Identification of the elastic properties of human arteries from full-field measurements

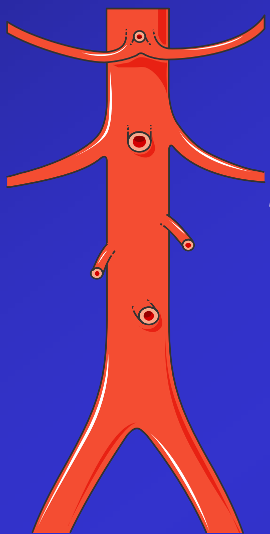
Stéphane Avril, Jean-Noël Albertini, Ambroise Duprey, Jean-Pierre Favre, Katia Genovese, Jean-Pierre Vassal

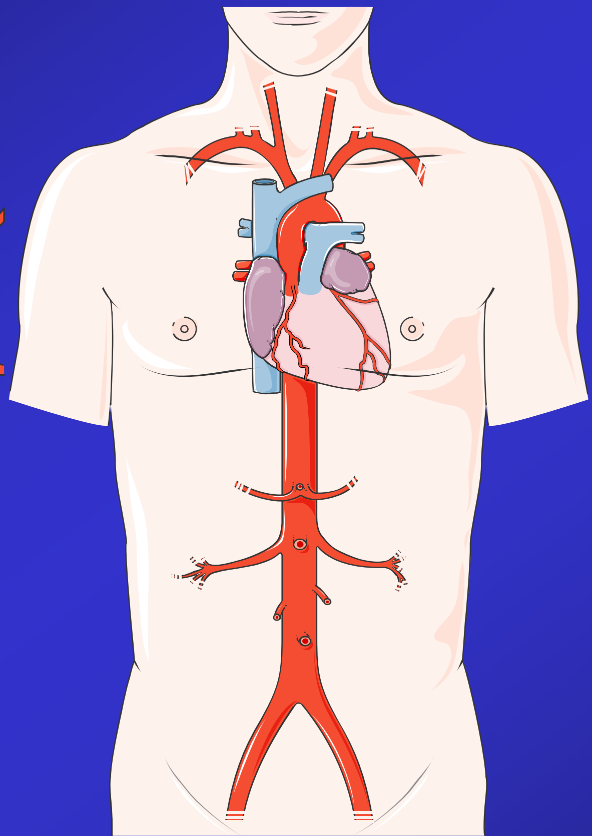
Experimental Mechanics in Biological Tissues

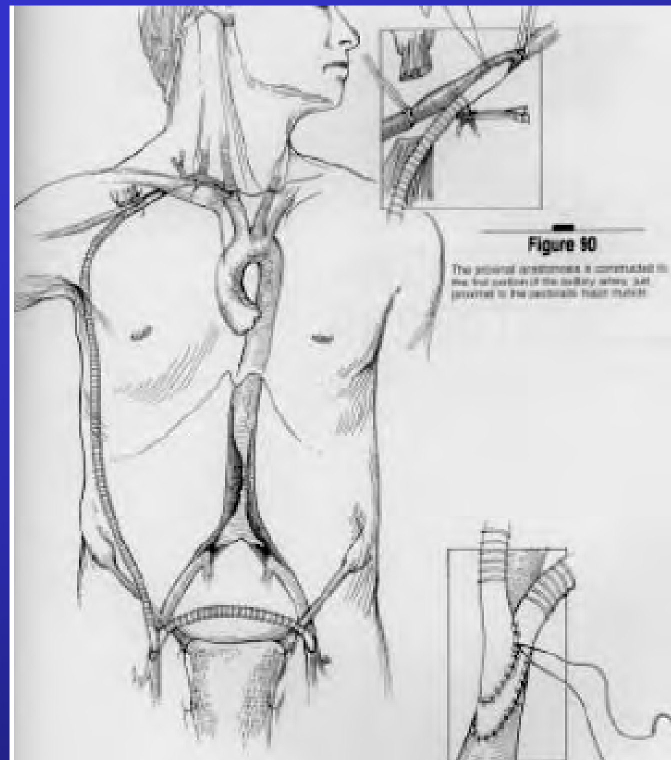
Tuesday 23rd June 2009
Venue: CC013 - James France Building, Loughborough University, UK.

BSSM
BRITISH SOCIETY FOR STRAIN MEASUREMENT

Cardiovascular surgery and mechanical engineering







Issue of thoracic aortic aneurysms

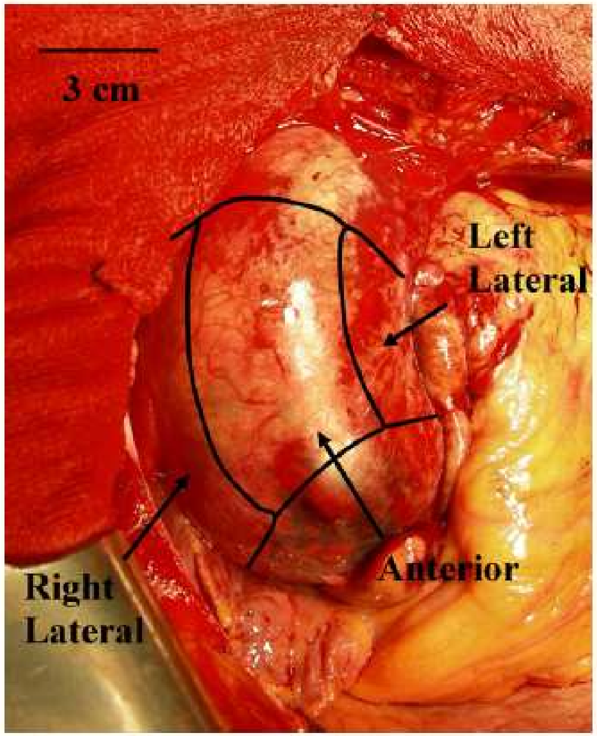
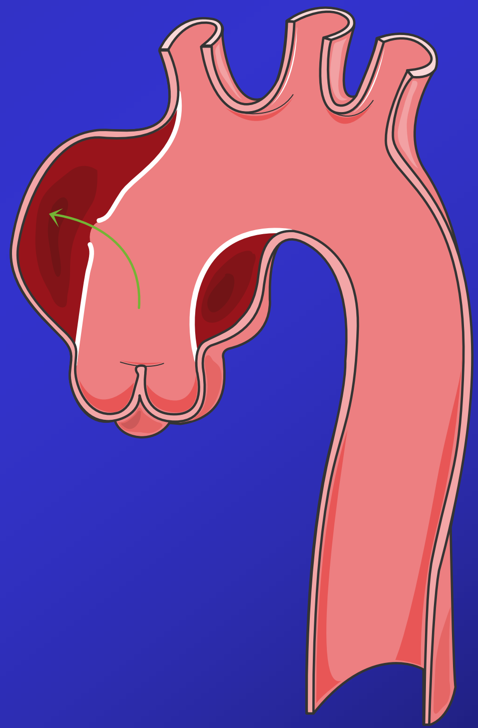
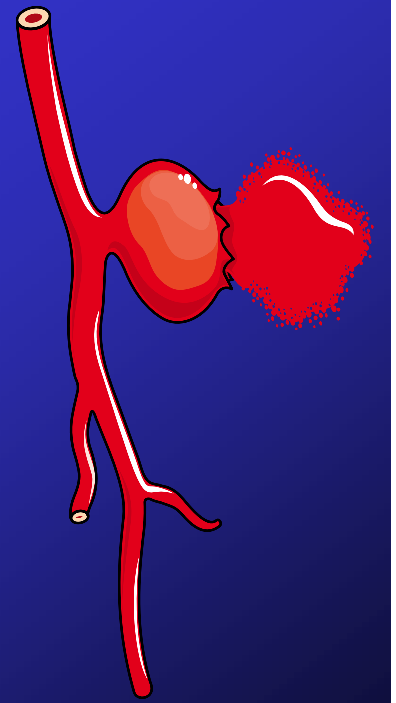
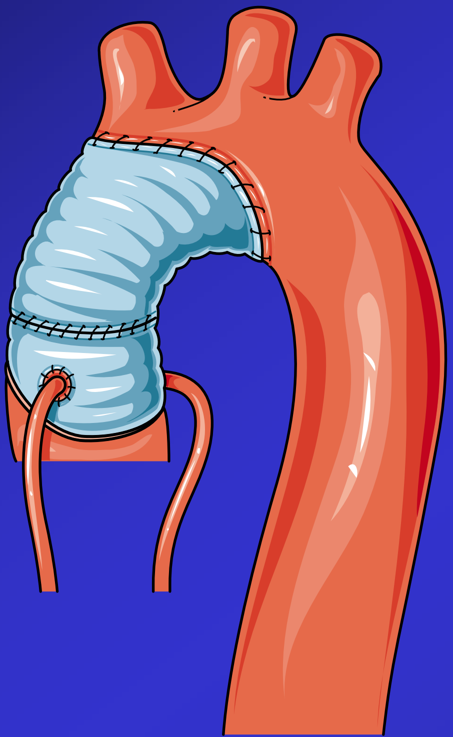


Fig. 1. Intact ATAA of a 67-year-old patient undergoing graft replacement of the ascending thoracic aorta. The anterior, left and right lateral regions are shown between thick lines; tissue specimens were harvested from these regions for mechanical testing.

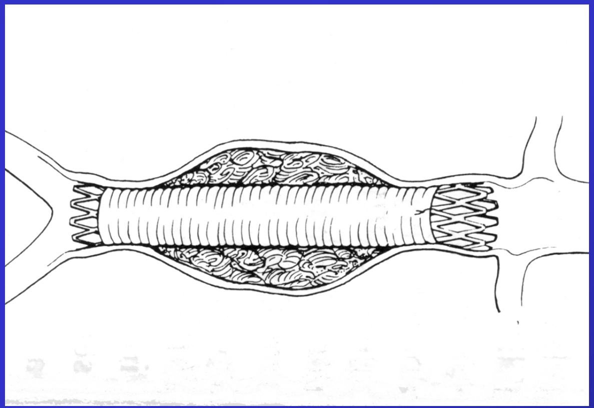


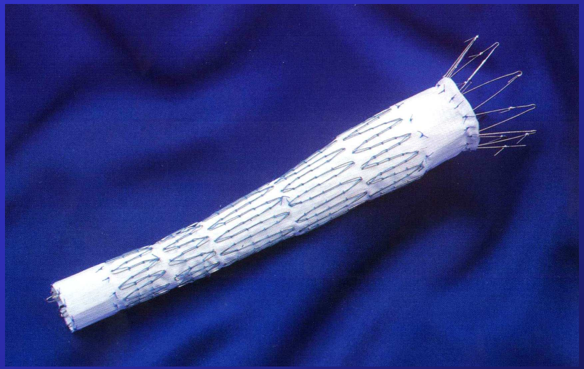


Treatments: state of the art



classical

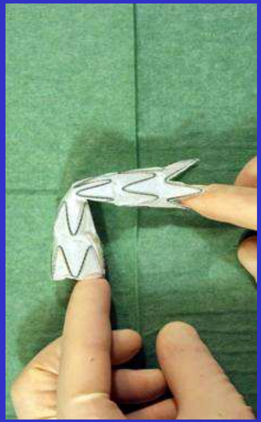


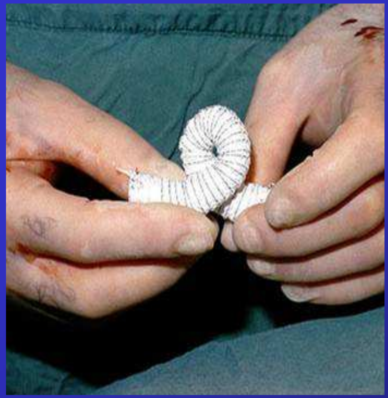


endovascular

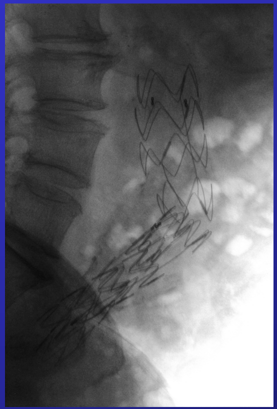
Design of treatments: to be improved

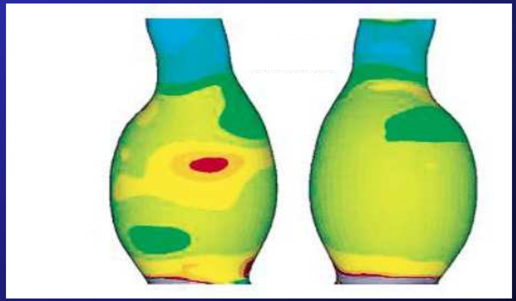
- Elastic biocompatibility





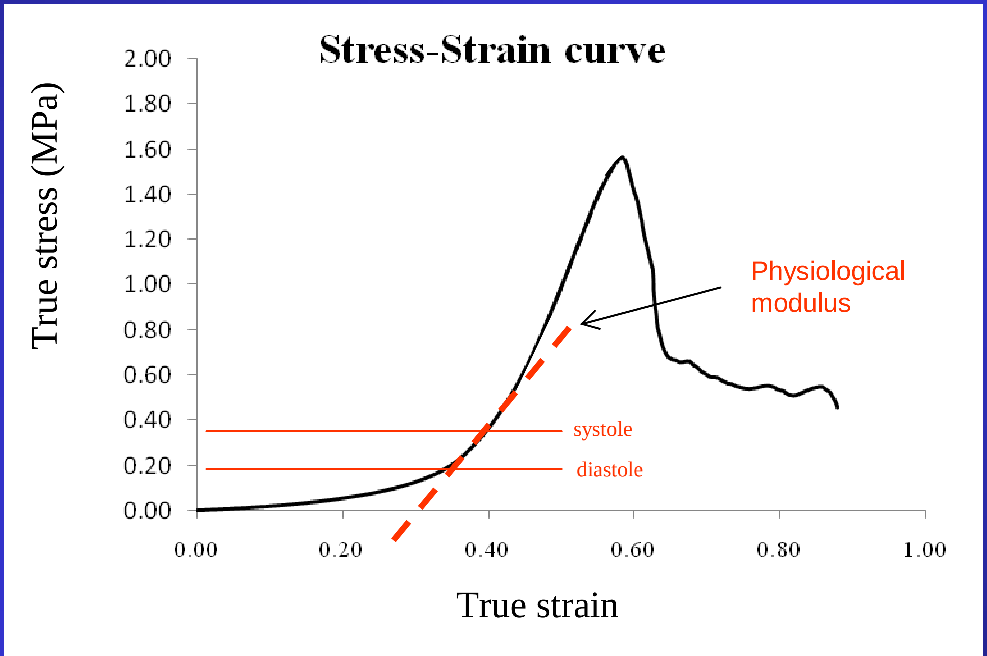
- Durability and risk prediction using FE



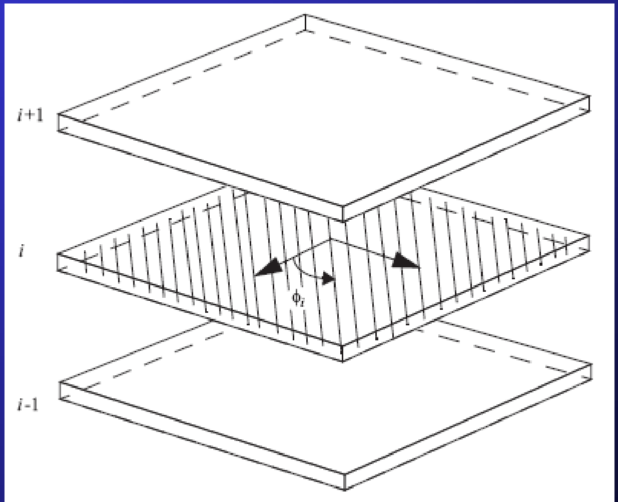


Fundamental requirement

- Accurate and personalized identification of the elastic properties of the thoracic aorta



Multi-layered anisotropic
Kroon & Holzapfel, 2008



On-going research at Saint-Etienne

- **Uniaxial tensile tests on strips**
- Biaxial tests on whole segments
- In vivo measurements

Ex Vivo Characterization of Biomechanical Behavior of Ascending Thoracic Aortic Aneurysms Using Uniaxial Tensile Testing

ESVB, 13th May 2009

Ambroise Duprey, Khalil Khanafer, Marty Schlicht, Stephane Avril, David Williams, Jean-Noel Albertini, Xavier Barral, Jean-Pierre Favre, Ramon Berguer

Submitted to the European Journal of Vascular and Cardiovascular Surgery, in revision.

Rationale

- > 30 studies dealing with mechanical testing of aorta published since the 60s
- Well-established properties :
  – Viscoelasticity
  – Non-linearity of stress-strain relationship
- Still under debate :
  – Anisotropy
  – Values of elastic modulus
- Important limitation for computational analysis

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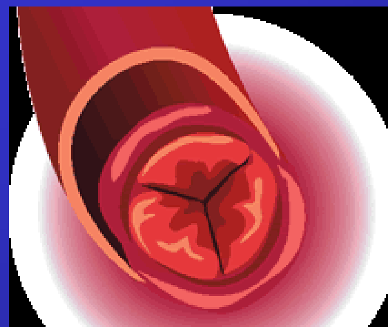
Objective

- Measurement of Maximum Elastic Modulus of aortic tissue from ATAA using uniaxial tensile testing
- Assessment of the influence of several parameters :
  - Valve type

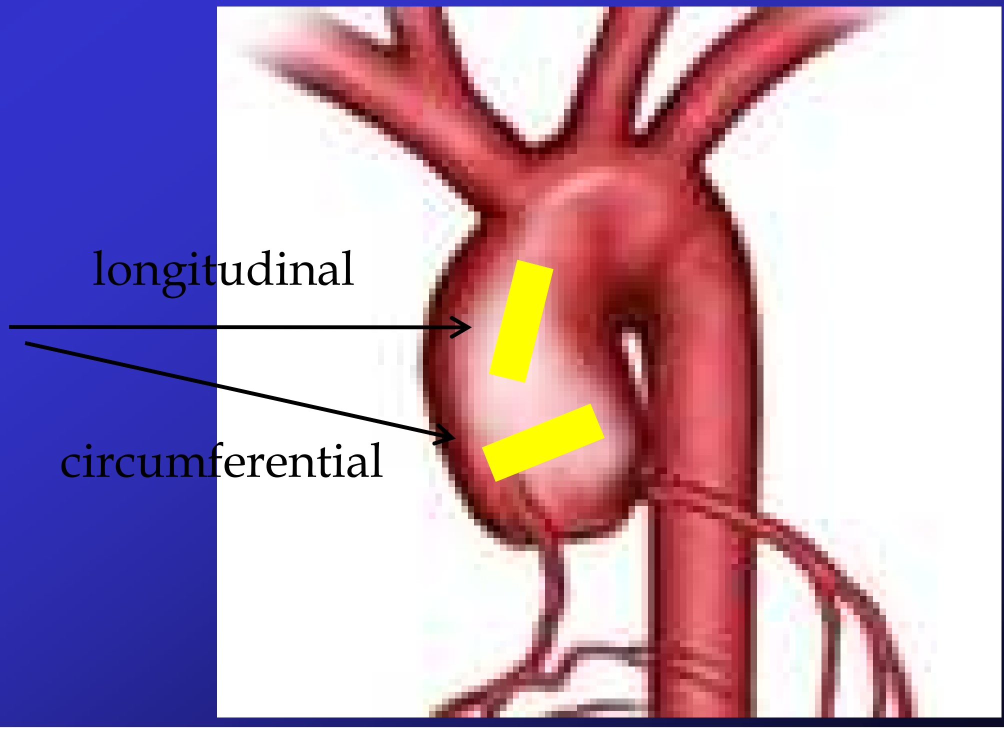
tricuspid



bicuspid

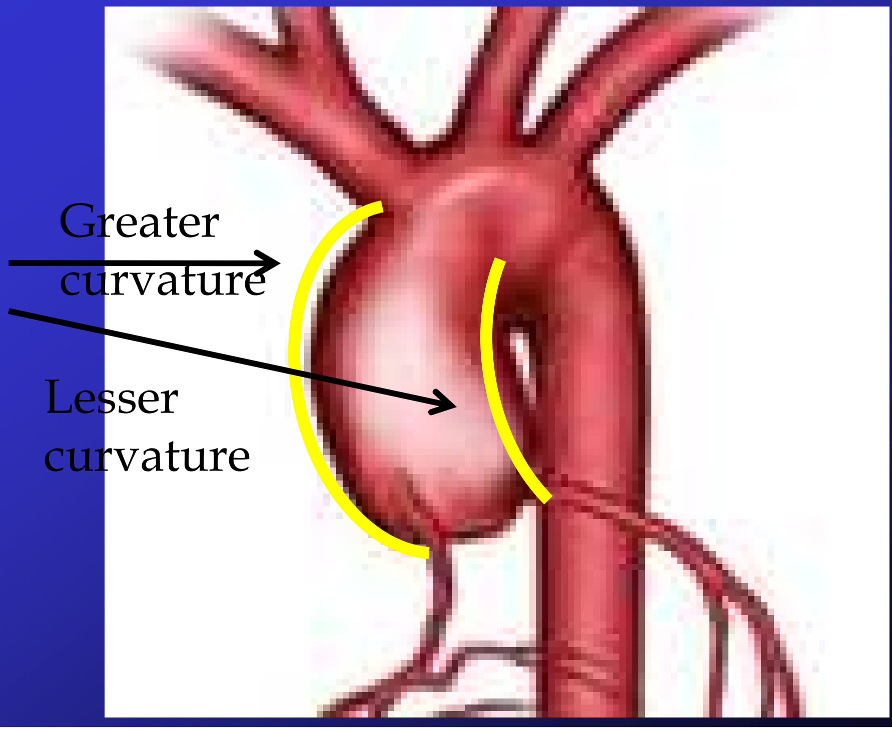
Objective

- Measurement of Maximum Elastic Modulus of aortic tissue from ATAA using uniaxial tensile testing
- Assessment of the influence of several parameters :
  - Stretch orientation



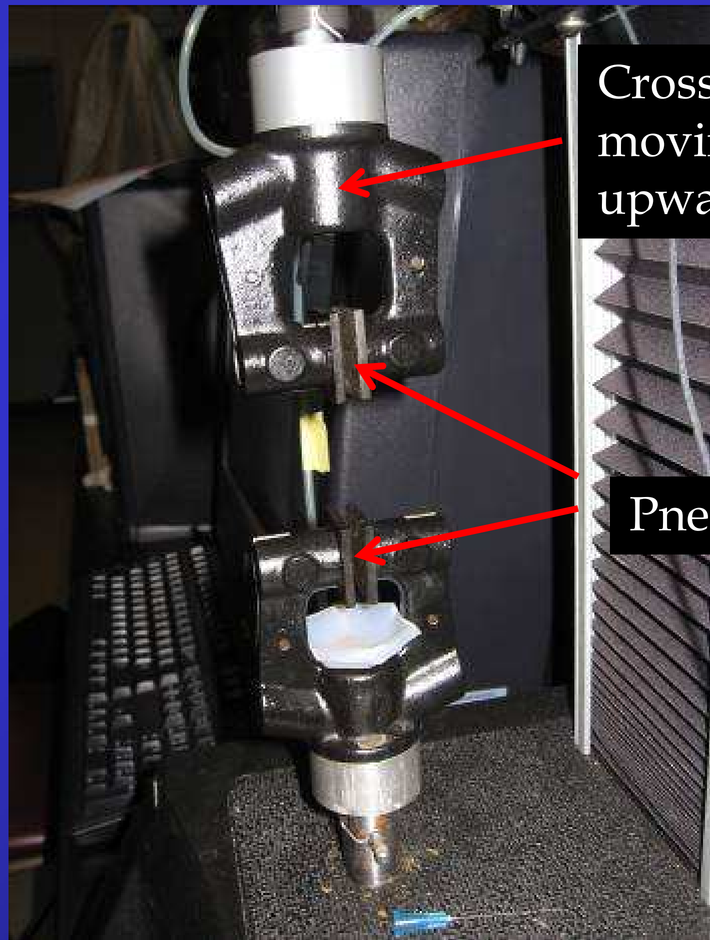
Objective

- Measurement of Maximum Elastic Modulus of aortic tissue from ATAA using uniaxial tensile testing
- Assessment of the influence of several parameters :
  - Location of the tissue



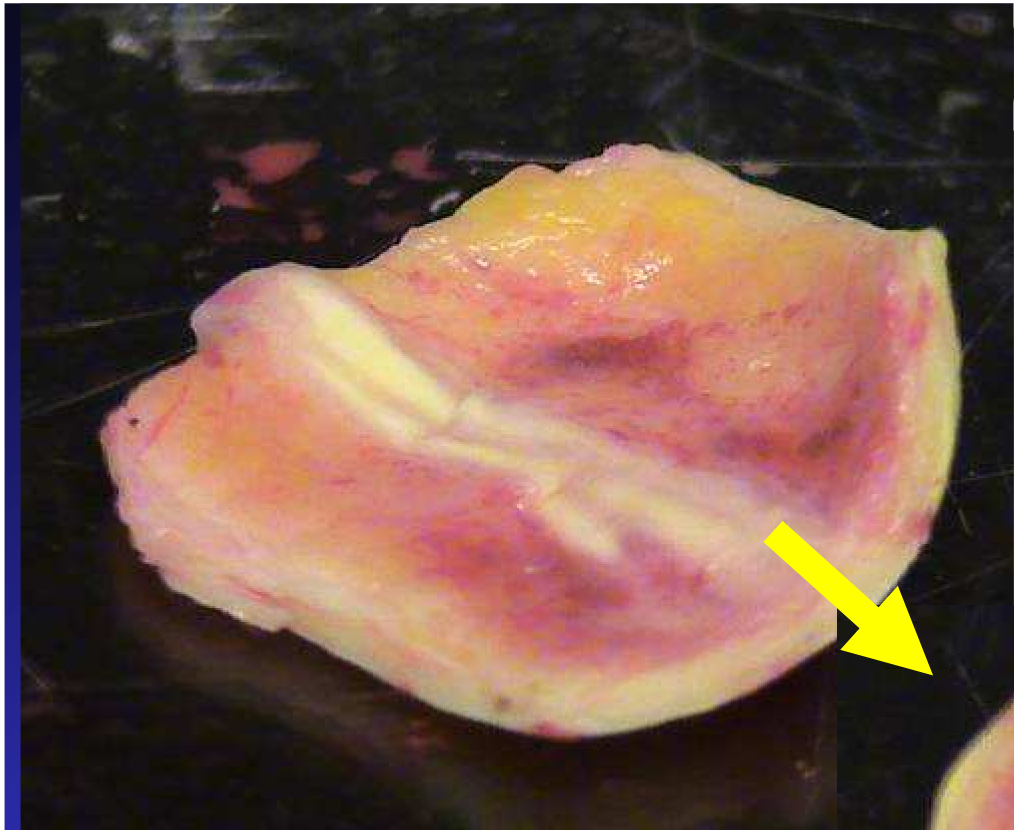
Materials and Methods

Tensile testing machine used for uniaxial mechanical testing

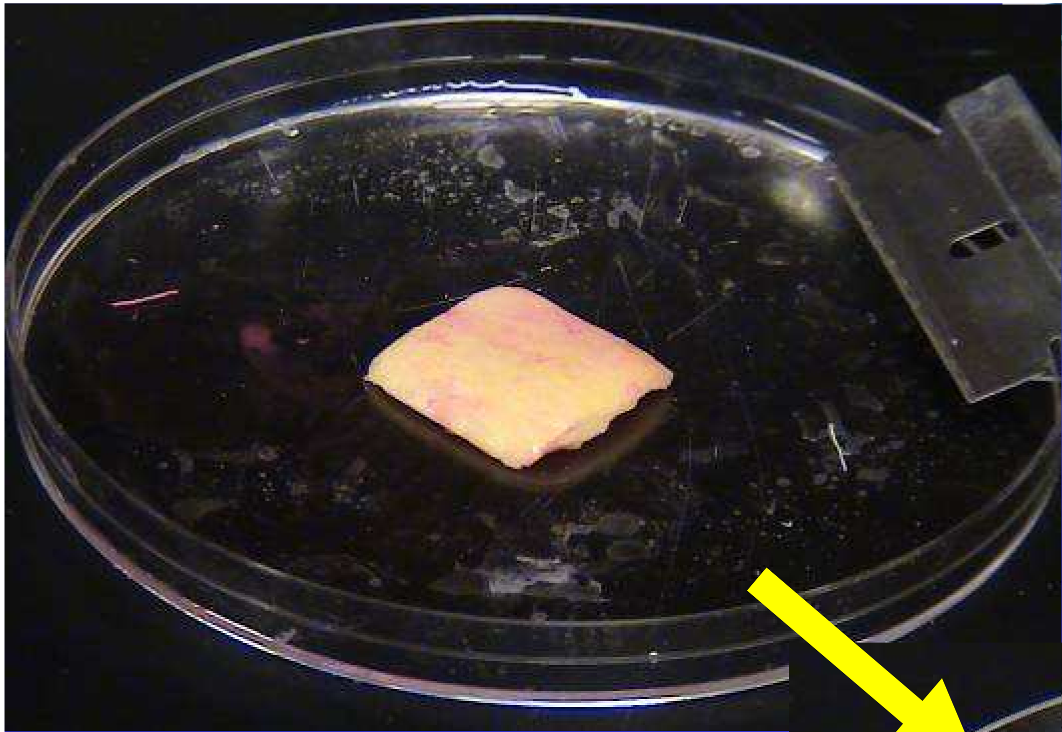


Materials and Methods

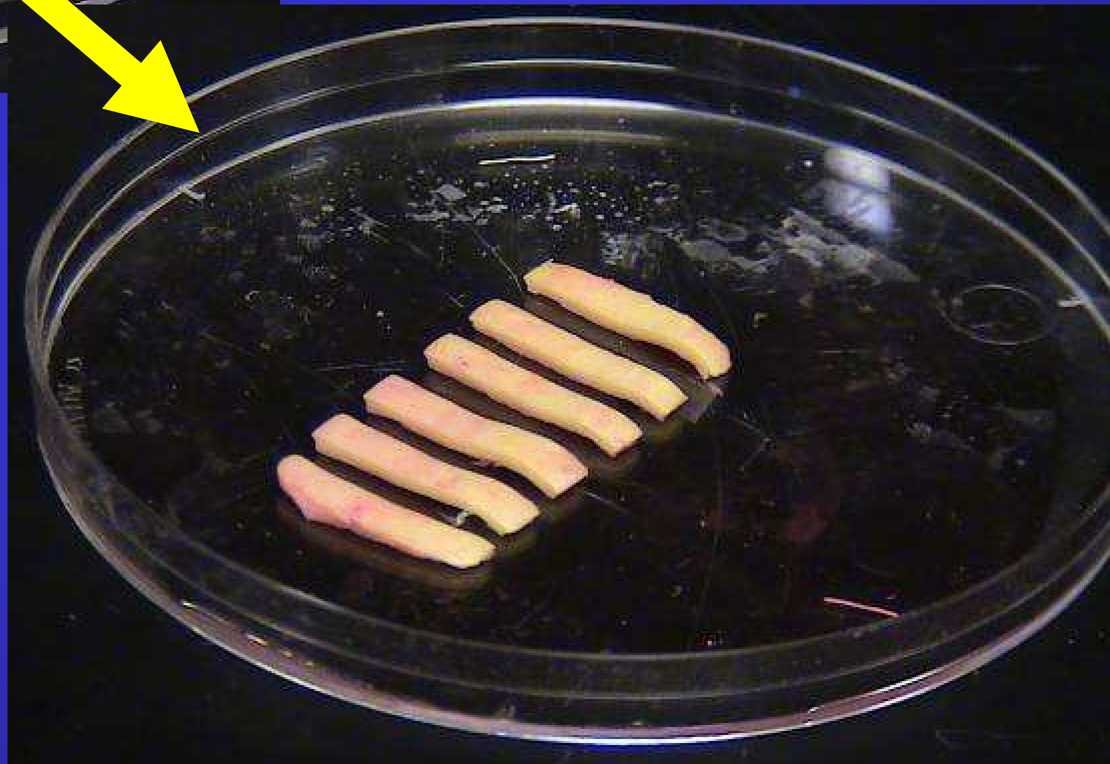
- Tissue freshly excised
- 86 specimens from 13 patients
- 7 bicuspid aortic valve
- Custom-designed tissue cutters
- Tested within 48h
- Preconditioning
- Cross head speed: 10mm/min

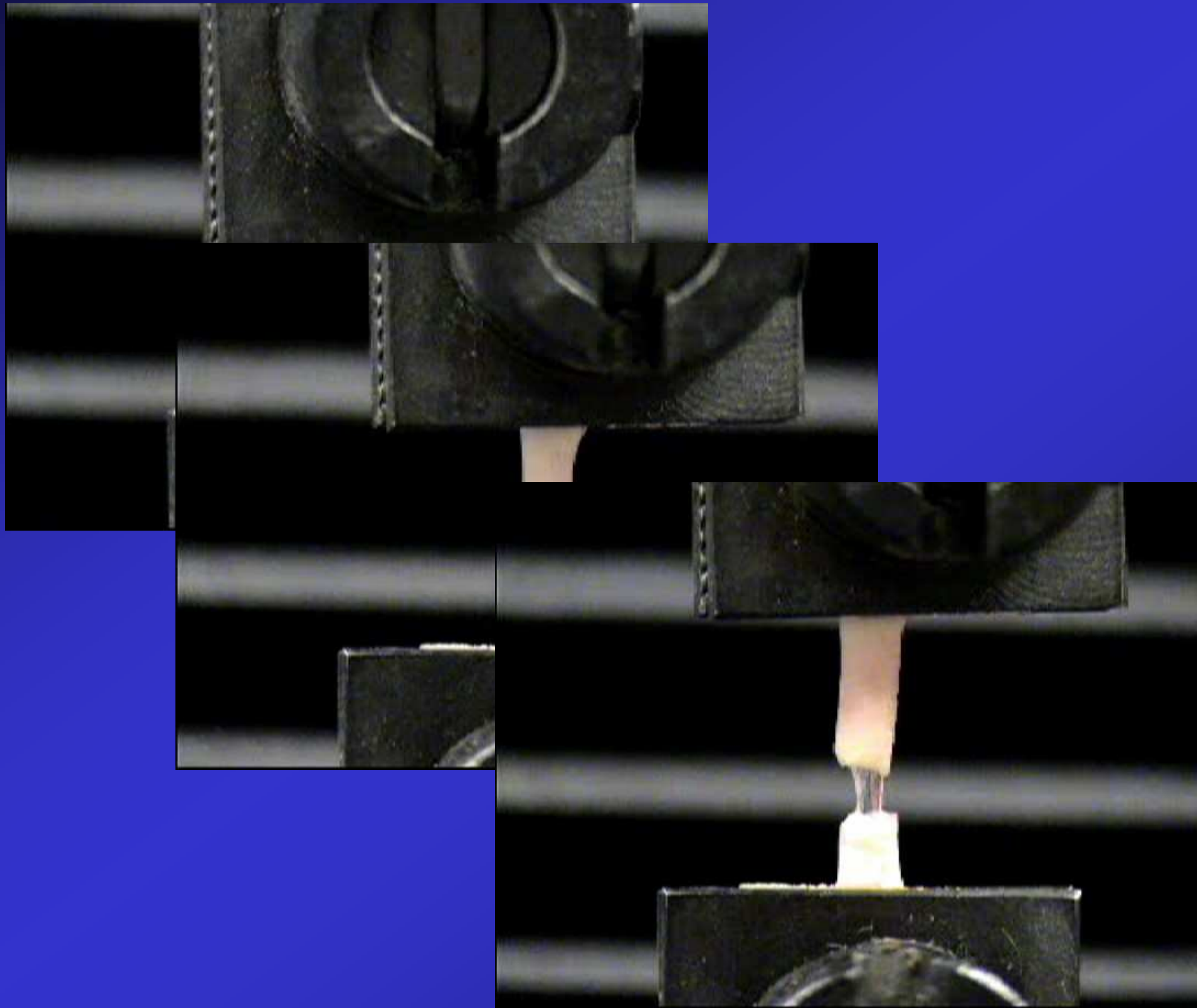


Adipose and loose connective tissue on the adventitial side of each specimen is removed

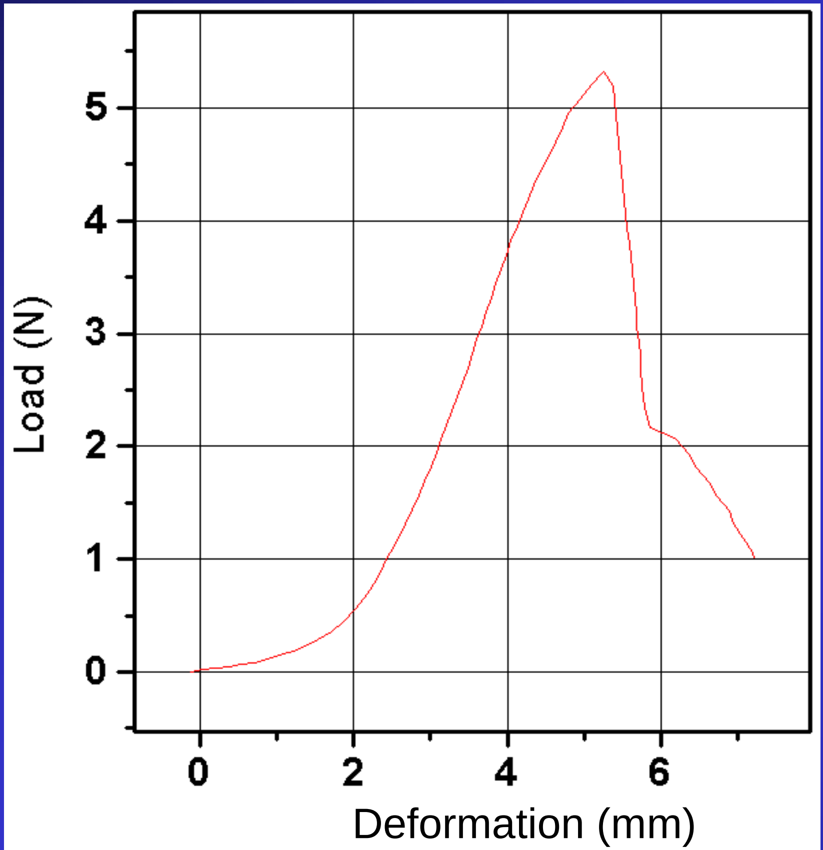


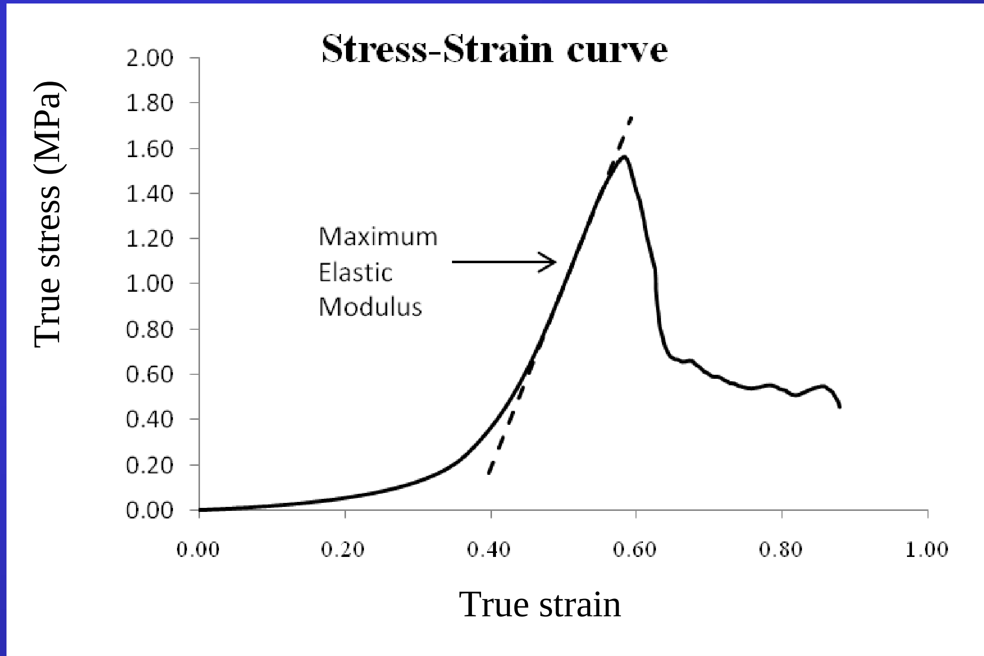
Tissue is cut along one chosen direction (longitudinal or circumferential) into strips of nearly equal width





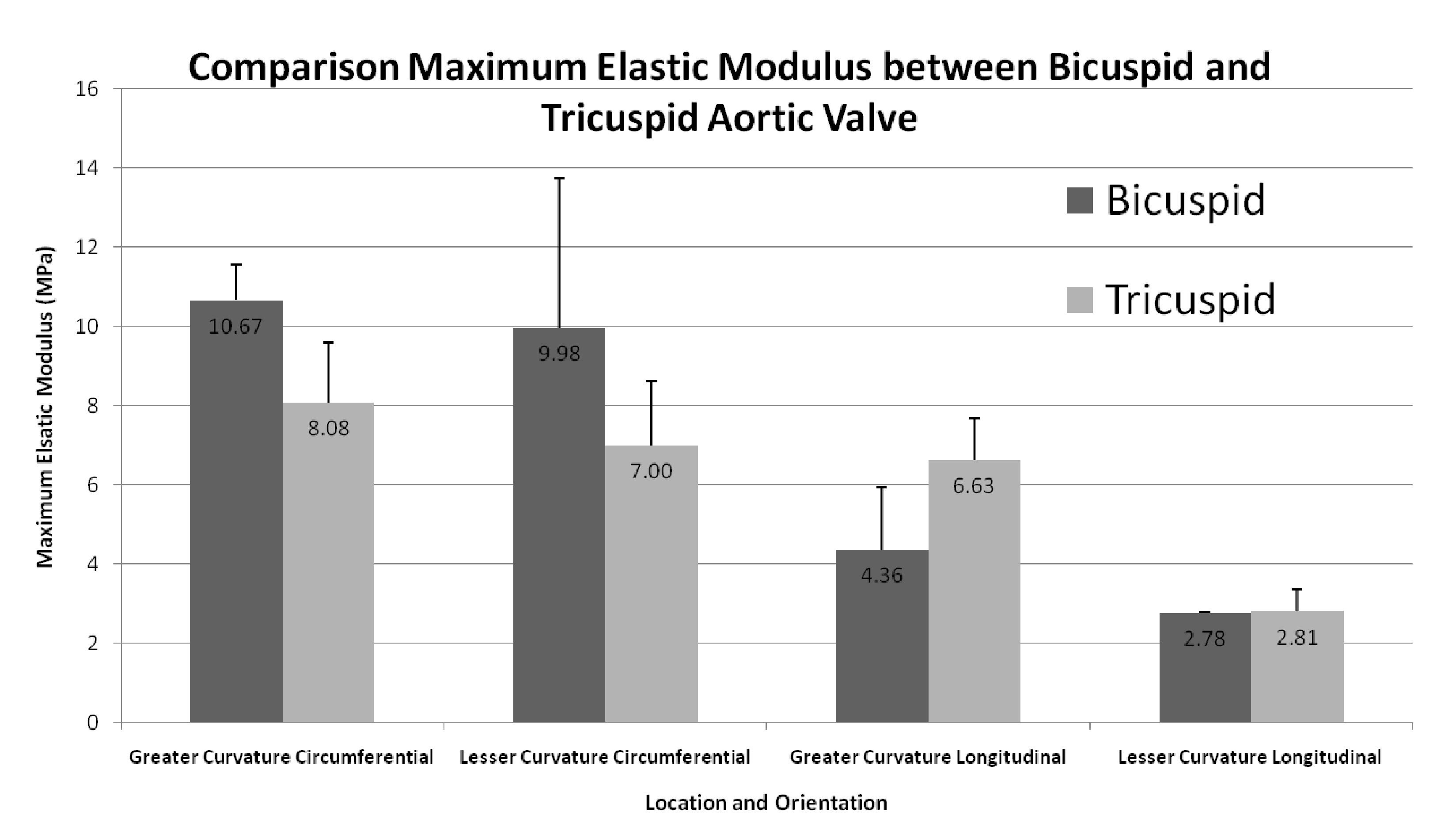
Data processing





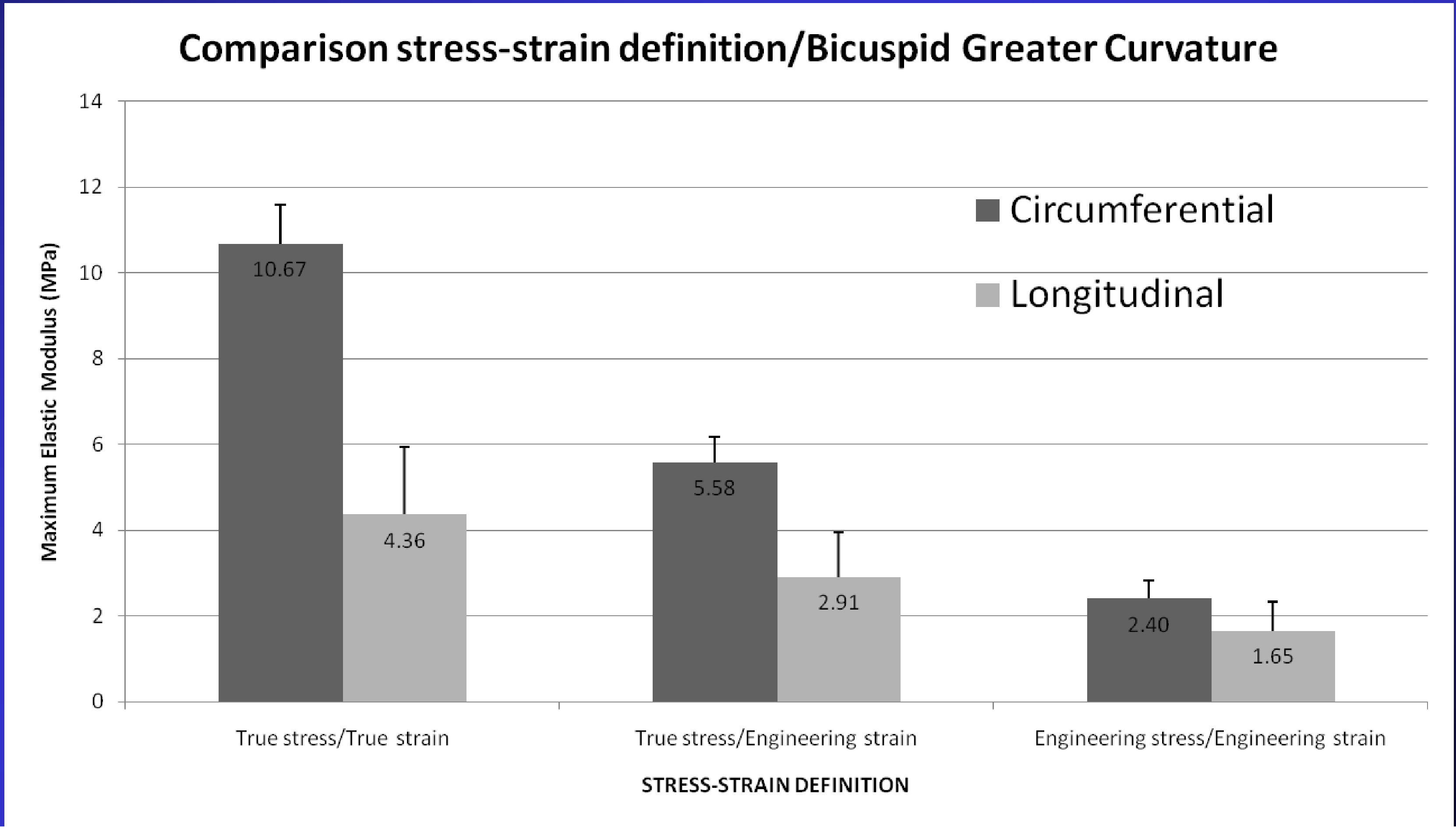
Results

- Influence of valve type and tissue location



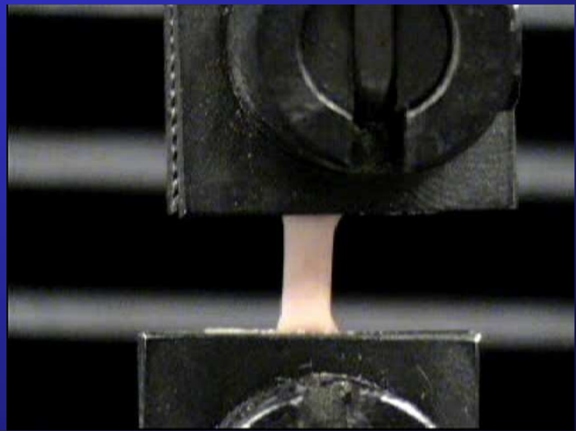
Results

- Strong influence of the stretch orientation

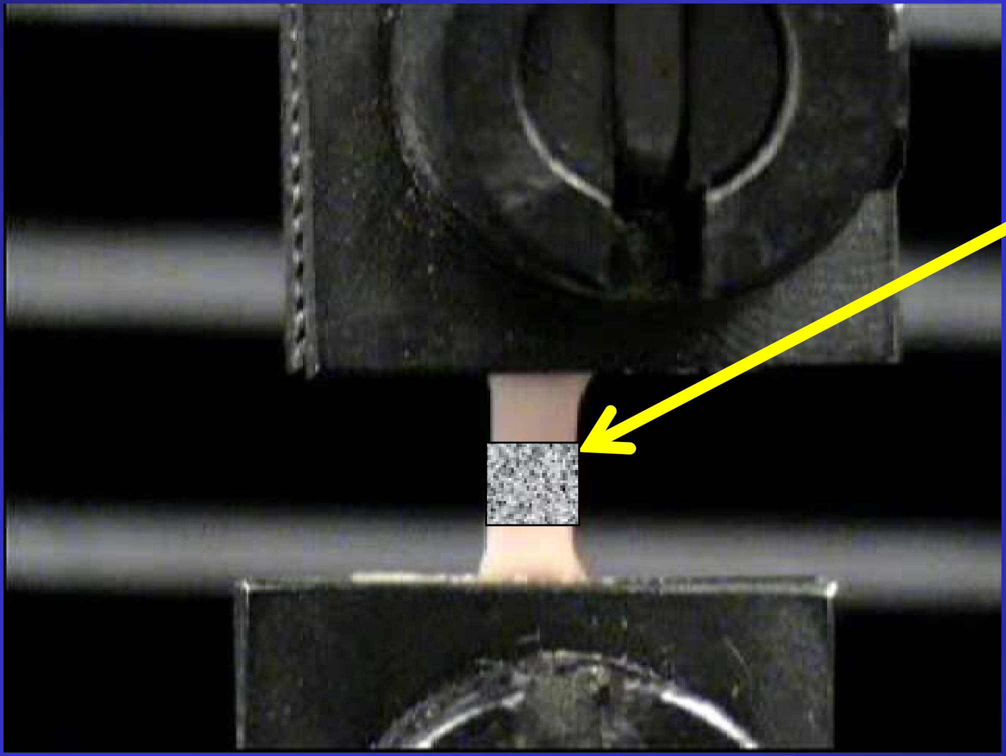


Conclusion

- Evidence of strong anisotropy
- But lots of testing issues…



Current and future work



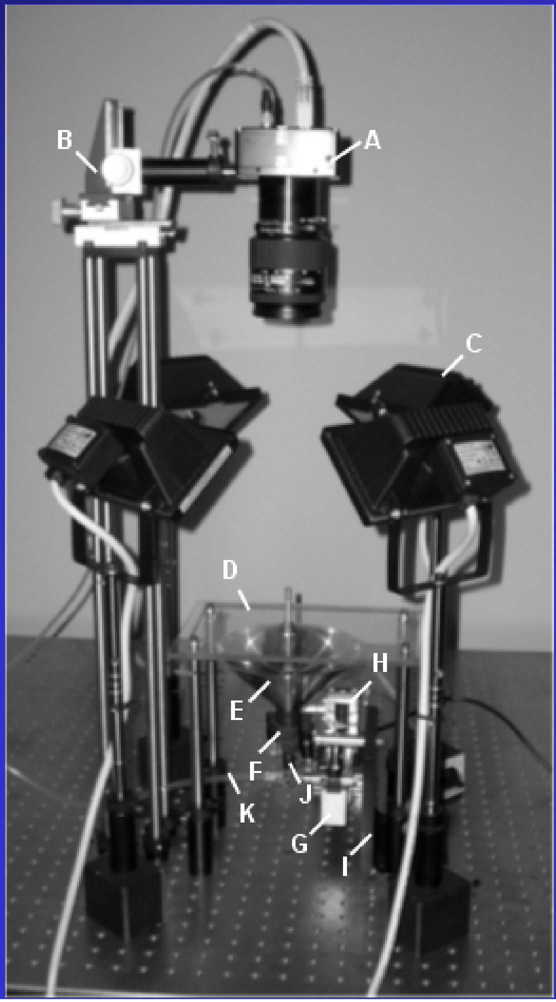
Digital image correlation

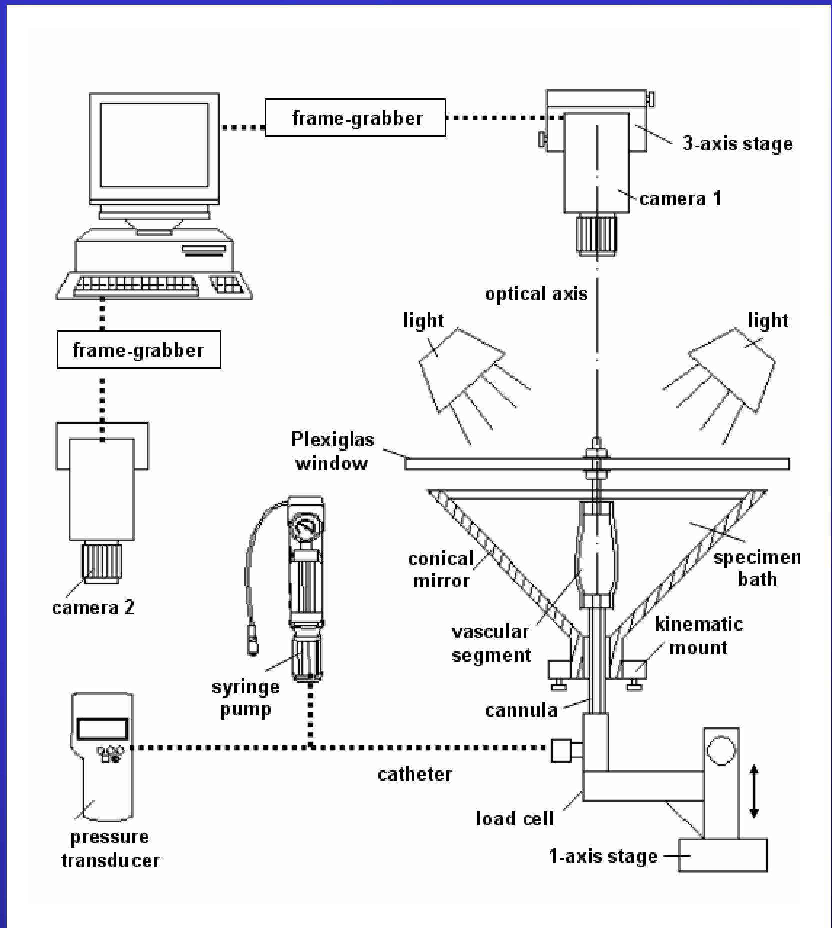
Inverse approach

On-going research at Saint-Etienne

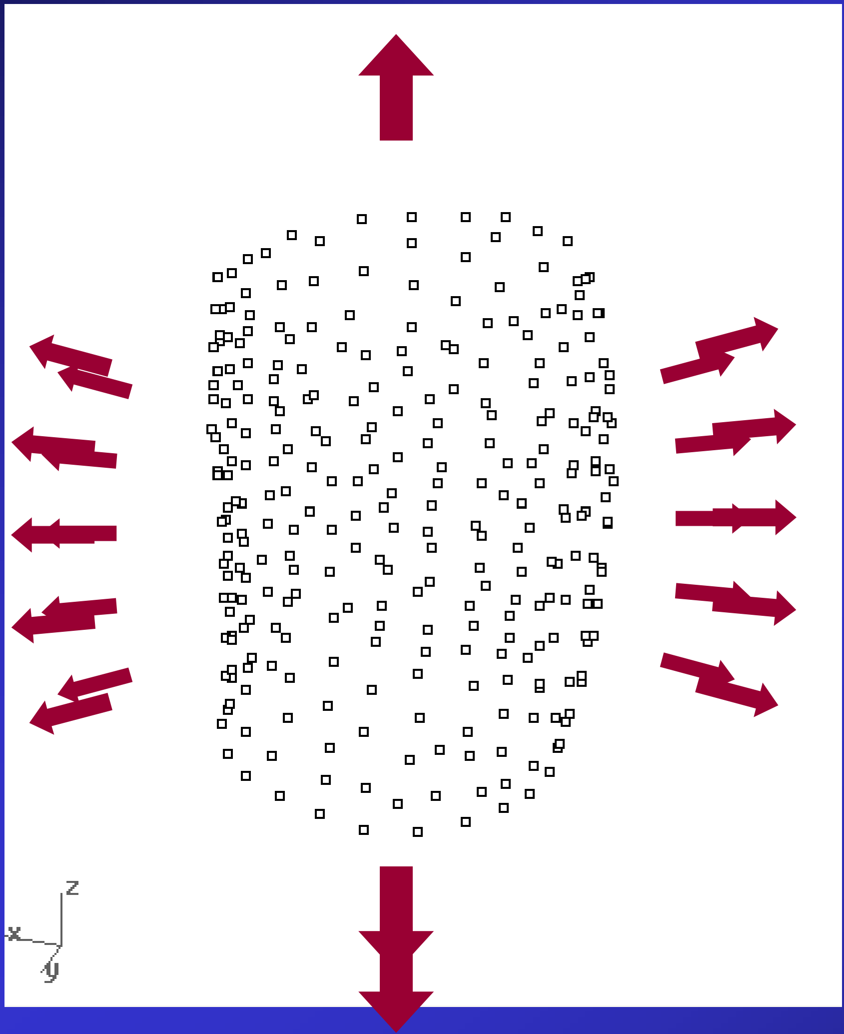
- Uniaxial tensile tests on strips
- **Biaxial tests on whole segments**
- In vivo measurements

New testing system developed by Dr. Katia Genovese





Deformation of the whole segment



Testing:

→ Preconditioning

8 pressure cycles 0 → 120 mmHg

8 axial cycles $\lambda_z = 1.1 \rightarrow \lambda_z = 1.4$

→ Applying axial pre-stretching

$\lambda_z = 1.1$

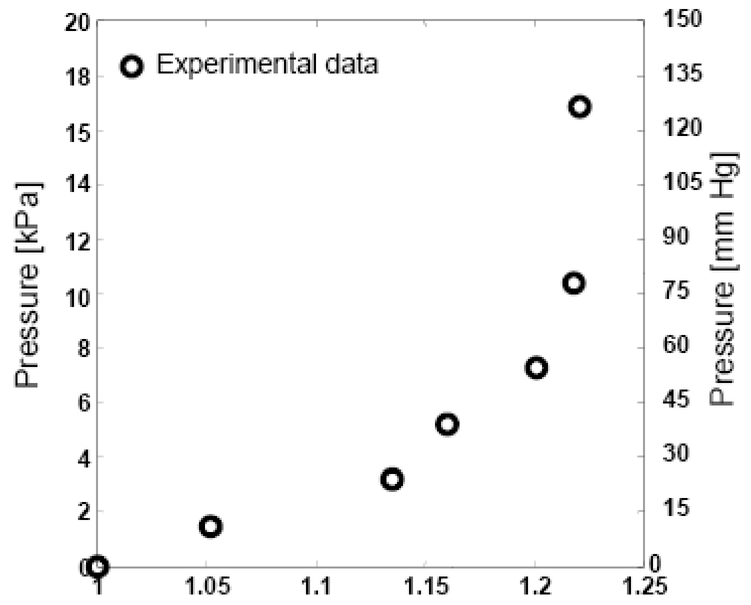
→ Applying pressure

pressure 0 mmHg → 130 mmHg

pressure rate 12 mmHg/s

Identification

Analysis of the global response



Circumferential stretch

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Identification

Simplifying assumptions :

- Constant thickness
- Homogeneous behaviour
- Isotropic hyperelasticity:

hyperelastic potential

Deformation gradient

$$\underline{\underline{\sigma}} = \rho\left[\left(2\frac{\partial \Psi}{\partial I_1} + 2I_1\frac{\partial \Psi}{\partial I_2}\right)\underline{\underline{F}}.^t\underline{\underline{F}} - 2\frac{\partial \Psi}{\partial I_2}\underline{\underline{F}}.^t\underline{\underline{F}}.\underline{\underline{F}}.^t\underline{\underline{F}}\right] + c\underline{\underline{I}}$$

invariants of the Cauchy tensor

Incompressibility condition

Fung strain energy function: $\Psi = C_{10}\left[e^{k(I_1-3)} - 1\right]$

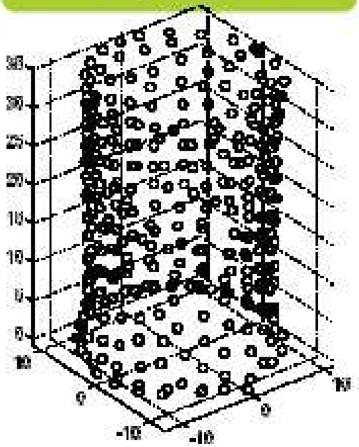
Identification

FE-based invert method

7 steps :

- Full field measurements
- Numerical geometry
- Realistic BC
- Constitutive equations
- Numerical response
- Cost function
- Minimization

Exp. data



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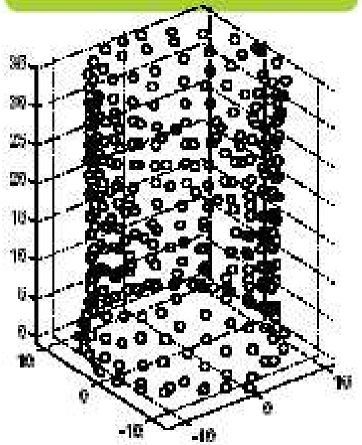

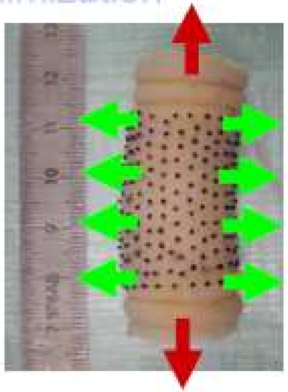

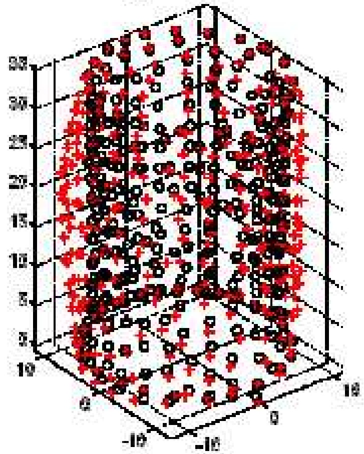

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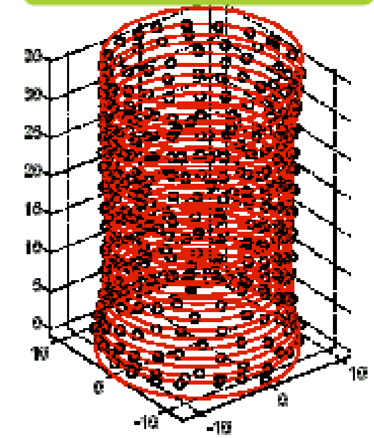
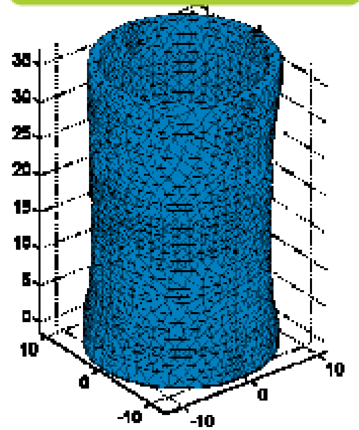
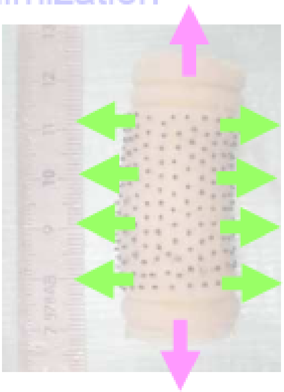


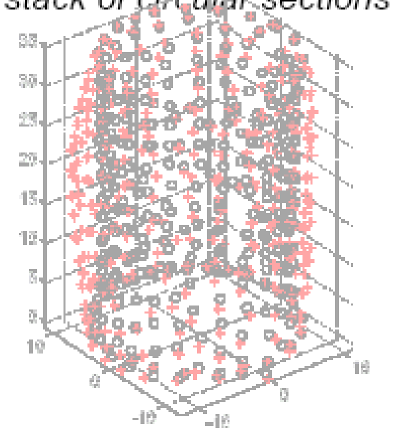
stack of circular sections

Num. model



homogeneous thickness
5000 tetrahedrons





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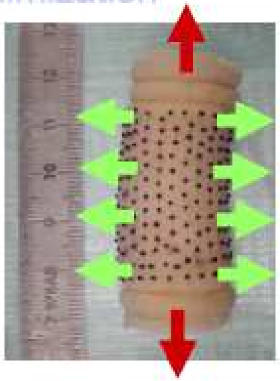

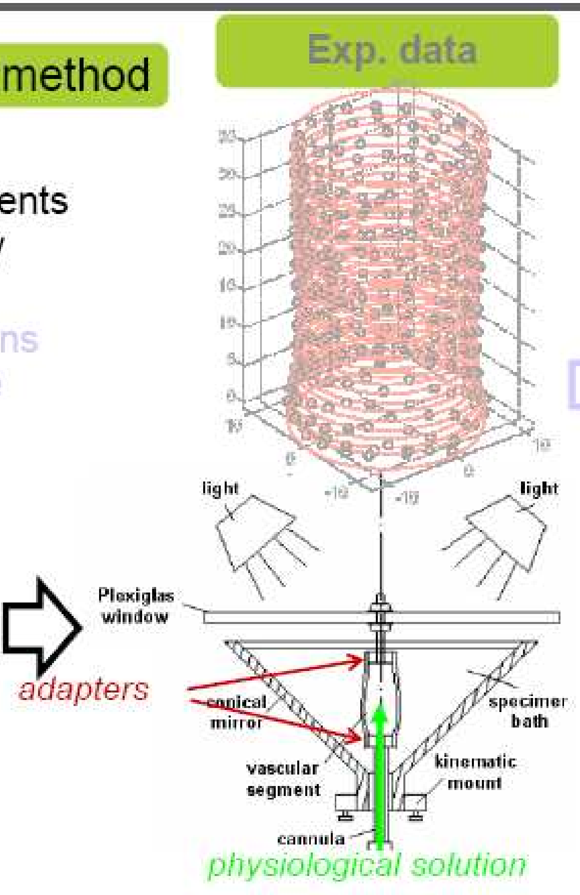

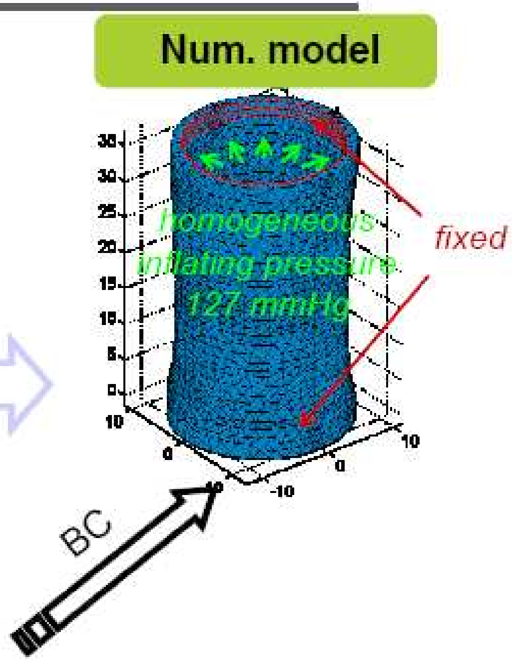

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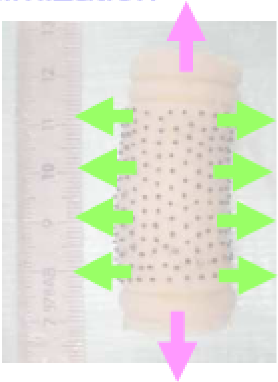
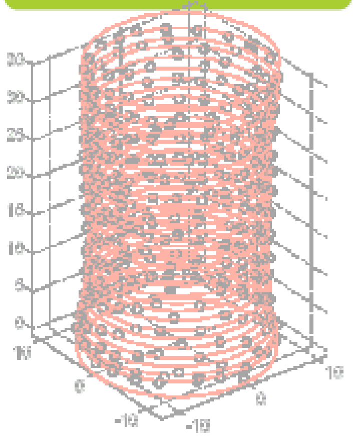
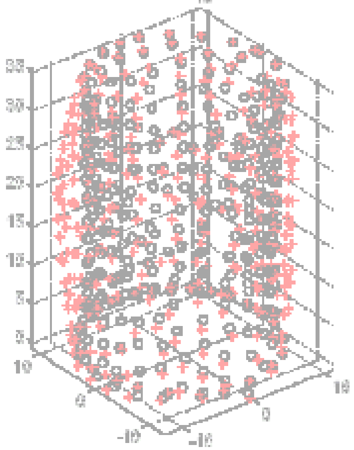
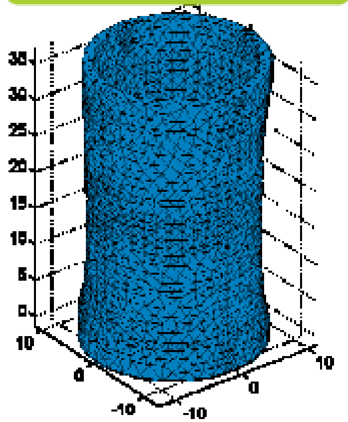


Exp. data





Num. model



$$C_{10}\left[e^{k(I_1-3)}-1\right]$$

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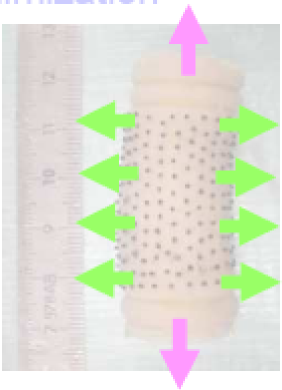

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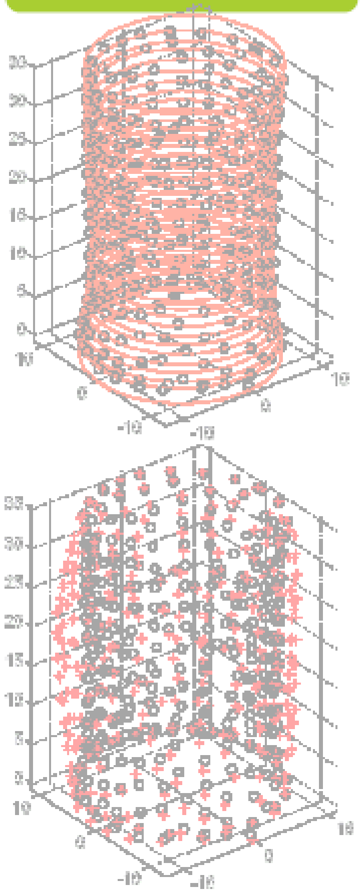

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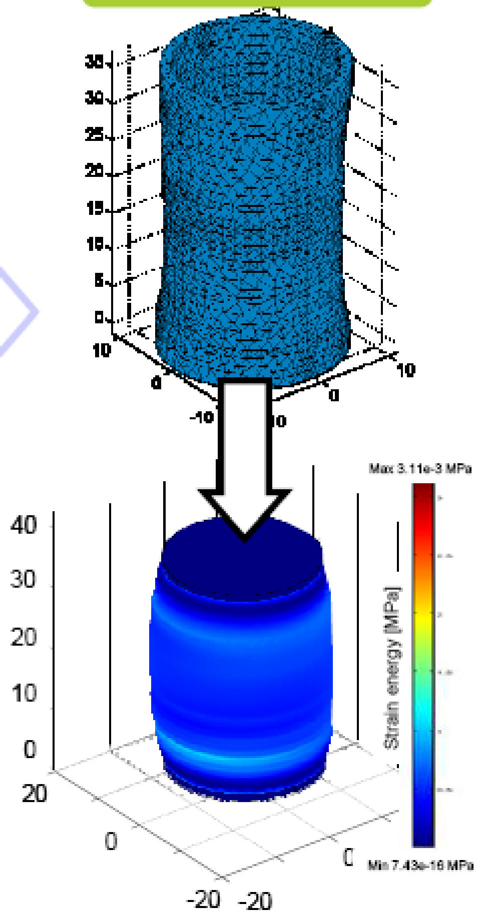

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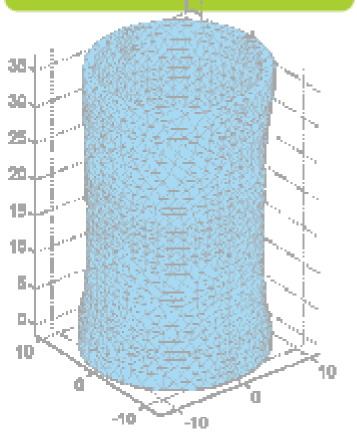
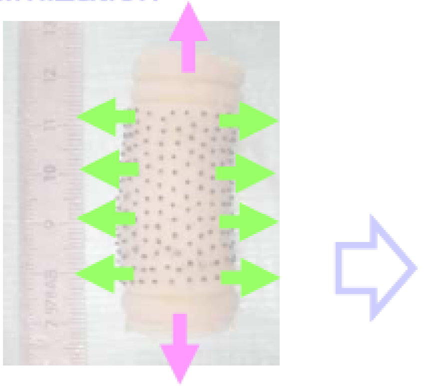
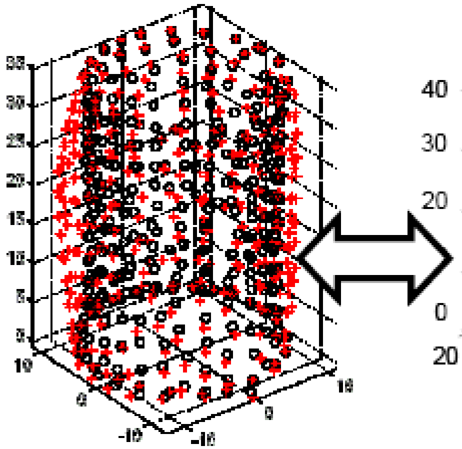
Exp. data

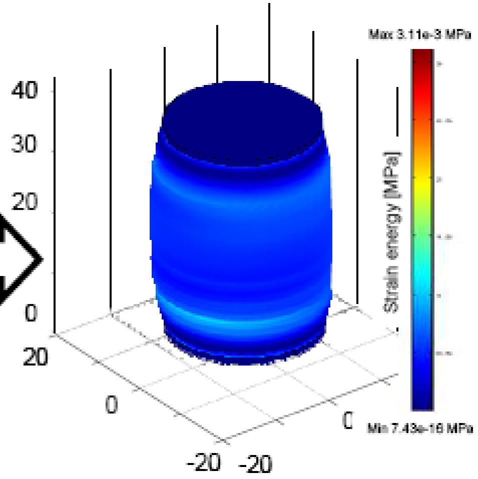
Num. model

$$F_c = \frac{1}{n}\sum_{i=1}^{n} \frac{\left\| \mathbf{U}^i_{\exp} - \mathbf{U}^i_{num} \right\|}{\left\| \mathbf{U}^i_{\exp} \right\|}$$









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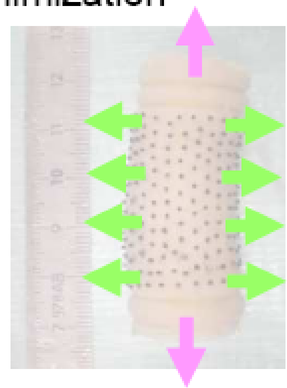
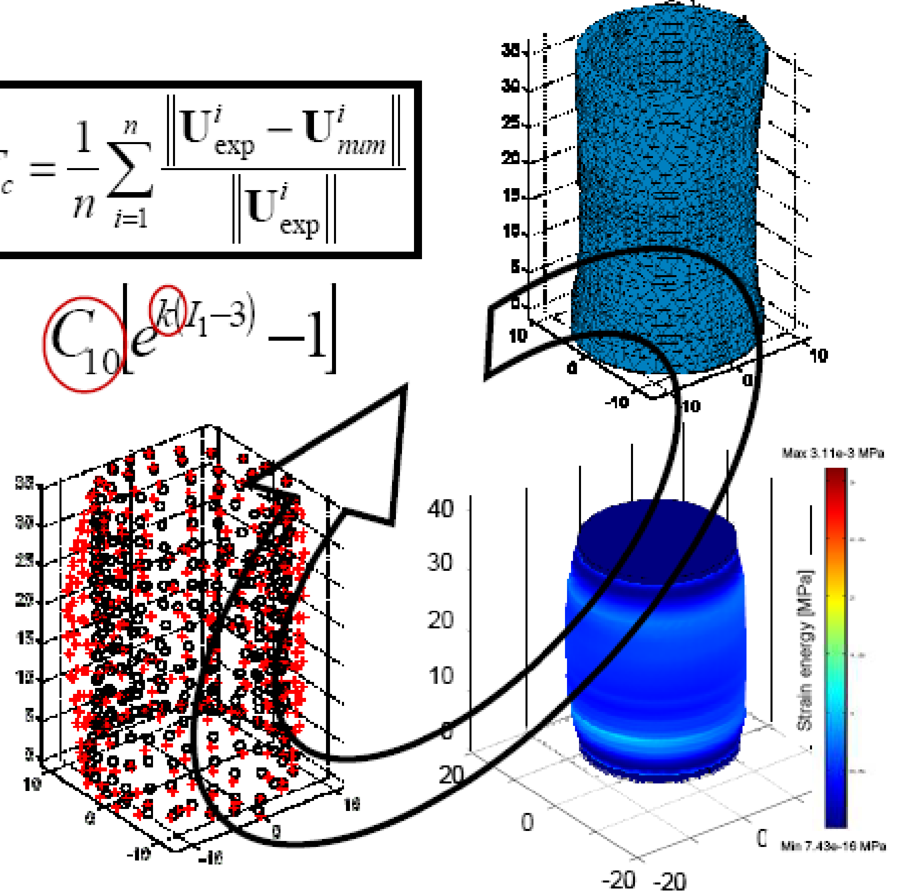


Exp. data

Num. model

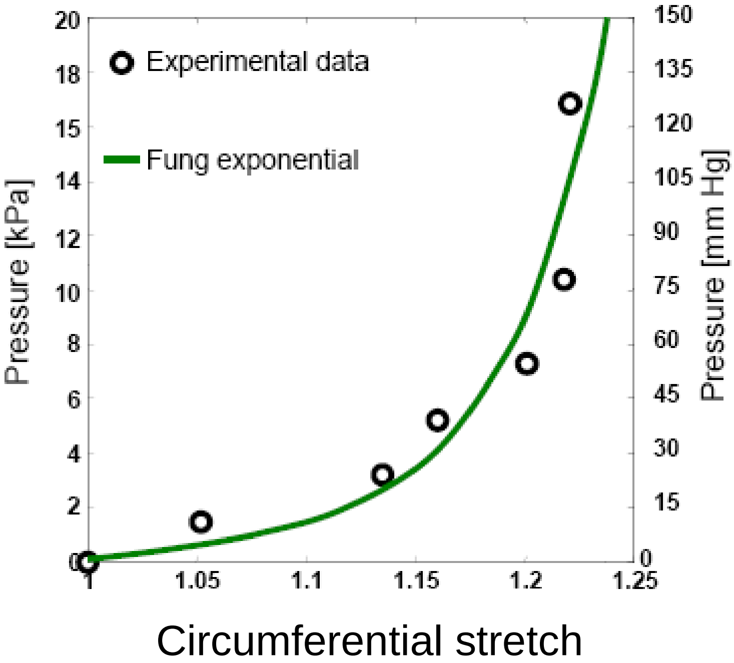
$$\boxed{F_c = \frac{1}{n}\sum_{i=1}^{n} \frac{\left\|\mathbf{U}^i_{\exp} - \mathbf{U}^i_{num}\right\|}{\left\|\mathbf{U}^i_{\exp}\right\|}}$$

$$C_{10}\left[e^{k(I_1-3)} - 1\right]$$



Identification

Results and comparison with the global response



→ **Fung exponential**

$$\Psi = C_{10}\left[e^{k(I_1-3)} - 1\right]$$

→ **with**

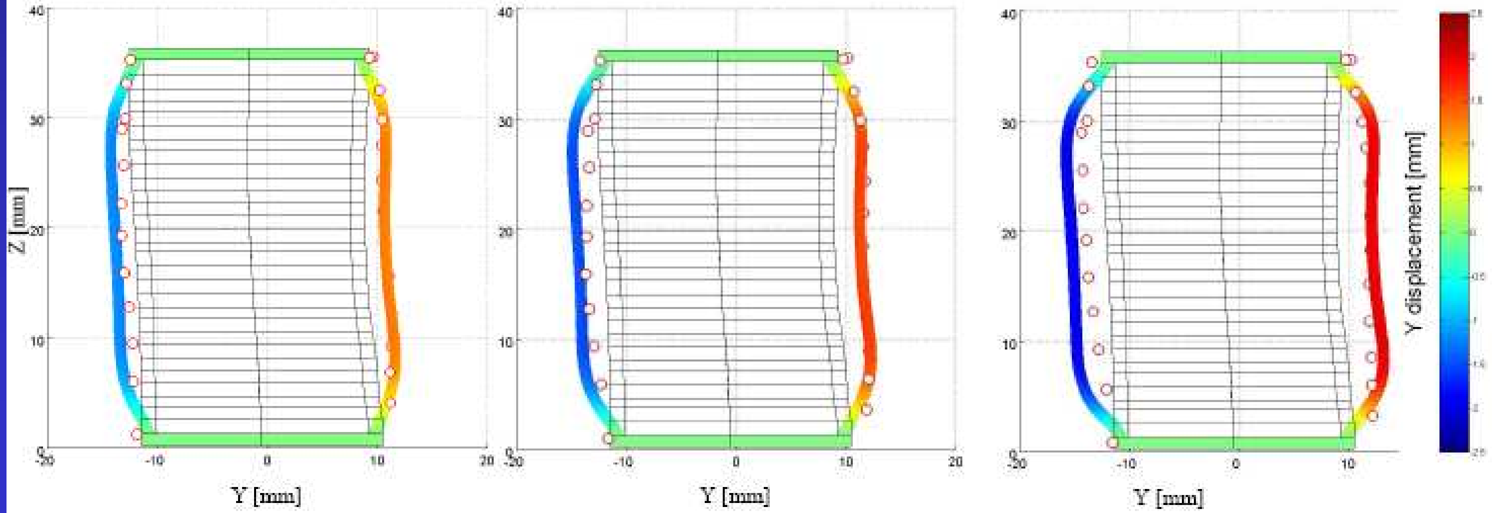
$C_{10} = 7.8\times10^{-4}$ MPa
$k = 13.8$

Validation study on human aorta

Results

→ Hyperelastic behavior :

Local heterogeneities
(mechanical properties, thickness, branches)

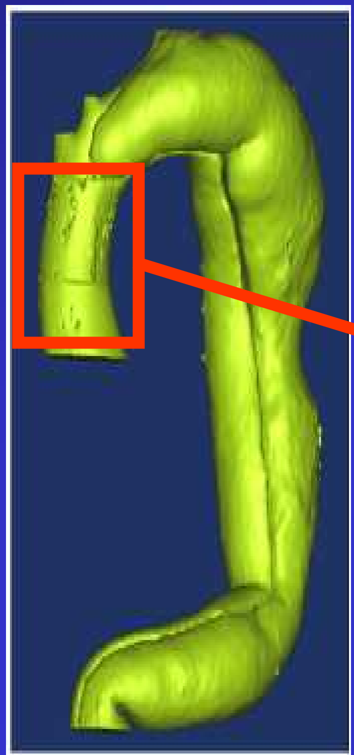


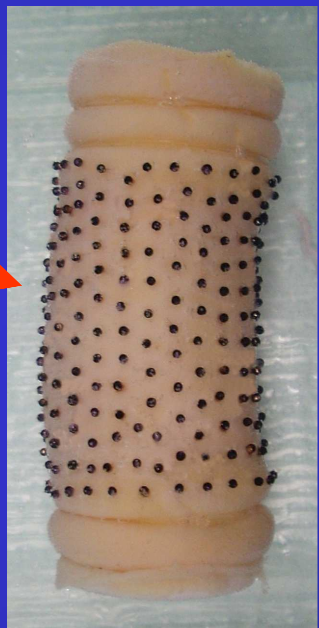
P = 24 mmHg   P = 55 mmHg   P = 127 mmHg

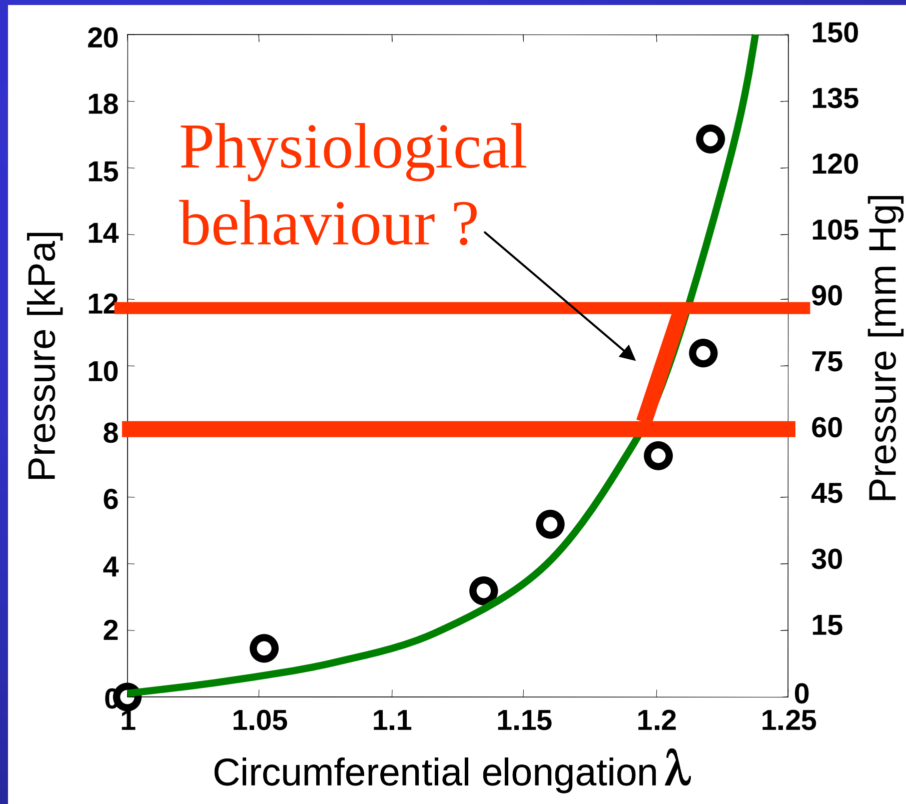
Current and future work

- Validation and identifiability verification
- Identification of spatial variations of the mechanical properties with longer segments
- Application of the procedure to multi-layer anisotropic hyperelastic models

Unsolved issue: where is the physiological behaviour?







On-going research at Saint-Etienne

- Uniaxial tensile tests on strips
- Biaxial tests on whole segments
- **In vivo measurements**

Measurement of the motions of arterial walls with CT scans

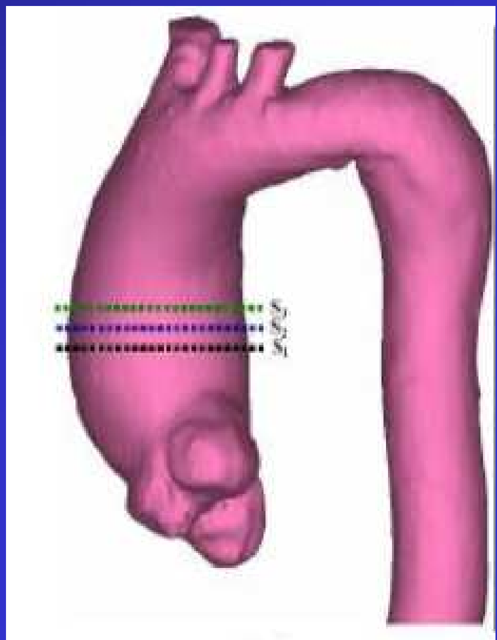
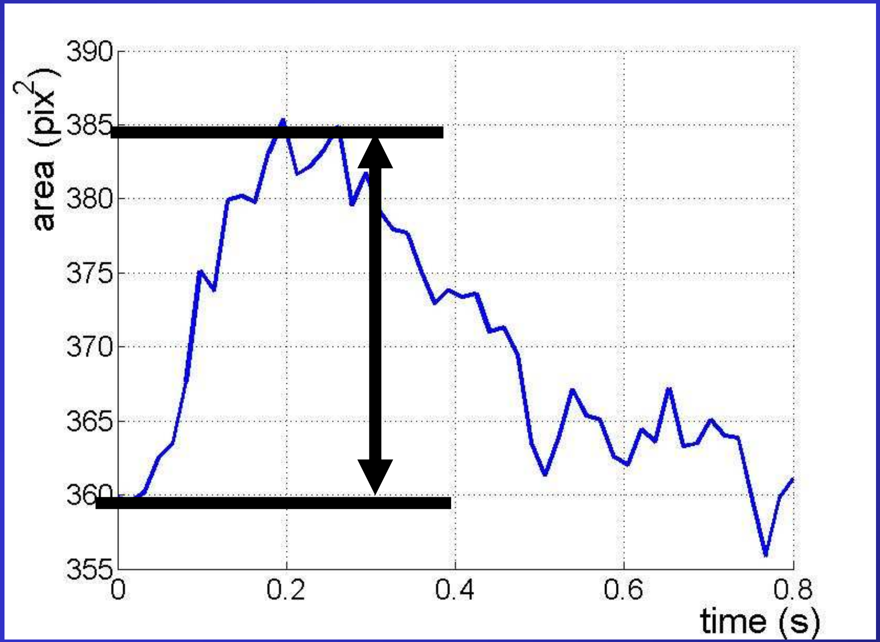
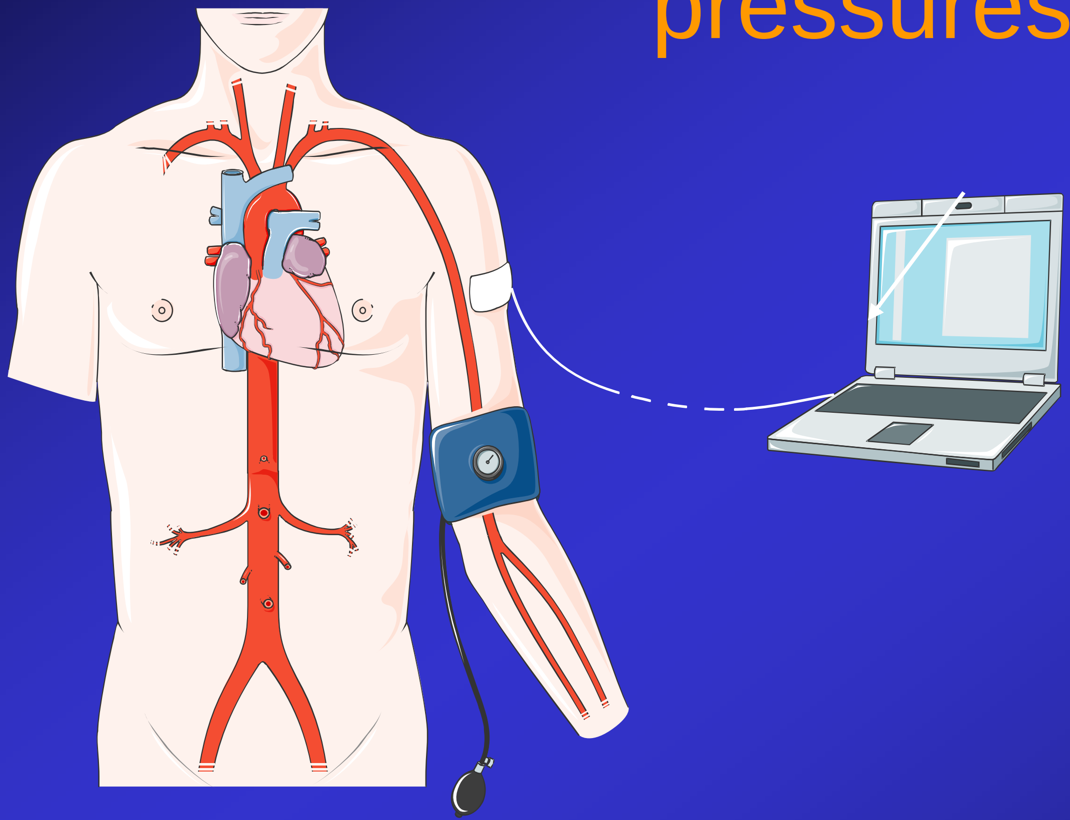


Image segmentation → Cross sectional area



$\varepsilon = dR/R_0 = dA/2A_0 = 0.035$

Measurement of diastolic and systolic pressures



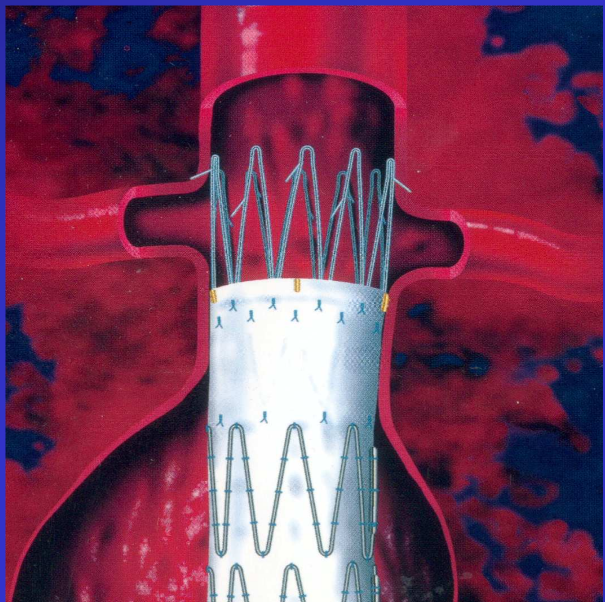
$\sigma = p\, R_0/e = 50 \times 0.13 \times 5/0.6 = 54.2$ kPa

$\mathbf{E = \sigma / \varepsilon = 1.5}$ **MPa**

Current and future work

- Update of pressure measurements
- 3D geometry reconstruction and deformation analysis
- Application to patients who need an excision for comparing in vivo and ex vivo properties

Unsolved issue: behaviour outside the physiological range



CONCLUSION

- Complementarity of in vivo et ex vivo approaches for characterizing the elastic properties of arteries
- What about viscoelasticity?
- What about fracture?