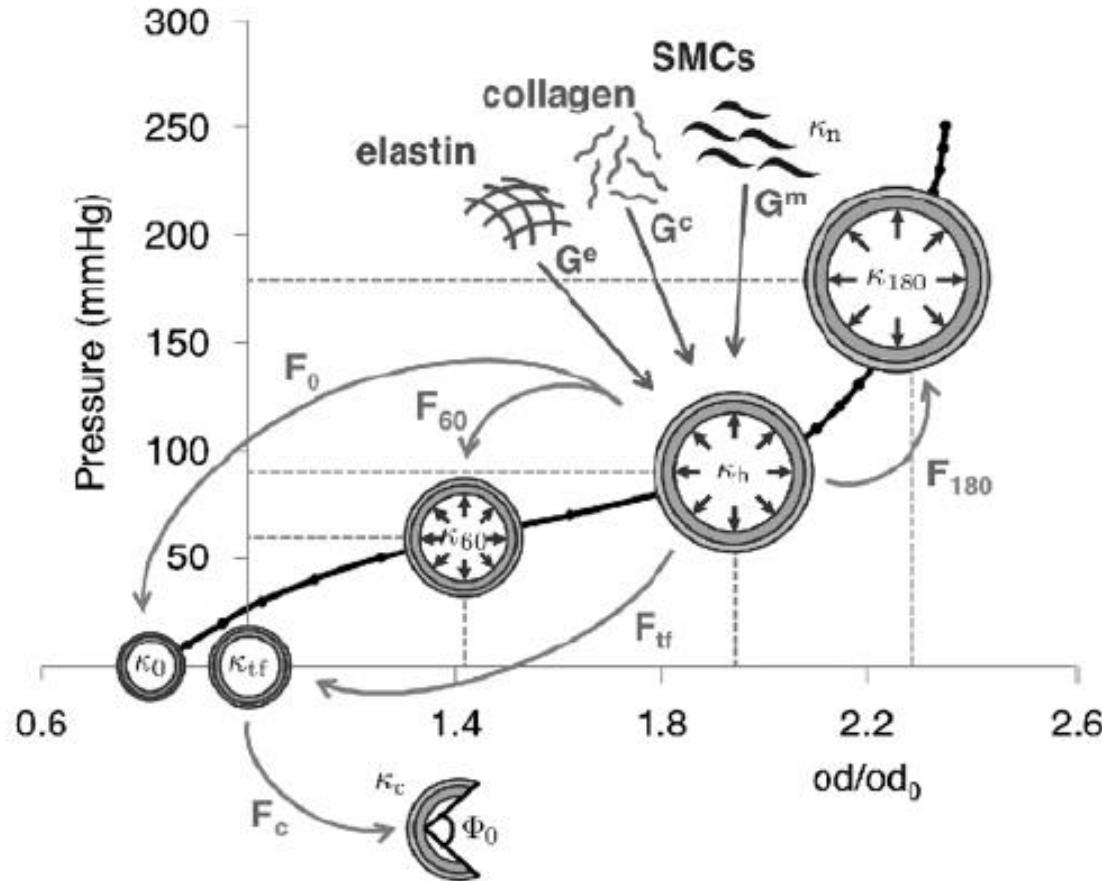


THEORETICAL WORK

Continuous process of proteolytic injury and tissue adaptation



Constrained mixture theory



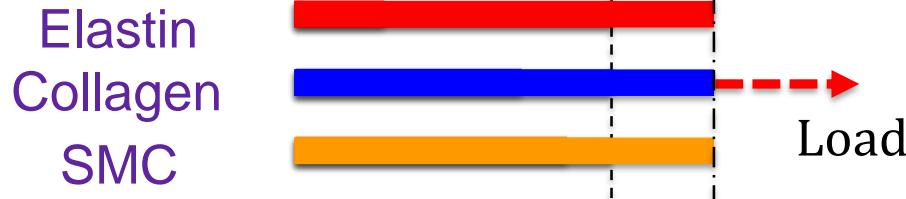
Layer-specific constitutive model

Strain-energy function based on the constrained mixture theory

$$W = (1 - D^e)\rho^e \overline{W}^e(\bar{I}_1^e) + \sum_{i=1}^n (1 - D^{c_i})\rho^{c_i} W^{c_i}(I_4^{c_i}) + \rho^m W^m(I_4^m) + U(J)$$

Deposition stretch (Λ_s^j) of each constituent

$$\mathbf{F}_{\text{tot}}^j = \mathbf{F}\Lambda_s^j$$



Layer-specific constitutive model

Volumetric contributions of strain-energy function

$$U(J) = \kappa(J - 1)^2$$

Active contribution of smooth muscle cells

$$\psi_{act}^{sm} = \frac{S_{actmax}}{\rho(0)} \left(\lambda_{act} + \frac{1}{3} \frac{(\lambda_m - \lambda_{act})^3}{(\lambda_m - \lambda_0)^2} \right)$$

Damage

$$D = G(\psi) = \frac{1 - \frac{\psi_0}{\psi}}{1 + H} \quad \text{with} \quad H = -\frac{\psi_0^2}{2\omega} \quad \text{and} \quad \psi = \sqrt{2W} \quad \omega = \frac{\Omega}{L_0}$$

Homogenized G&R constrained mixture model

Strain-energy function based on the constrained mixture theory

$$W = (1 - D^e)\rho^e \overline{W}^e(\bar{I}_1^e) + \sum_{i=1}^n (1 - D^{c_i})\rho^{c_i} W^{c_i}(I_4^{c_i}) + \rho^m W^m(I_4^m) + U(J)$$

Elastic and inelastic decomposition of deformation gradient

$$\mathbf{F}_{\text{tot}}^j = \mathbf{F}_{\text{e}}^j \mathbf{F}_{\text{gr}}^j$$

$$\mathbf{F}_{\text{gr}}^j = \mathbf{F}_{\text{r}}^j \mathbf{F}_{\text{g}}^j$$

\mathbf{F}_{r}^j and \mathbf{F}_{g}^j should be calculated if the artery is not in the homeostatic state

Homogenized G&R constrained mixture model

Collagen mass production

$$\dot{\varrho}^j(t) = \varrho^j(t) k_\sigma^j \frac{\sigma^j(t) - \sigma_h^j}{\sigma_h^j} + \dot{\xi}^j(t)$$

Inelastic deformation due to remodeling

$$\left[\frac{\dot{\varrho}^j(t)}{\varrho^j(t)} + \frac{1}{T^j} \right] [\mathbf{S}^j - \mathbf{S}_{\text{pre}}^j] = \left[\frac{\partial \mathbf{S}^j}{\partial \mathbf{C}_e^j} : (\mathbf{C}_e^j \mathbf{L}_r^j) \right] \quad \mathbf{L}_r^j = \dot{\mathbf{F}}_r^j \mathbf{F}_r^{j-1}$$

Cyron et al, Biomech Model Mechanobiol (2016) 15:1389–1403, Braeu et al, Biomech Model Mechanobiol (2017) 16(3):889-906

Homogenized G&R constrained mixture model

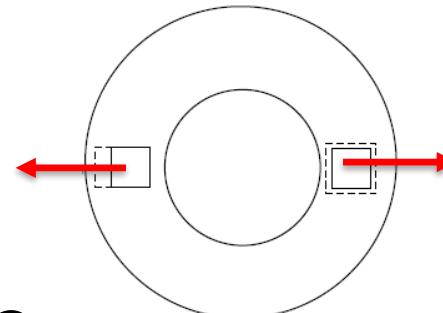
Inelastic deformation due to growth

$$\dot{\mathbf{F}}_g = \dot{\mathbf{F}}_g^j = \sum_{j=1}^n \dot{\mathbf{G}}^j$$

$$\dot{\mathbf{G}}^j = \frac{\dot{\varrho}^j(t)}{\varrho^j(t) [\mathbf{F}_g^{j-T} : \mathbf{B}^j]} \mathbf{B}^j$$

$$\mathbf{B}^j = a_g \otimes a_g$$

Anisotropic
growth



$$\mathbf{B}^j = \frac{1}{3} \mathbf{I}$$

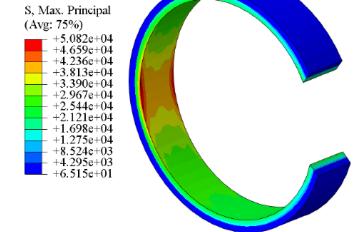
Isotropic
growth



COMPUTATIONAL WORK

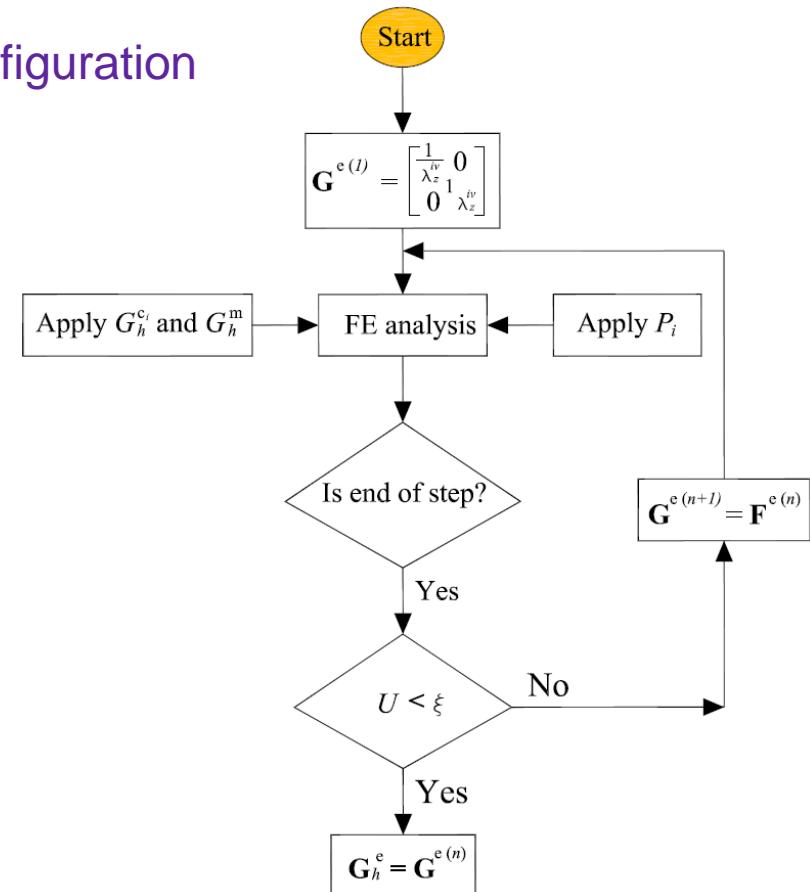
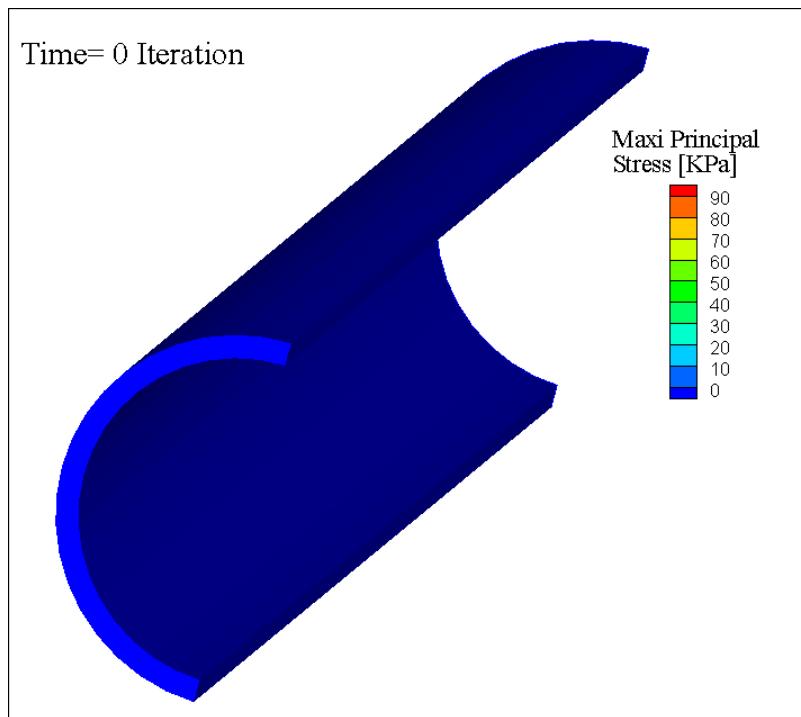


Finite-element implementation



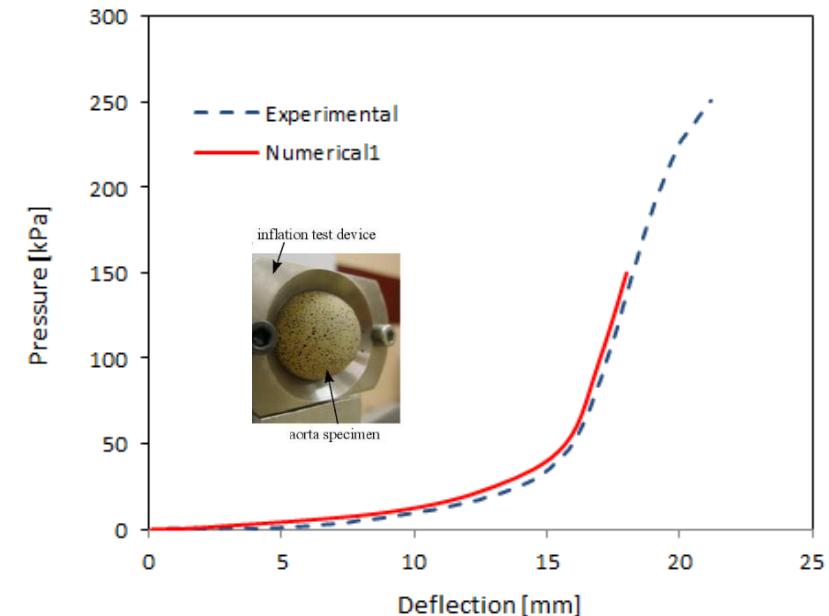
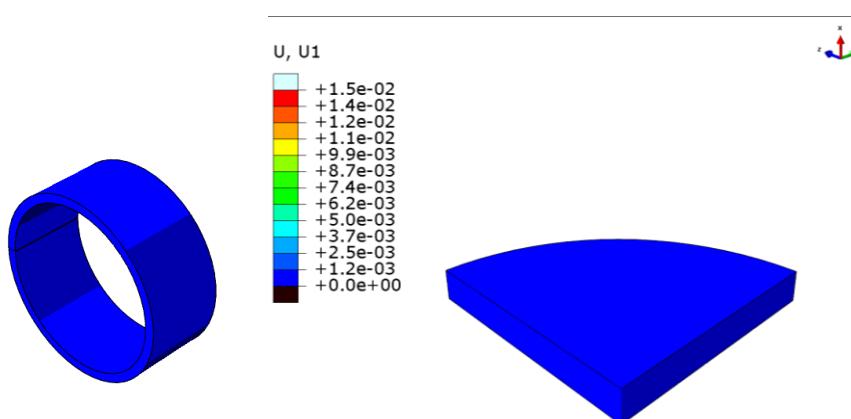
- FE software ABAQUS coupled with UMAT
- Reference configuration is the in vivo configuration

Bellini et al, ABME, 2014
Mousavi et al, BMMB, 2017

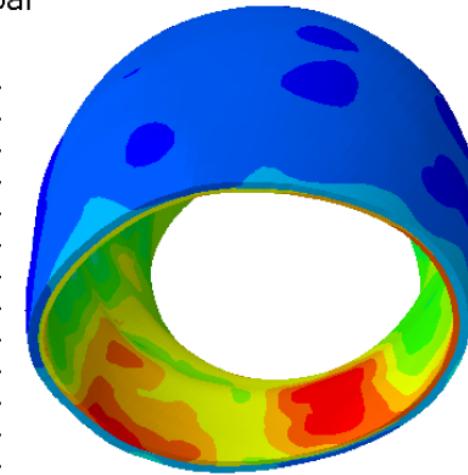
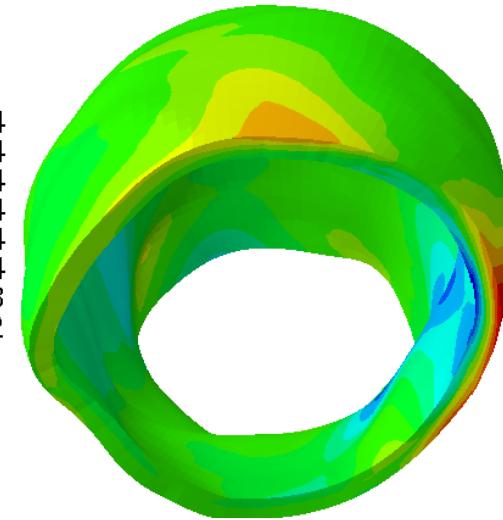
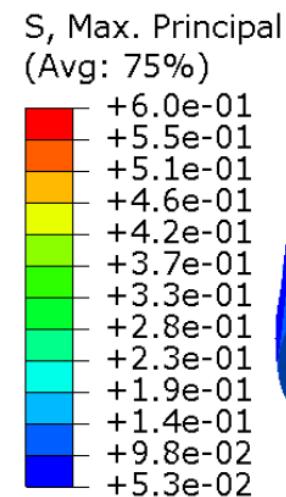
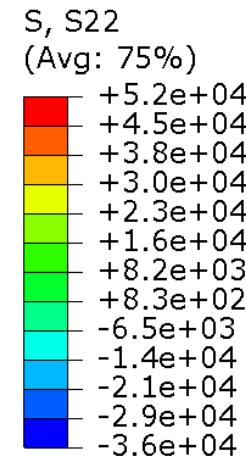
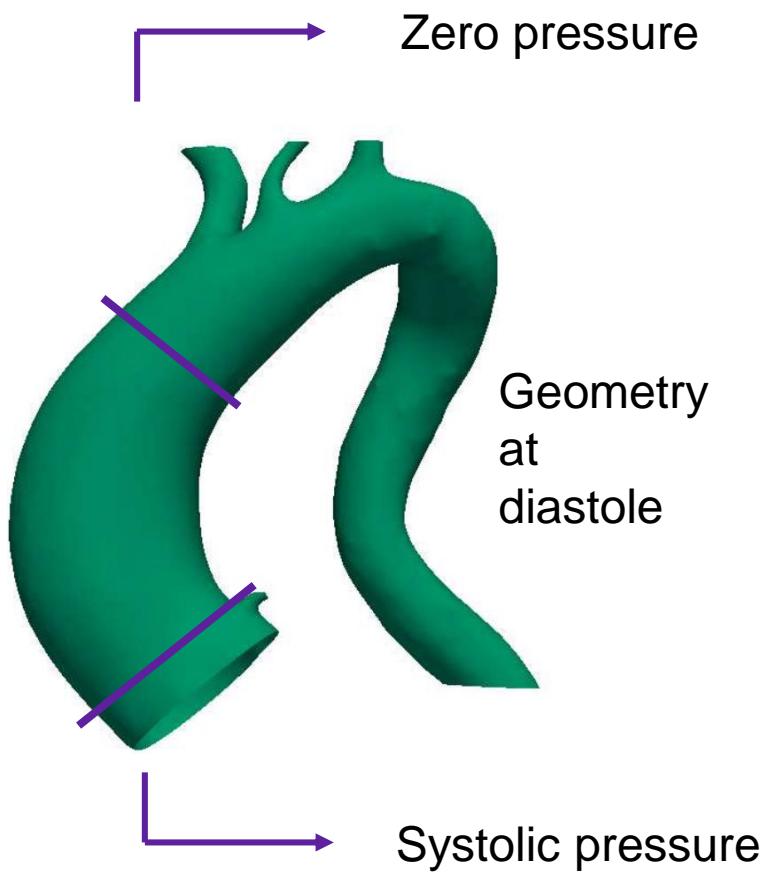


Modeling of a bulge inflation test including pre-test deformation

Model parameters are calibrated against pressure/deflection curves



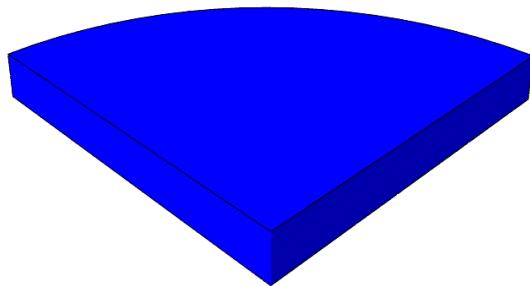
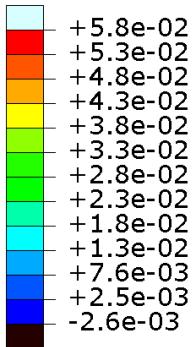
Hoop stress in patient specific ATAA



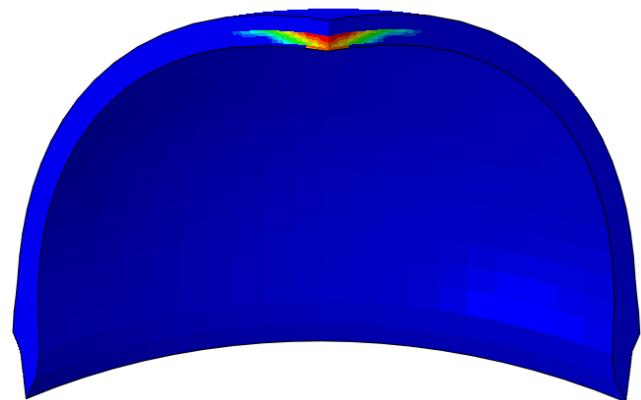
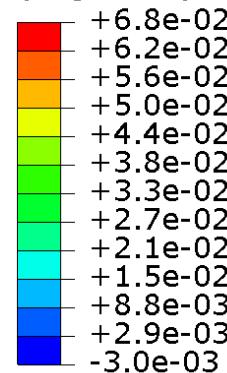
Prediction of mechanical damage in bulge inflation tests

Damage during bulge inflation test (luminal side in)

(Avg: 75%)



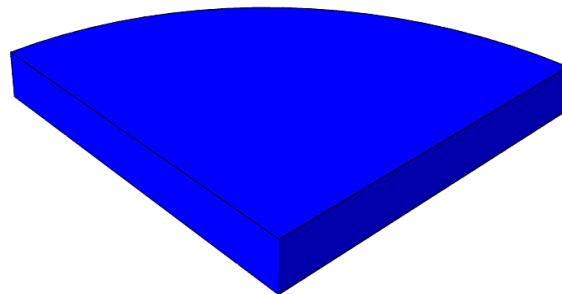
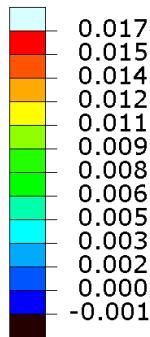
(Avg: 75%)



Prediction of mechanical damage in bulge inflation tests

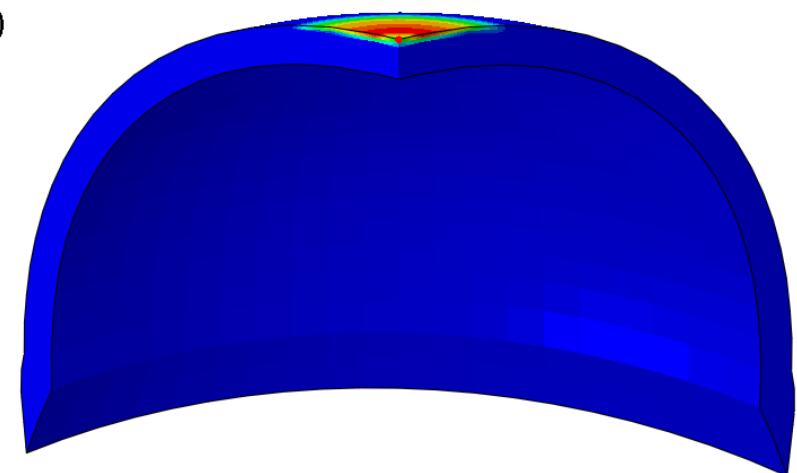
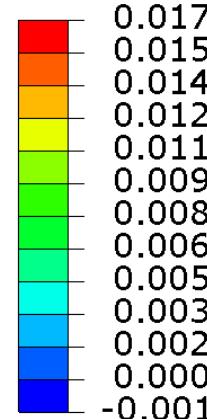
Damage during bulge inflation test (luminal side out)

(Avg: 75%)



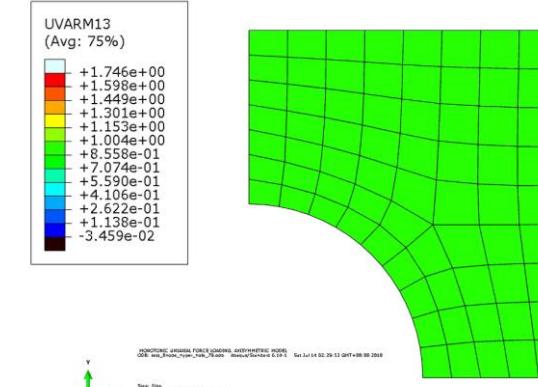
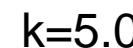
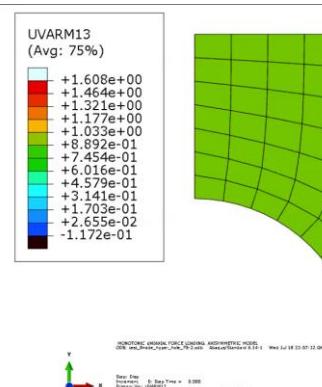
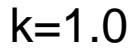
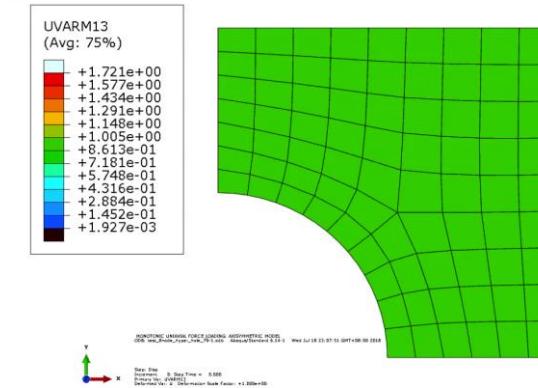
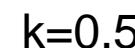
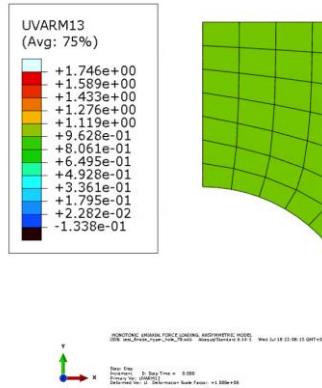
SDV15

(Avg: 75%)





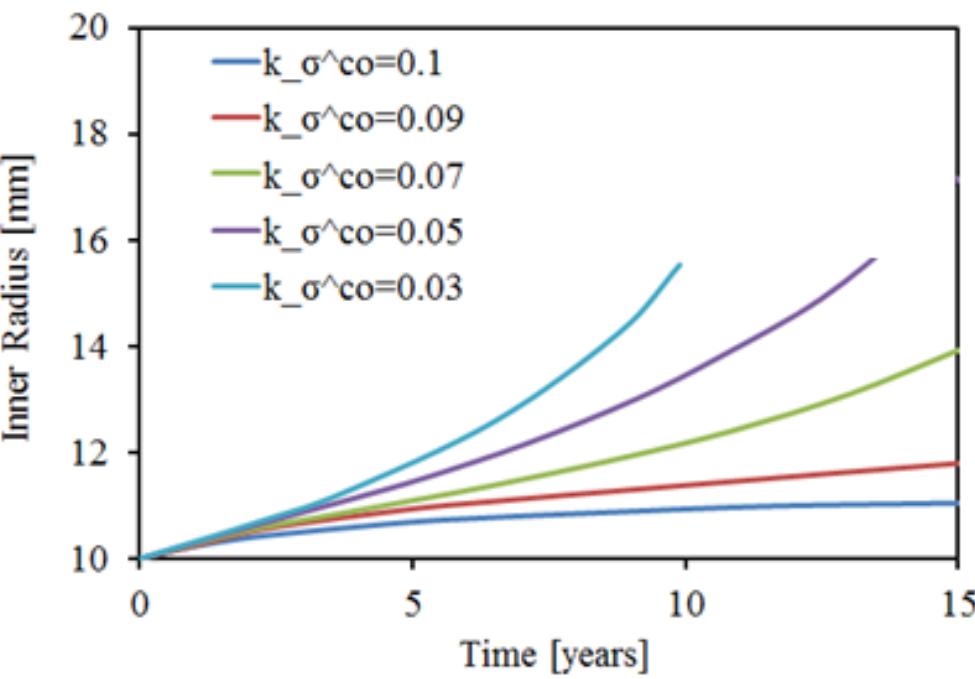
Gradient-enhanced G&R healing model



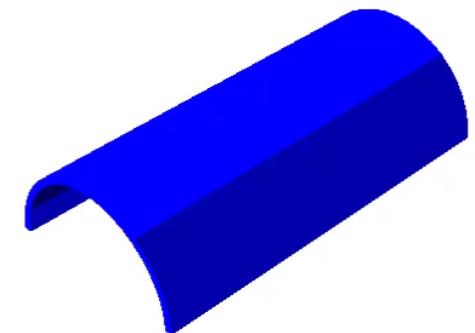
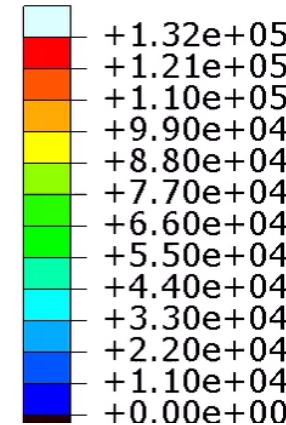


Growth and remodeling with continuous medial proteolytic injury

Effects of rate of collagen mass production and of loss of SMC contractility

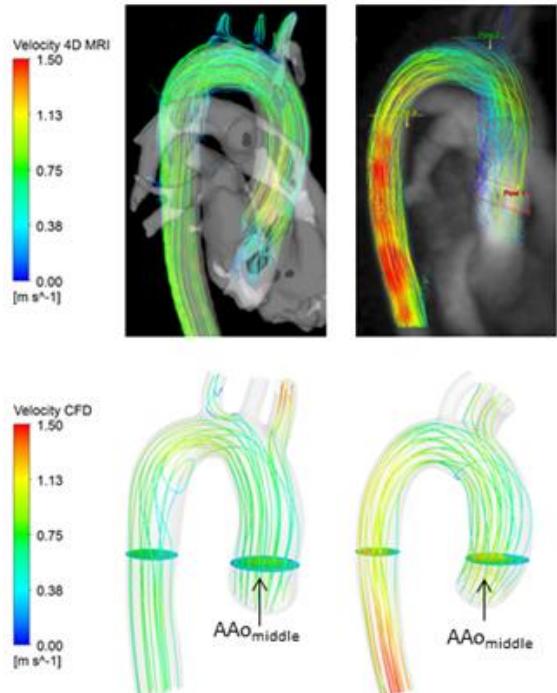


S , Max. Principal
(Avg: 75%)

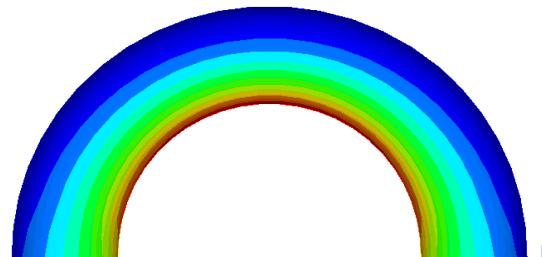


Growth and remodeling with continuous medial proteolytic injury

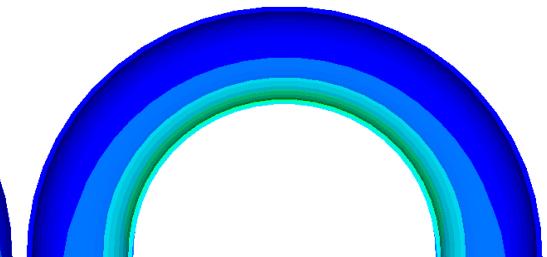
Effects of curvature



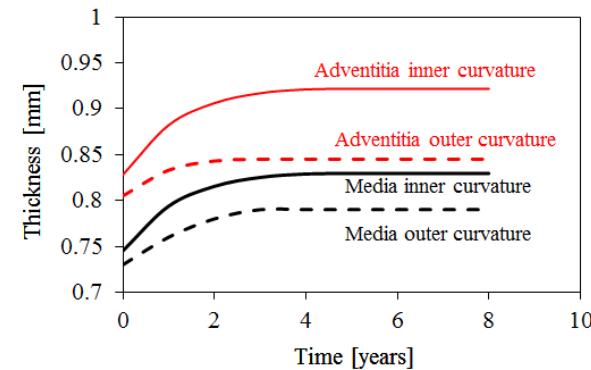
Adventitia



Media



1.0 1.43





SUMMARY

- Novel numerical model based on the constrained mixture theory including damage and G&R ;
- Layer specific model which can capture the response of each layer of arterial wall if any growth and remodeling occurs;
- Need to improve computational and experimental sides.

Computational mechanics in the OR for vascular surgery?

www.predisurge.com



Acknowledgements

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 - **Claudie Petit**
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- **Ambroise Duprey**
 - **Jean-Pierre Favre**
 - **Jean-Noël Albertini**
 - **Salvatore Campisi**
 - **Magalie Viallon**
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