INSPIRING INNOVATION | INNOVANTE PAR TRADITION

Yale

Ecole Nationale Supérieure des Mines SAINT-ETIENNE

CHU CENTRE HOSPITALIER UNIVERSITAIRE SAINT-ÉTIENNE

Centre for Biomedical and Healthcare Engineering
LGF CNRS UMR 5307

Prof. Stéphane Avril

Pointwise identification of material properties in soft biological tissues and applications to thoracic aneurysms

MINISTÈRE DE L'ÉCONOMIE DES FINANCES ET DE L'INDUSTRIE

Where do I come from?

LYON-SAINT-ETIENNE

Historical site

Founded in 1816

- Created by Royal Decree in 1816
- Graduate & Post-graduate School of Engineering
- Ranked in the top ten French engineering schools (out of 240)
- French Ministry of Industry
- Mission:
  - Contribute to companies' competitiveness
  - Educate highly qualified managers with strong technical and scientific skills
  - Develop applied research to meet the needs of industry

- 1,570 students, 15% foreign students
- 4 campuses
- 175 PhD students
- 415 publications per year
- 5 research laboratories
  - Chemical engineering
  - Material sciences
  - Mathematics and computer science
  - Microelectronics
  - Biomedical and healthcare engineering

Center for Biomedical and Healthcare Engineering

Centre Ingénierie et Santé

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

Research topics

Healthcare engineering

Soft tissue biomechanics and prosthesis

Biomaterials and inhaled nanoparticles

23 permanent staff

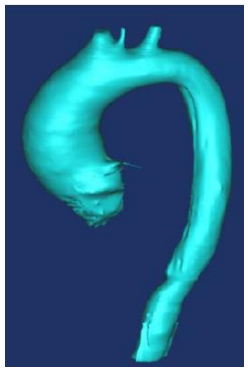
37 postgraduate students and postdocs

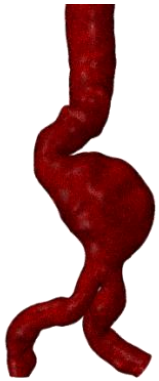
Personalized medicine

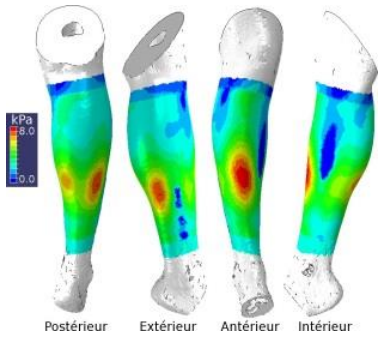
Prevention

Biomechanics of soft tissues

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



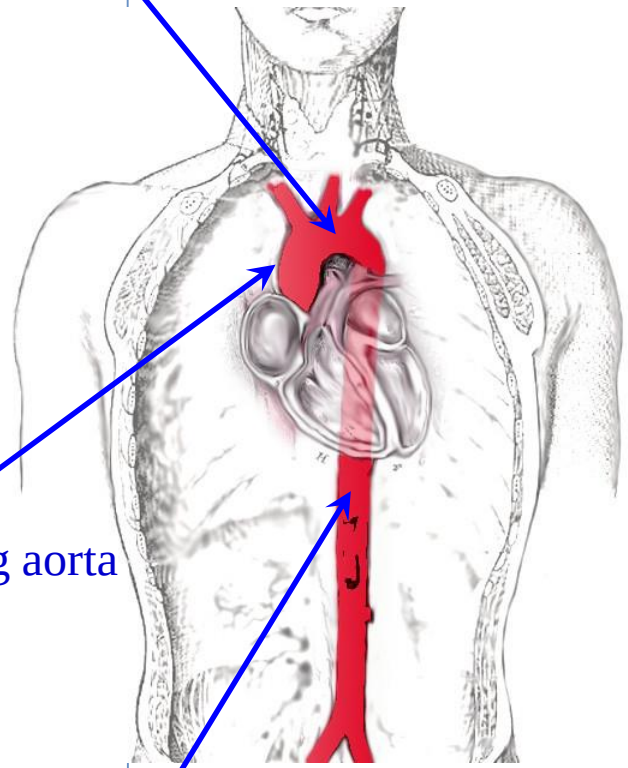




Recent contribution to ATAA biomechanics

Aortic aneurisms

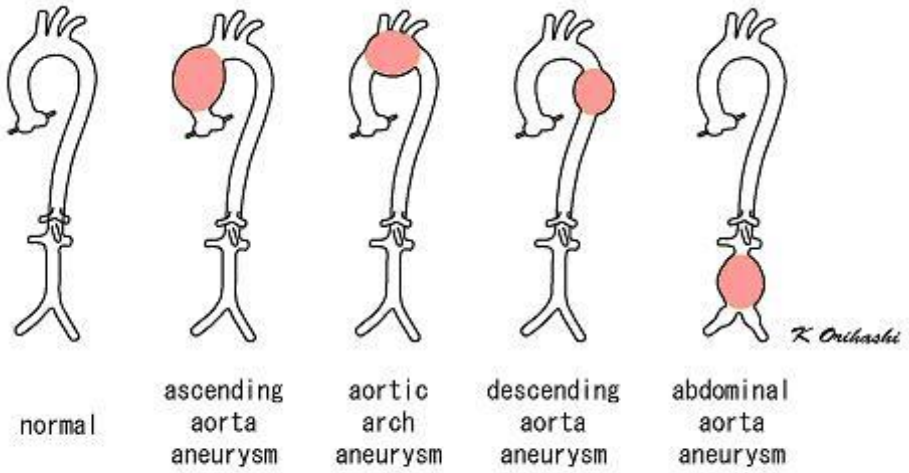
arch of aorta



ascending aorta

descending aorta
(thoracic aorta and abdominal aorta)

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



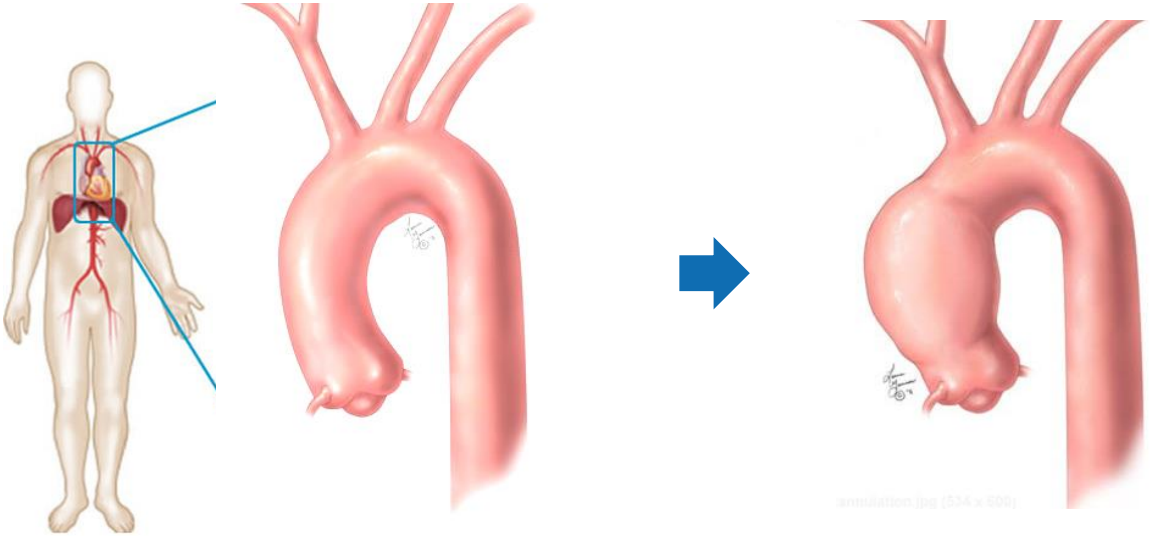
Various aortic aneurysms

➡ aneurysm rupture

➡ a fatal medical emergency

Ascending thoracic aortic aneurysm (ATAA):

"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)*



Healthy Ascending Thoracic Aorta

Ascending Thoracic Aortic Aneurysm (ATAA)

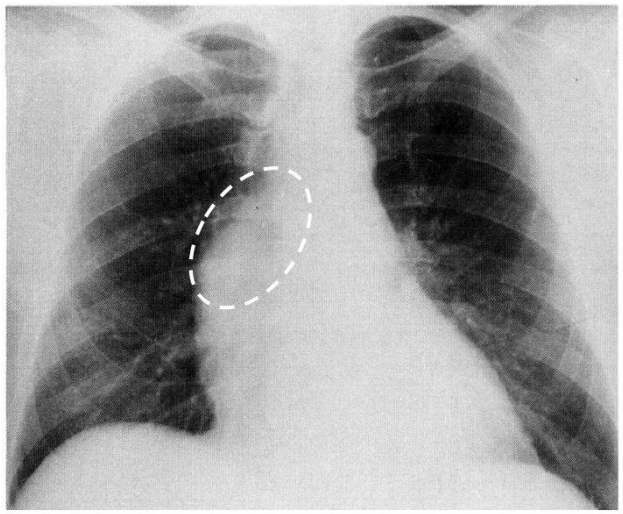
(http ://www.ucaorta.org)

Major public health issue:

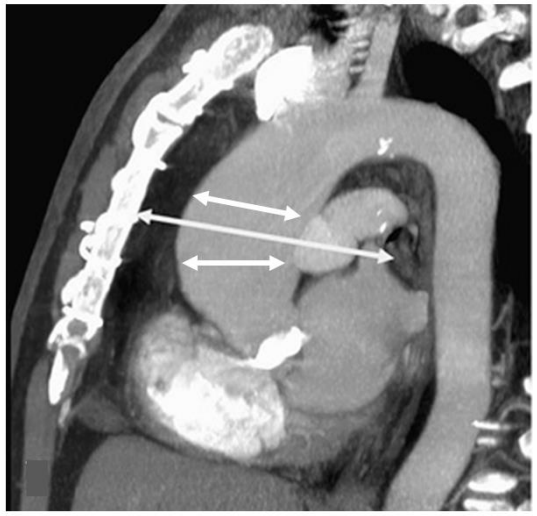
- Approximately **6 cases per 100 000** persons every year *(Clouse 1998; Isselbacher 2005)*
- Approximately **35 000 cases** every year in **Europe** and 15 000 in the U.S.A.

Detection and diagnosis

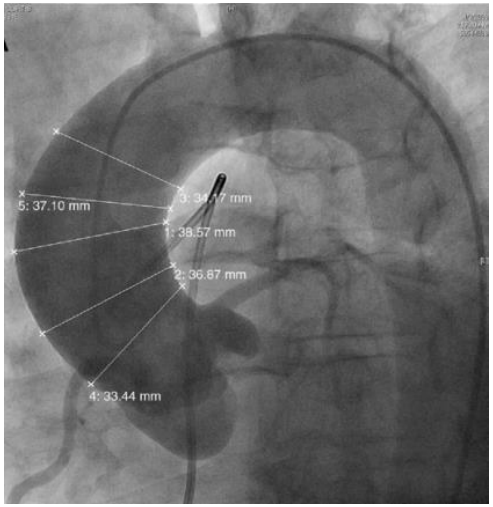
(Sullivan et al., 1988; Evangelista, 2010; Elefteriades et al., 2010)



X-ray



MRI



Aortogram

- Spontaneous detection
- Morphological measurements
- **Diameter criterion (>55 mm)**

Problem and objectives

"Small aneurysms can also rupture"

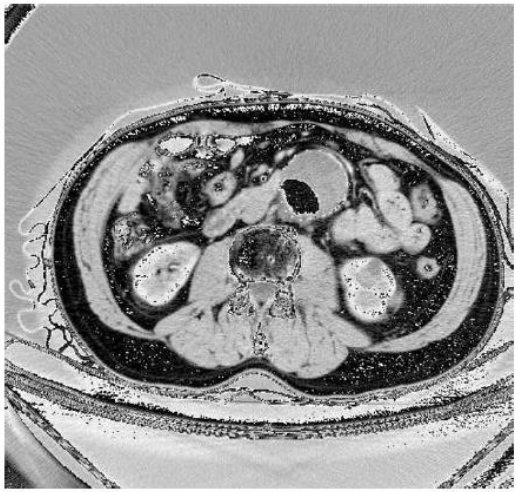
(Nicholls et al., 1998)

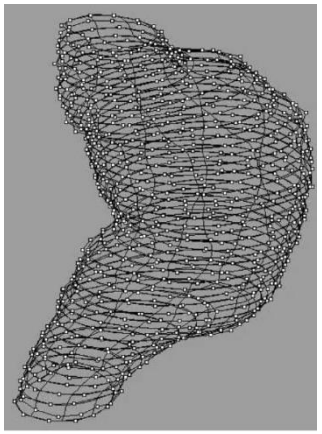
"Bigger aneurysms may never rupture" *(Elefteriades et al., 2010)*

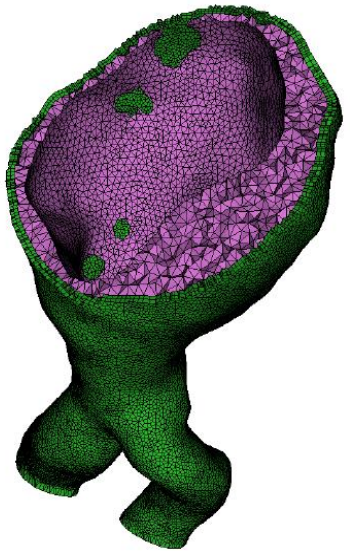
The morphological measurements are not always reliable

We need to create new tools based on the biomechanical properties of the aneurysm to help surgeons to make decisions of intervention

Quantify the risk of rupture for each patient…

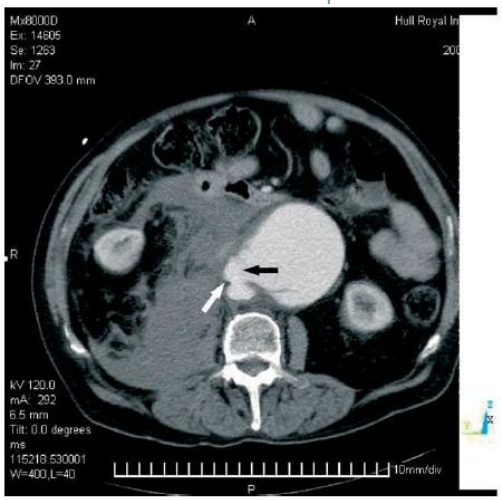


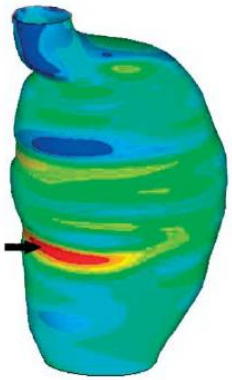


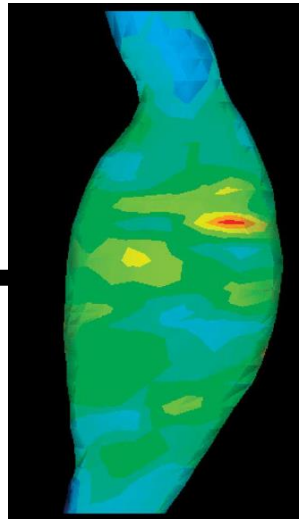


[McGloughlin T. Biomechanics and mechanobiology of aneurysms. 2012, Springer

www.vascops.com





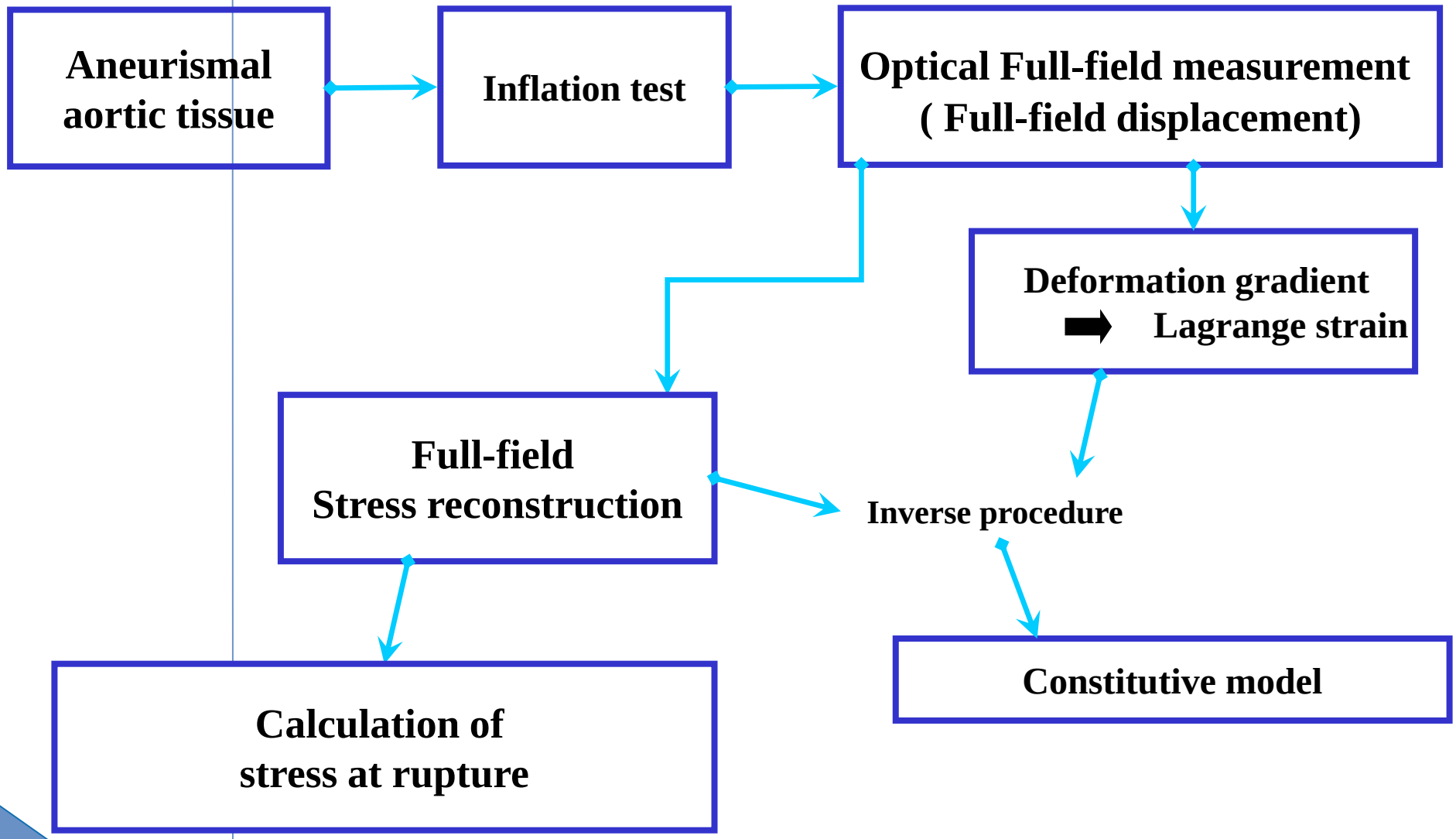


Quantify the risk of rupture for each patient???

Lack of local analyses

Where and how does the rupture initiates?

Methodology



Methodology

Aneurismal aortic tissue

Inflation test

Optical Full-field measurement (Full-field displacement)

Deformation gradient ➡ Lagrange strain

Full-field Stress reconstruction

Inverse procedure

Constitutive model

Calculation of stress at rupture

Materials

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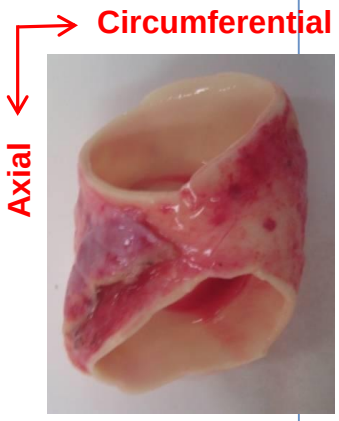
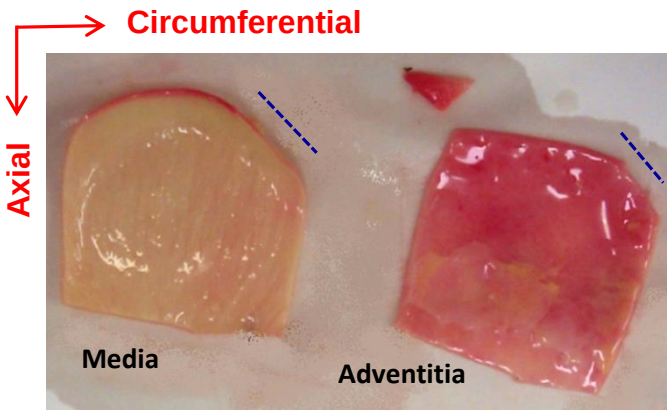
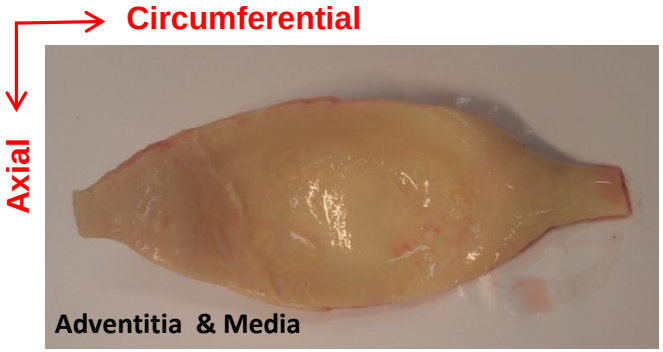


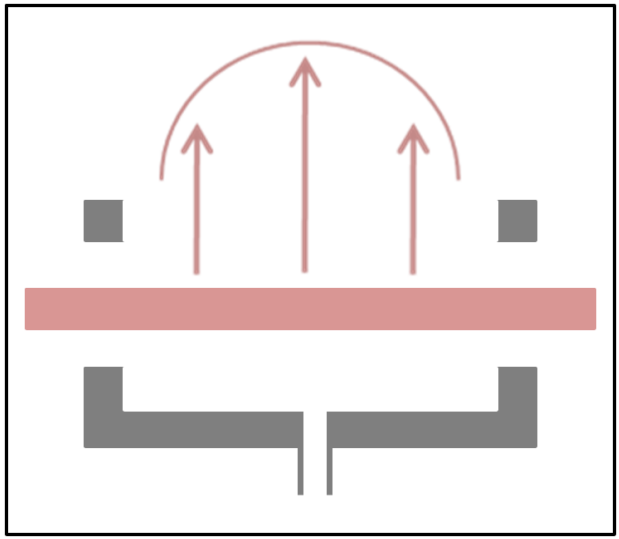
I) Aneurysm excised specimen.



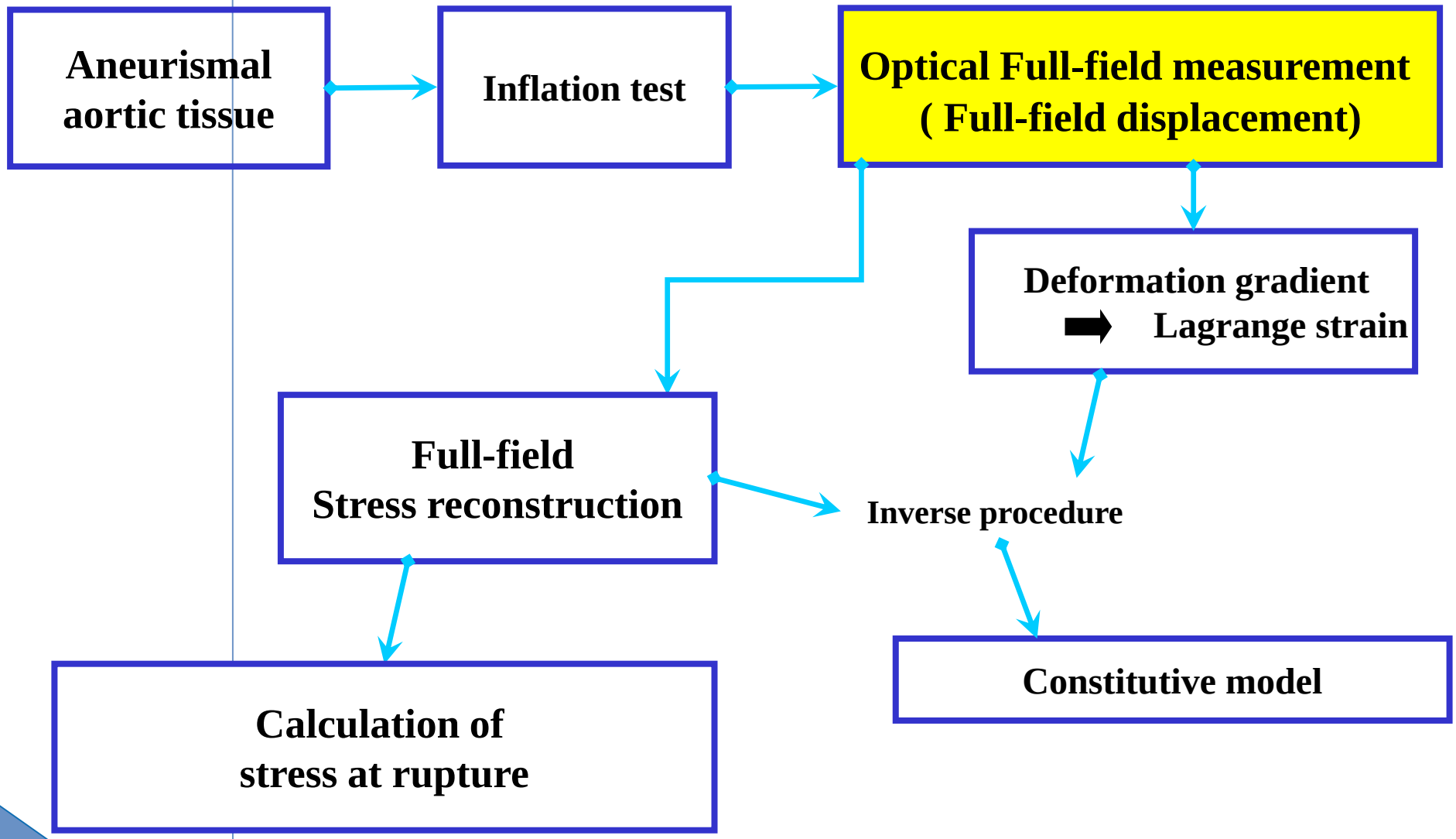
II) Separation of Media and Adventitia.



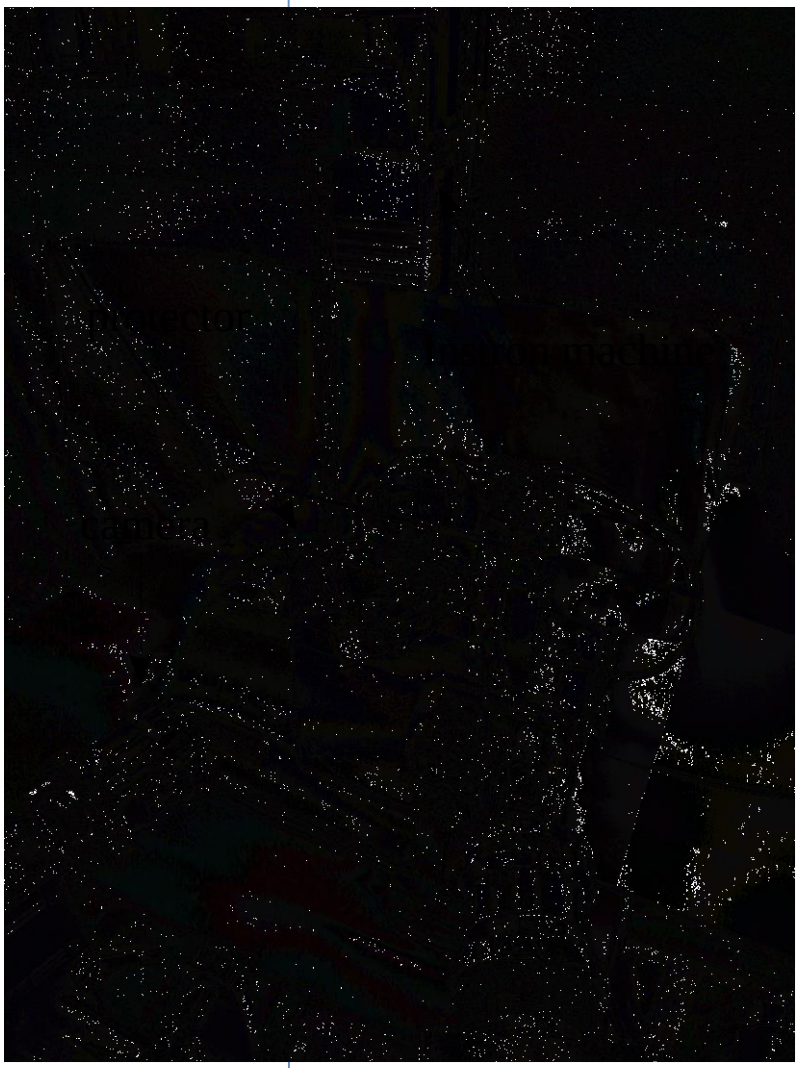
II) Media and Adventitia.



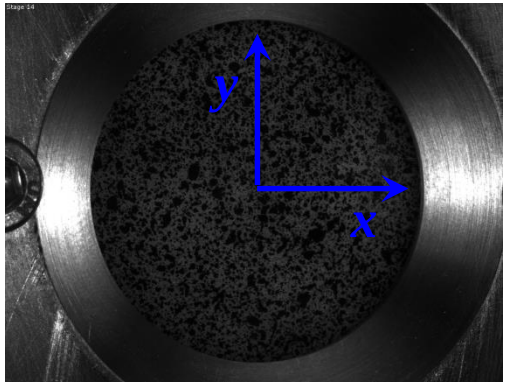
Methodology



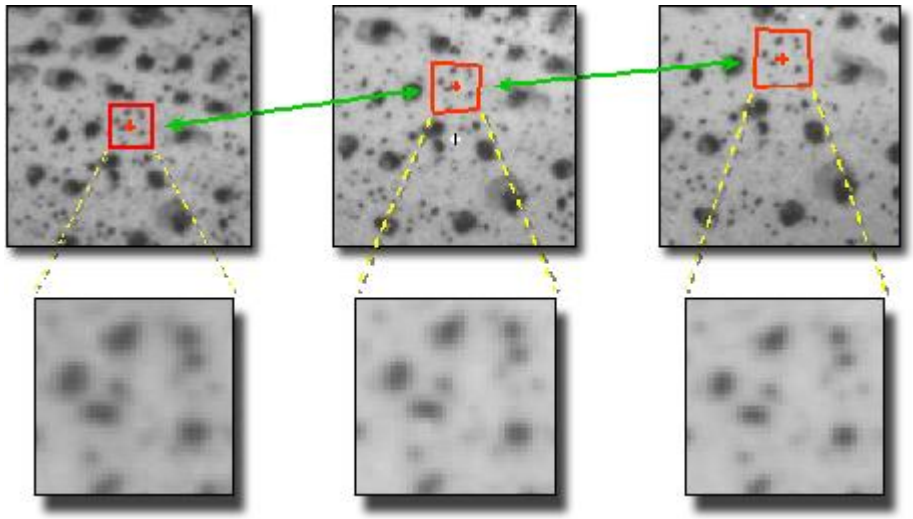
Digital image stereocorrelation



Undeformed

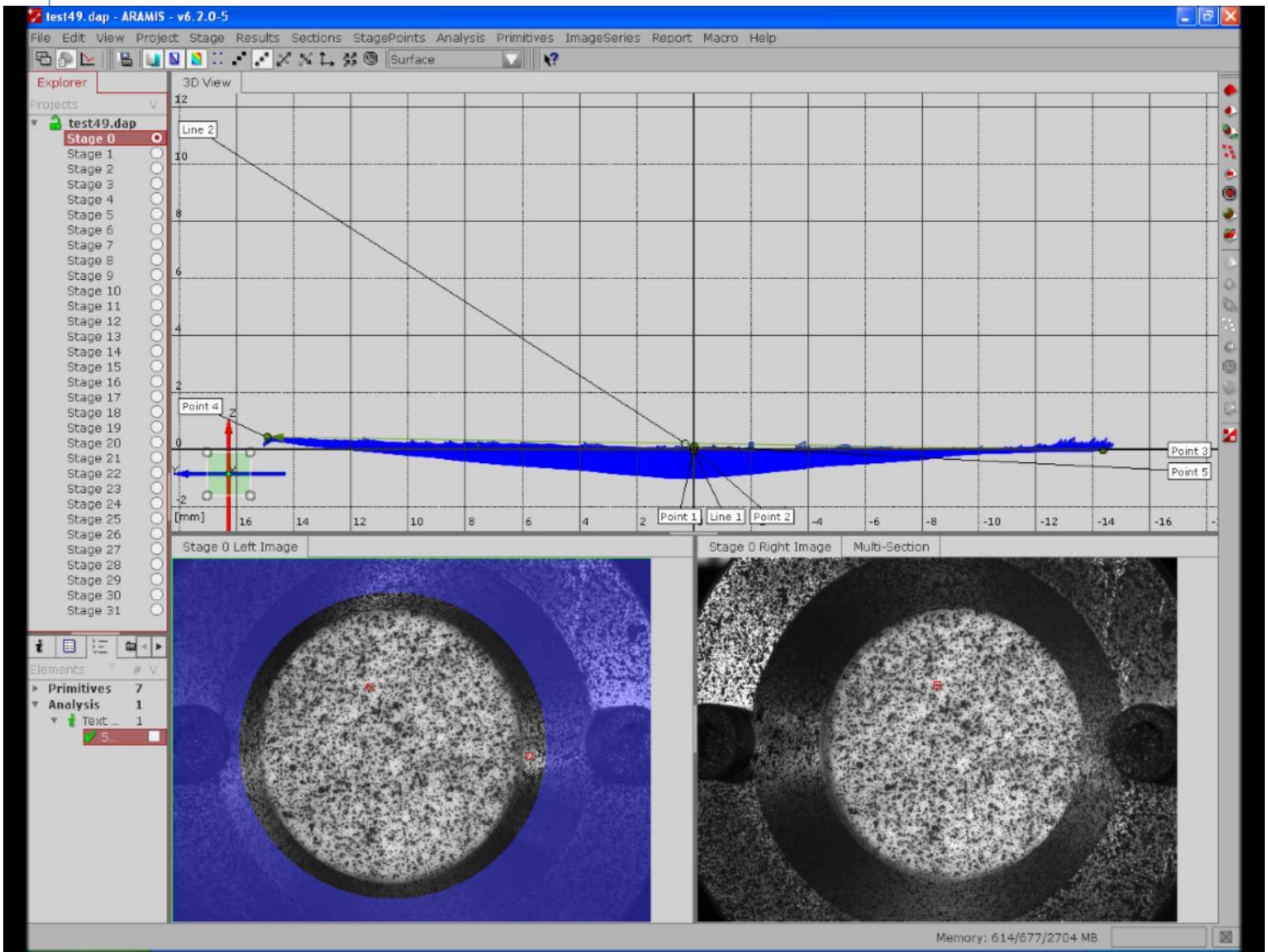


Deformed



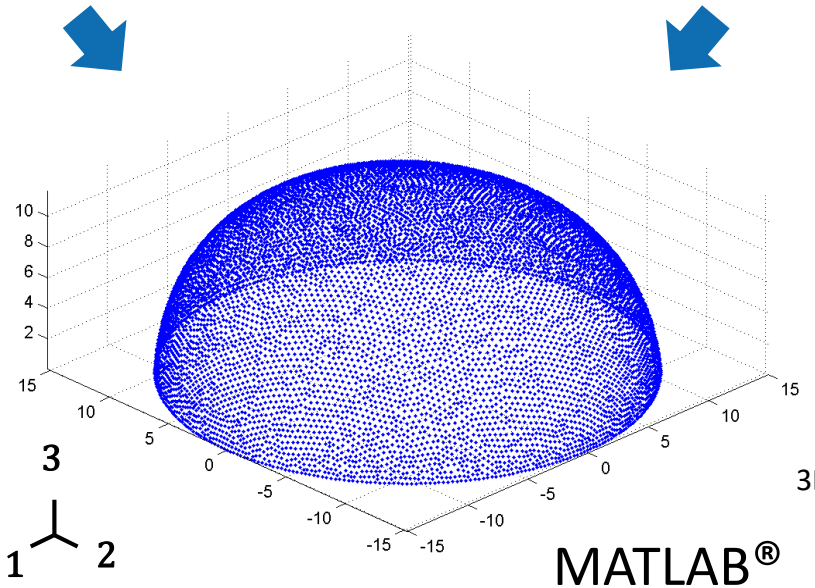
tracks the gray value pattern
in each subset during deformation

Inflation test



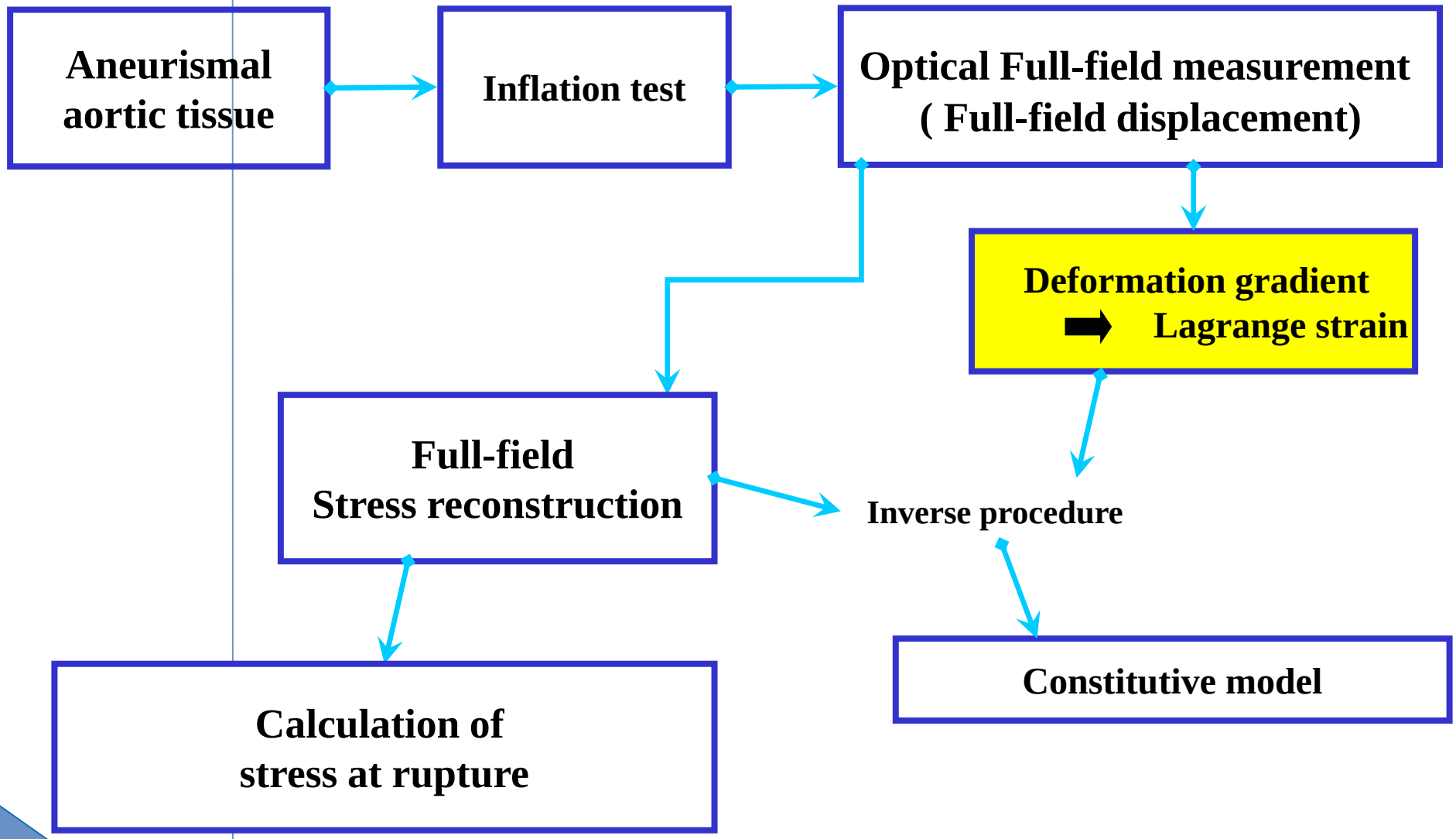
DIC system
(Aramis®)

Export 3D coordinates for every data point



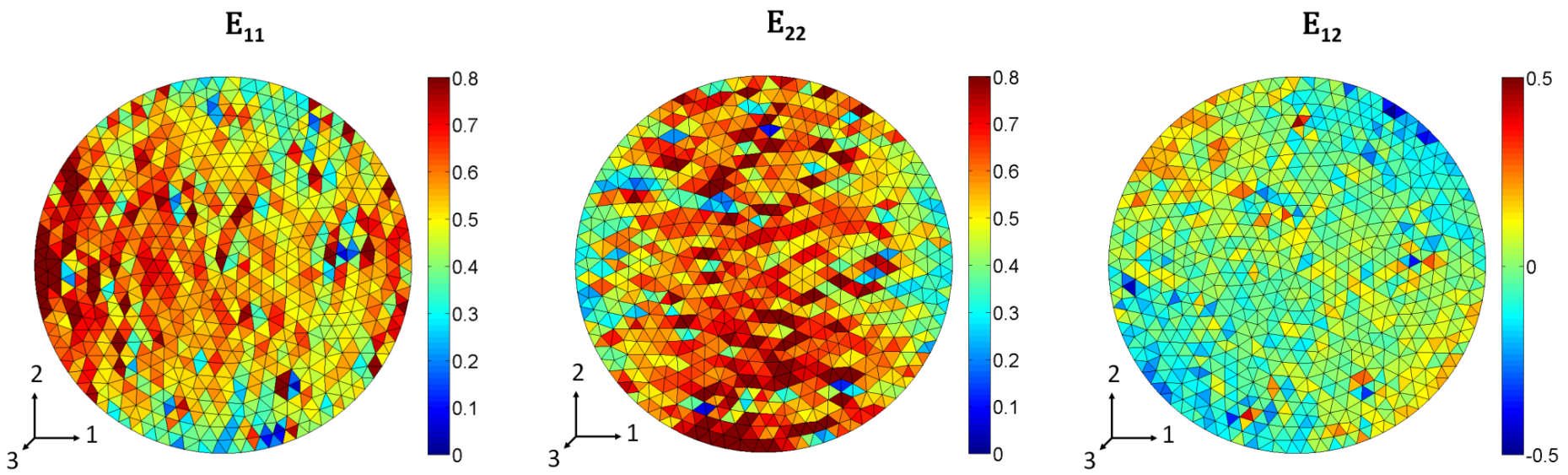
3D reconstruction

Methodology



Derivation of the strain fields

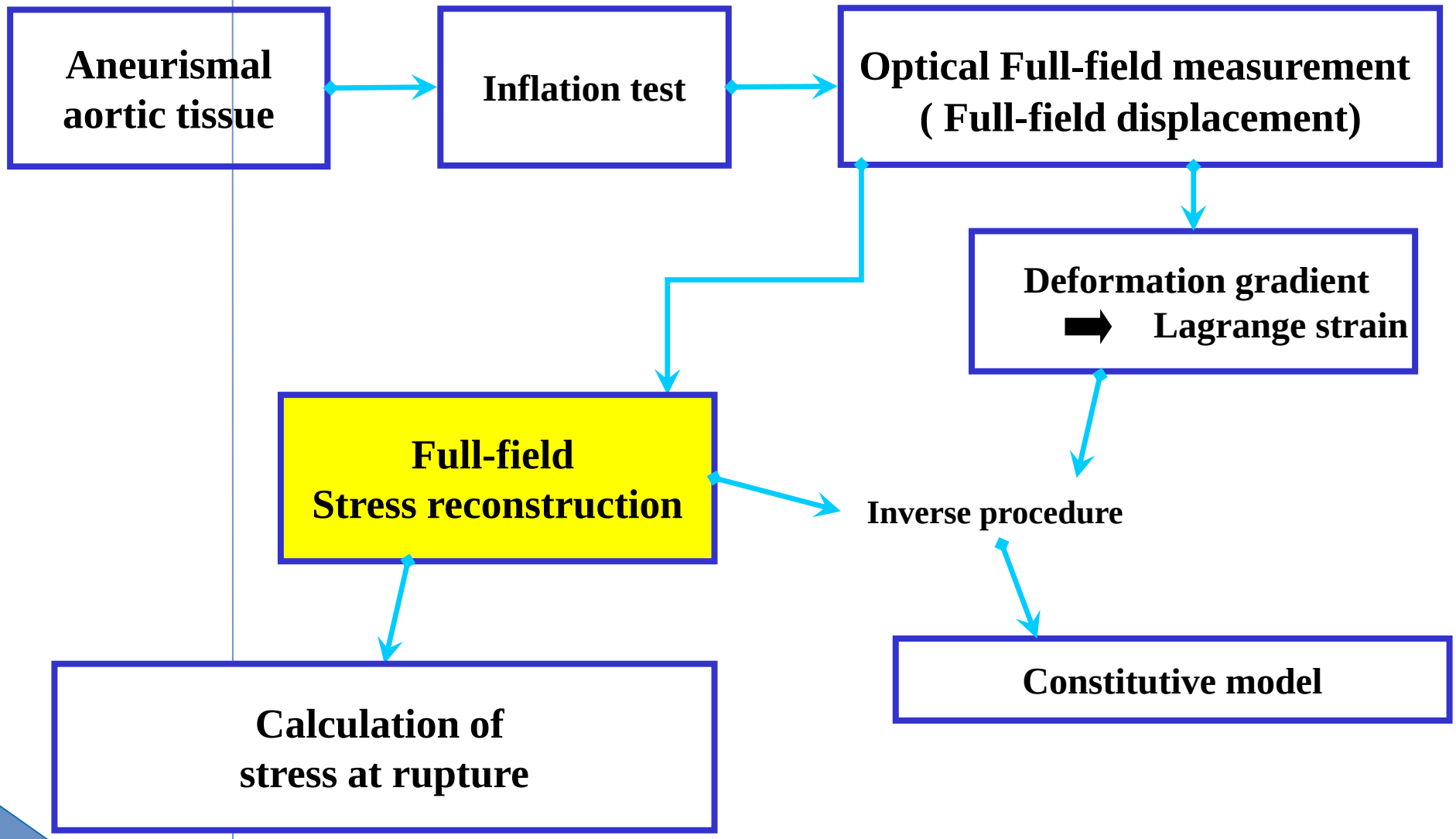
Green-Lagrange strain tensor $E = \frac{1}{2}(F^T F - I) = \begin{bmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{bmatrix}$



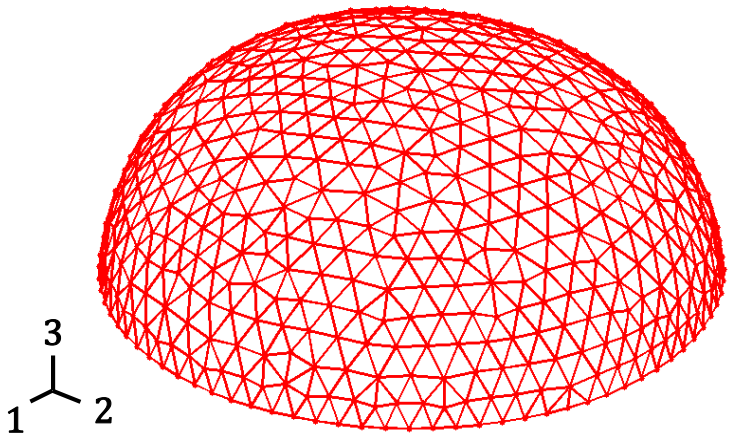
Global least-squares approximation $U = \underset{U}{\text{Arg min}} \sum_{i \in \Omega} (u_{ap}(\underline{x}_i) - \tilde{u}(\underline{x}_i))^2$

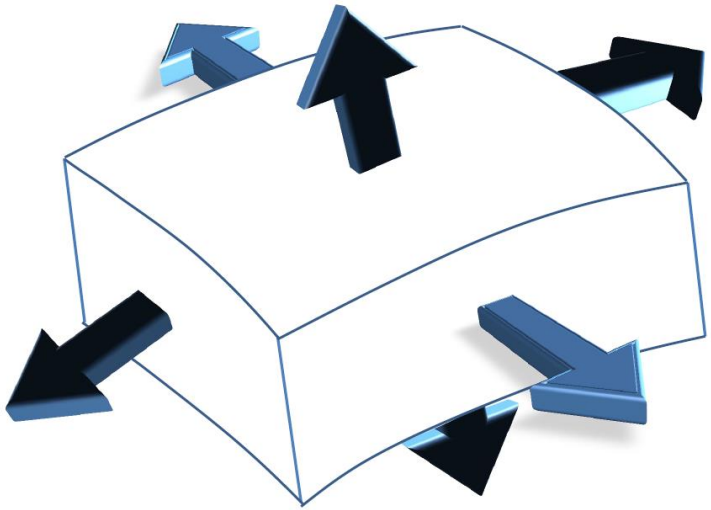
Differentiation of the shape functions

Methodology



Stress reconstruction

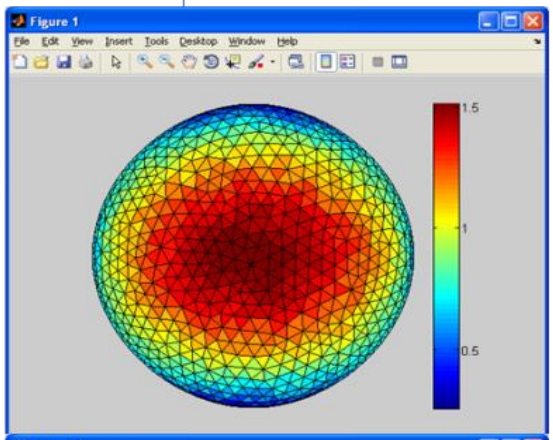
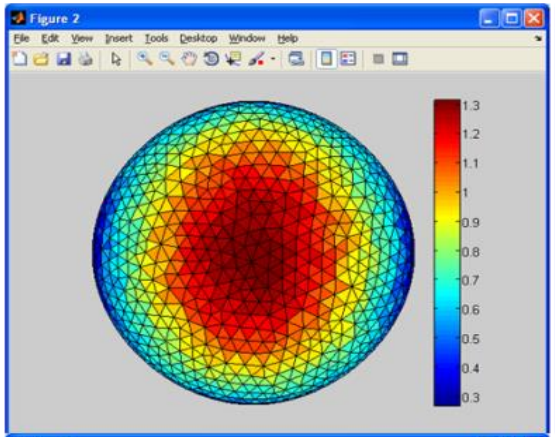
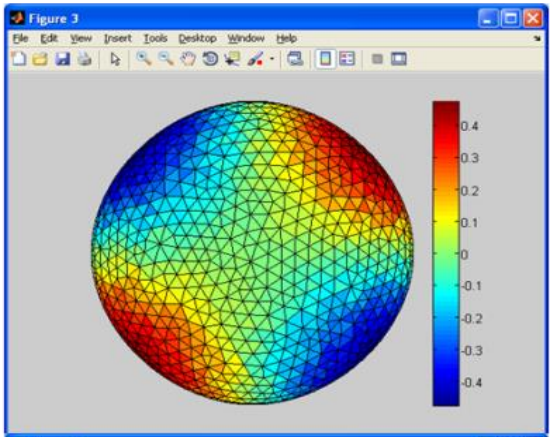
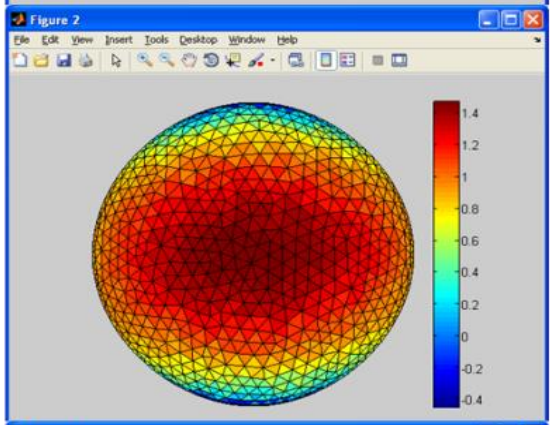
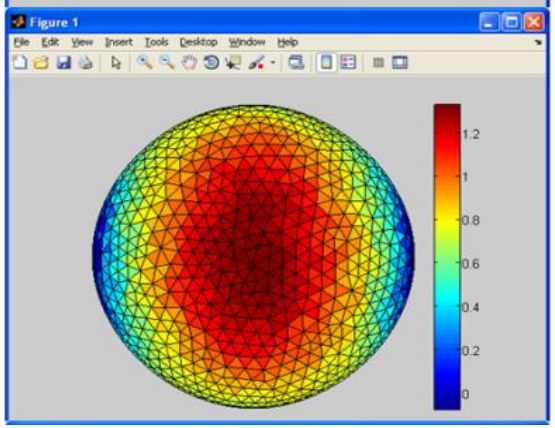
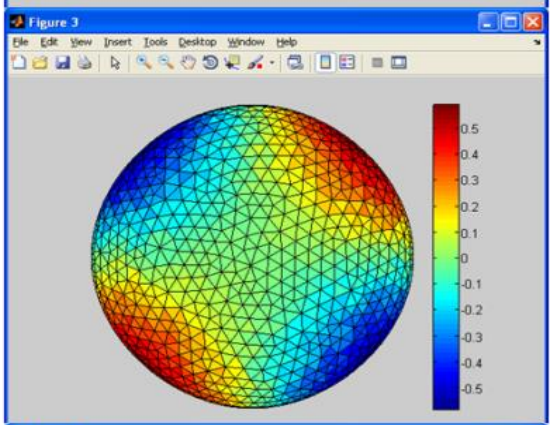




$$div(\boldsymbol{\sigma}) + f = 0$$

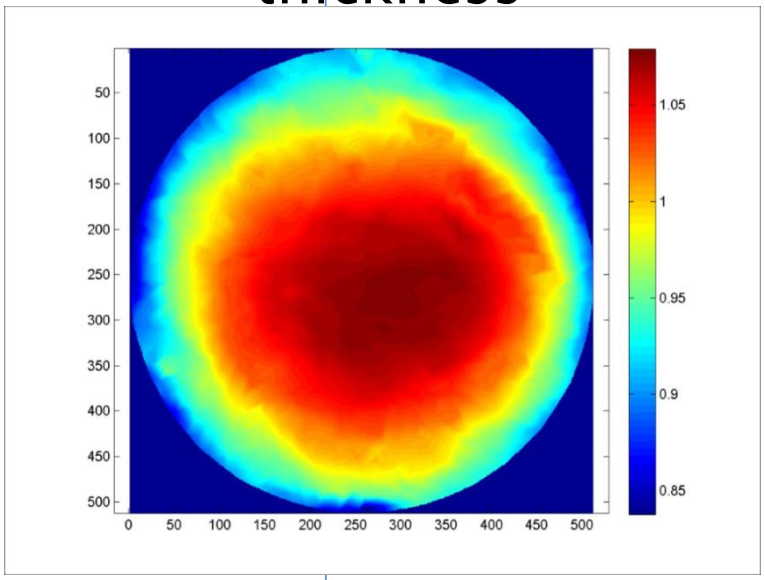
$$[A] \cdot [\boldsymbol{\sigma}] = [B]$$

Validation

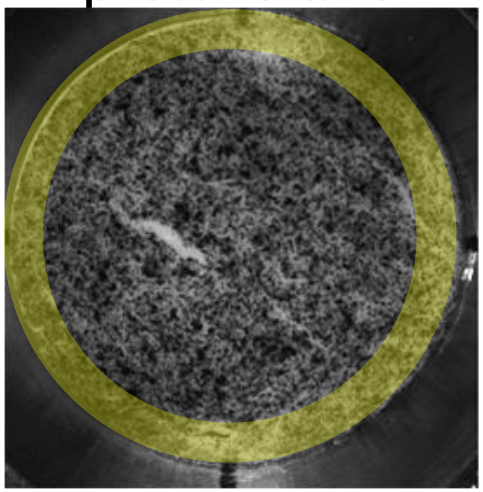
	sigma_11	sigma_22	sigma_12
a)			
b)			

Thickness evolution

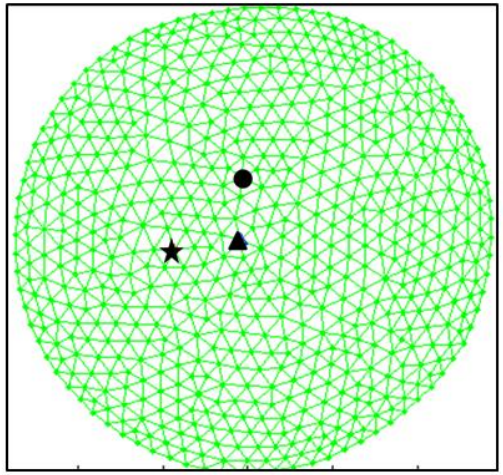
Local thickness



Rupture picture and



Mesh



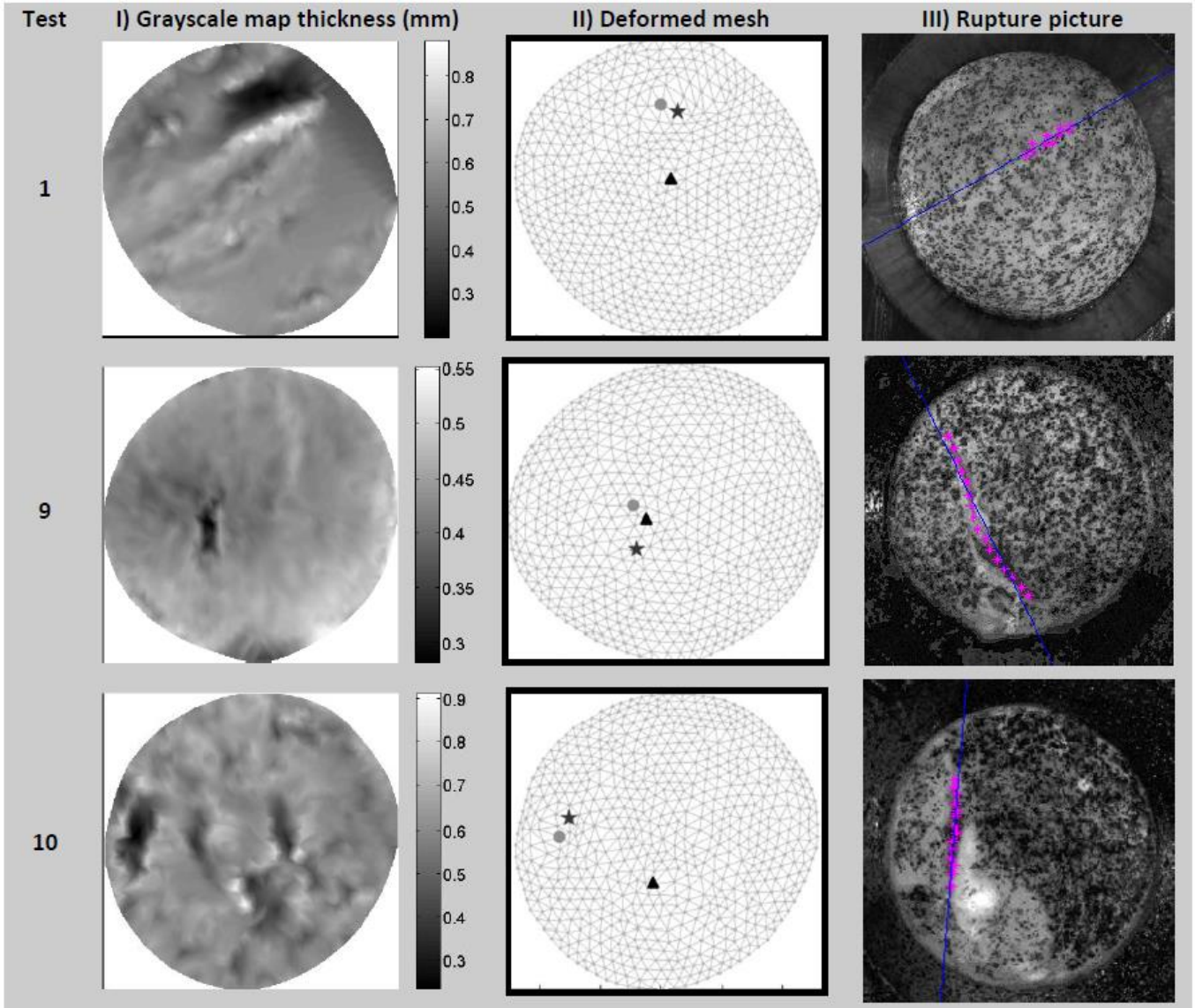
● = NodeMAX

▲ = NodeTOP

★ = NodeRUP

A. Romo, S. Avril, P. Badel, A Duprey, J.P. Favre. In vitro analysis of localized aneurism rupture. Journal of Biomechanics -2014, vol 47, N°3, pp 607-616.

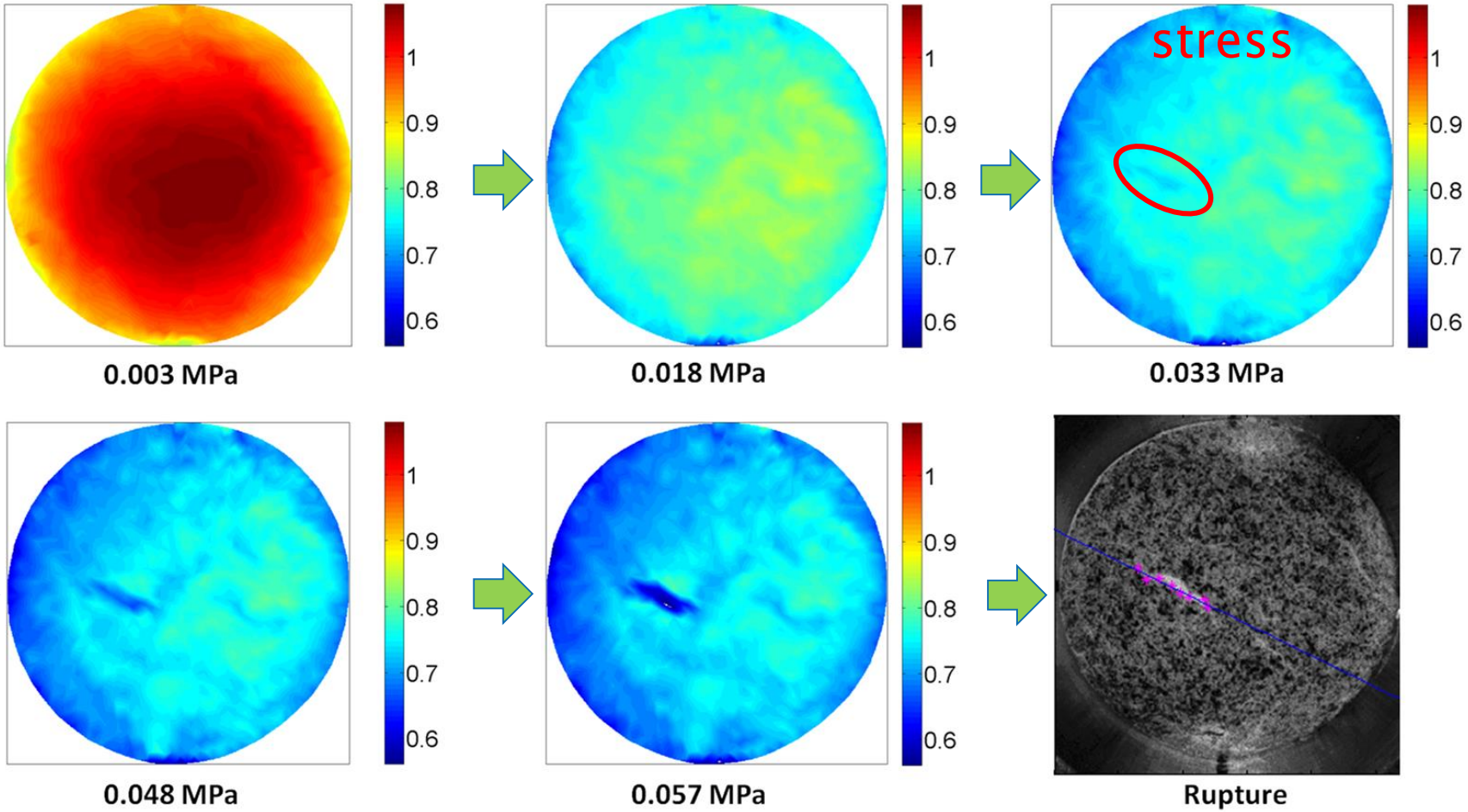
Rupture modes



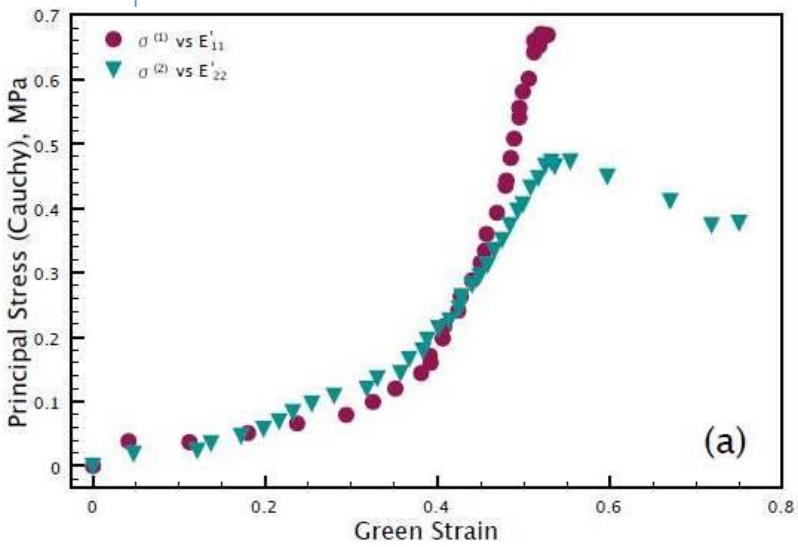
Rupture prediction

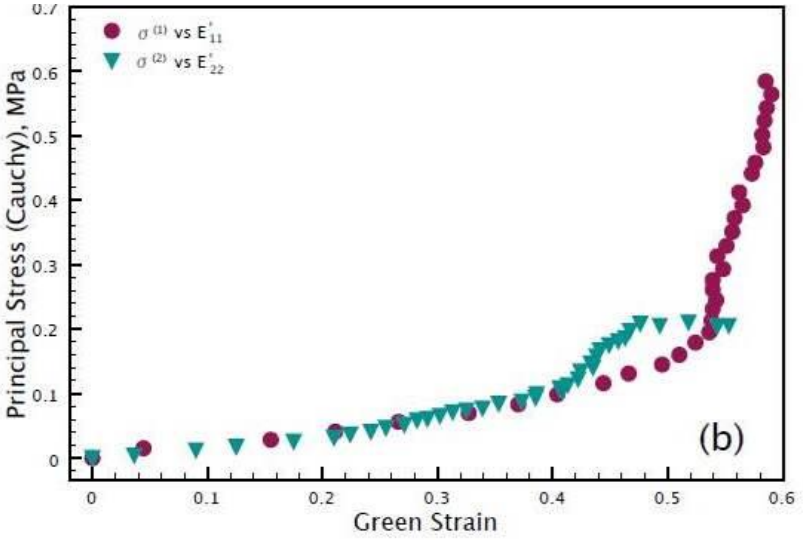
Thickness evolution (mm)

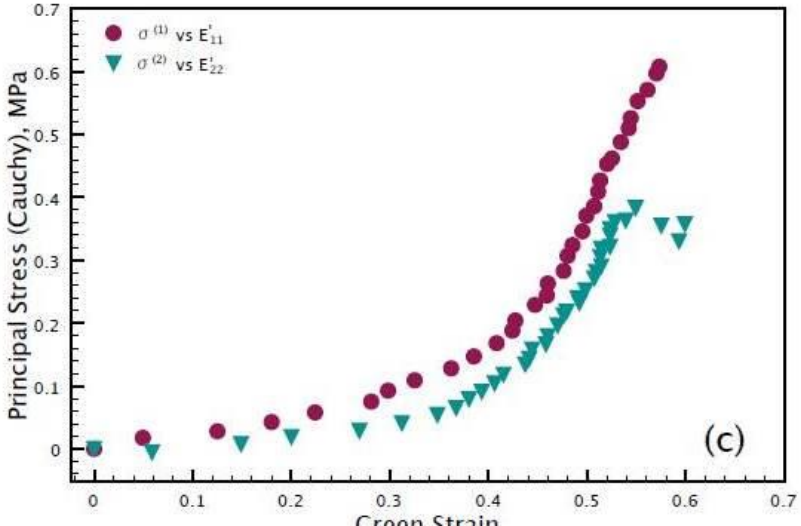
55% of the ultimate stress

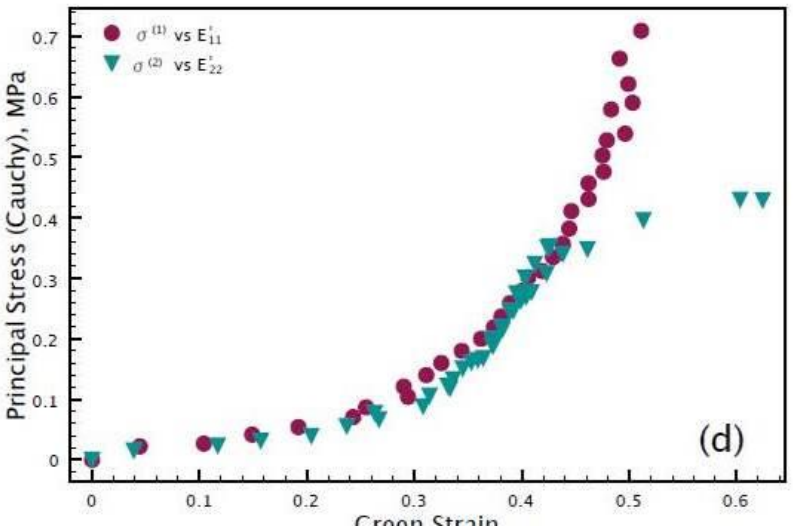


Ultimate stress-strain behaviour

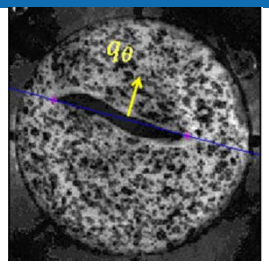




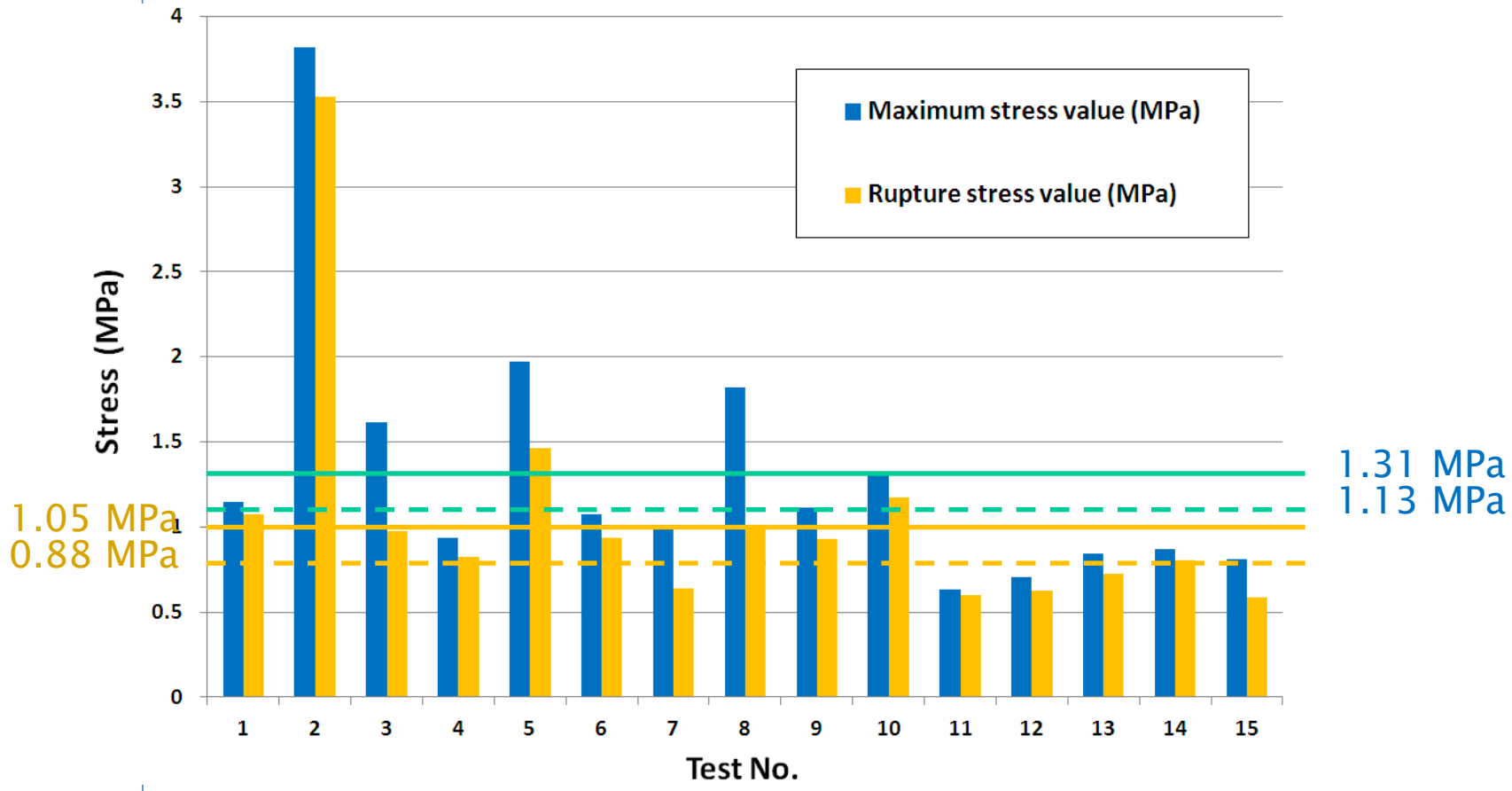




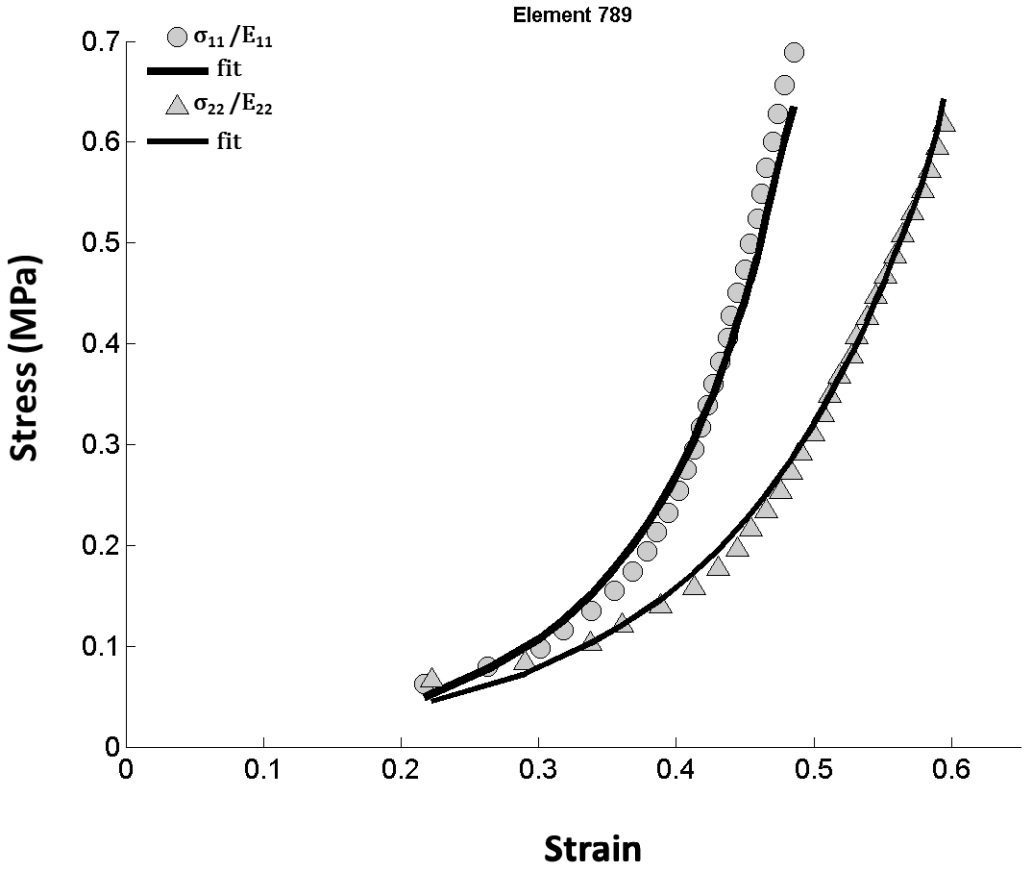
Rupture stress



$$\sigma^{Rup} = (\sigma \cdot \overrightarrow{q_\theta}) \cdot \overrightarrow{q_\theta}$$



Pointwise stress-strain data



Constitutive model

Strain energy fonction: $\Psi = \Psi_g + \Psi_f$

Isotropic behaviour — *Anisotropic behaviour*

Neo-Hookean parameter fixed in **5 kPa**

(Weisbecker et al. 2012)

Ground substance and elastin

Collagen fibers

2nd Piola-Kirchhoff stress tensor: $S = S_g + S_f$

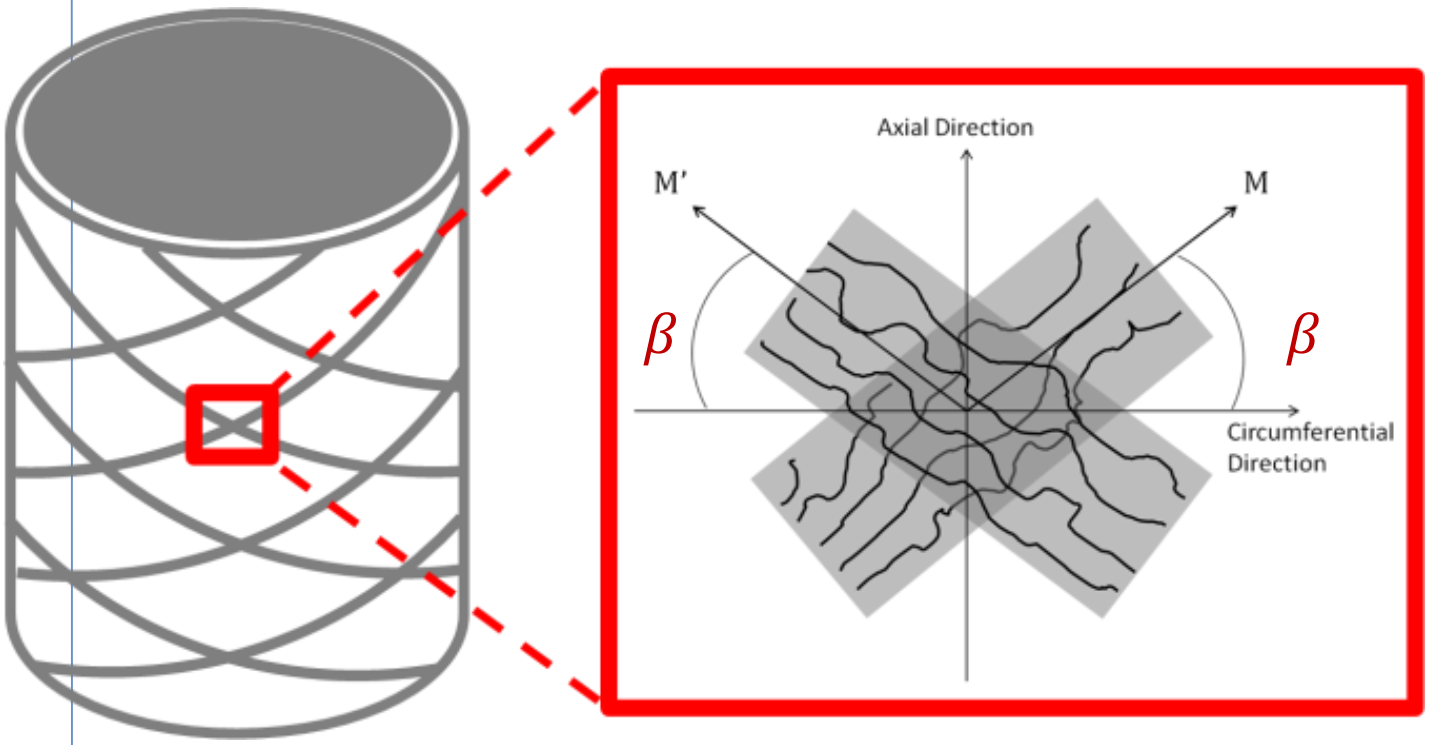
$$\sigma = F \cdot S_g \cdot F^T + F \cdot S_f \cdot F^T + cI$$

$$\sigma' = \sigma - F \cdot S_g \cdot F^T - cI = F \cdot S_f \cdot F^T$$

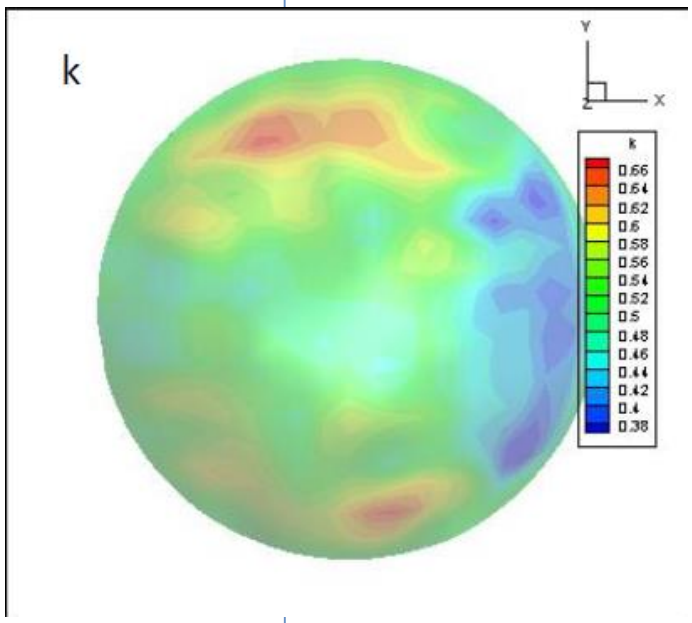
Constitutive model

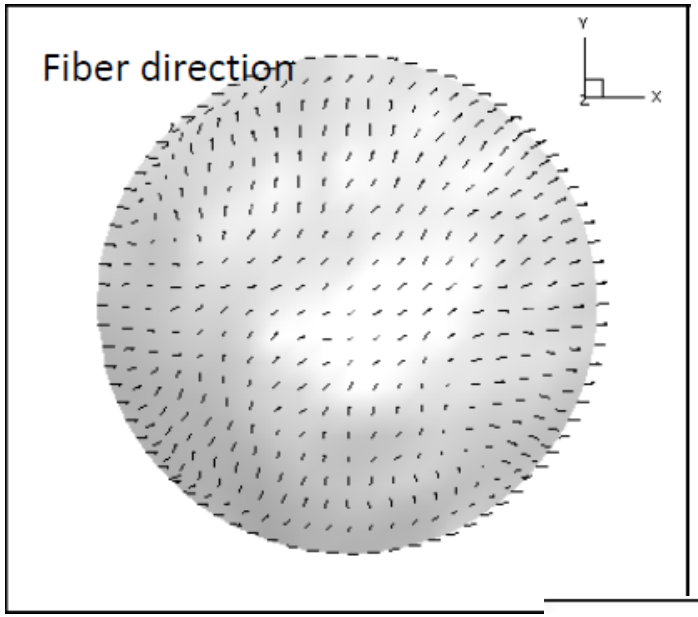
$$\Psi_f(I_4, I_6) = \frac{k_1}{2k_2} \sum_{i=4,6} \{exp[k_2(I_i - 1)^2] - 1\},$$

(Holzapfel et al., 2000)

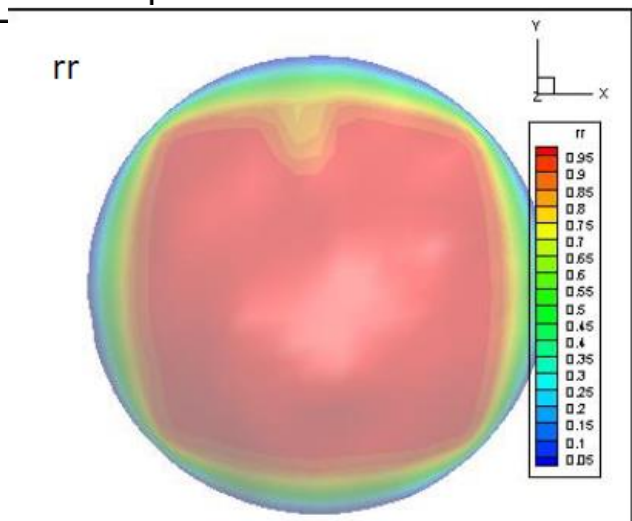


Identification of local distributions of material properties





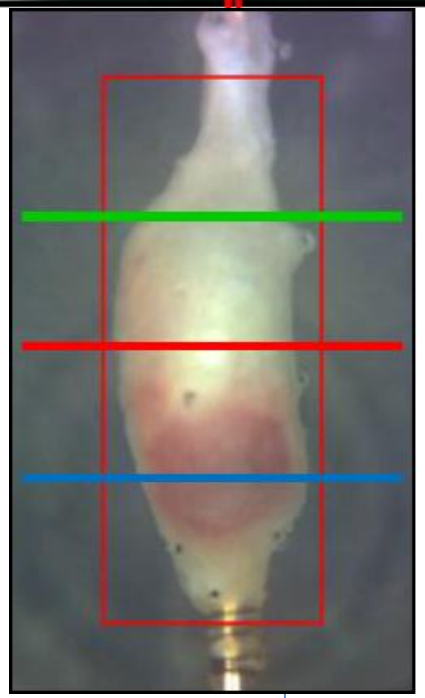
Coefficients of determinations:

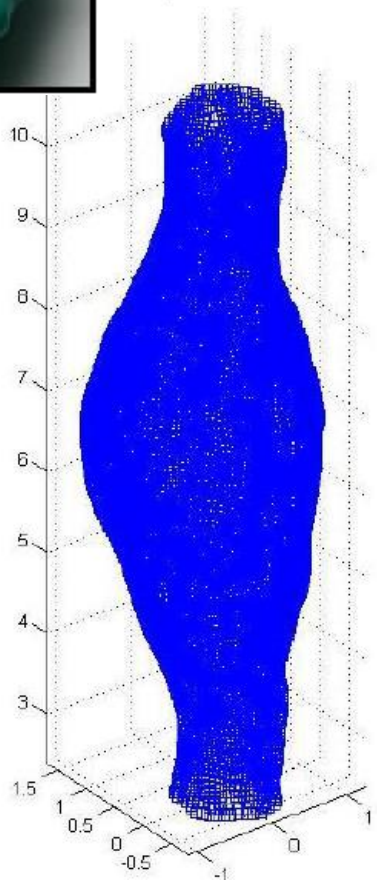


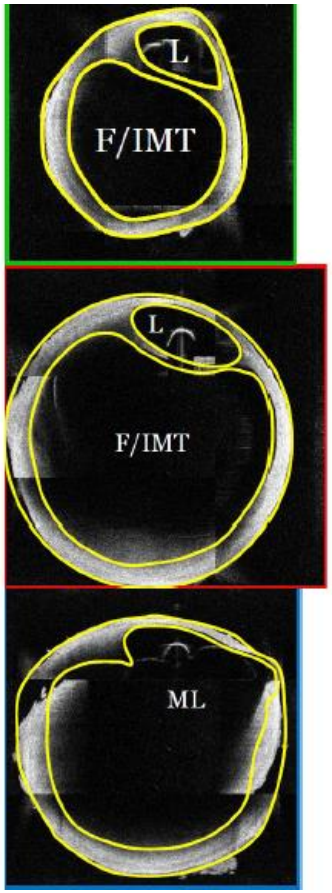
Conclusion and future directions

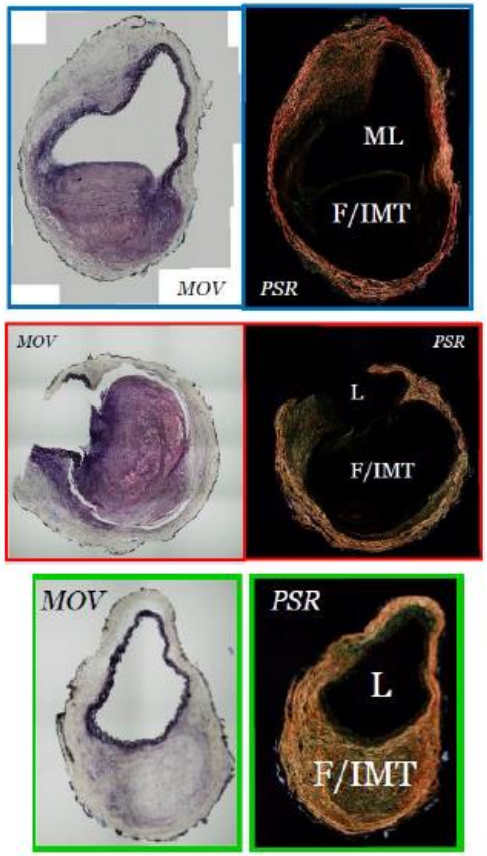
Mechanobiology of aneurisms

3D pointwise material property identification at different stages of aneurism growth

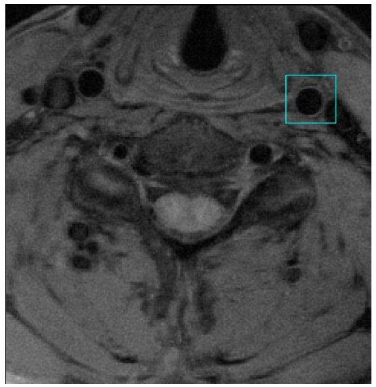


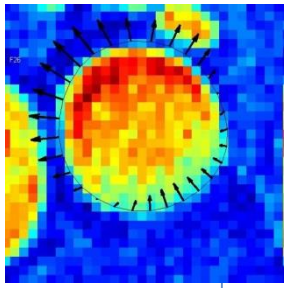


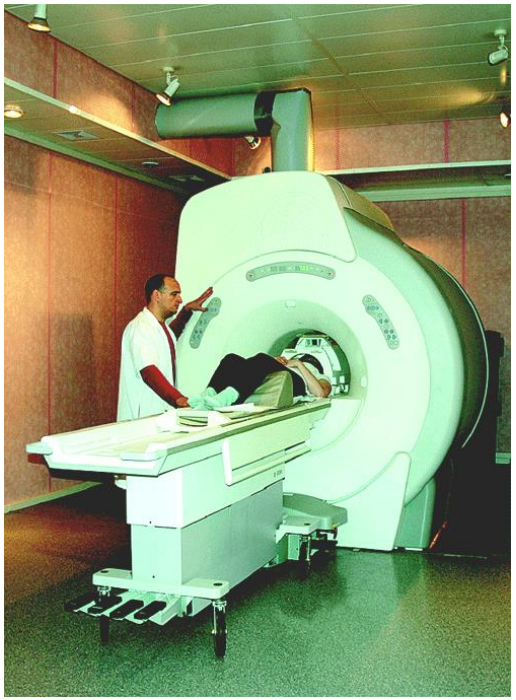




In vivo identification of material properties



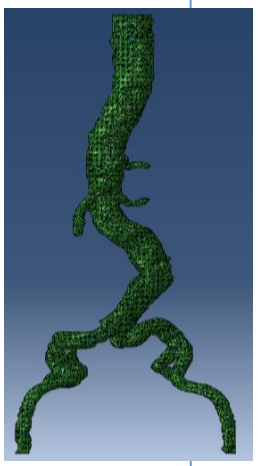


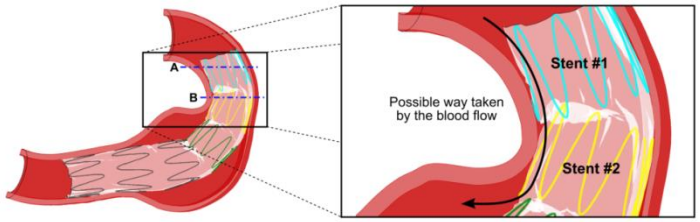


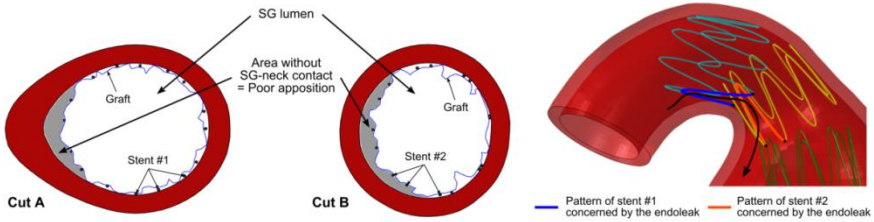
US elastography

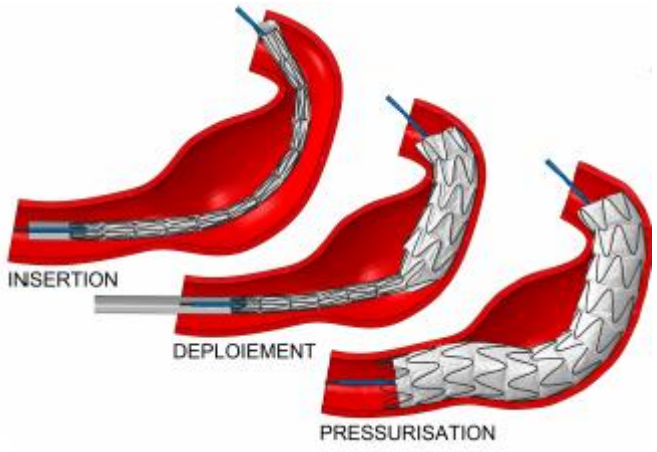
S. Avril, F. Schneider, C. Boissier, ZY Li. In vivo velocity vector imaging and time-resolved strain rate measurements in the wall of blood vessels using MRI. Journal of Biomechanics, 2010, 44(5) pp 979-983.

Predictive planning software solution for endovascular surgery









Acknowledgements

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