



Centre for Biomedical and Healthcare Engineering CNRS UMR 5307

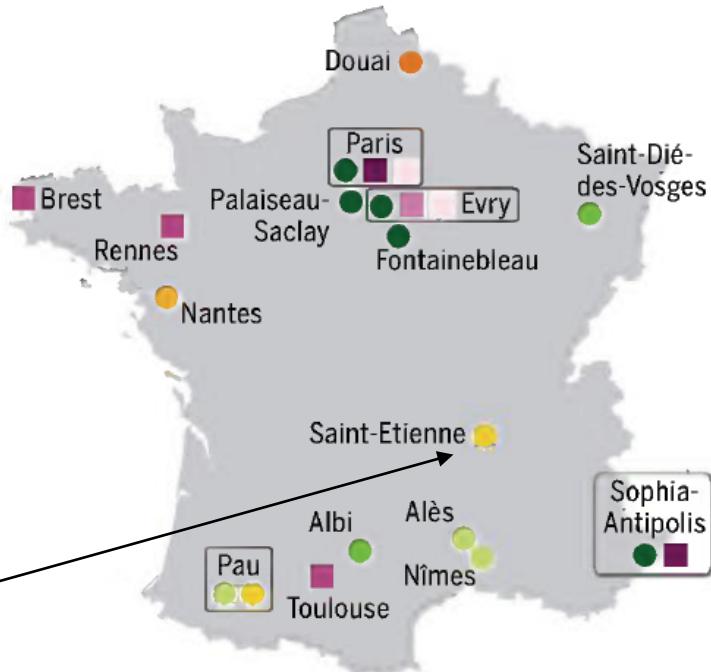
Mr Aaron Romo, Prof Stéphane Avril, Dr Pierre Badel, Dr Ambroise Duprey, Prof Jean-Pierre Favre, Prof Sam Evans

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Full-field strain measurement and material identification in soft tissue biomechanics

Location



Center for Biomedical and Healthcare Engineering



Campus with hospital, medical school, prevention center, college of engineering and companies manufacturing medical devices

Healthcare engineering



Biotoxicity of inhaled nanoparticules

4 topics



22 permanent staff
35 postgraduate students and postdocs



Soft tissue biomechanics

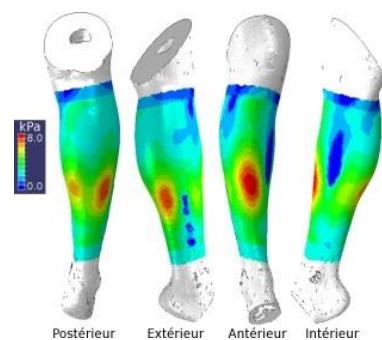
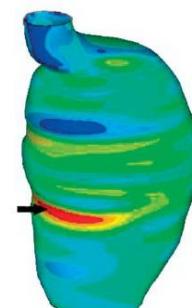


Biomaterials for bone replacement

Biomechanics of soft tissues



The aim is to employ biomechanical models to adapt the treatments of cardiovascular and osteoarticuar diseases to each patient





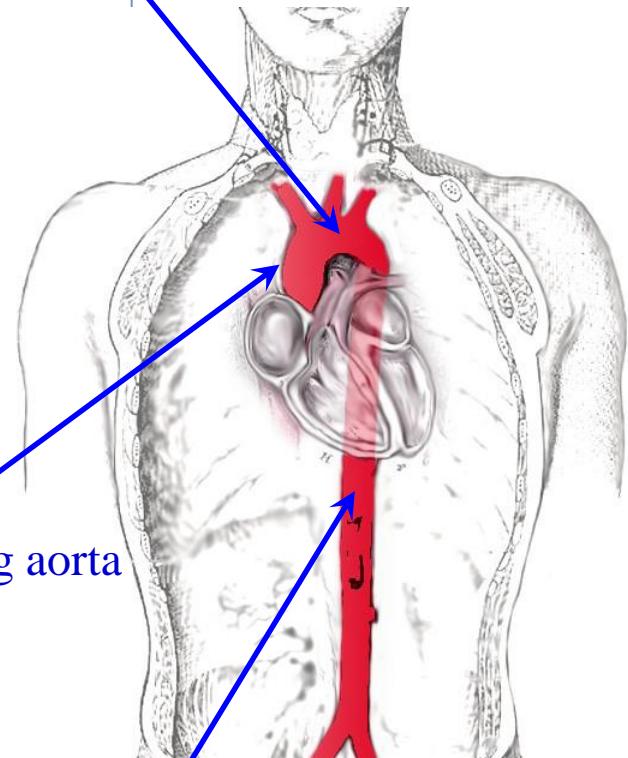
Today's talk...

Aortic aneurisms



BSSM Cardiff – 2013/09/05 – Stéphane AVRIL

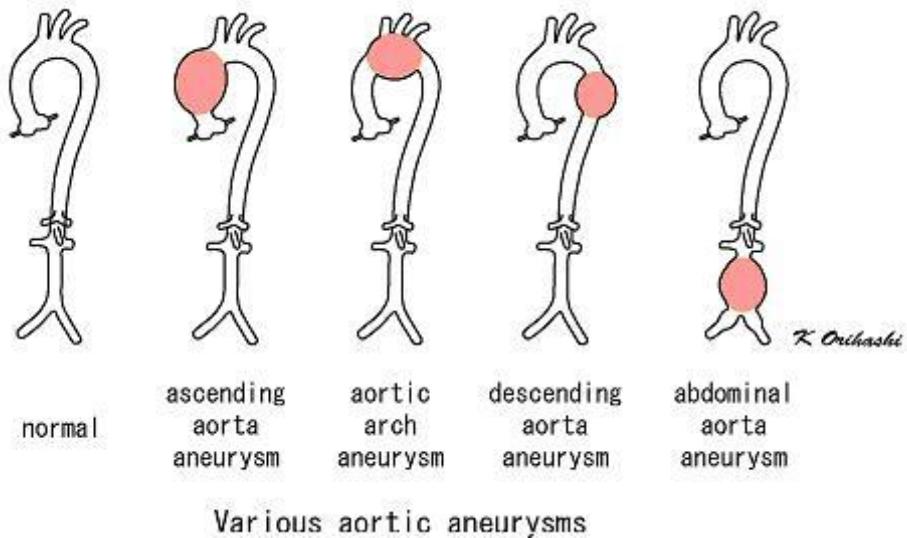
arch of aorta



descending aorta

(thoracic aorta and abdominal aorta)

- ▶ a local dilation of the aorta due to aortic wall weakening



- ▶ aneurysm rupture
- ▶ a fatal medical emergency

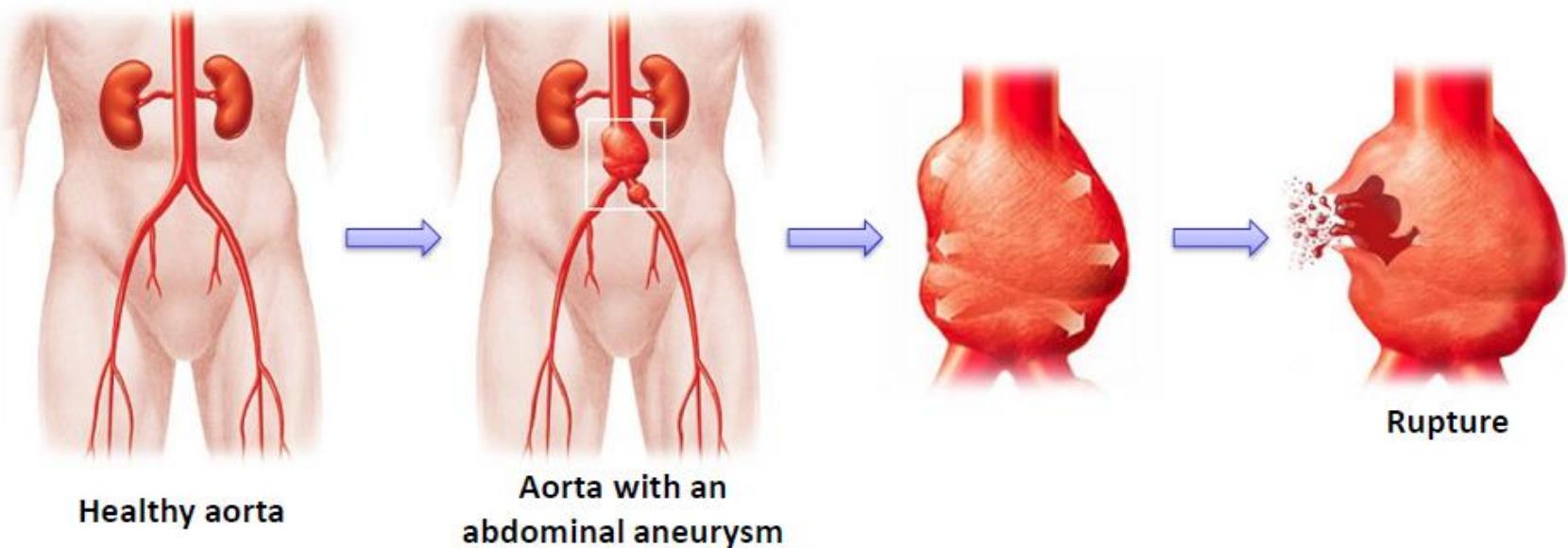


Aortic aneurisms

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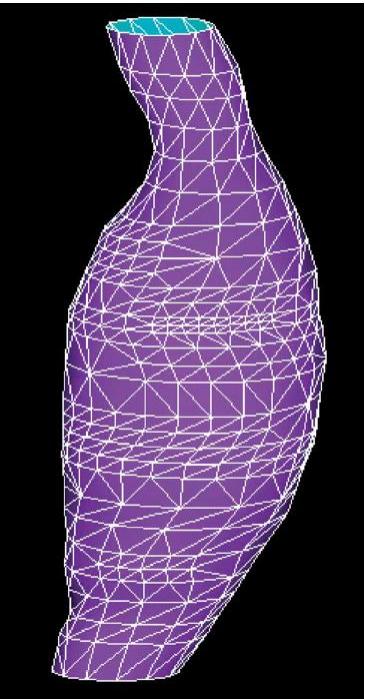
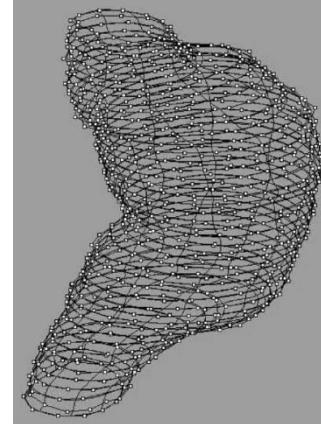
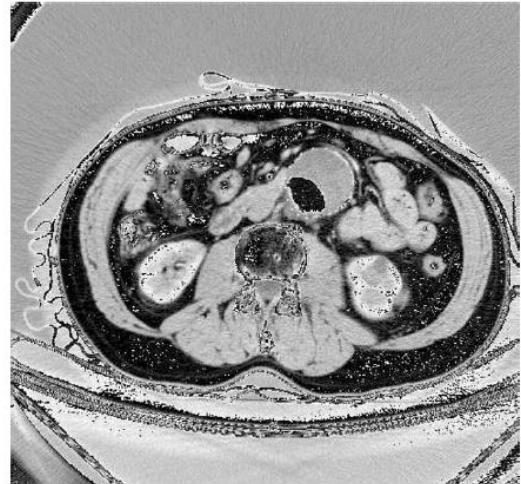
► Abdominal aortic aneurysm (AAA):

- ▶ “Permanent localized dilatation of the aorta having at least a 50% increase in diameter compared to the expected normal diameter of the aorta” (*Johnston et al., 1991*)
- ▶ Death by **aneurysm rupture**
- ▶ **Major public health issue:**
 - ▶ 500000 new discovered cases per year worldwide
 - ▶ 15000 death per year in the U.S (13th cause of death)

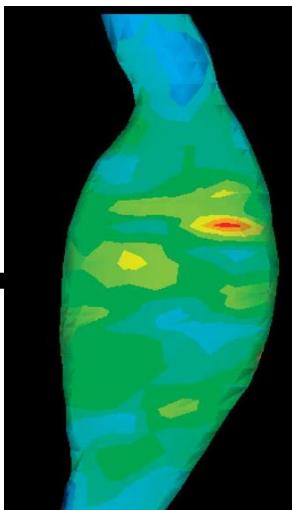
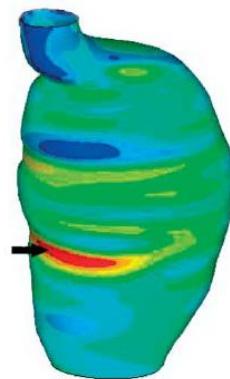
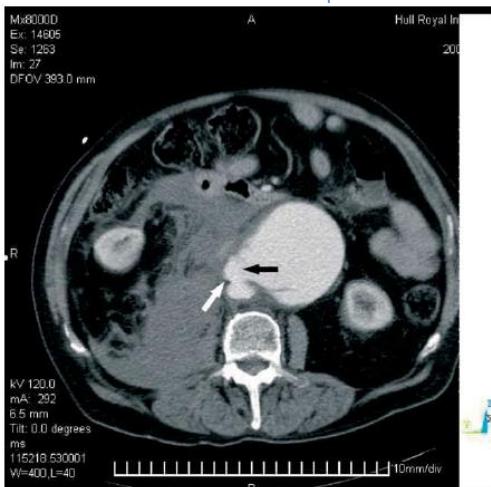




PREVENTION OF ATAA RUPTURE FROM A BIOMECHANICAL POINT OF VIEW???



[McGloughlin T. Biomechanics and mechanobiology of aneurysms. 2012, Springer





What are the patient-specific material properties of the tissue?

What is the patient-specific strength of the tissue?



BIOMECHANICAL EXPERIMENTAL APPROACHES

Tensile rupture mode

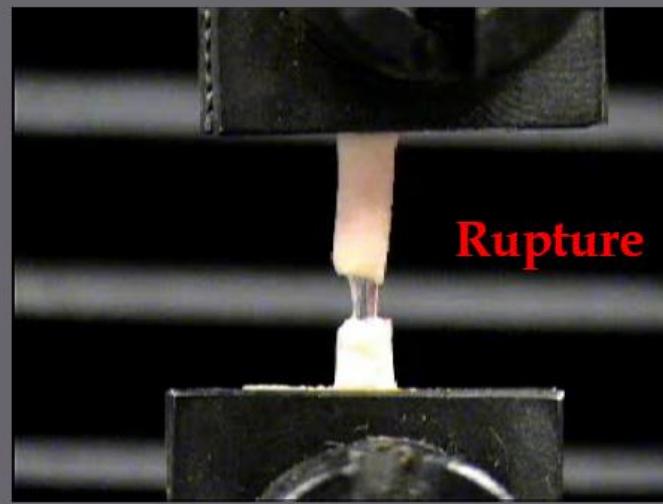
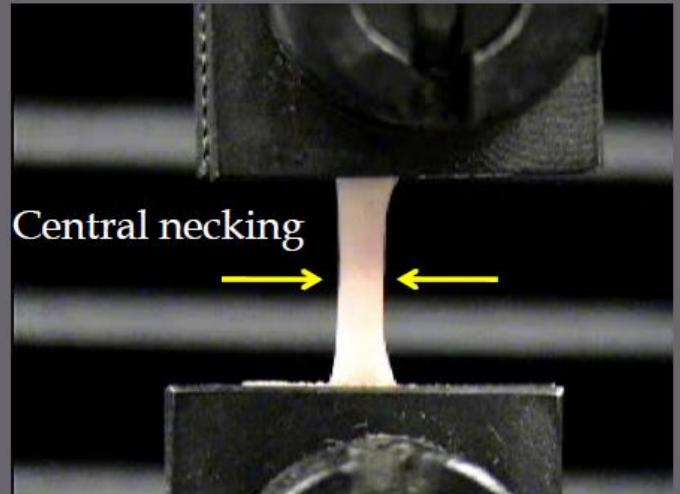
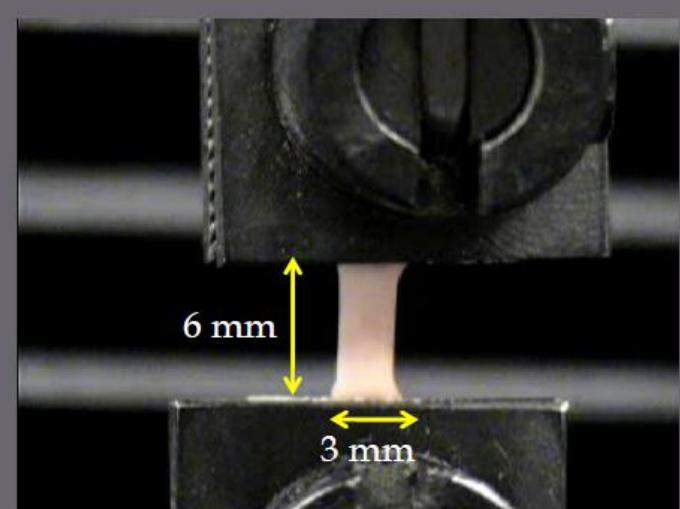
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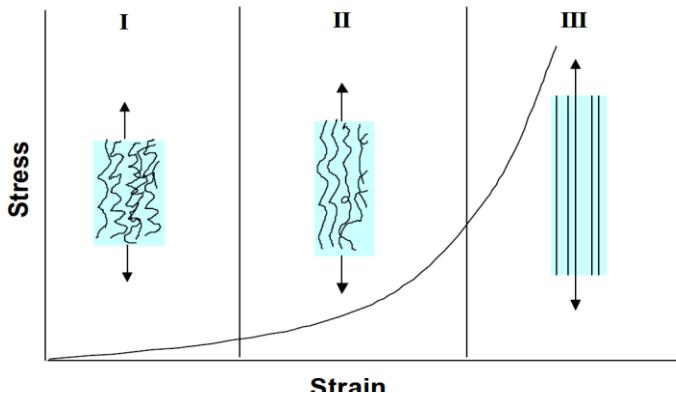
INNOVANTE PAR TRADITION



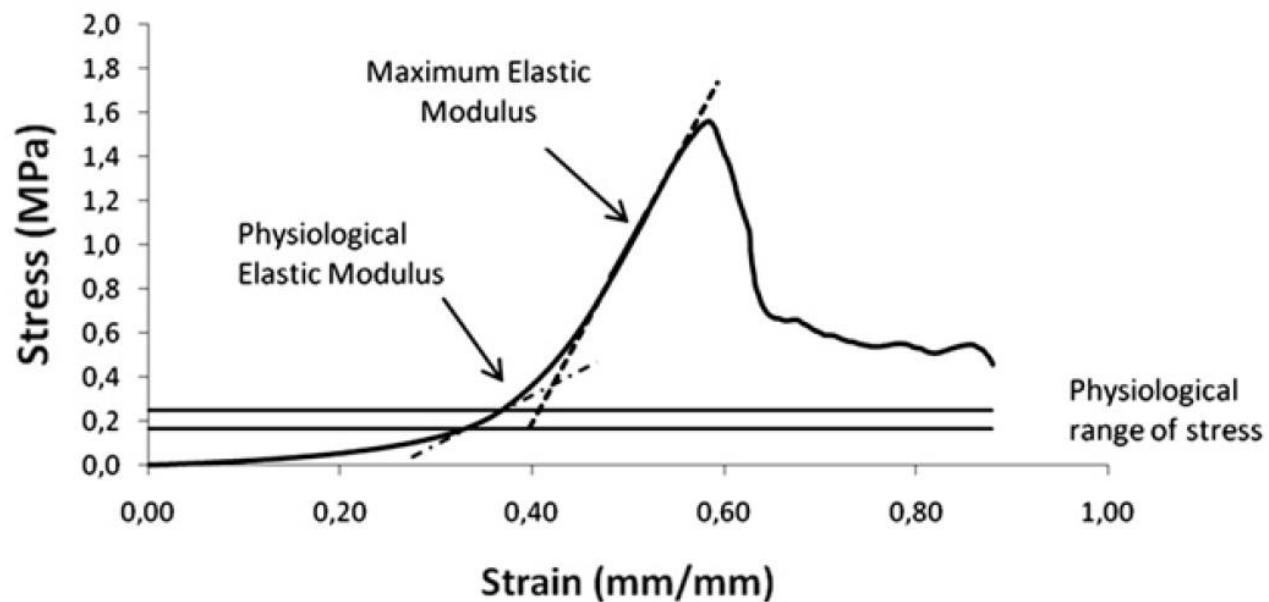
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[Duprey et. al., In-vitro characterisation of physiological and maximum elastic modulus of ascending thoracic aortic aneurysms using uniaxial tensile testing, *Eur. J. Vascular & Endovascular Surgery*, 2010]



Stress-Strain curve



Biomechanical comparison of aneurismal and healthy tissue

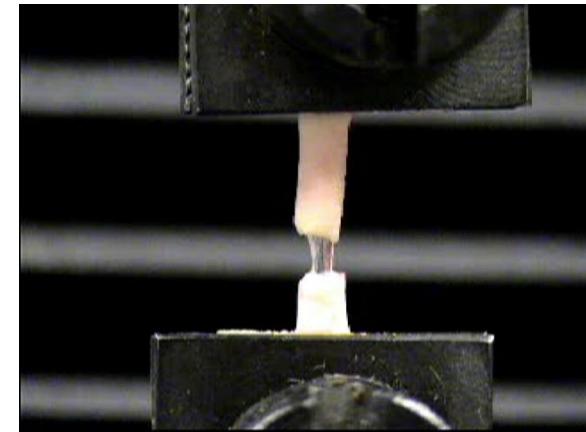
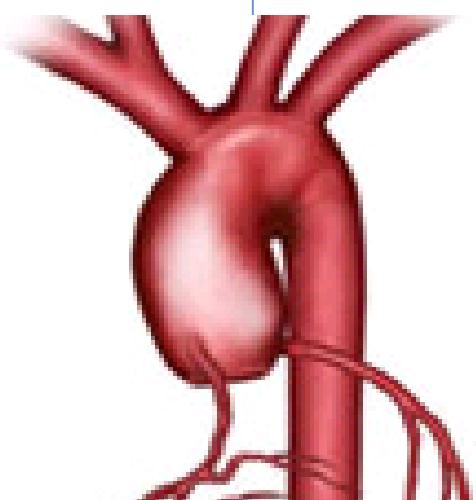
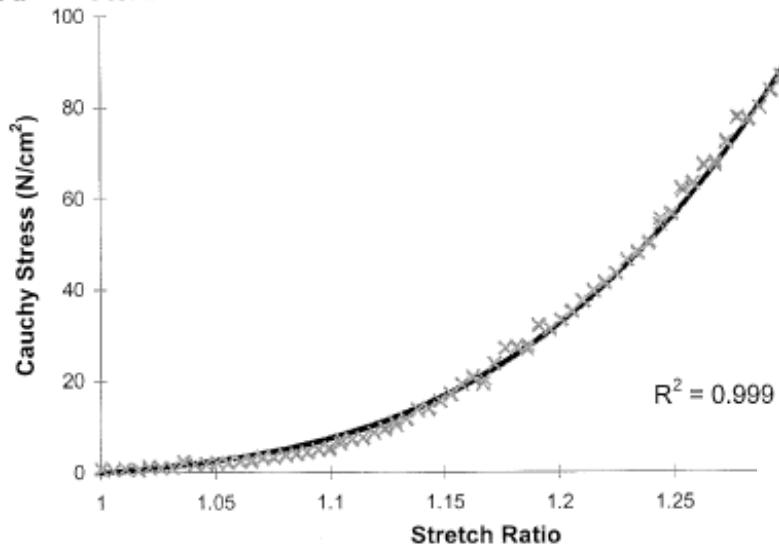
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INSPIRING INNOVATION | INNOVANTE PAR TRADITION

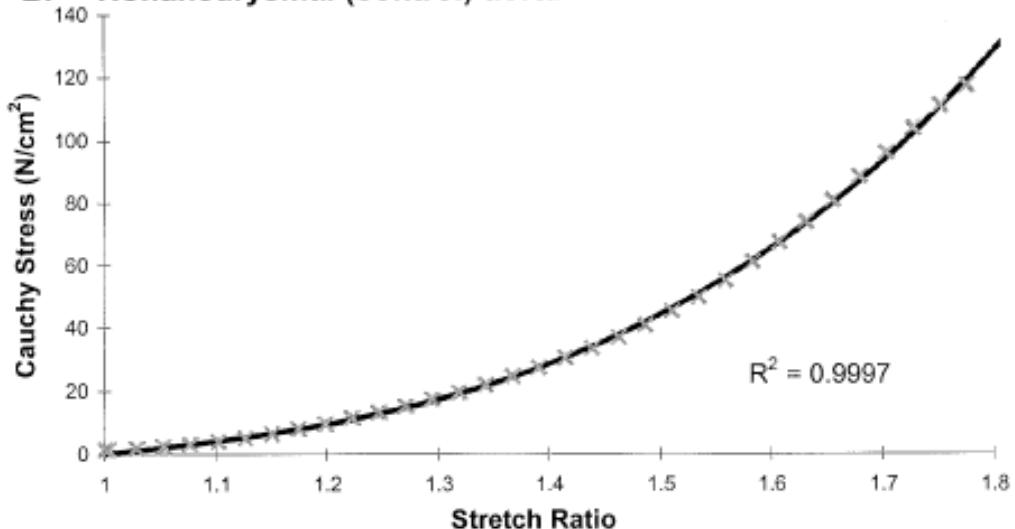


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A. ATAA



B. Nonaneurysmal (control) aorta



Vorp DA, Schiro BJ, Ehrlich MP, Juvonen TS, Ergin MA, Griffith BP. Effect of aneurysm on the tensile strength and biomechanical behaviour of the ascending thoracic aorta. Ann Thorac Surg 2003; 75(4):1210-4.

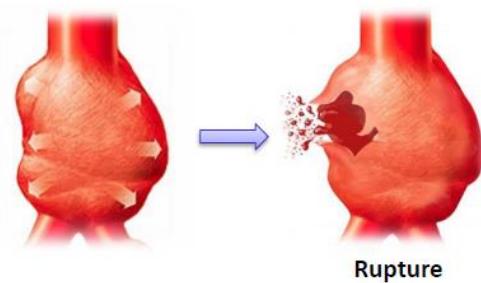
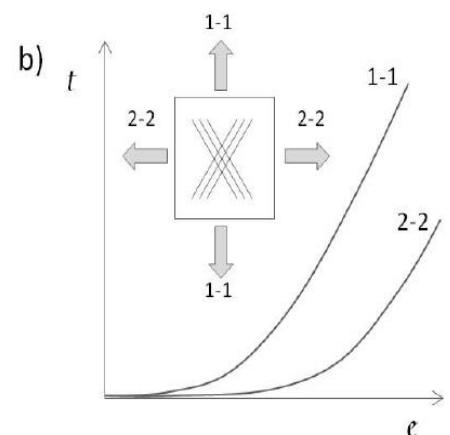
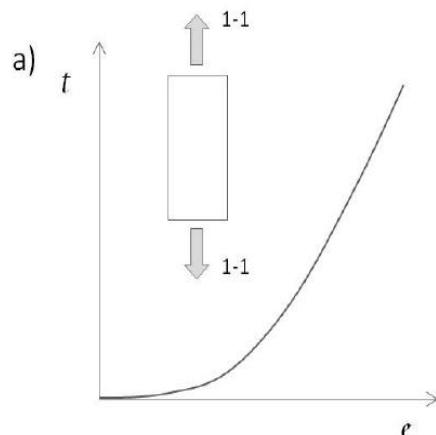
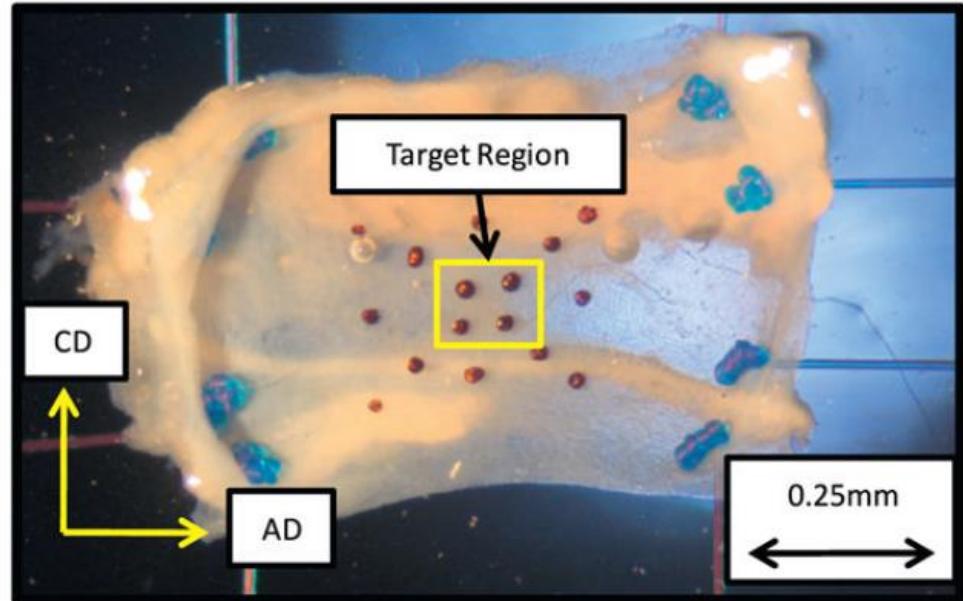
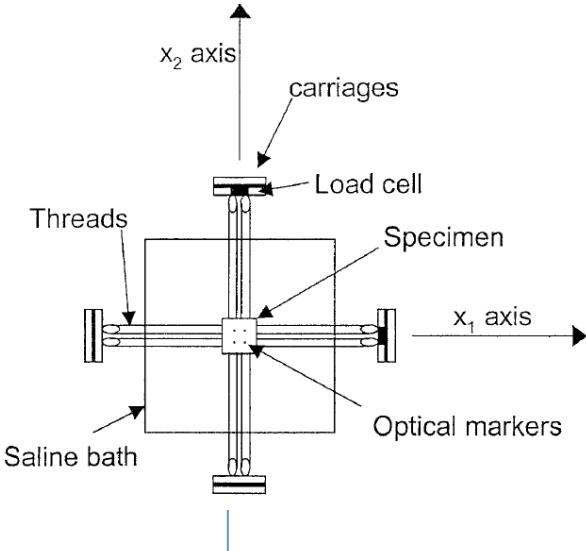
Need of biaxial tension

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Rupture

Delamination properties...

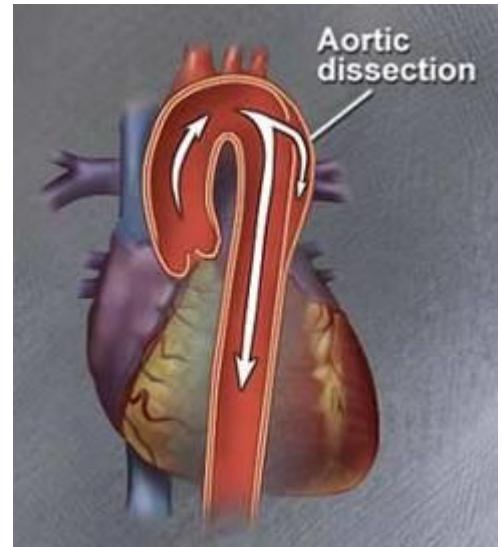
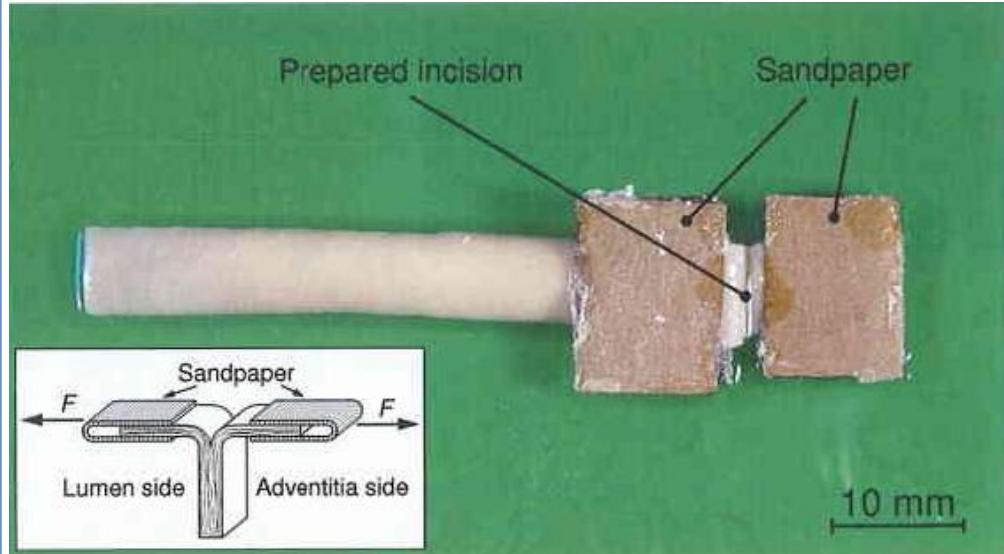


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$$W < 10 \text{ mJ/cm}^2$$

Sommer G, Gasser TC, Regitnig P, Auer M., Holzapfel G.A. Dissection properties of the human aortic media: an experimental study. ASME J Biomech Eng 2008; 130:021007.



Lack of local analyses

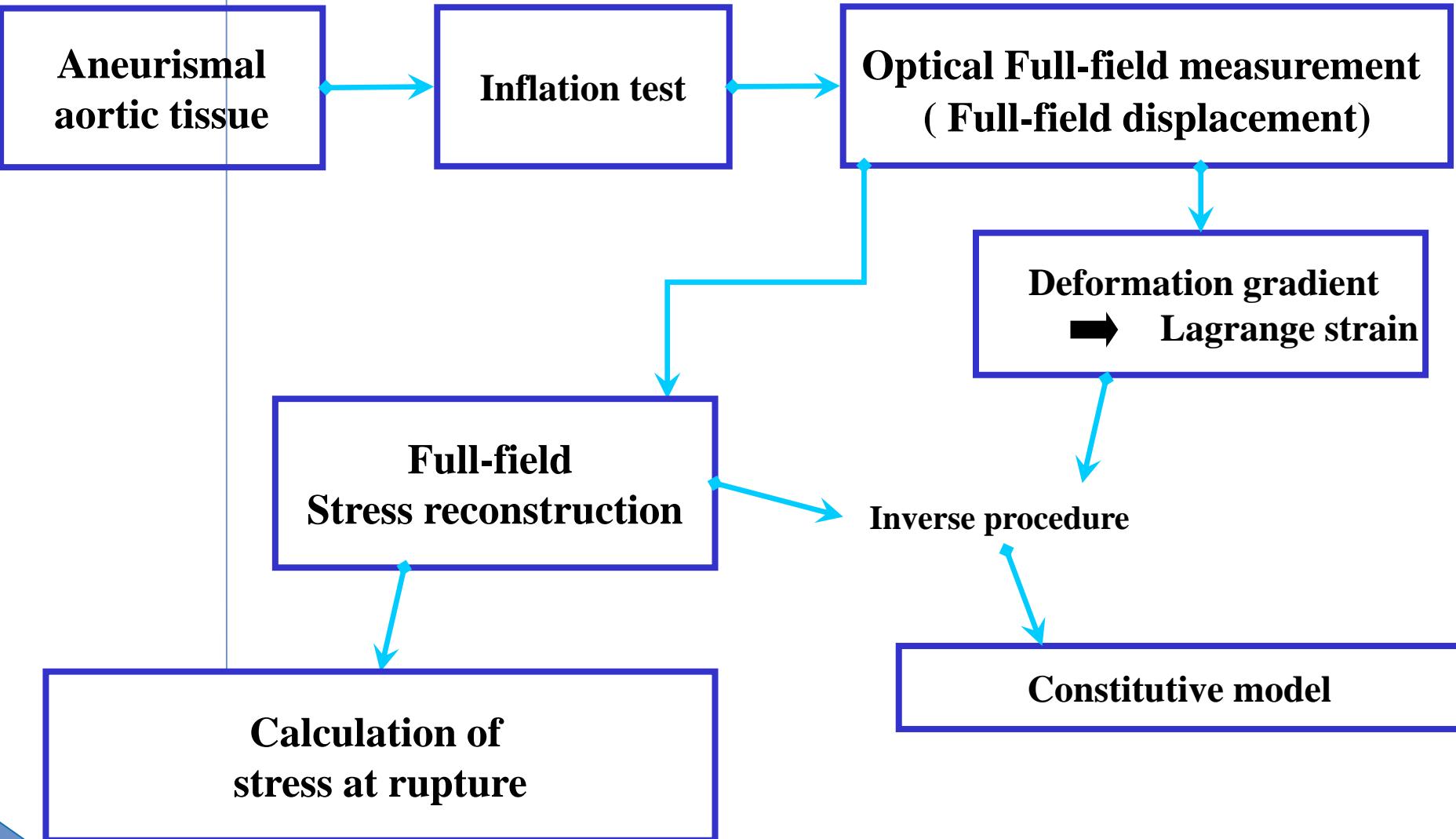
Where and how does the
rupture initiates?



MATERIALS AND METHODS

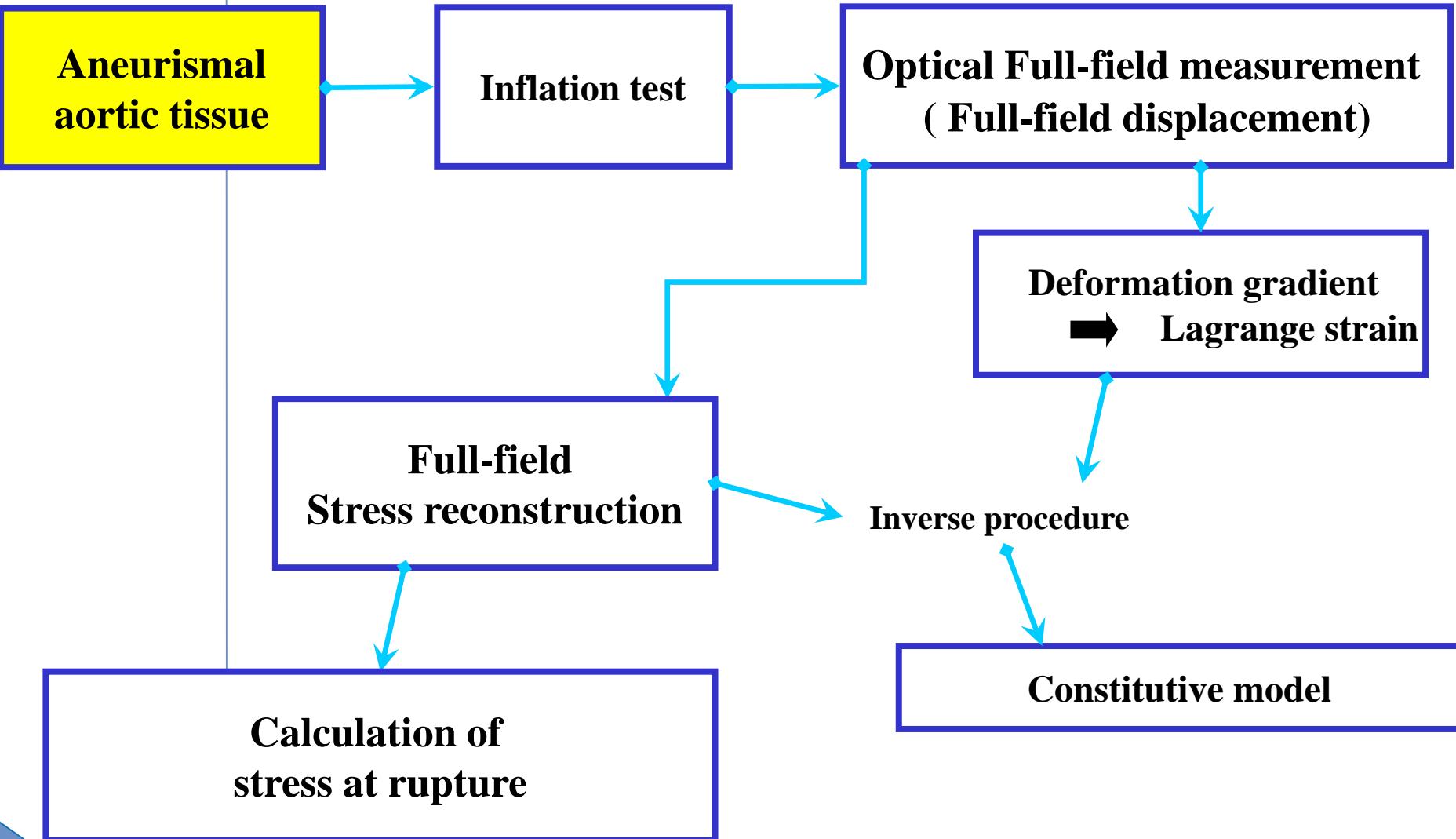


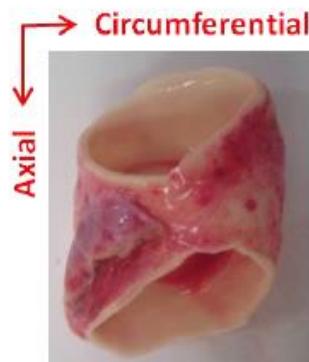
Methodology



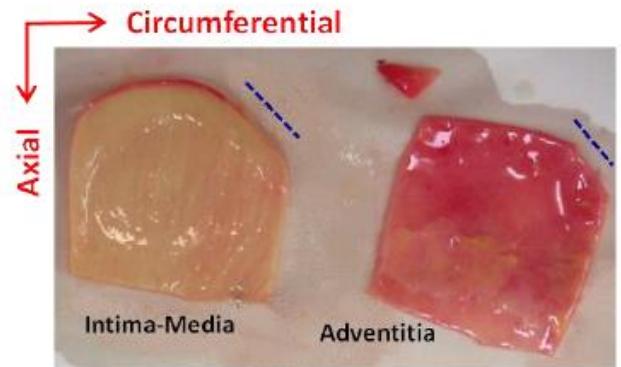


Methodology





a) Excised tissue sample.



b-i) Separated aortic layers.



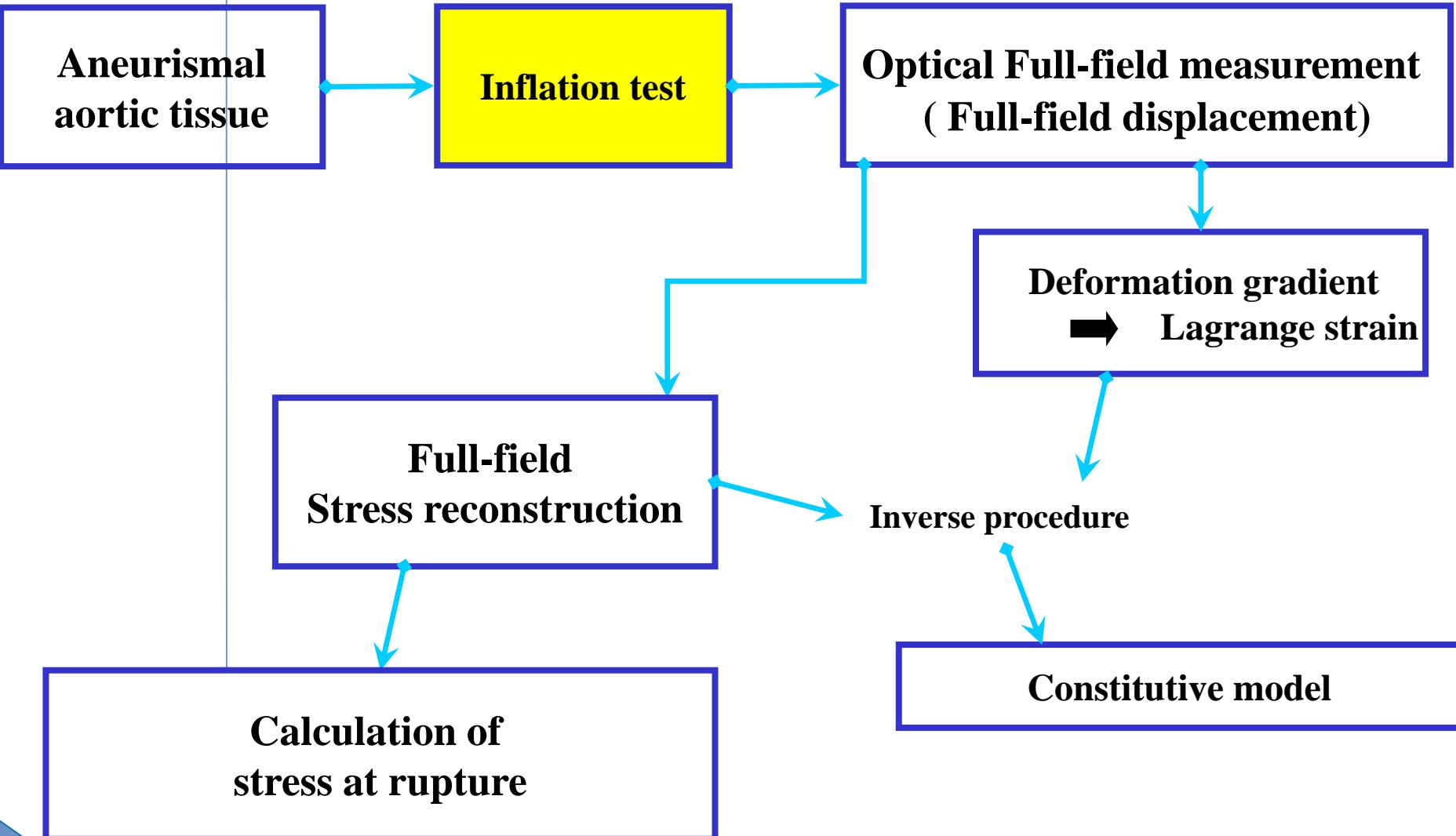
b-ii) Entire aortic layer.



c) Inflation test device. Speckle pattern is made before starting the inflation test



Methodology



Inflation test

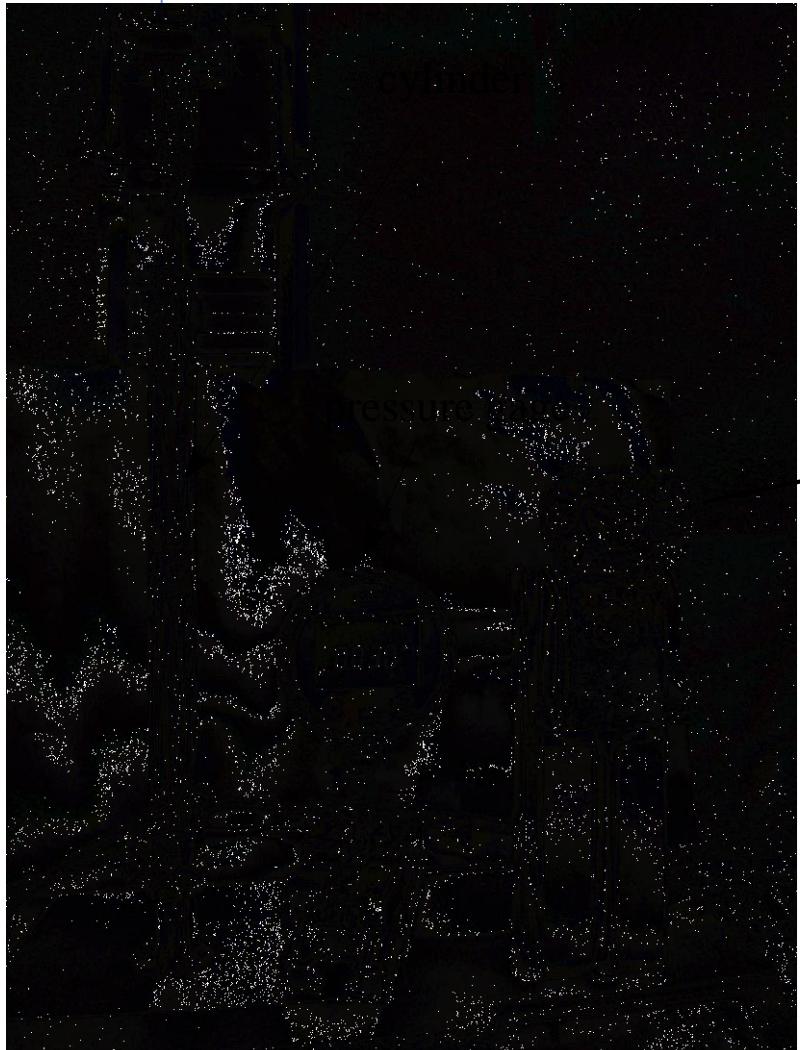
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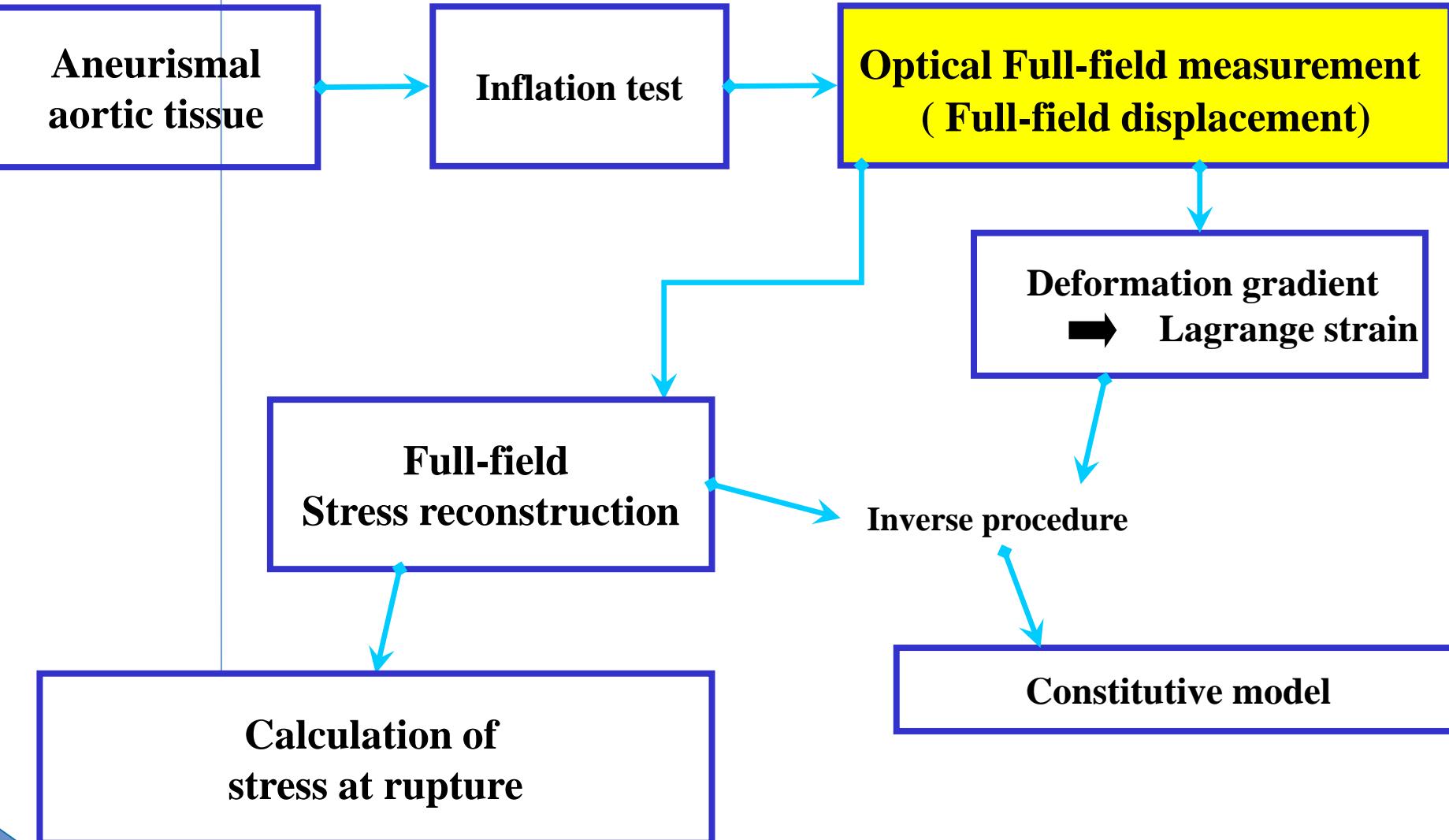
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in vivo loading environments
(biaxial stress state due to internal pressure)
can be generated

inflation device





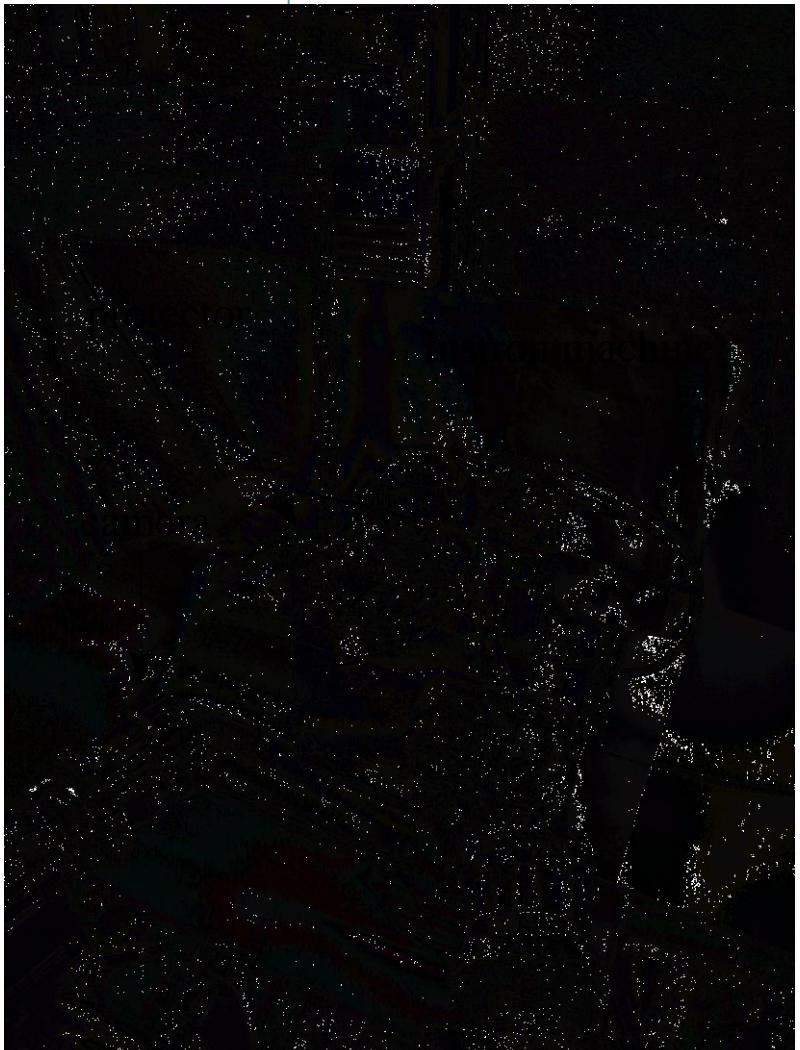
Digital image stereocorrelation

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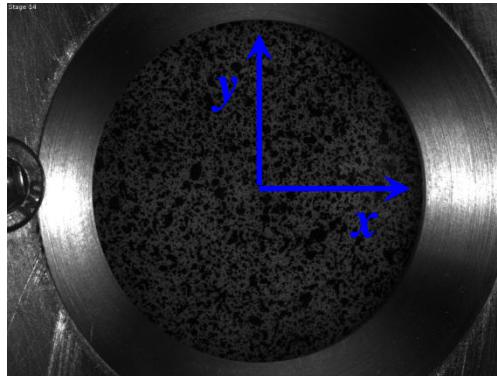
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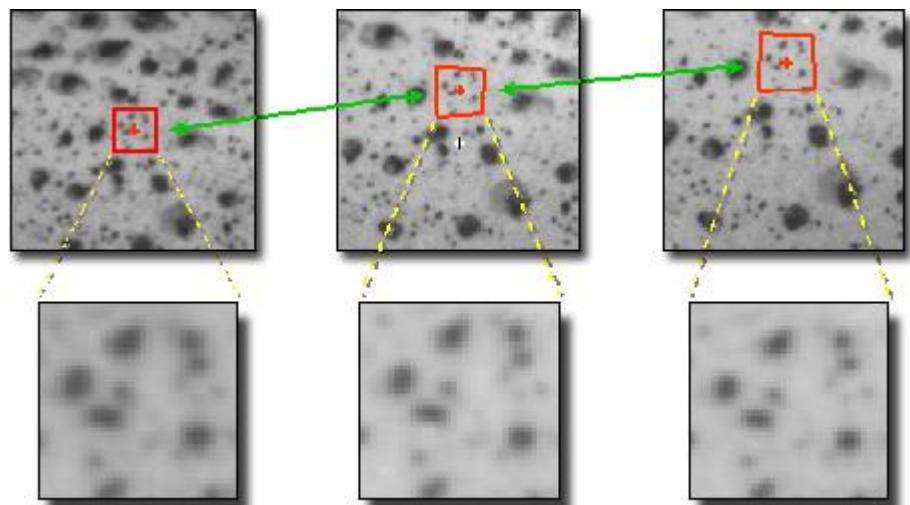
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Undeformed



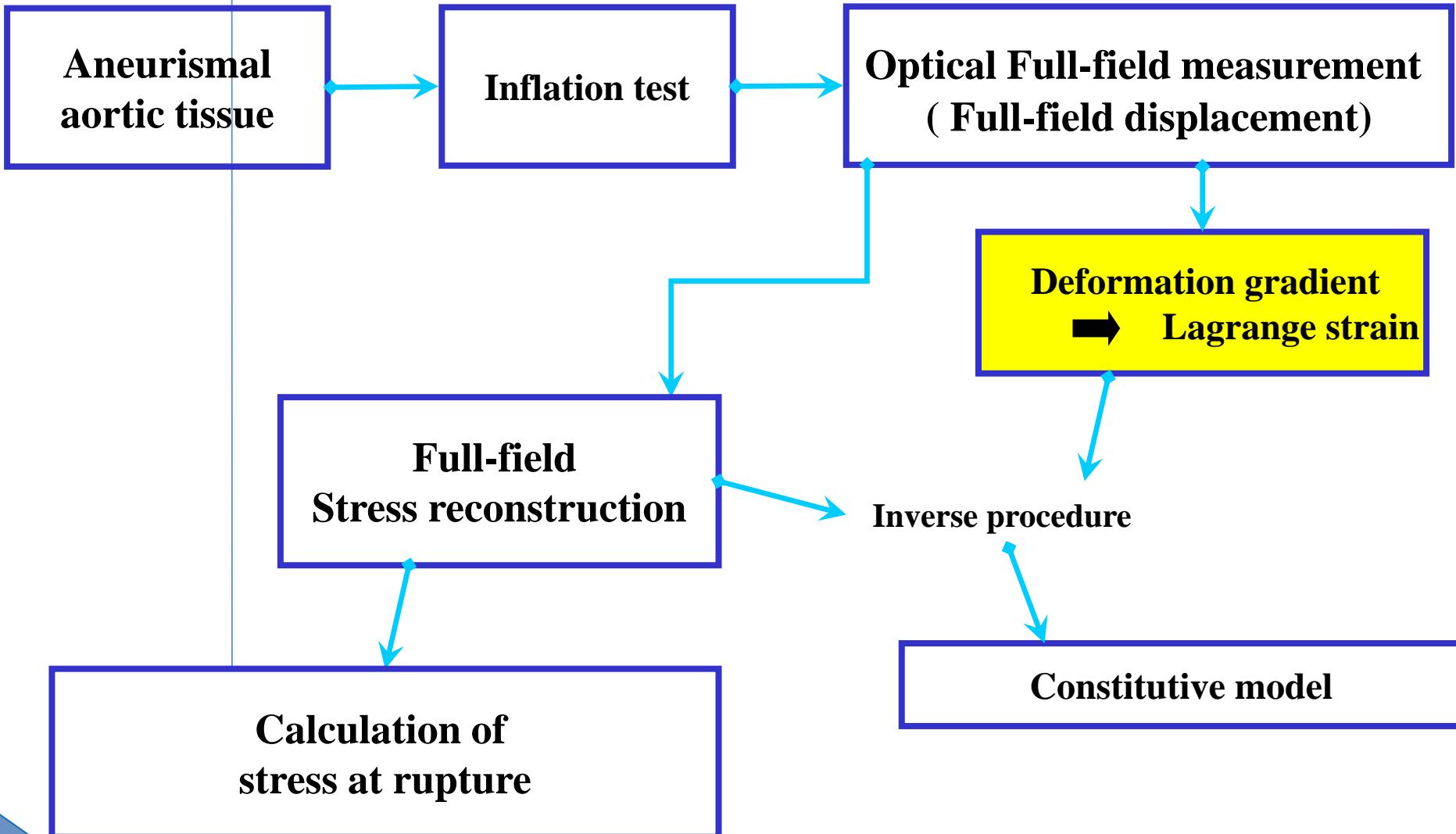
Deformed



tracks the gray value pattern
in each subset during deformation



Methodology



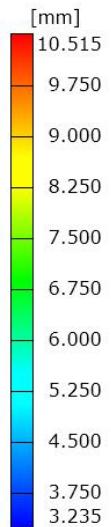
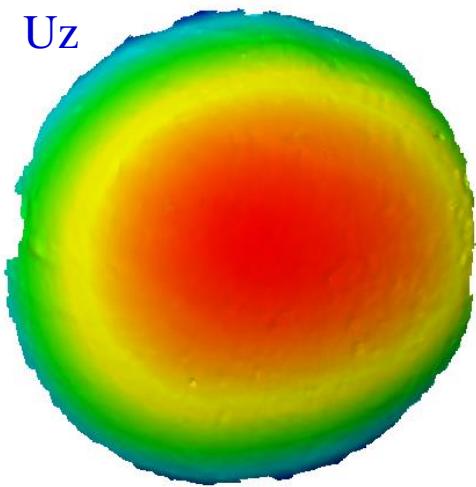
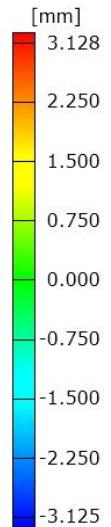
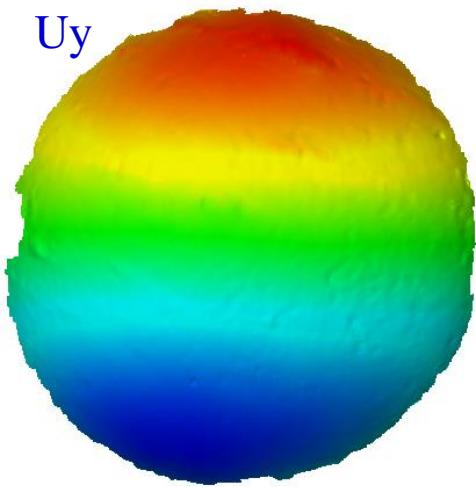
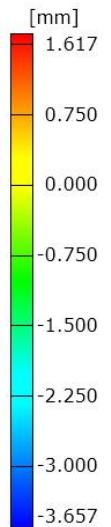
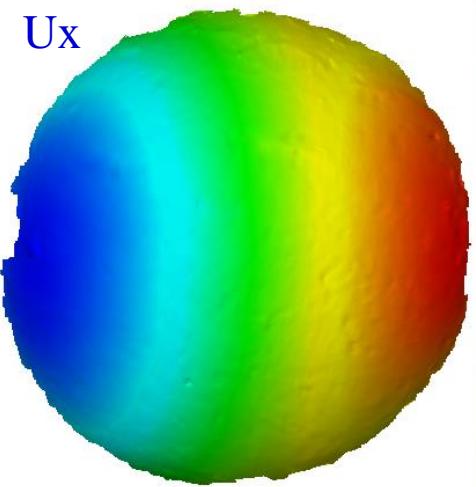
Measured displacement fields

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Theory of finite deformation

Deformation gradient F

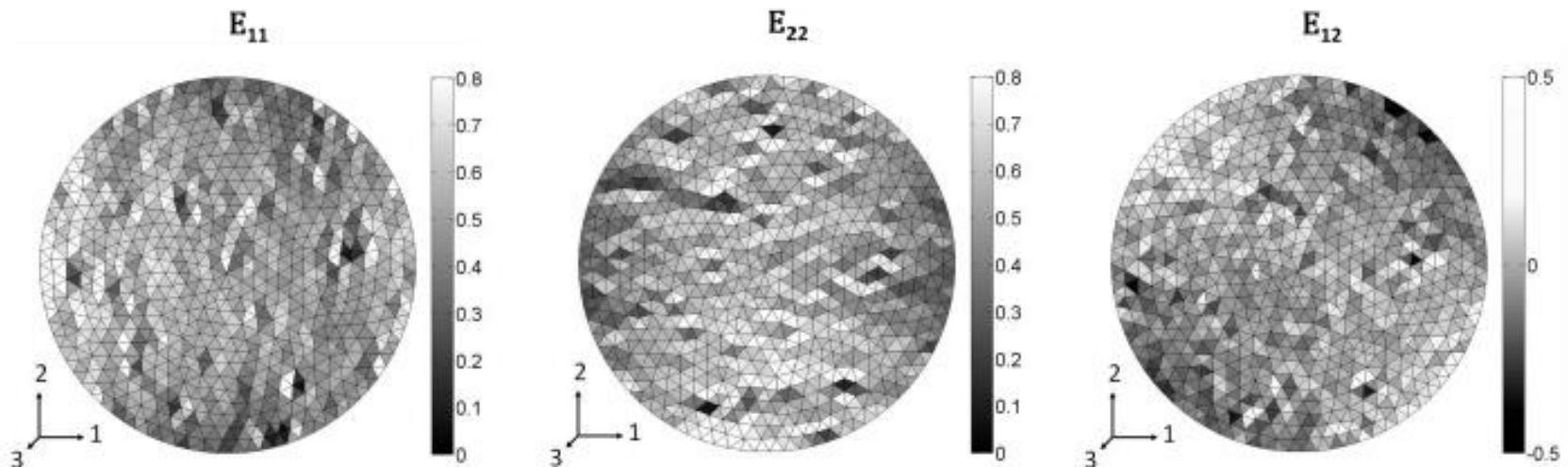
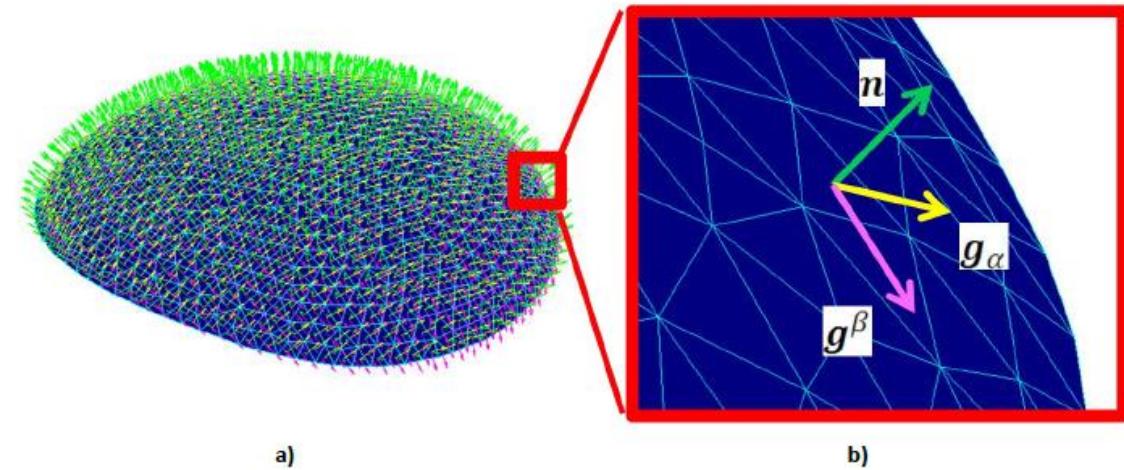
from the undeformed and deformed coordinates of each measurement data point

right Cauchy-Green tensor $C = F^T F$

Assumption: plane stress
homogeneous initial thickness
incompressibility

Green-Lagrange strain tensor $E = 1/2(C - I)$

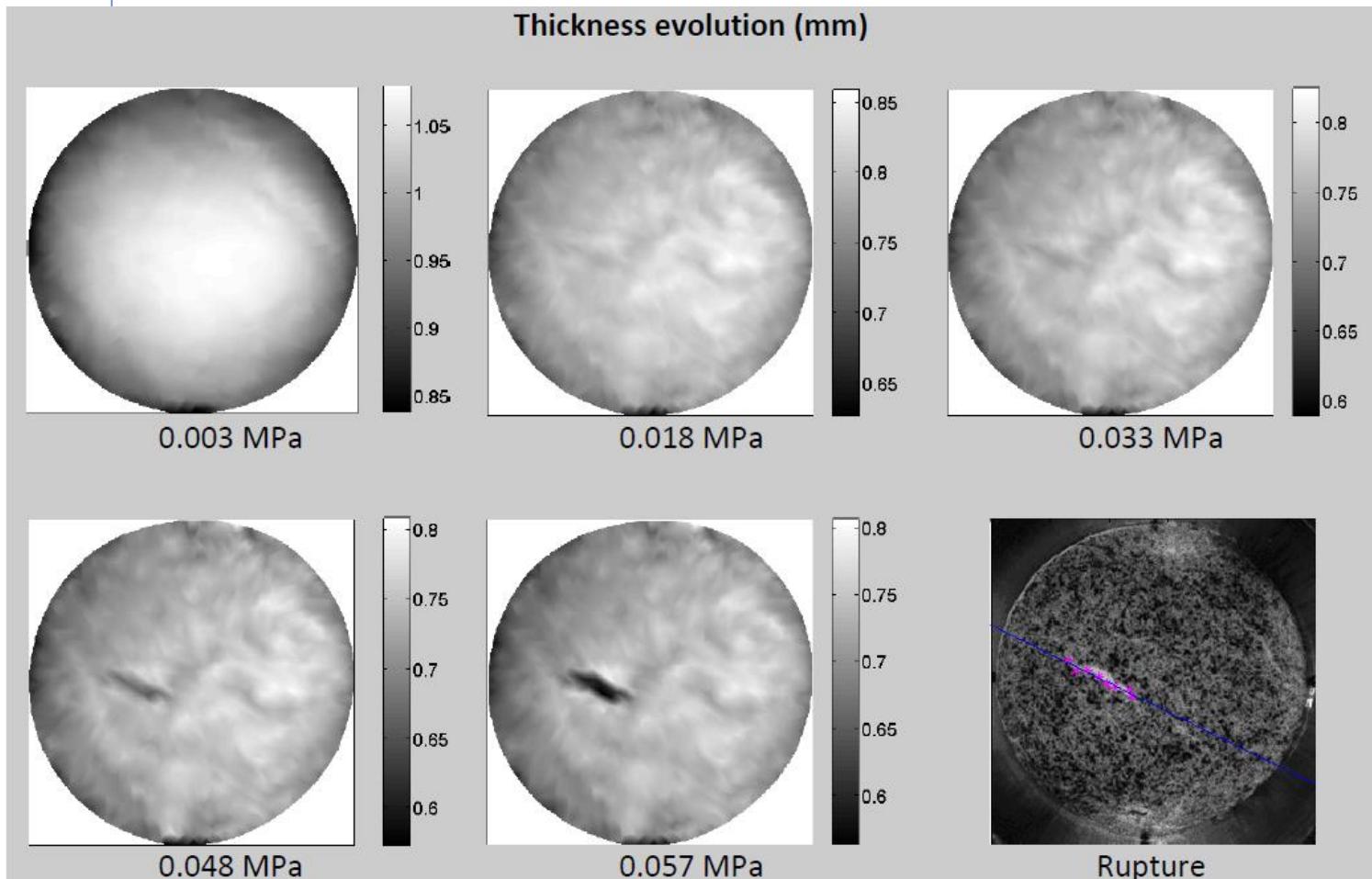
Derivation of the strain fields





Thickness evolution

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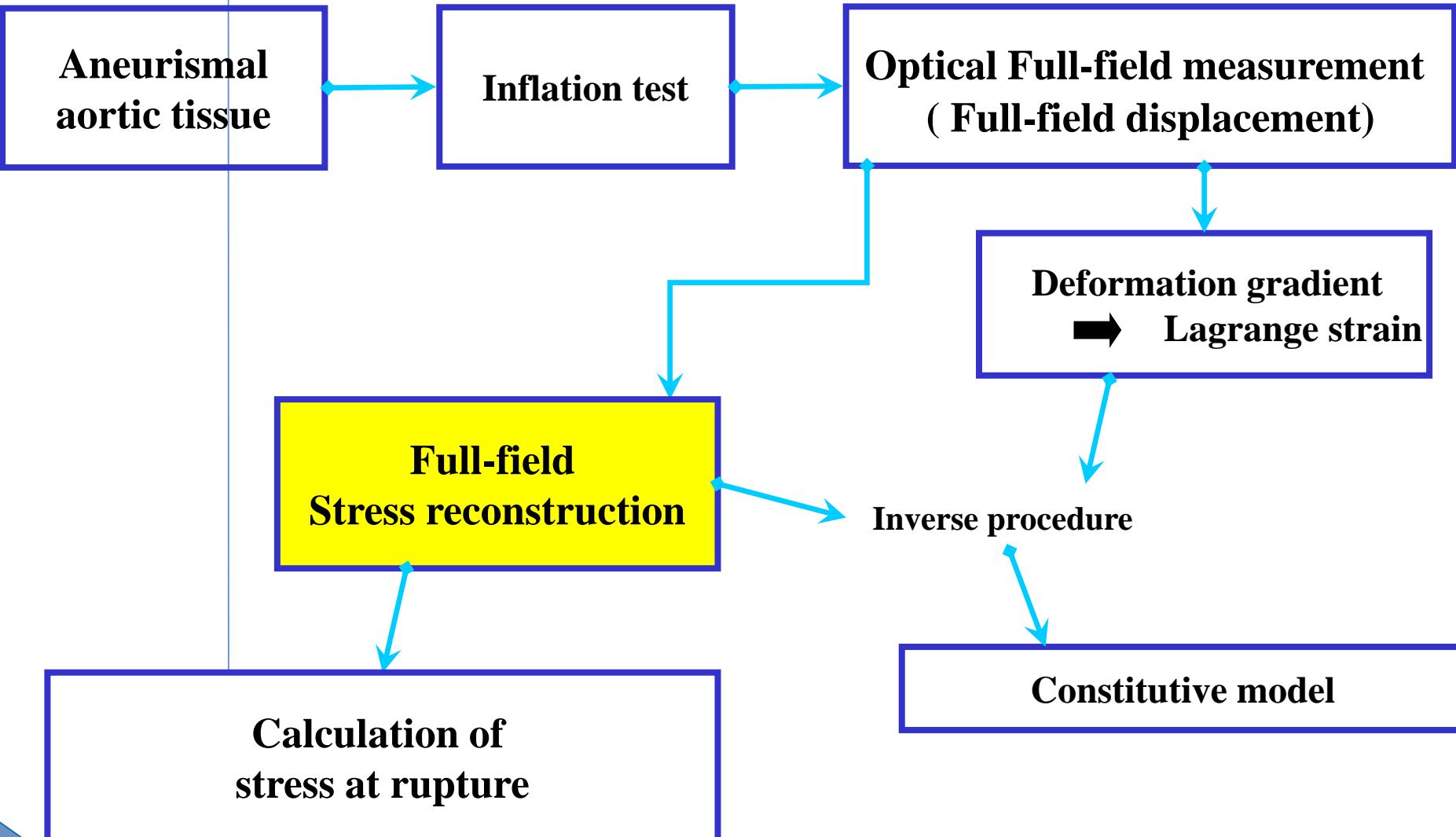


Incompressibility assumption:

$$h = \frac{h_0}{F_{11}F_{22} - F_{12}F_{21}}$$



Methodology

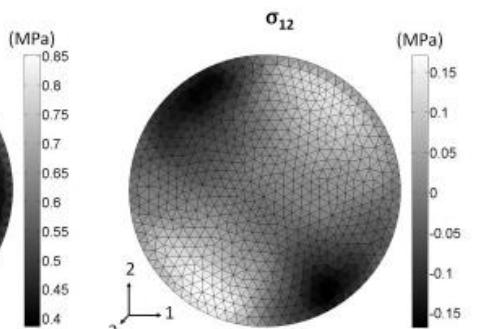
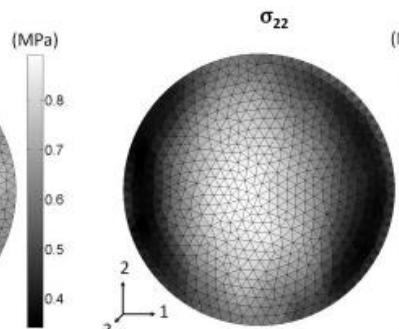
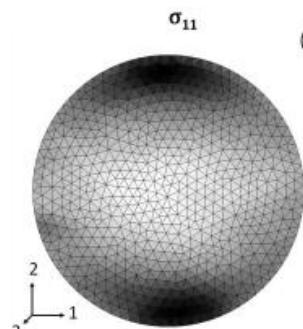
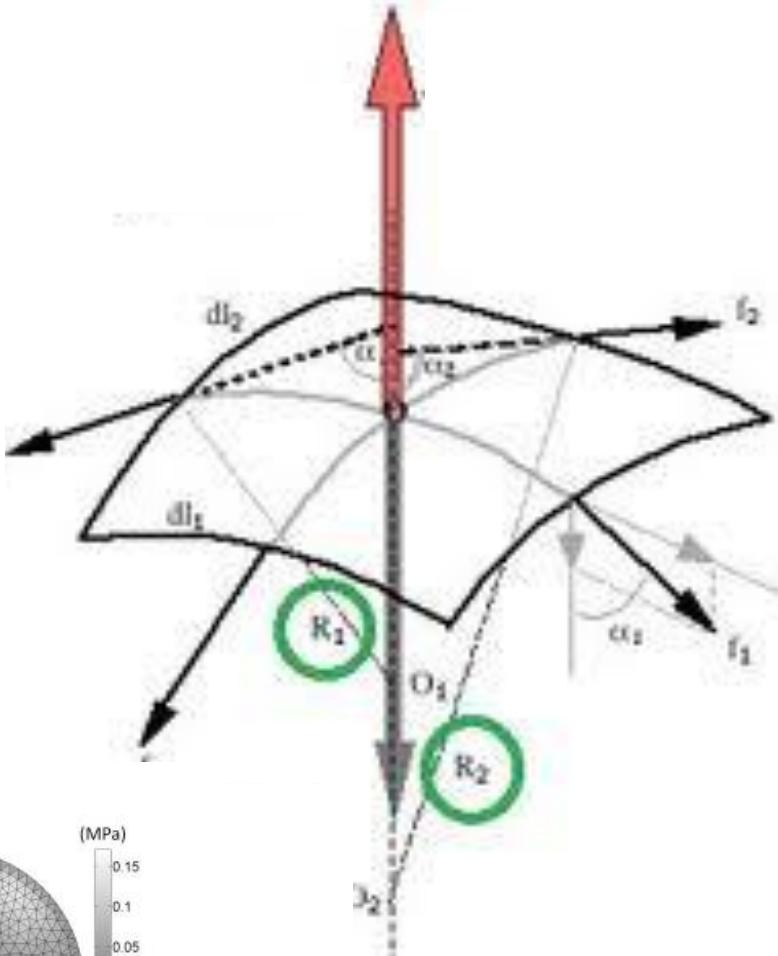
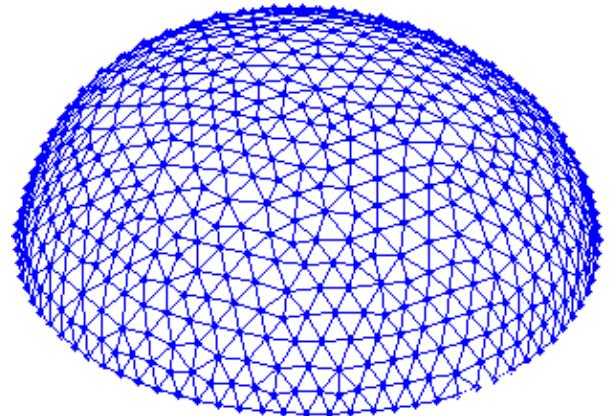




Stress reconstruction

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➤ Membrane elastostatics

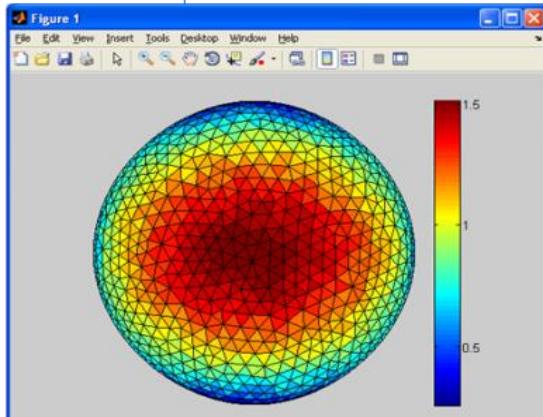


Validation

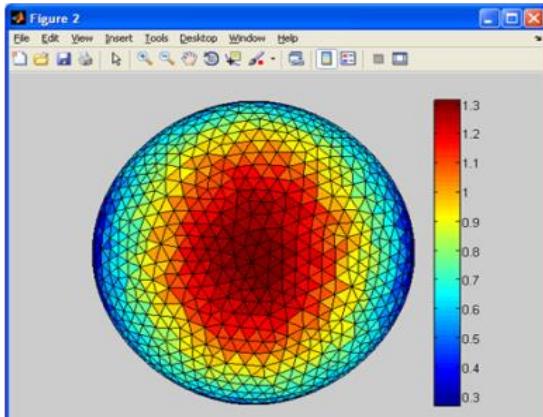


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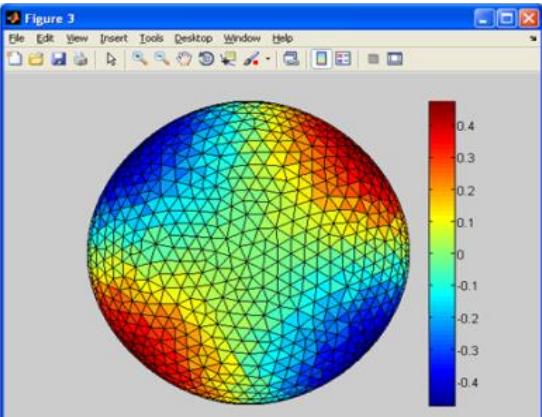
sigma_11



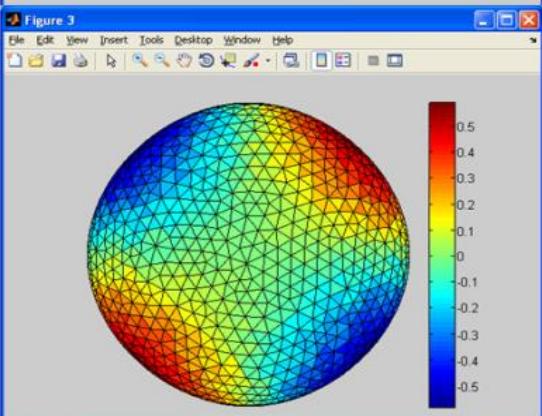
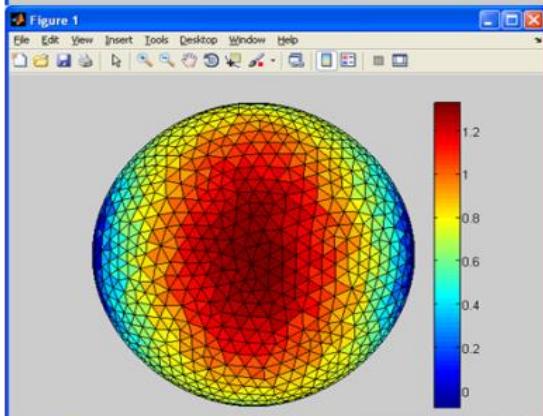
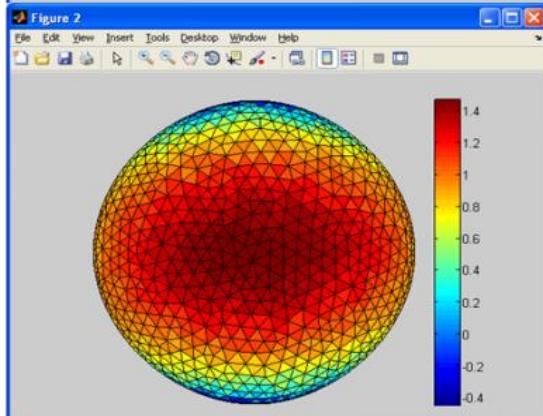
sigma_22



sigma_12



b)





Aneurismal aortic tissue

Inflation test

Optical Full-field measurement (Full-field displacement)

S. Avril, P. Badel, A Duprey. Anisotropic and hyperelastic identification of in vitro human arteries from full-field measurements. Journal of Biomechanics –2010, vol 43, N°15, pp 2978–2985.

J. Kim, S. Avril, A Duprey, JP Favre. Experimental characterization of rupture in human aortic aneurysms using full-field measurement technique. Biomechanics and Modeling in Mechanobiology, 2012.

Deformation gradient → Lagrange strain

Full-field Stress reconstruction

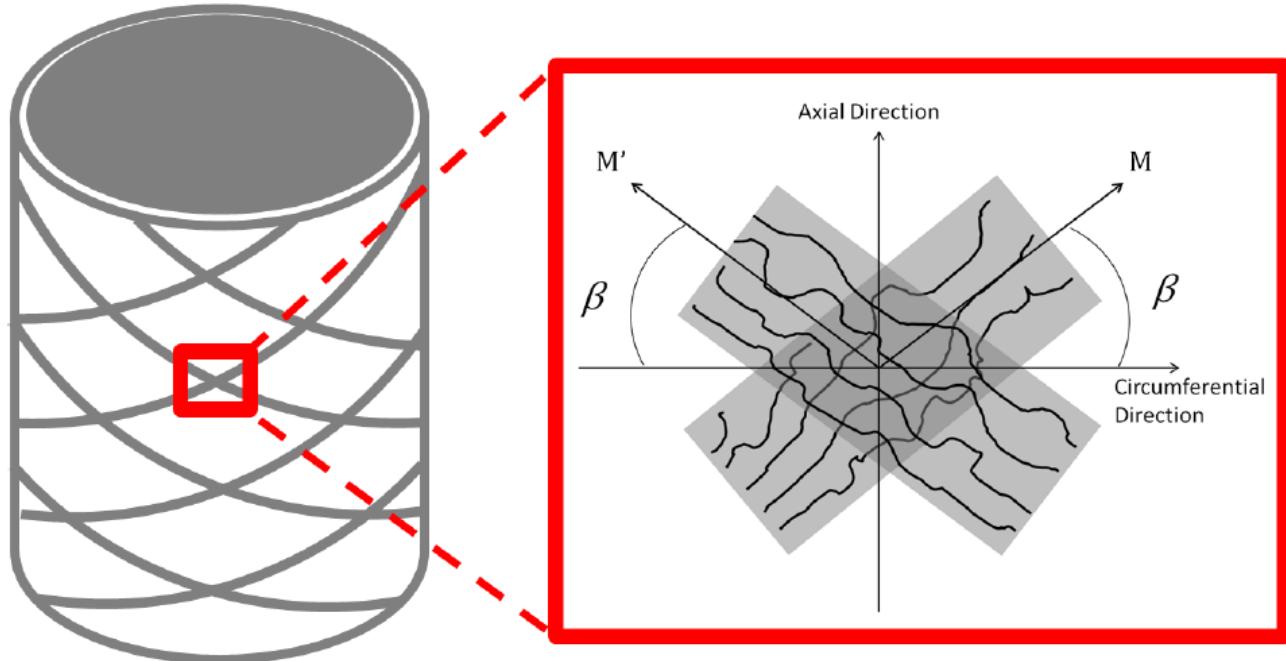
Calculation of stress at rupture

Inverse procedure

Constitutive model



Constitutive model



Incompressibility:

$$J = 1$$

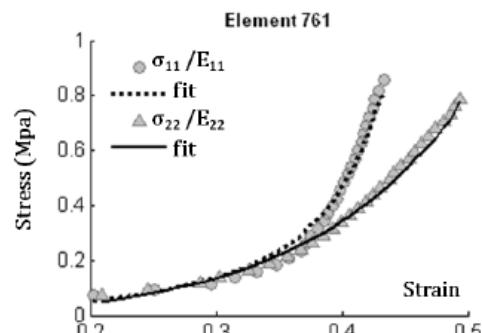
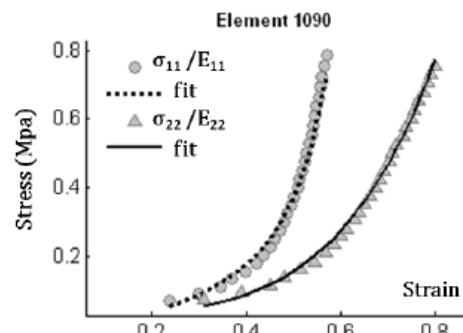
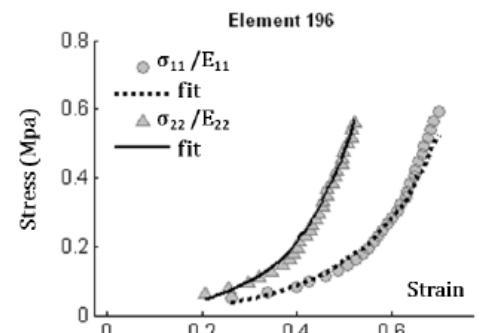
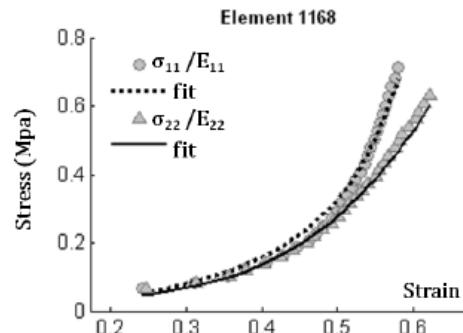
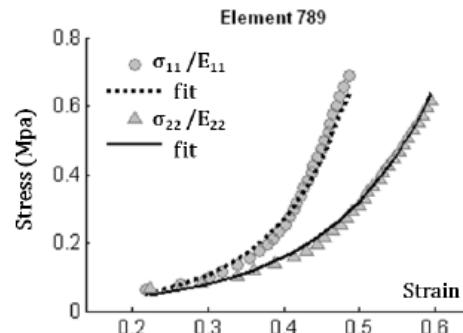
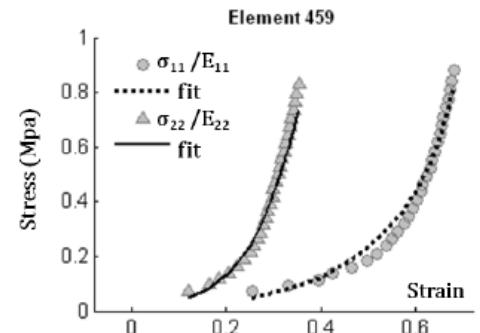
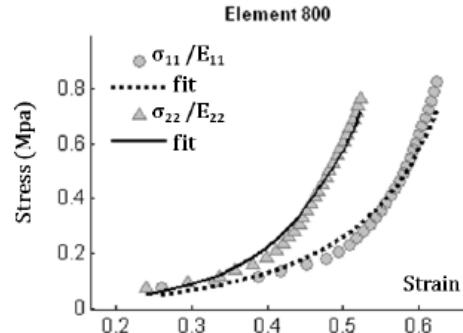
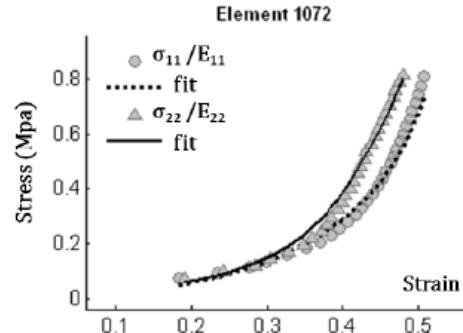
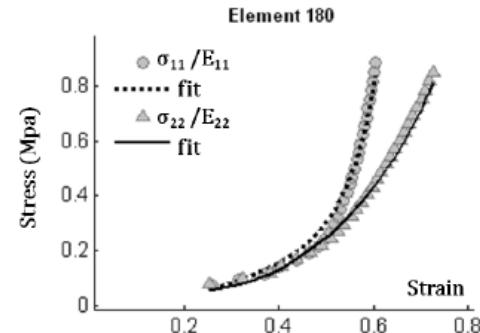
$$\Psi(I_1, I_4, I_6) = \Psi_g(I_1) + \Psi_f(I_4, I_6),$$

$$\Psi_g(I_1) = C_{10}(I_1 - 3)$$

$$\Psi_f(I_4, I_6) = \frac{\kappa_1}{2k_2} \sum_{i=4,6} \{ \exp[k_2(I_i - 1)^2] - 1 \},$$



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RESULTS



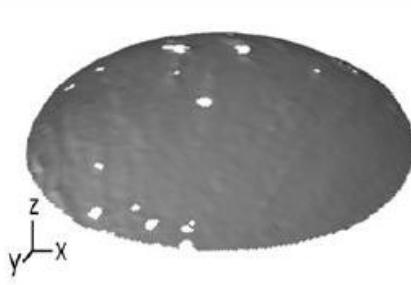
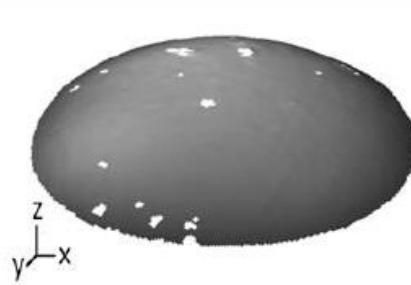
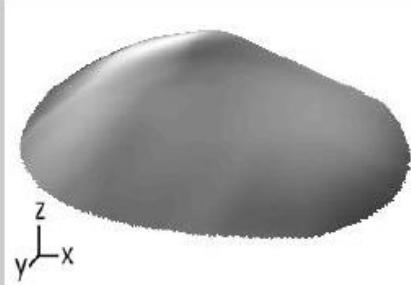
Test

I) Stress fields (σ_{11})

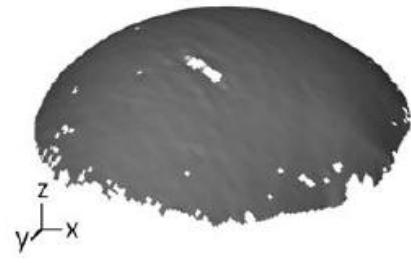
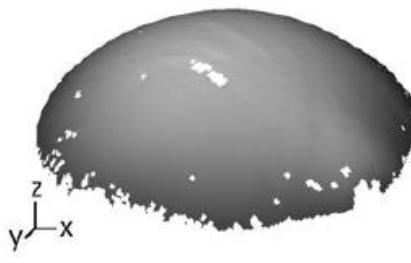
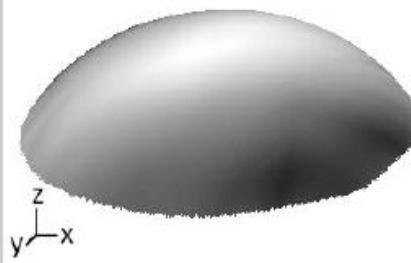
II) Displacement fields (U_z)

III) Strain Fieds (E_{22})

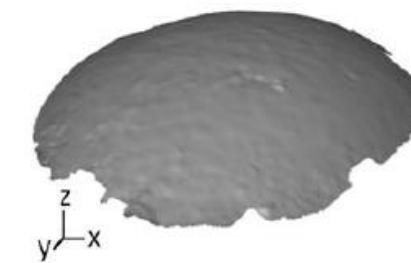
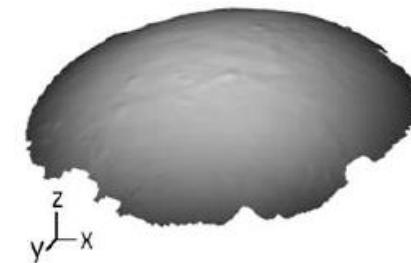
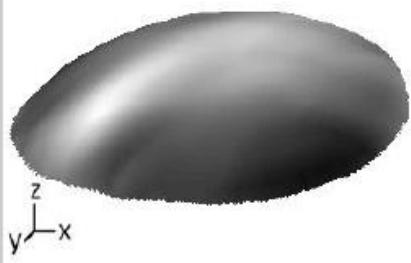
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9



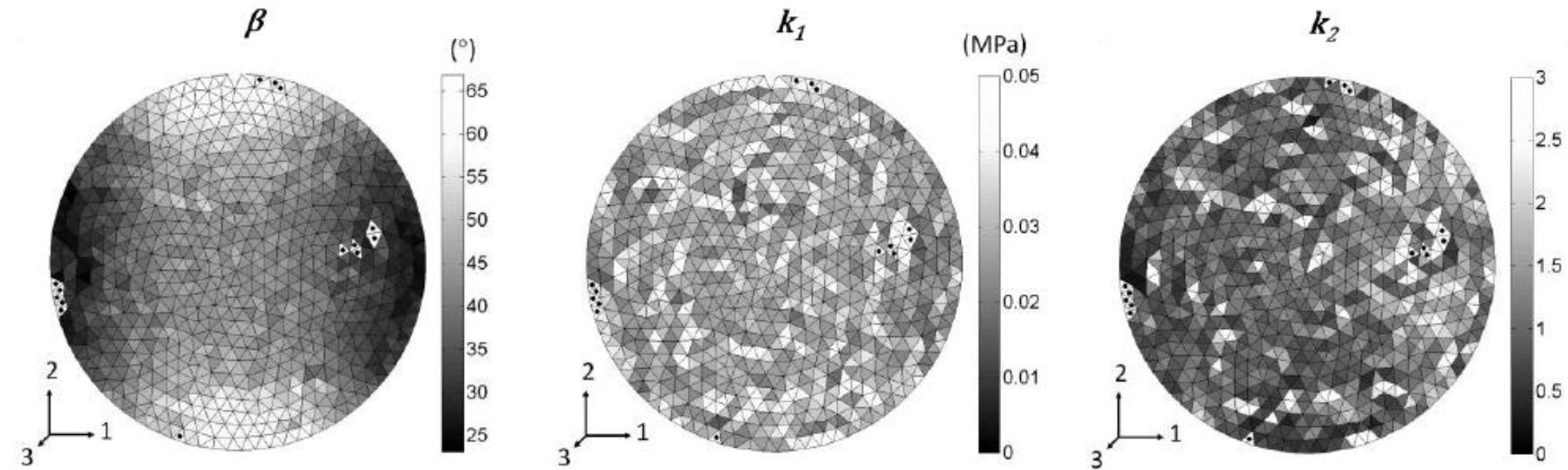
10





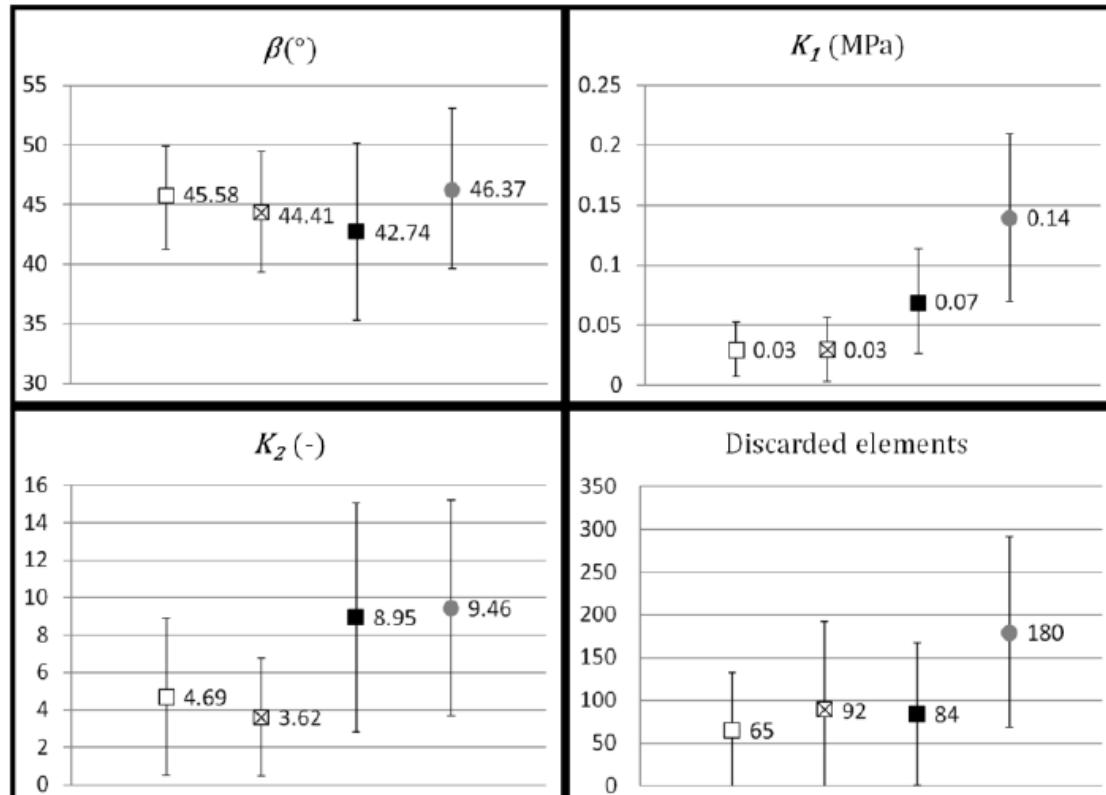
Local distribution of material properties

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Statistical analysis of the results



(14)

□ ATAA media

(24)

■ ATAA entire wall

(10)

⊗ ATAA adventitia

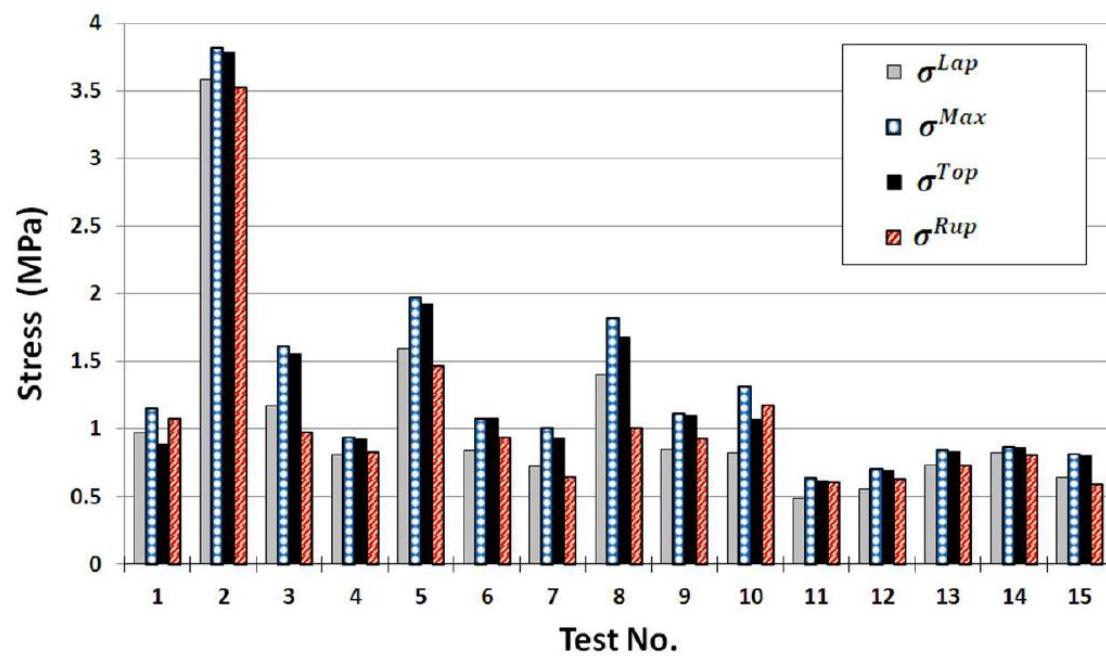
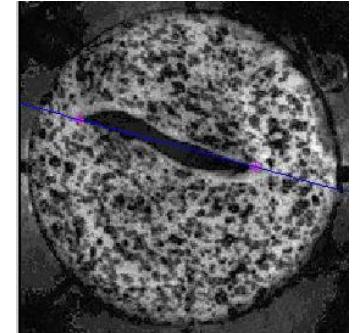
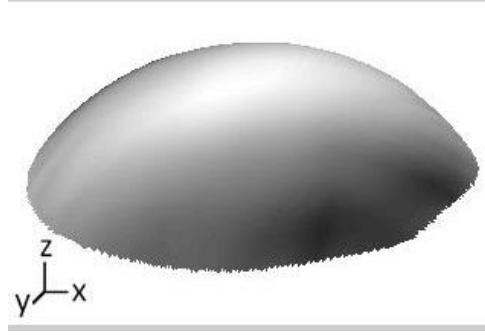
(7)

● ACC entire wall

Ultimate stresses



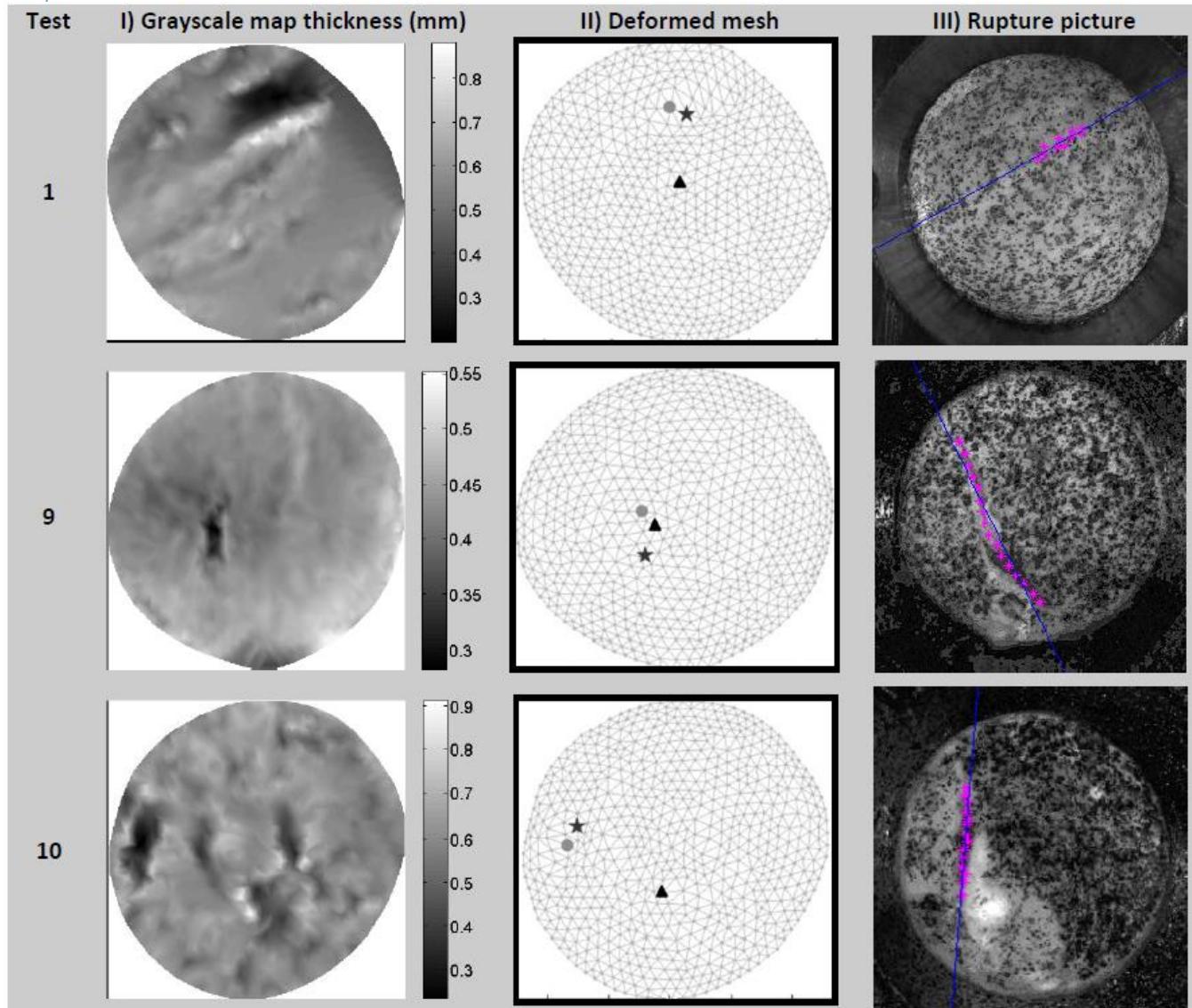
inflation device





Rupture modes

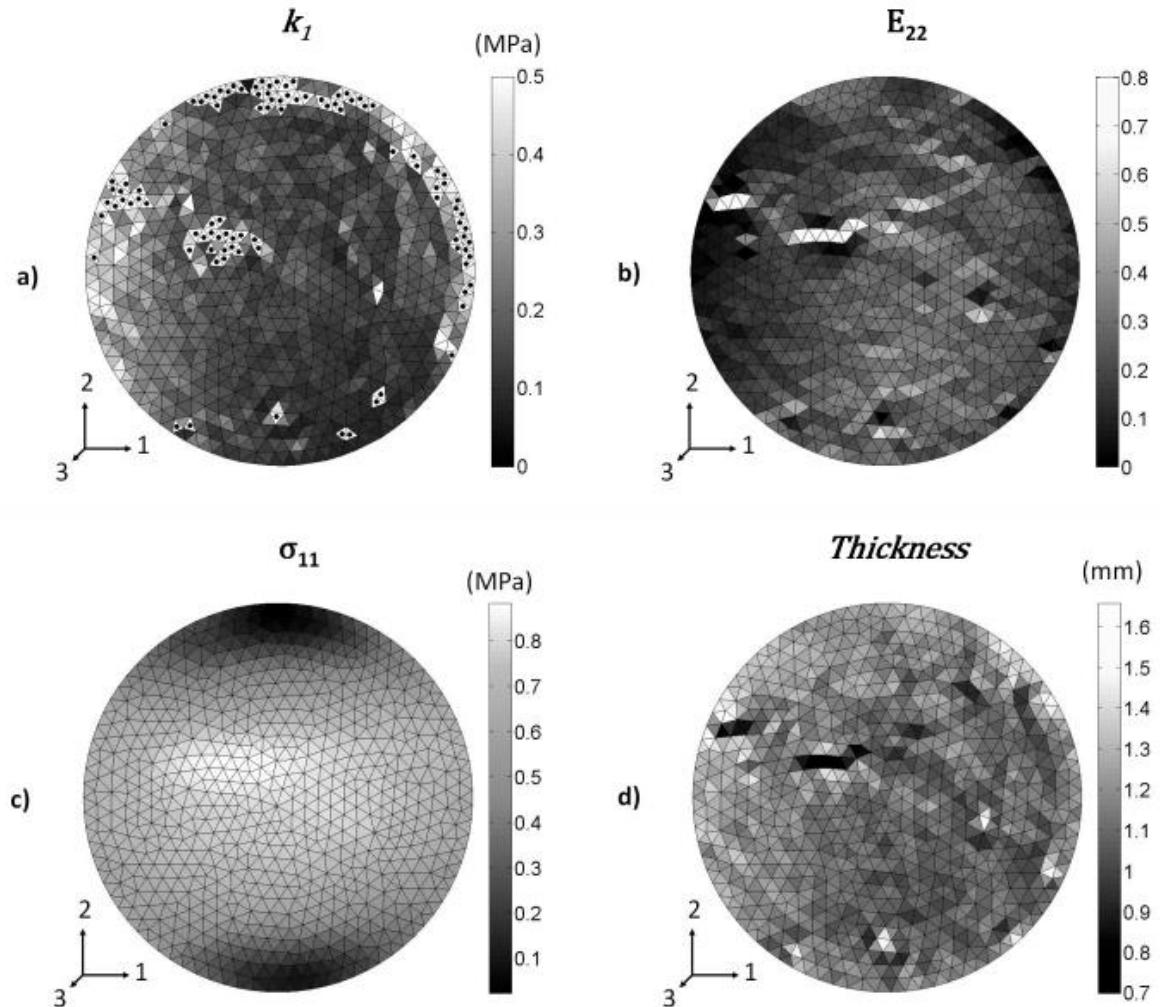
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Rupture initiation

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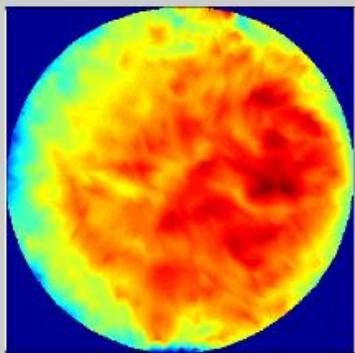
Conclusions



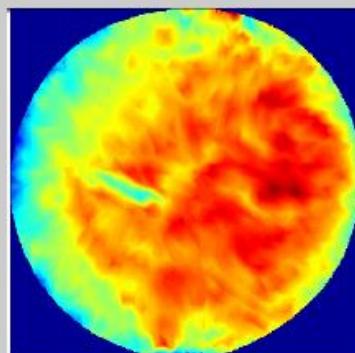
Modes of rupture???

The tissue thinning starts to localize very early before the rupture

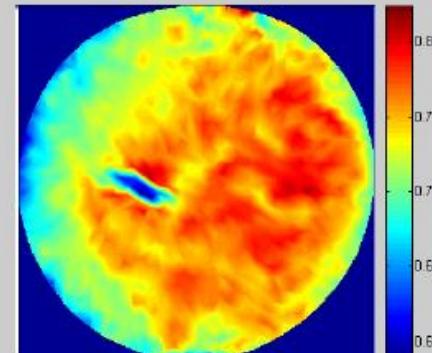
-> presence of aneslatic response in very local areas



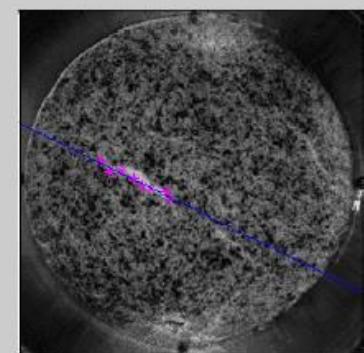
Thickness distribution at
50% of the ultimate
stress



Thickness
distribution at
70% of the ultimate
stress



Thickness distribution at
90% of the ultimate stress



Picture at rupture

Conclusions



- The strength of the tissue is heterogeneous
- Existence of weaker zones in the tissue
- Damage develops in the weaker zones
- Damage leads to rupture when the pressure increases.
- What is the microstructural specificity of the weaker zone?
- Does it affect the elastic response in the physiological domain?



- Accurate measurement of the thickness distribution
- Validity of the incompressibility assumption
- Effect of loading conditions and environment

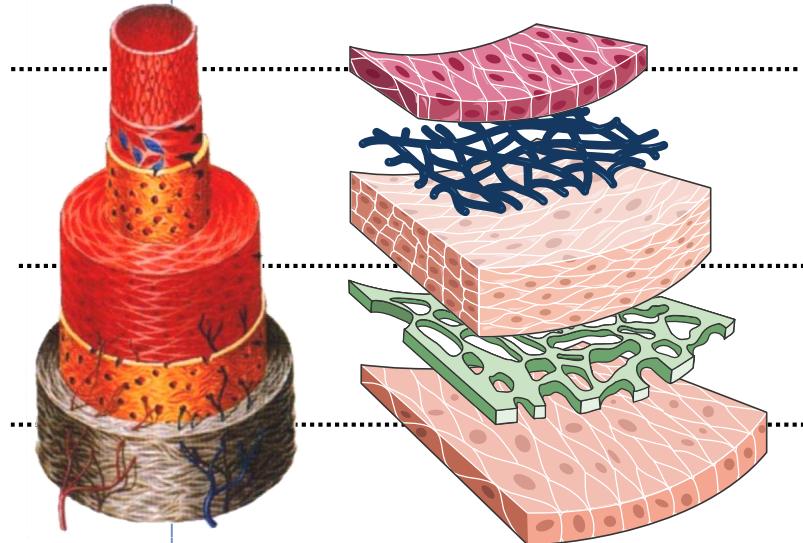




Future work



Microscopic analysis



Intima

Biologic sensor and filter

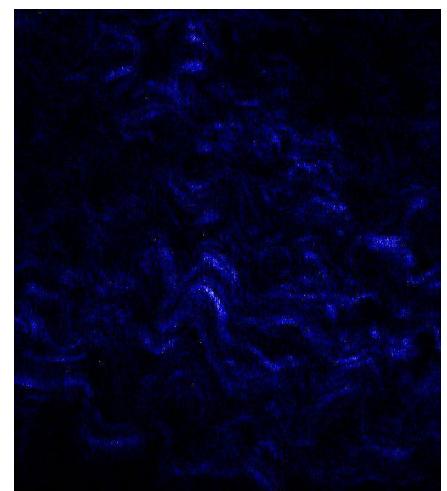
Media

Smooth muscle cells
Elastin fibers
Collagen fibers

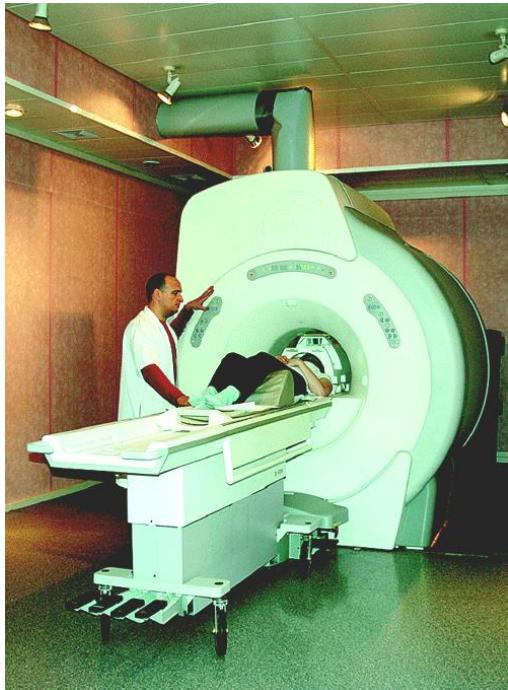
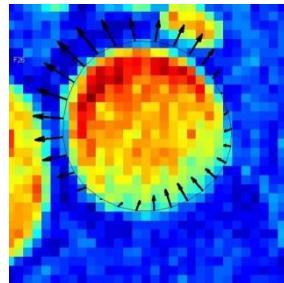
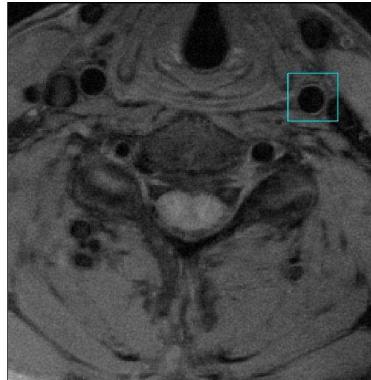
Adventitia **Collagen fibers**



Multiphoton-second harmonic generation (MP-SHG) microscope
600x



In vivo imaging



S. Avril, F. Schneider, C. Boissier, ZY Li. In vivo velocity vector imaging and time-resolved strain rate measurements in the wall of blood vessels using MRI. *Journal of Biomechanics*, 2010, 44(5) pp 979–983.

US elastography



