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Instituts thématiques Inserm

SAINBIOSE
Santé, Ingénierie, Biologie, Saint Etienne

LUX ET VERITAS
YALE

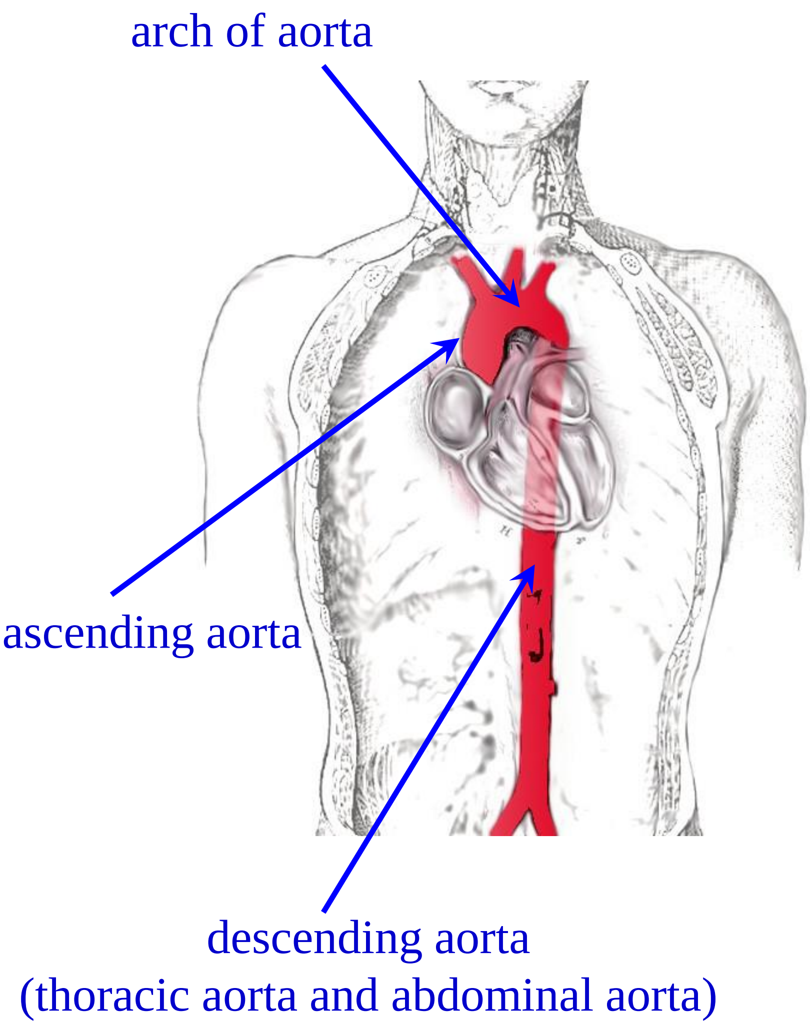
Mechanics and mechanobiology of the wall of the thoracic aorta

Stéphane AVRIL

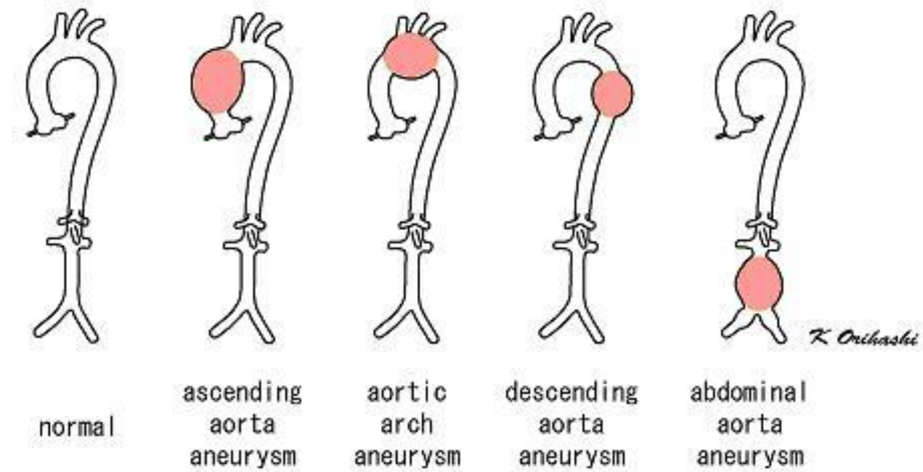
UJM EMSE.SE MOD MAD

INSPIRING INNOVATION INNOVANTE PAR TRADITION

AORTIC ANEURISMS



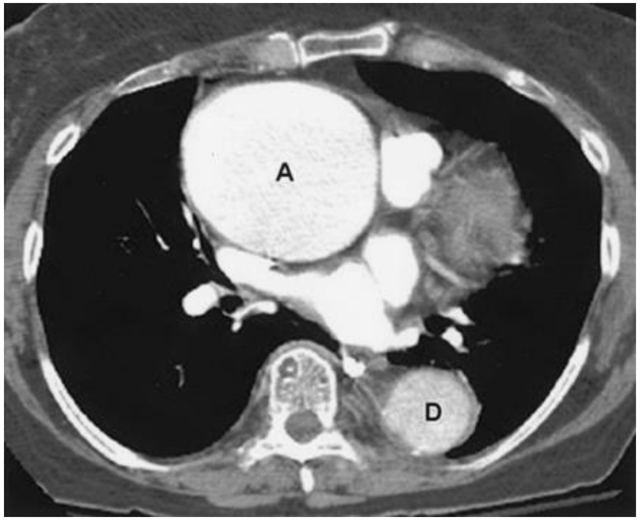
- a local dilation of the aorta due to aortic wall weakening

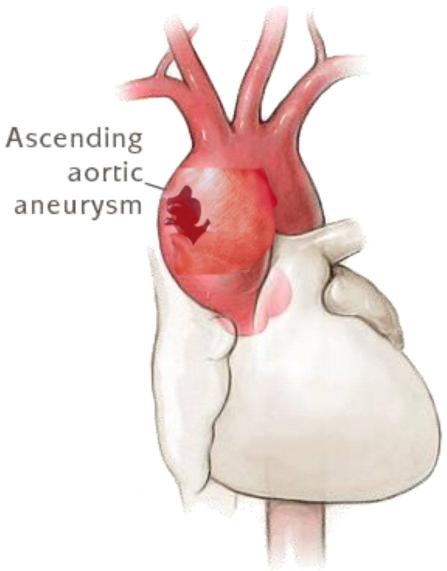


Various aortic aneurysms

SOCIETAL AND MEDICAL ISSUES

Thoracic aortic aneurysms per year: 15000 people in the US, +30000 people in Europe with a male preponderance. 50-60% involves the ascending aorta.





How can we predict the aneurysm's rupture?

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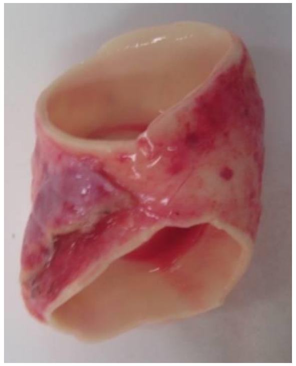
Characterization of the modes of rupture

Romo et al. Journal of Biomechanics - 2014.

Circumferential

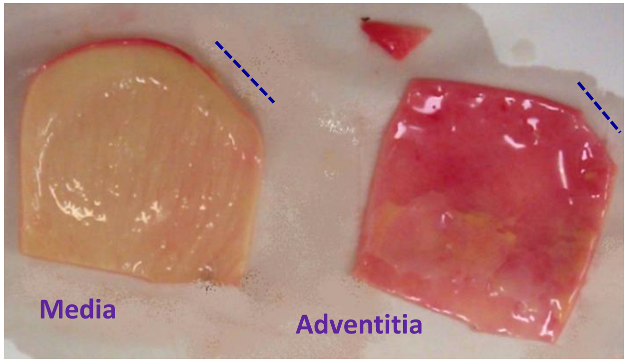
Axial



I) Aneurysm excised specimen.

Circumferential

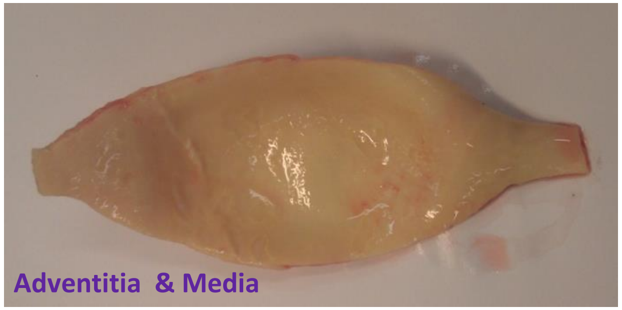
Axial



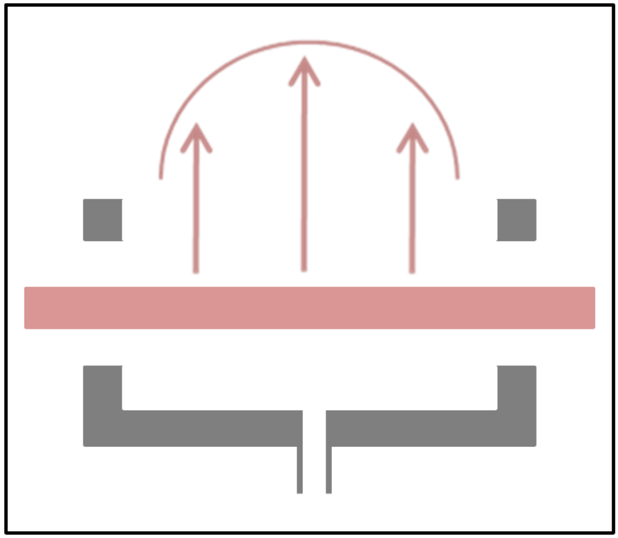
II) Separation of Media and Adventitia.

Circumferential

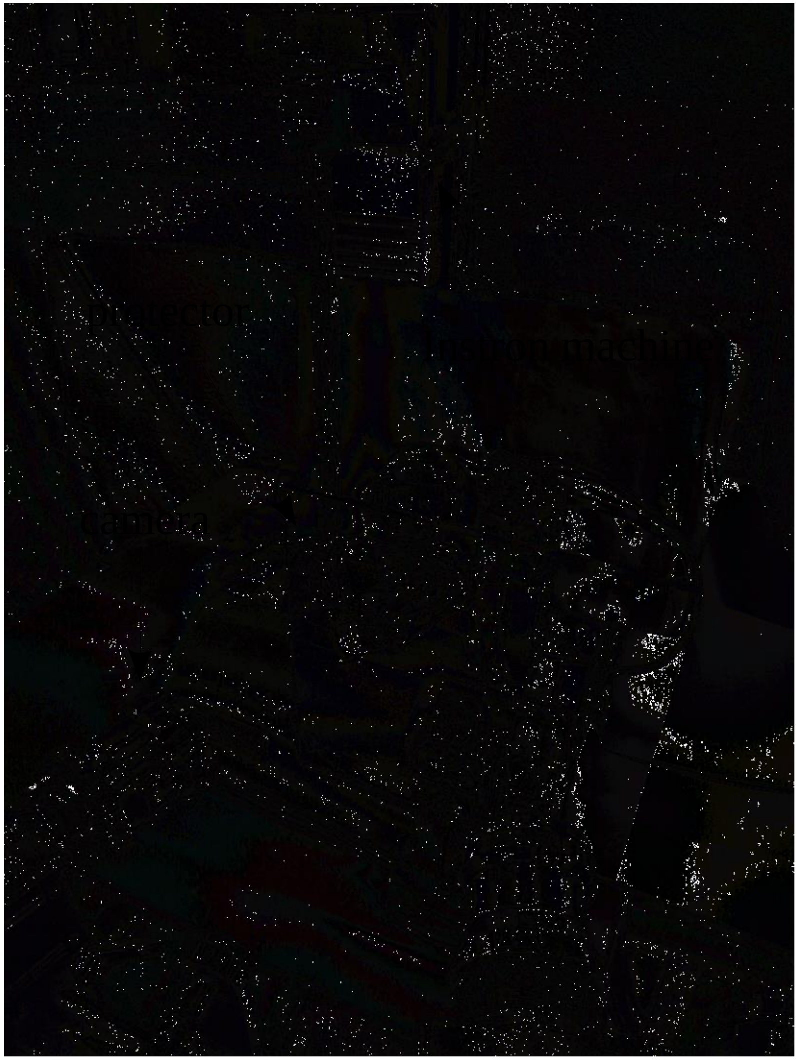
Axial



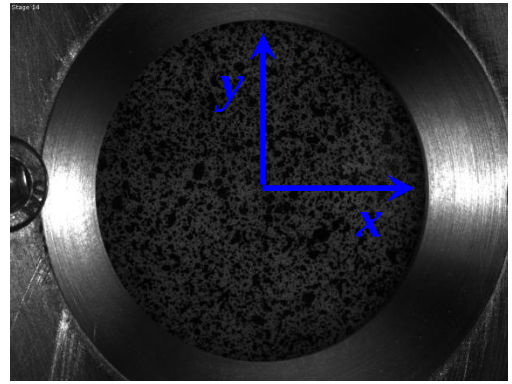
II) Media and Adventitia.



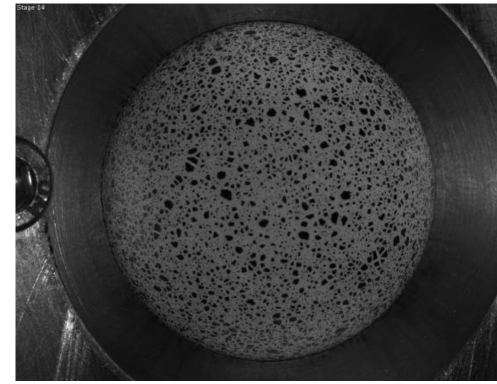
Full-field measurements

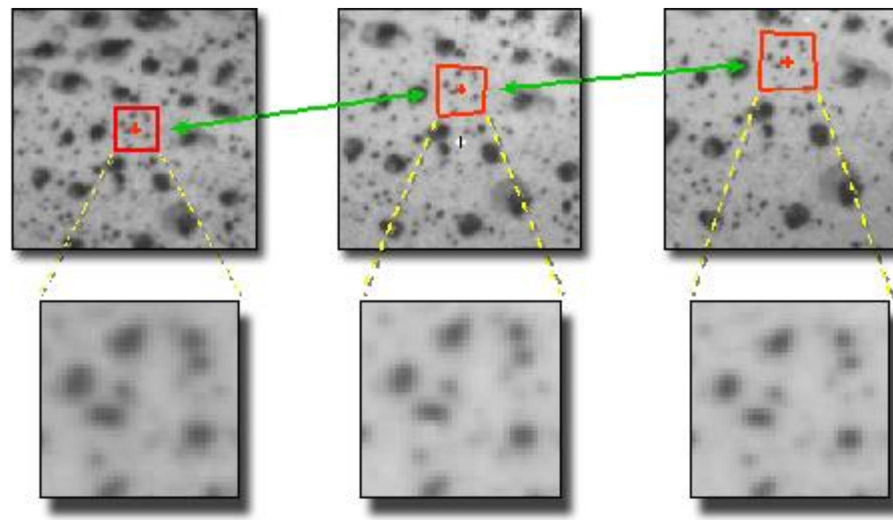


Undeformed

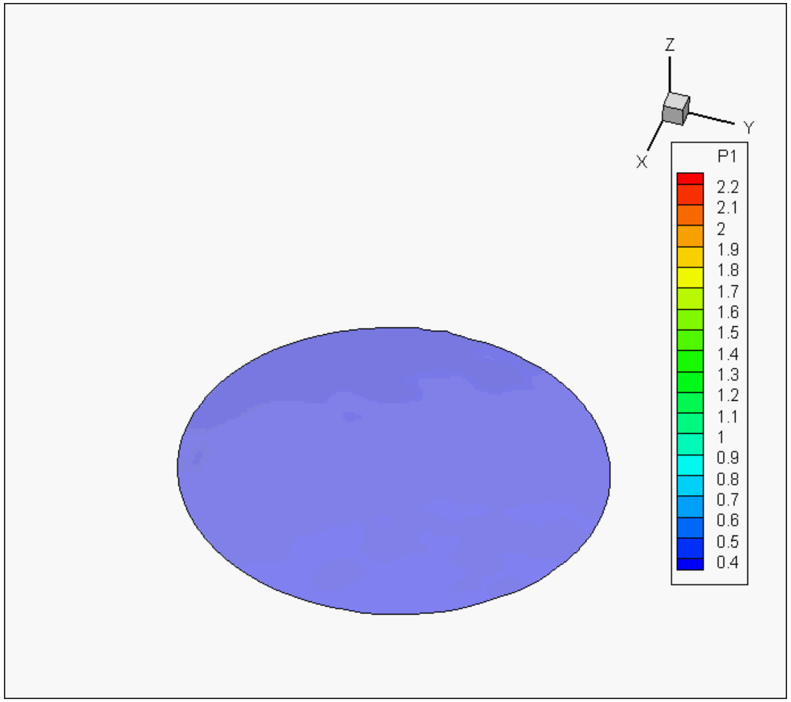


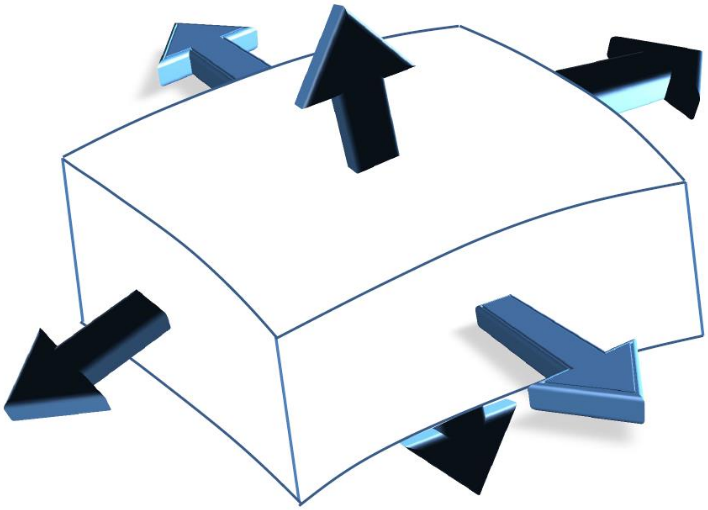
Deformed





Local stress reconstruction



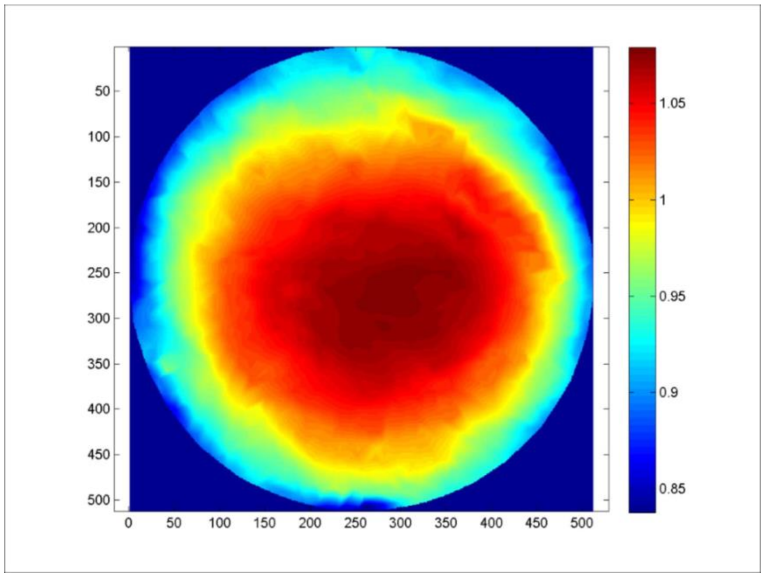


$$div(\boldsymbol{\sigma}) + f = 0$$

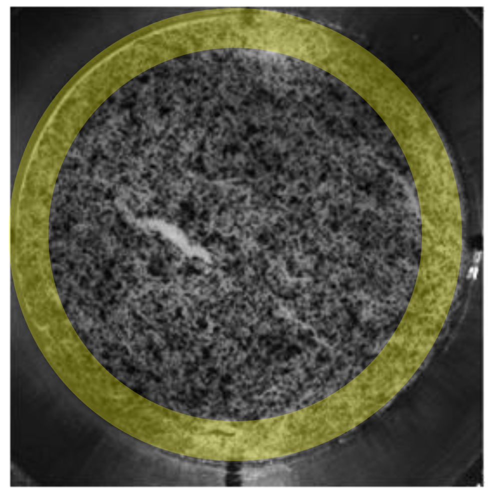
$$[A] \cdot [\boldsymbol{\sigma}] = [B]$$

Local analysis of rupture

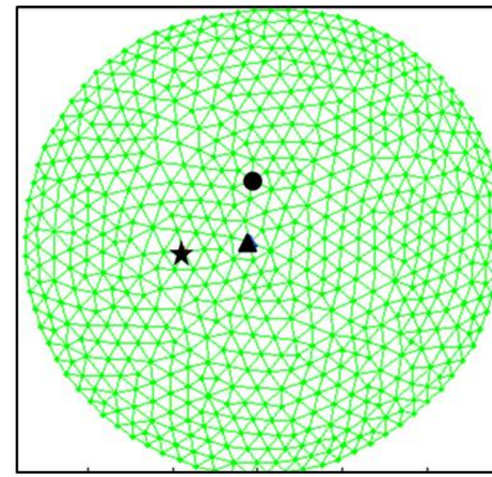
Local thickness evolution (mm)



Rupture picture and area of interest



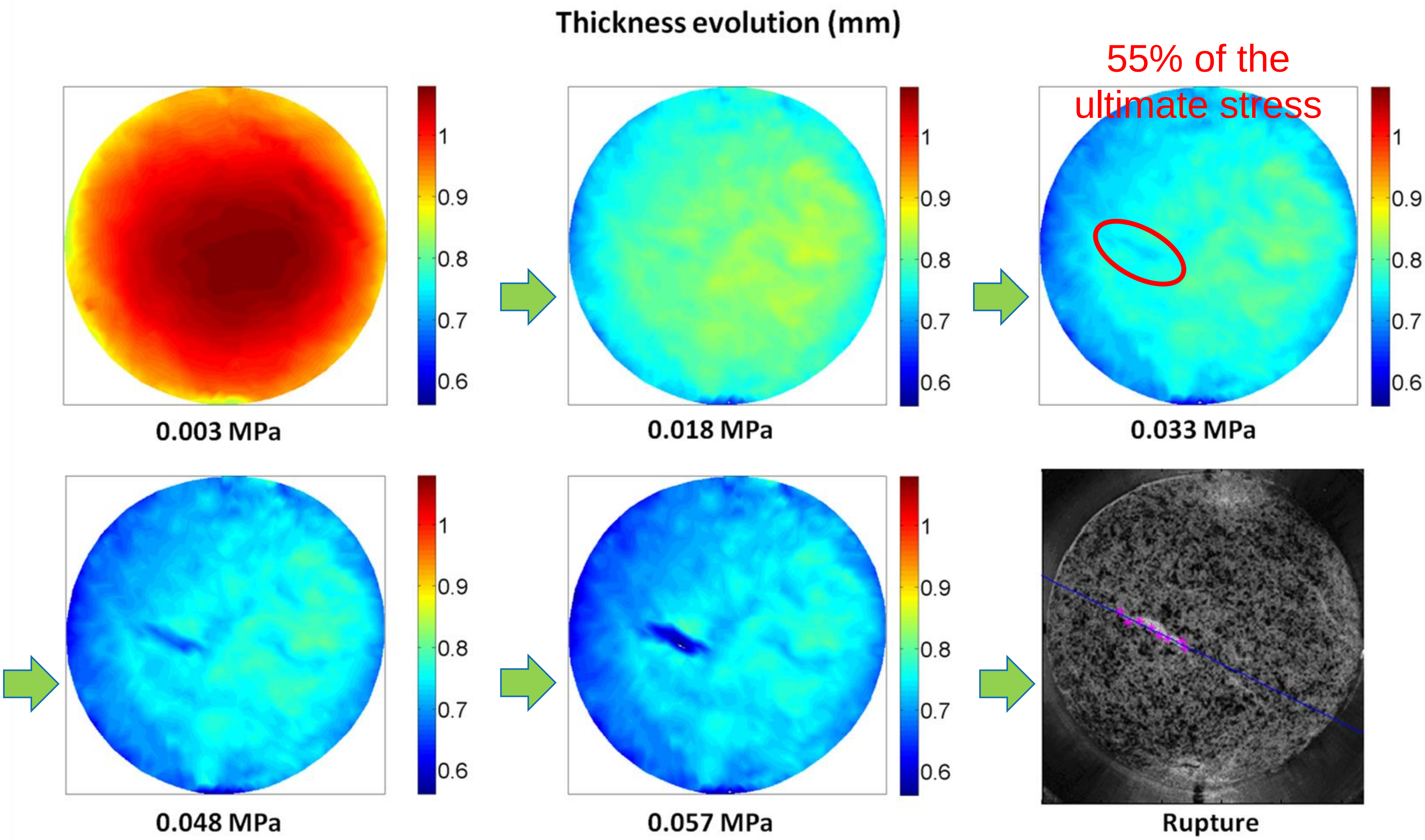
Mesh



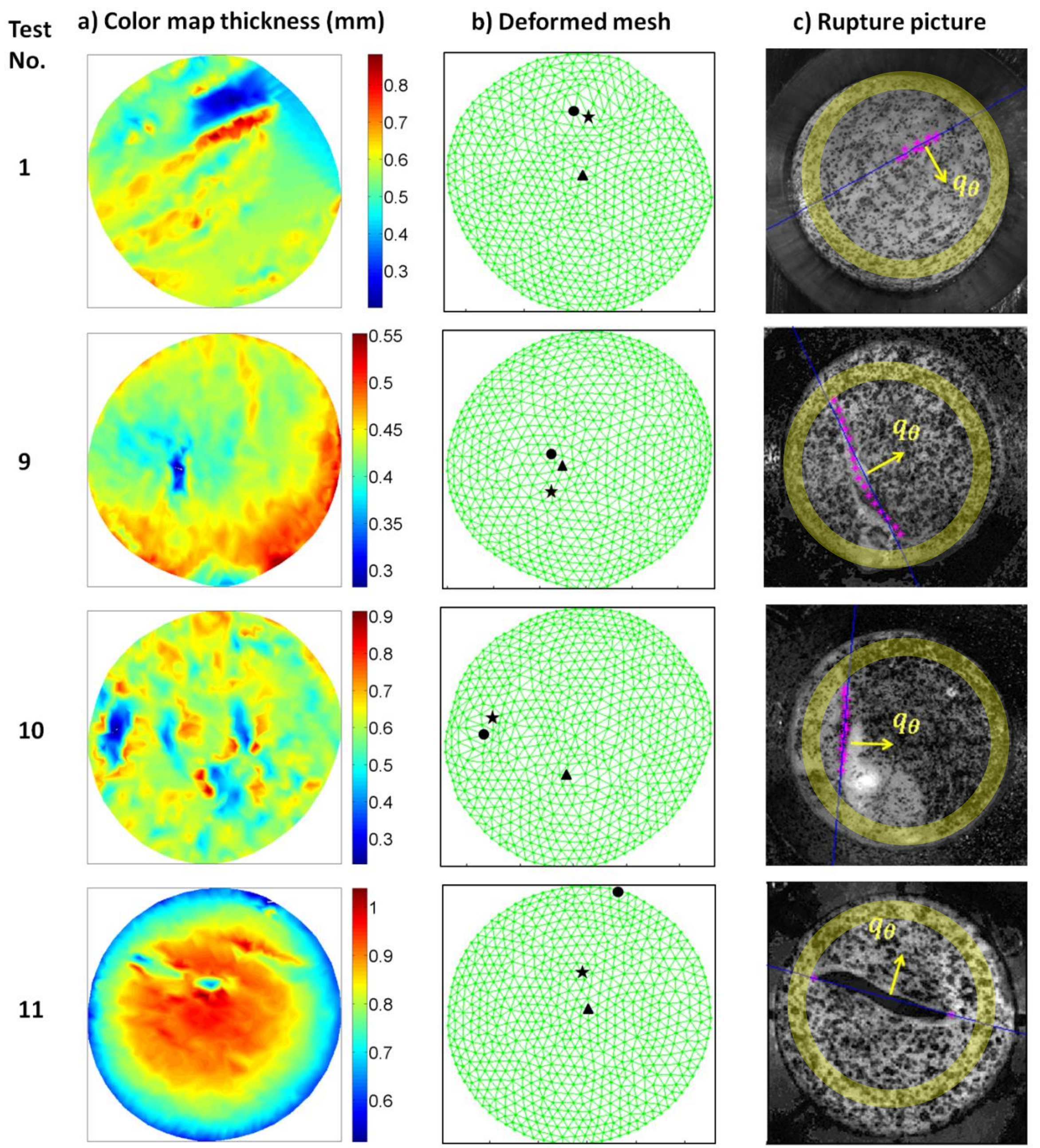
● = NodeMAX
▲= NodeTOP
★= NodeRUP

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.

Local damage initiation



Rupture modes



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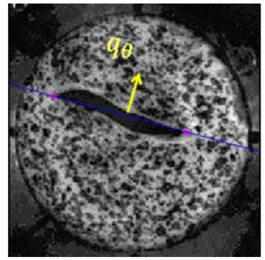
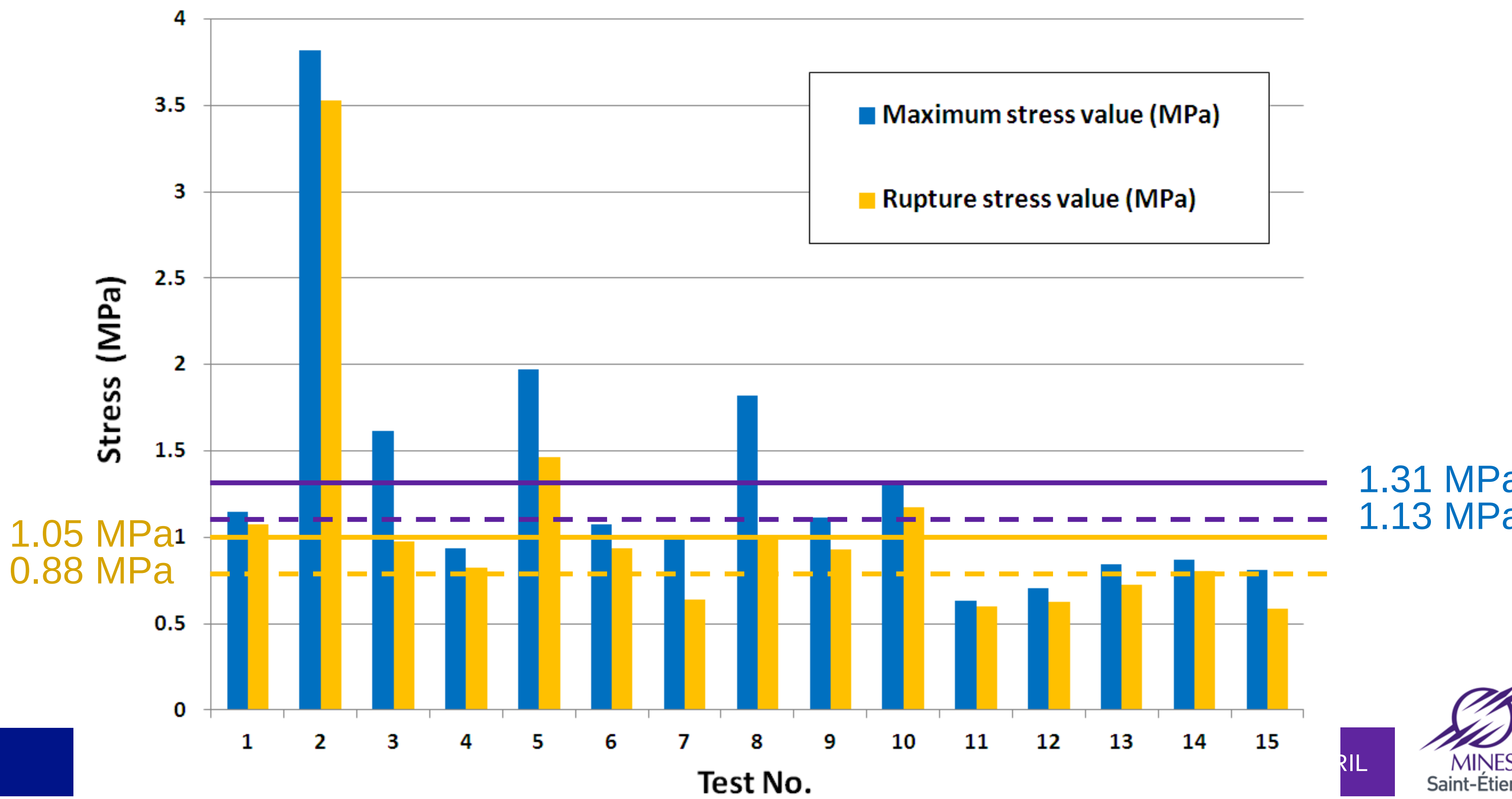
Ultimate stress values



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



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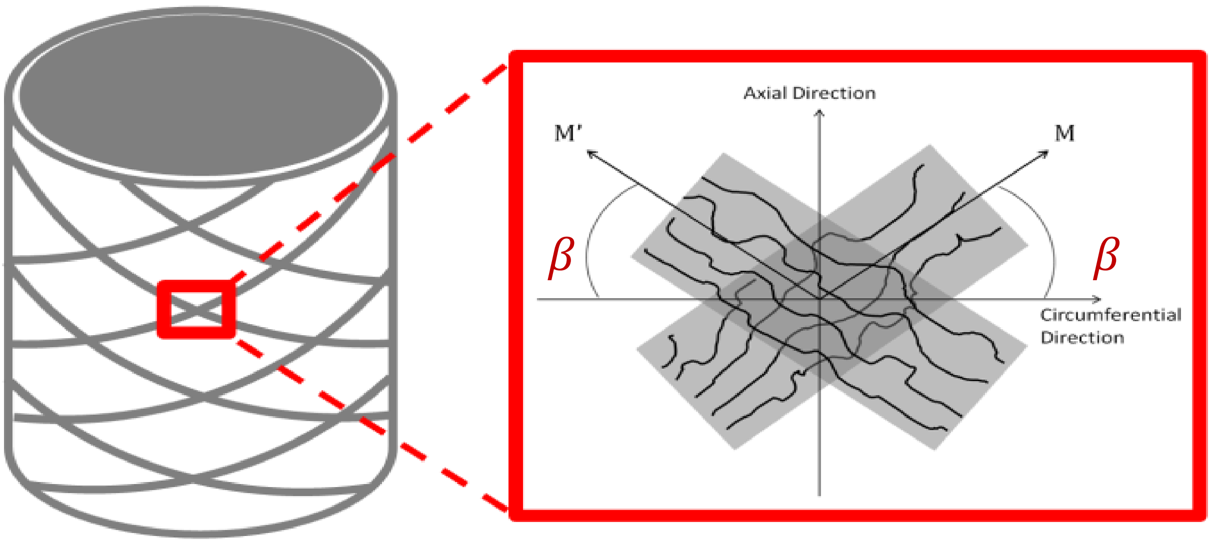
Fit a strain energy density function at every point

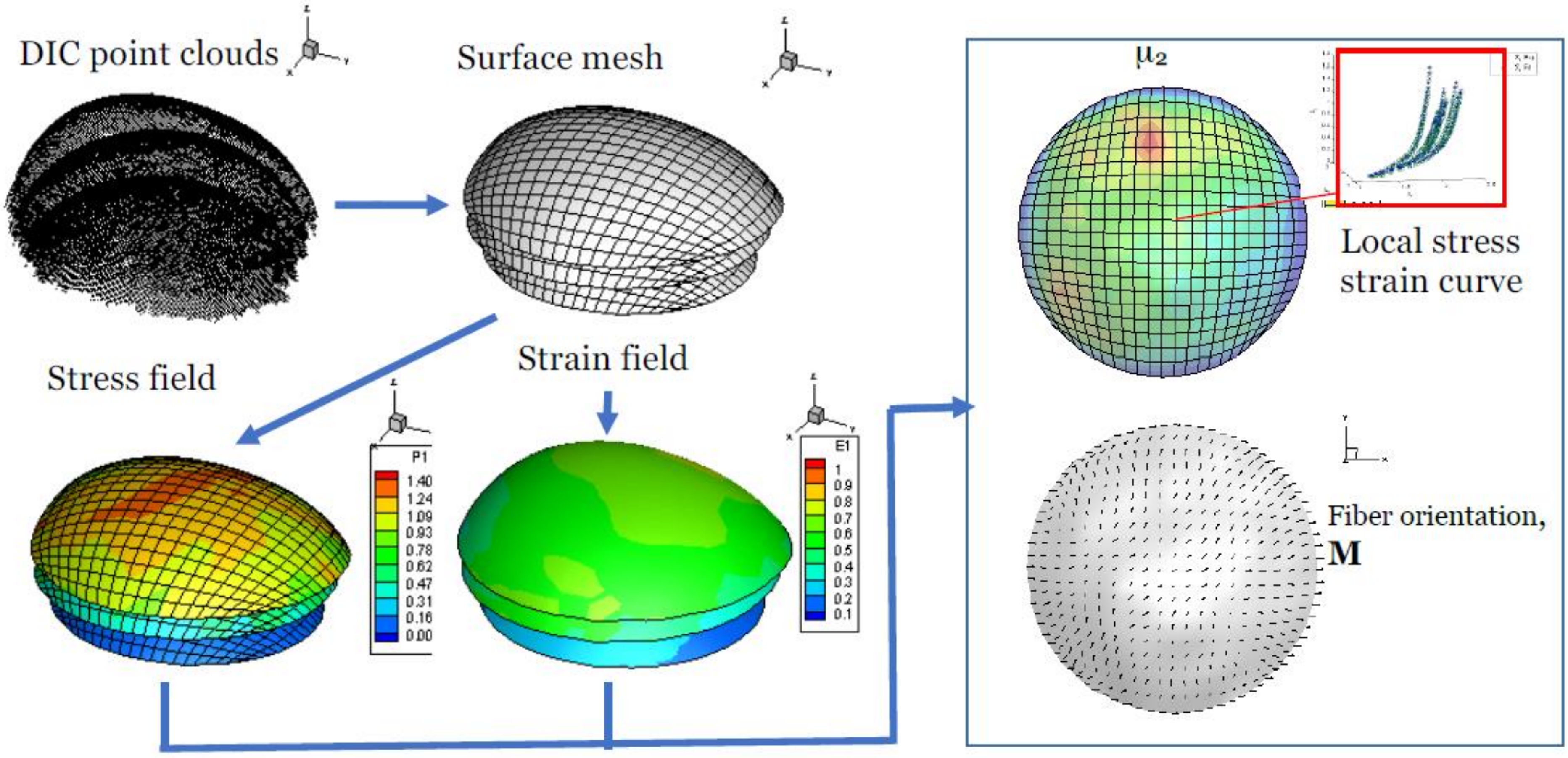
Strain energy function:

$$w = \frac{\mu_1}{2}\left(I_1 - \ln(I_2) - 2\right) + \frac{\mu_2}{4\gamma}\left(e^{\gamma(I_k - 1)^2} - 1\right)$$



Identification of a hyperelastic constitutive model

Davis et al. Biomechanics and Modeling in Mechanobiology - 2015.



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Results

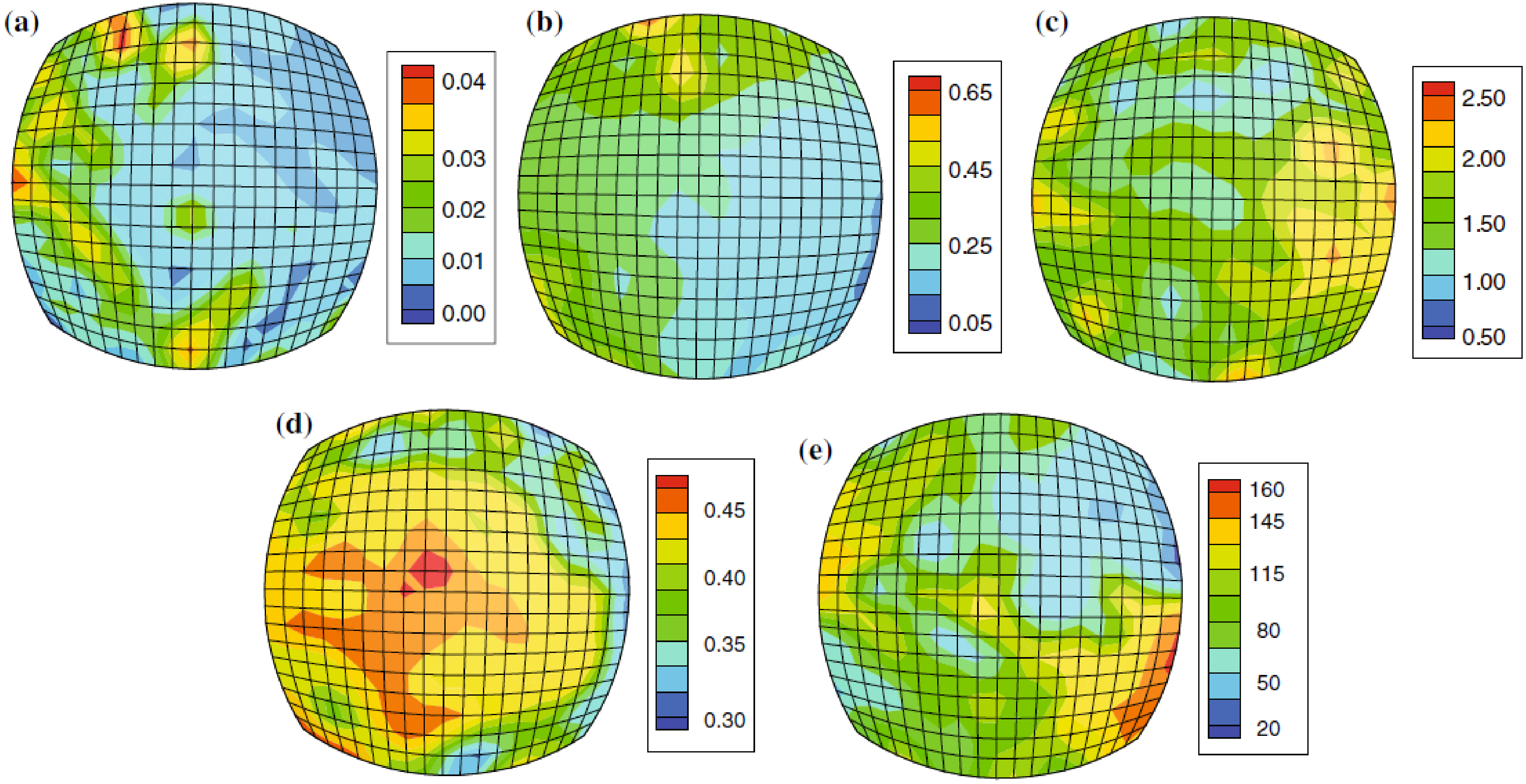


Fig. 5 Distribution of the identified material parameters over the ATAA. **a** μ_1 (N/mm). **b** μ_2 (N/mm). **c** γ. **d** κ. **e** θ (°)

Results

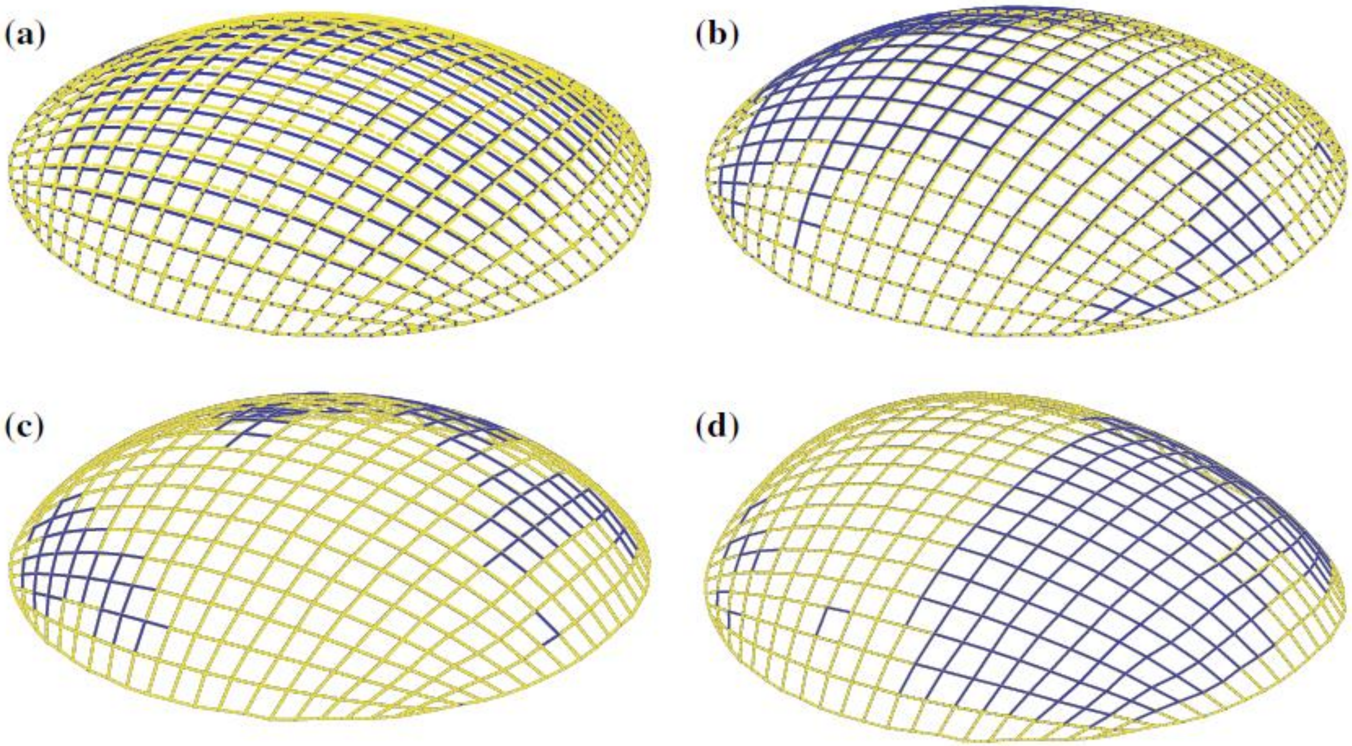


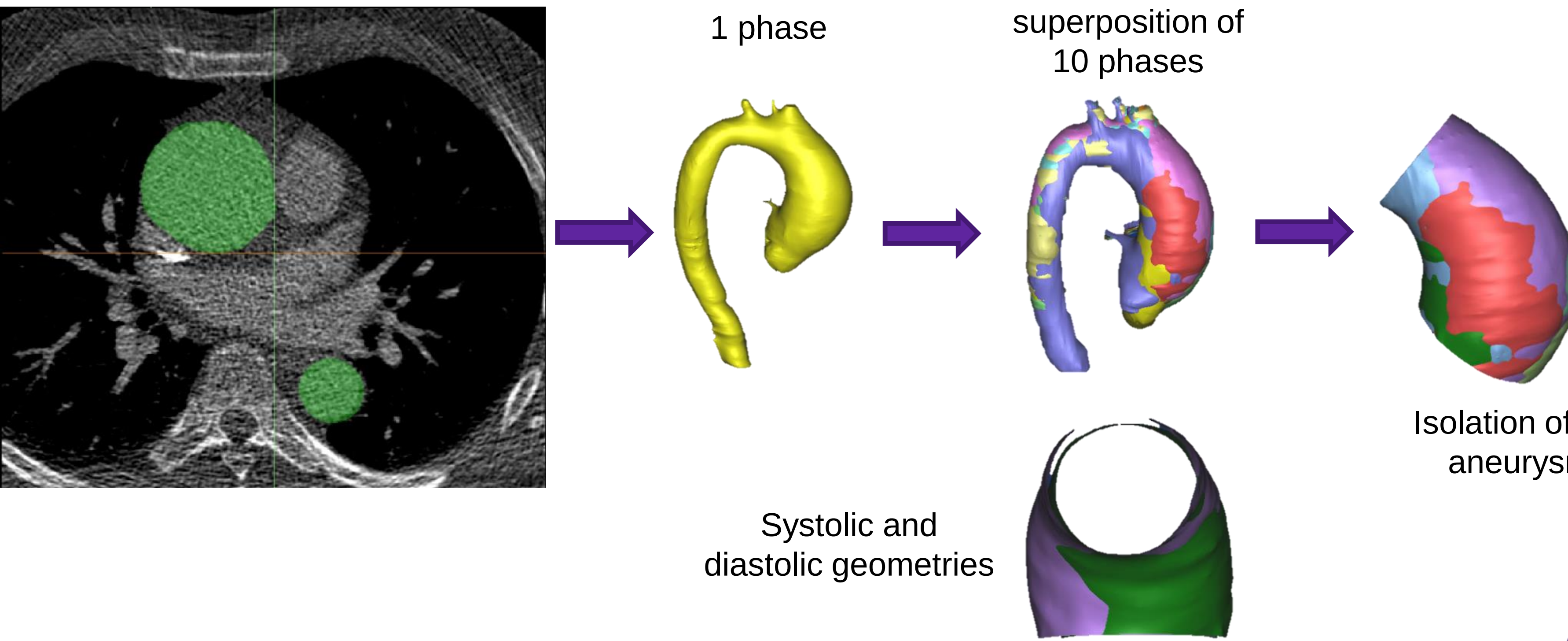
Fig. 6 Comparison of the geometry constructed from the DIC point clouds (*blue*) and those predicted from the forward finite element analysis using the pointwise material properties (*yellow*) at **a** 15 kPa, **b** 30 kPa, **c** 75 kPa, and **d** 117 kPa. Note that the geometry is almost a perfect match leading the *blue* and *yellow lines* to overlap

Application to computational retrospective predictions

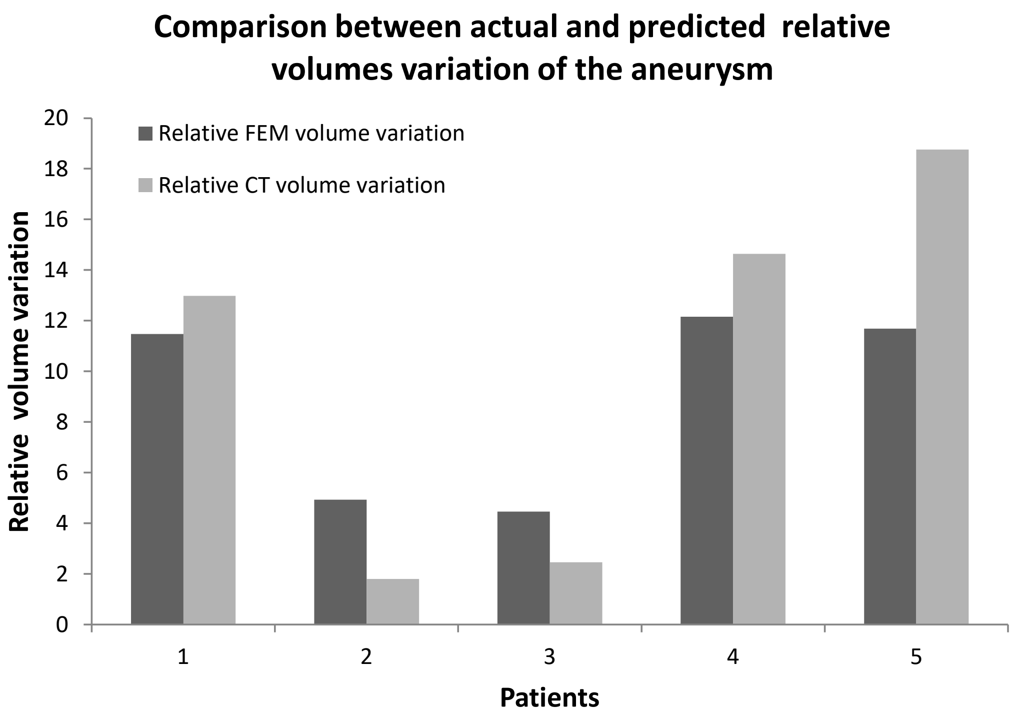
Trabelsi et al. Journal of Biomechanics - 2015.

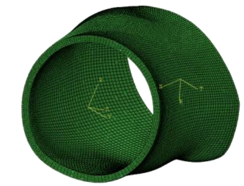
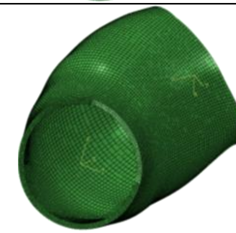
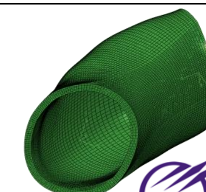
Image acquisition and 3D reconstruction

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



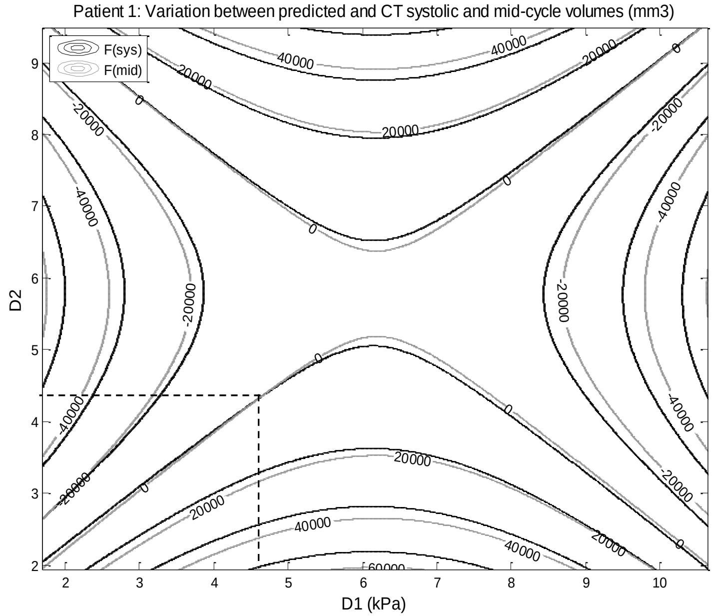
Good prediction of in vivo volume variations



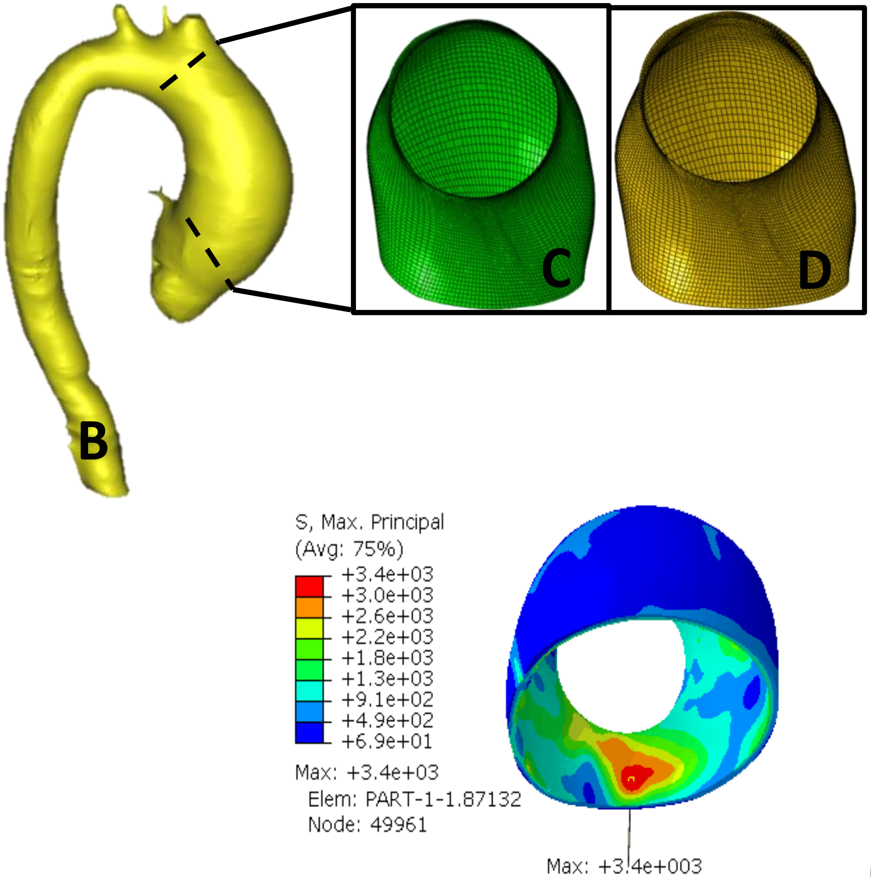
	CT image geometry (diastolic geometry)	Zero-pressure geometry
Patient 1		
Patient 2		
Patient 3		
Patient 4		
Patient 5		

Identification of hyperelastic parameters by calibrating the volume changes

Trabelsi et al. Journal of Biomechanics - 2015.



INVERSE ANALYSIS



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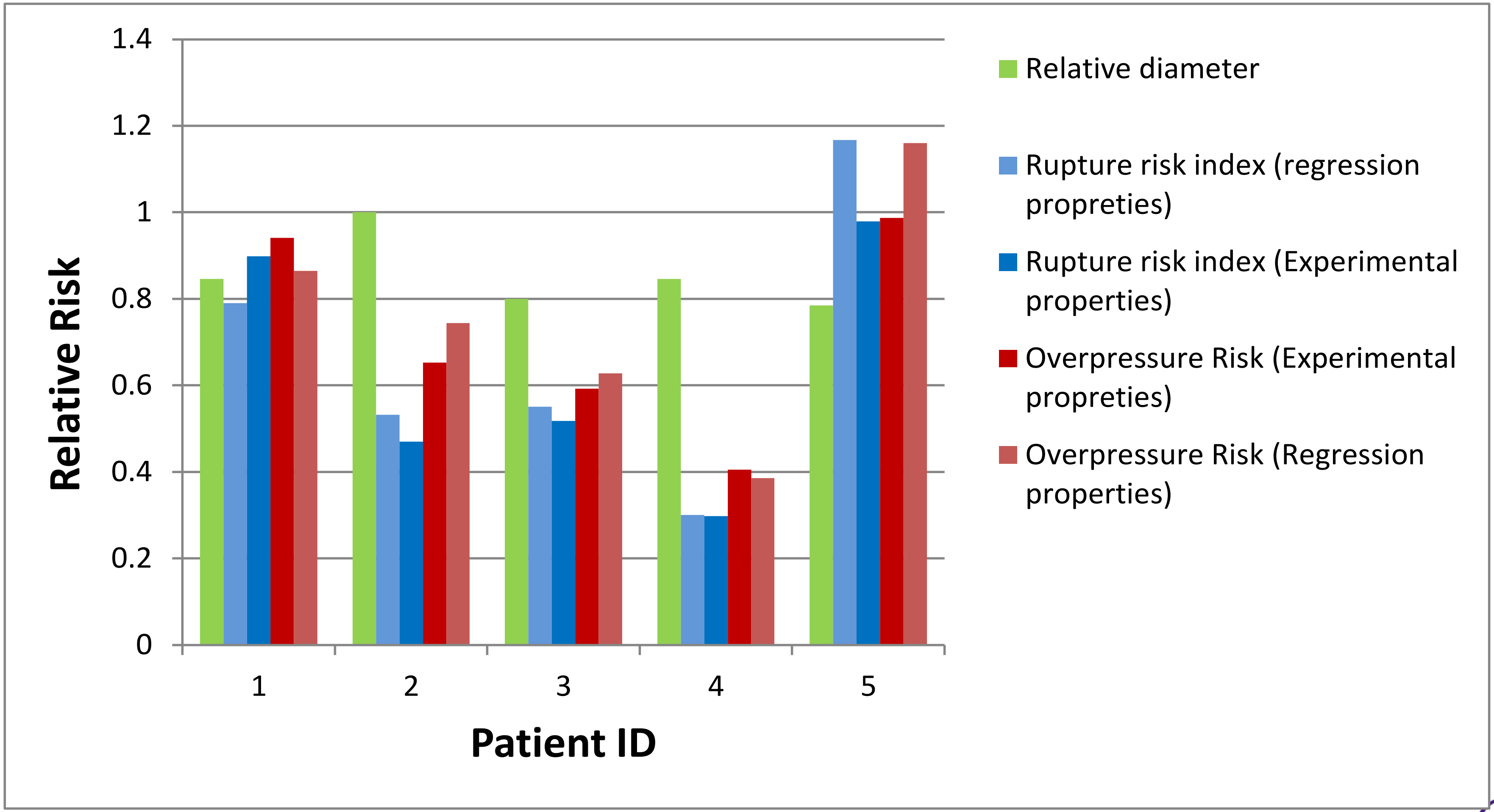
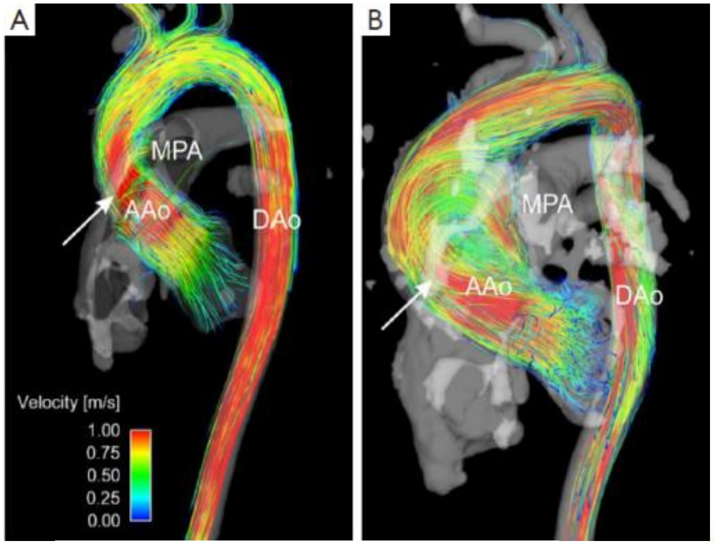
Stress analysis and rupture risk estimation



Future work: predicting and stopping aneurism growth



4D MRI

European Research Council

New generation of models for soft tissues

In vivo mechanobiological instability and rupture prediction

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Internal lengthscales

Nonlocal biomechanics and mechanobiology

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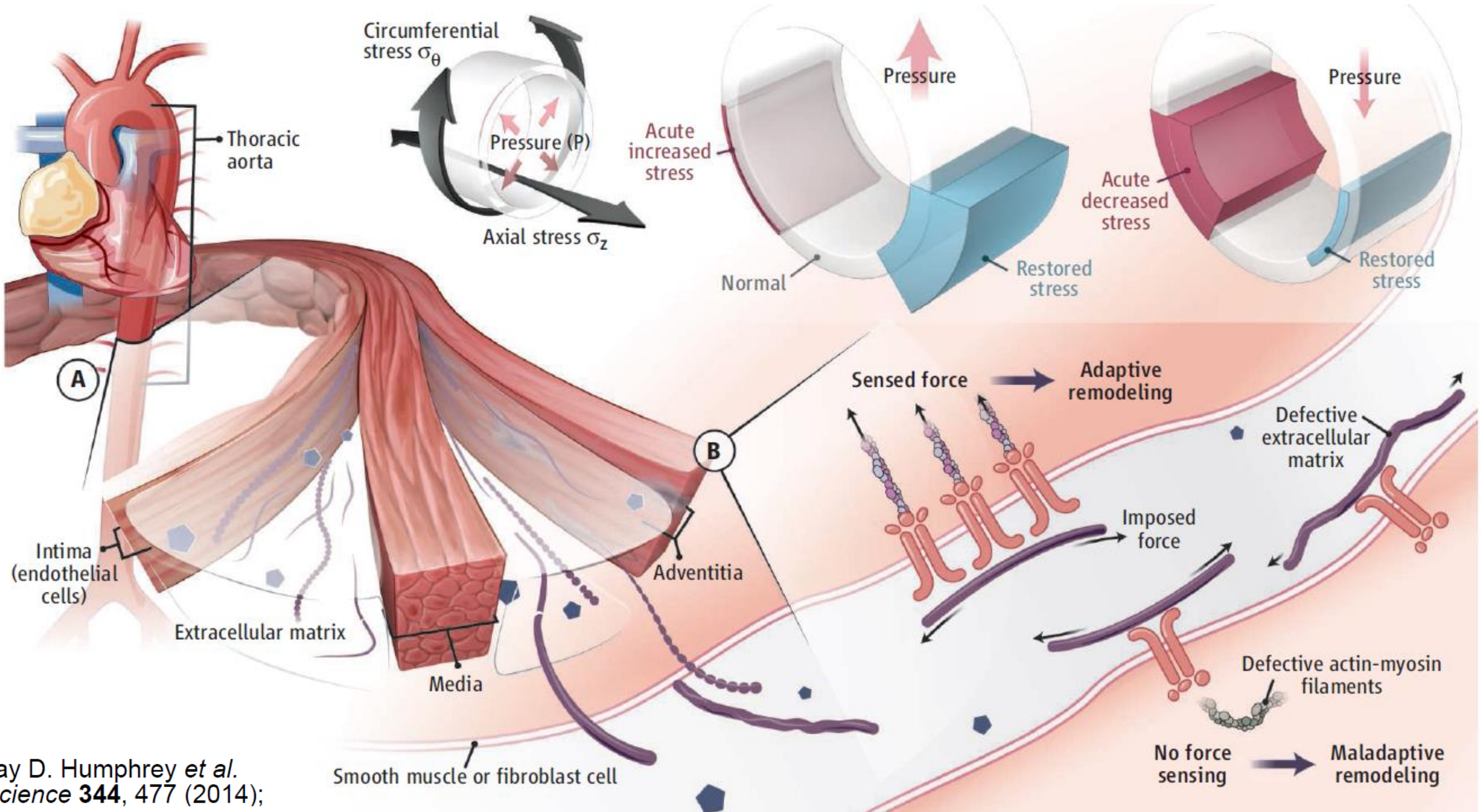
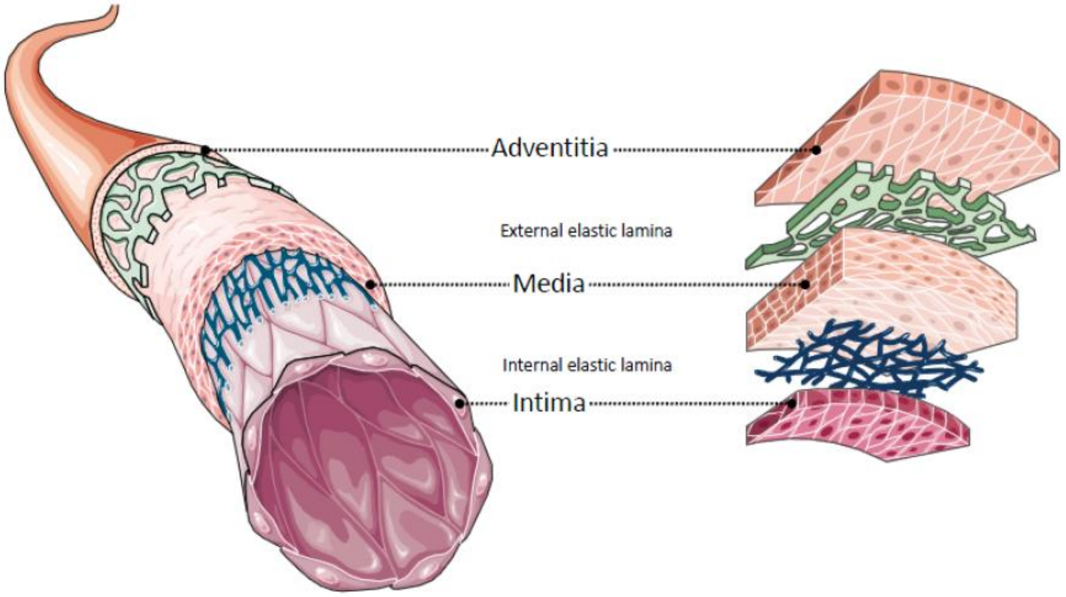
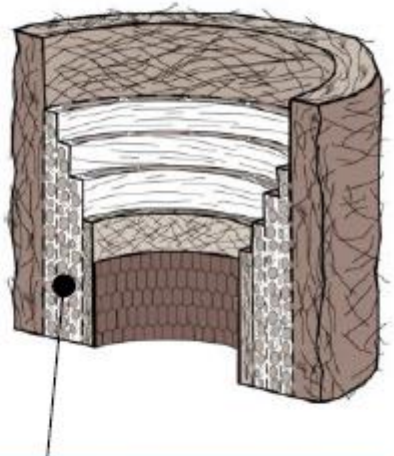
MECHANOBIOLOGY OF THE THORACIC AORTA

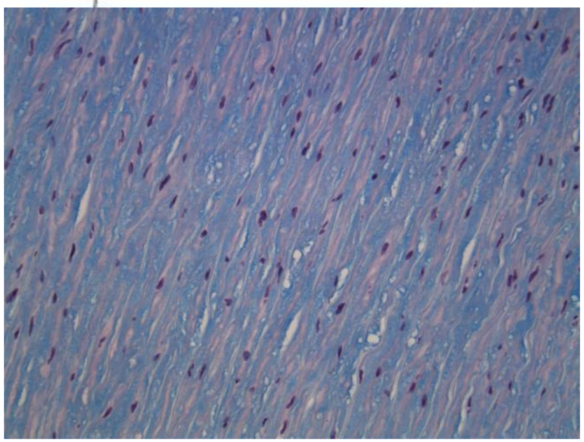


Jay D. Humphrey *et al.*
Science **344**, 477 (2014);

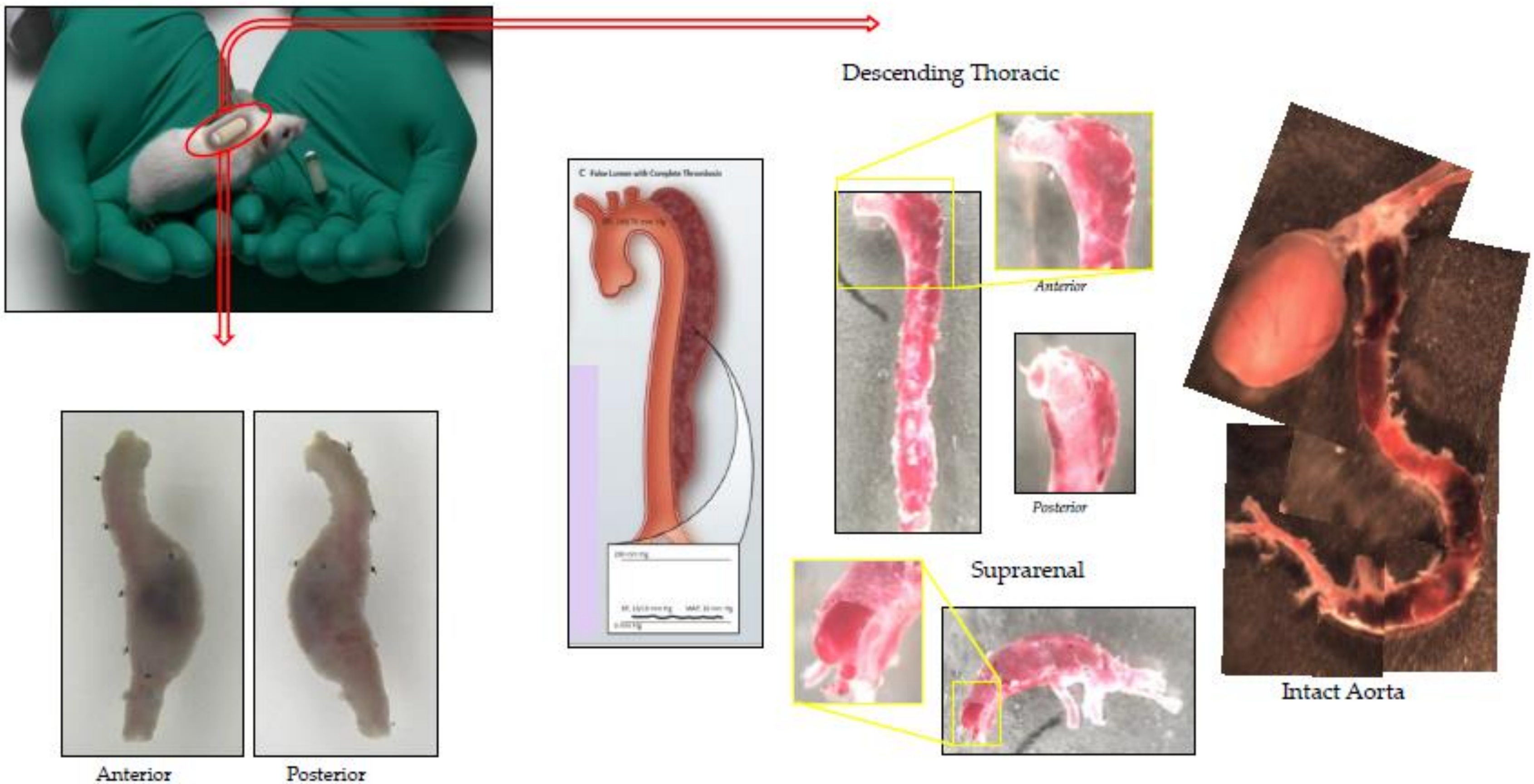
PATIENTS WITH ATAA HAVE A DISORGANIZED MEDIA WITH FRAGMENTED ELASTIN AND PRESENCE OF VACUOLES



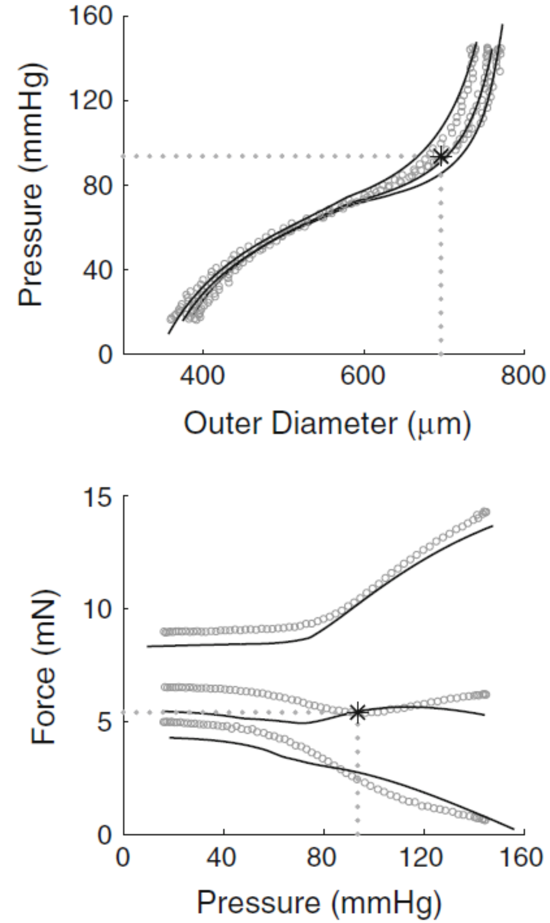




FUNDAMENTAL STUDY USING A MOUSE « MODEL »

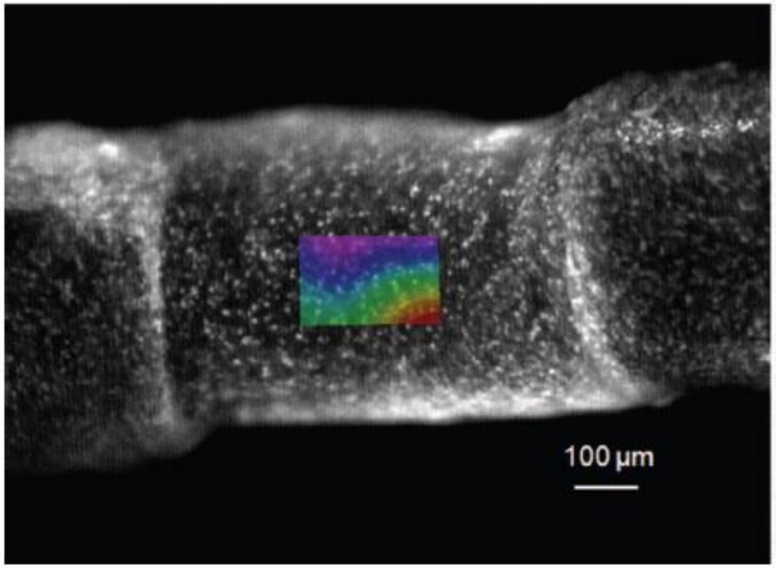


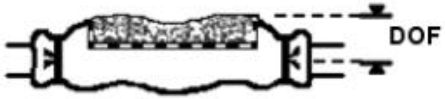
MECHANICAL CHARACTERIZATION
TENSION - INFLATION



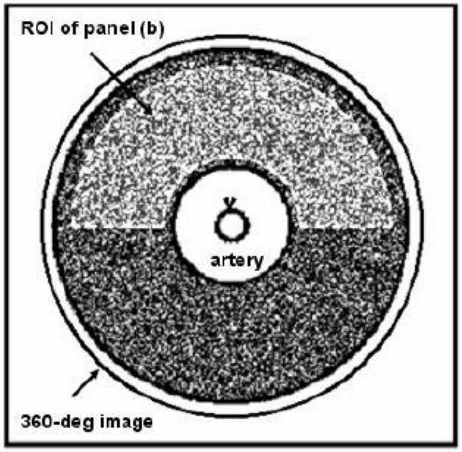
MEASUREMENT OF THE RESPONSE USING DIGITAL IMAGE CORRELATION

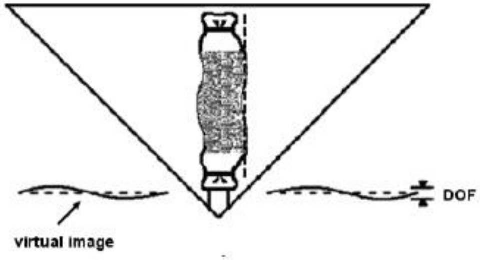
classical





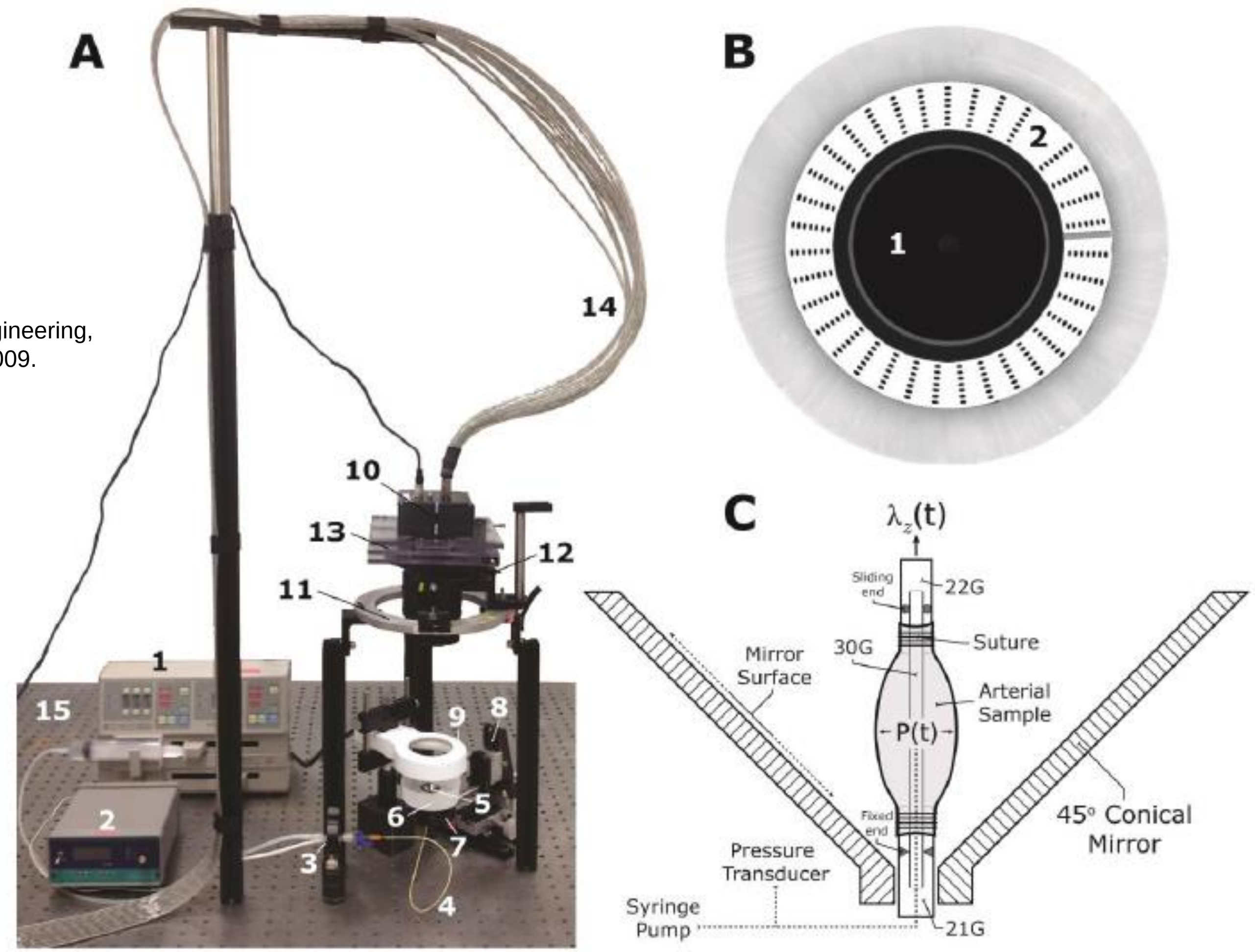
panoramic





PANORAMIC DIGITAL IMAGE CORRELATION

K. Genovese.
Optics and Lasers in Engineering,
Vol. 47, pp. 995-1008, 2009.



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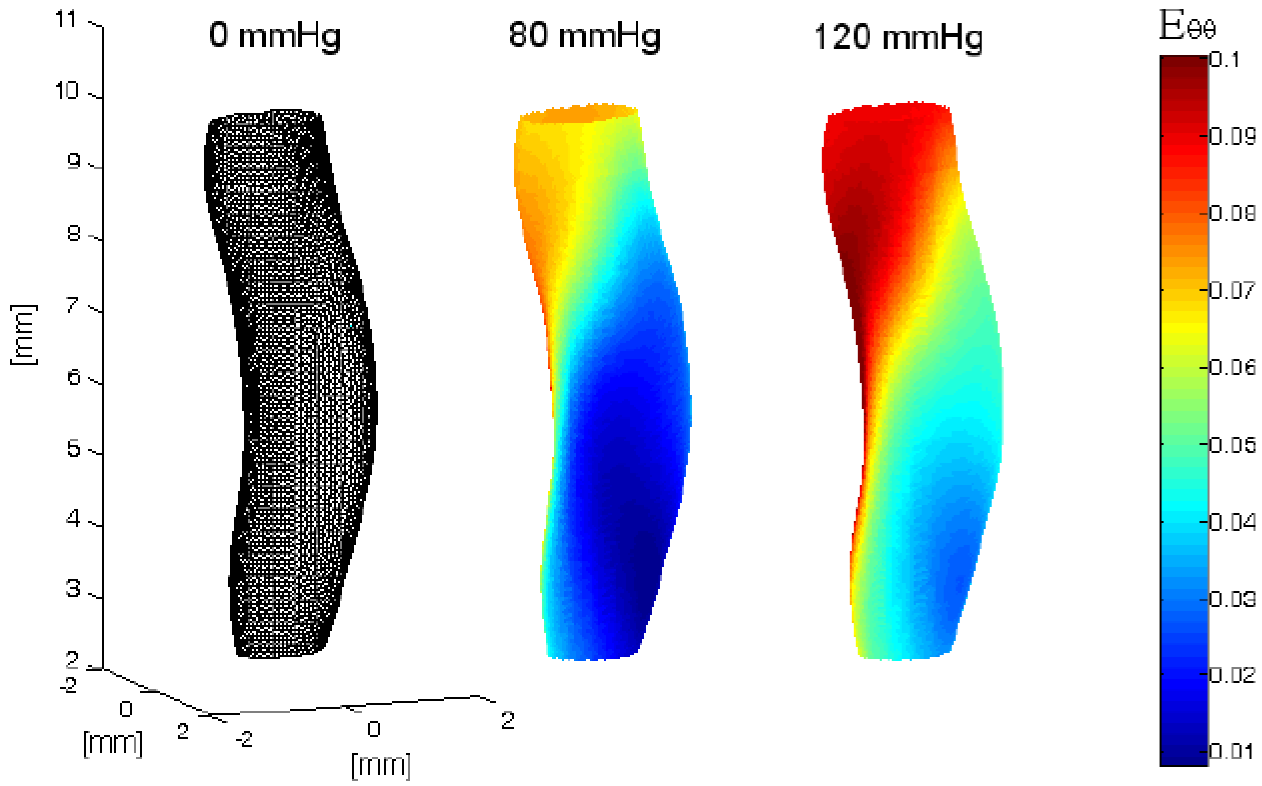
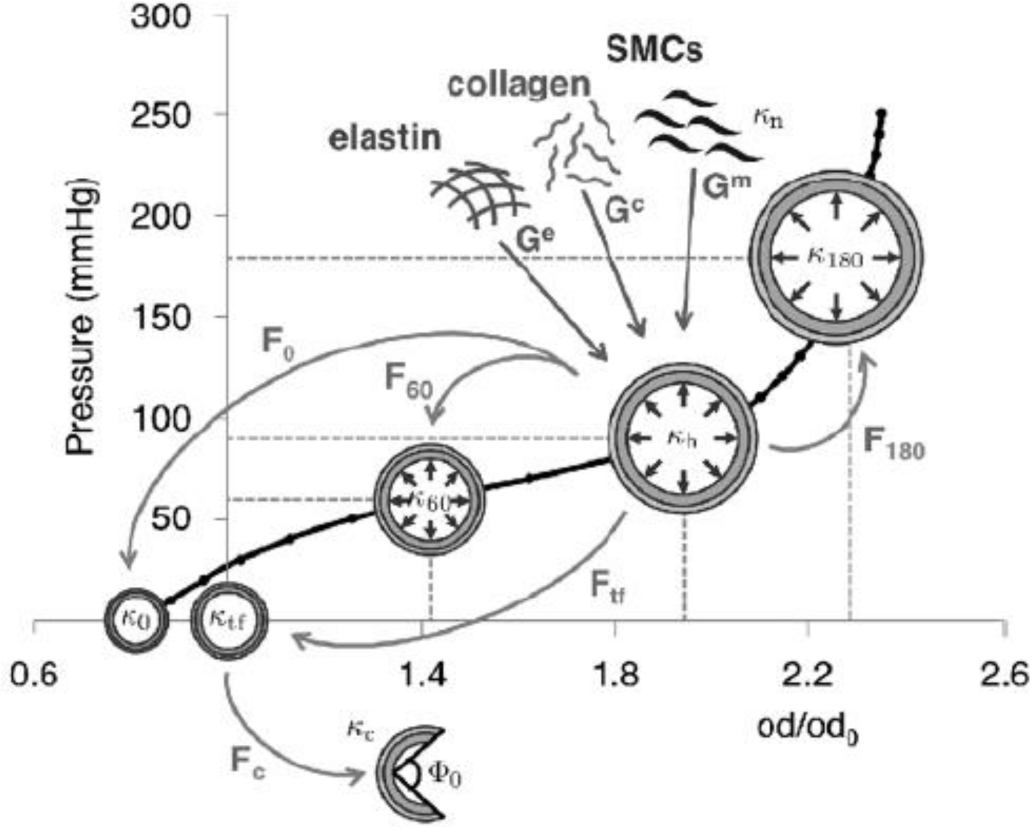
EXAMPLES



0 mmHg
80 mmHg
120 mmHg
Eθθ
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
[mm]
11
10
9
8
7
6
5
4
3
2
-2
0
2
-2
0
2
[mm]
[mm]

CONSTITUTIVE MODEL



PARAMETERS TO BE IDENTIFIED

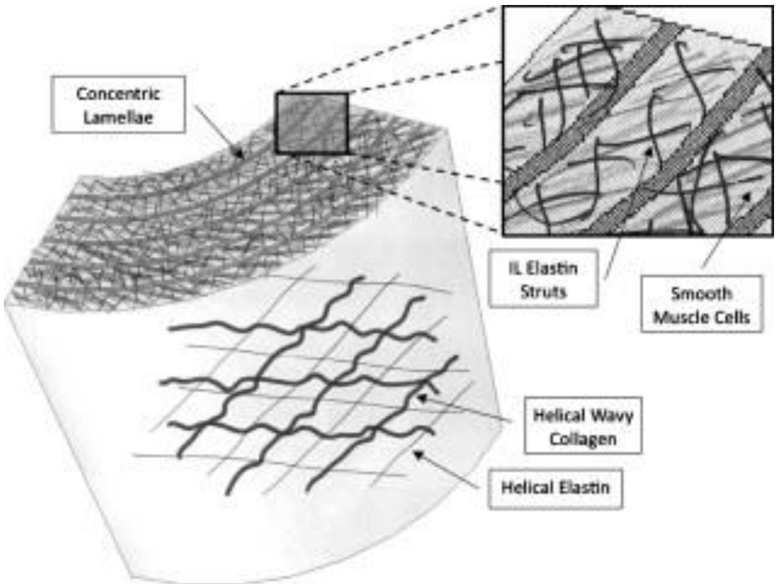
Strain energy functions:

$$W = \phi^{e} W^{e}(\mathbf{F}^{e}) + \phi^{m} W^{m}(\lambda^{m}) + \sum_{j=1}^{4} \phi^{c_j} W^{c_j}(\lambda^{c_j})$$

$$W^{e}(\mathbf{F}^{e}) = \frac{c^{e}}{2}\left[\operatorname{tr}\left((\mathbf{F}^{e})^{T}\mathbf{F}^{e}\right) - 3\right]$$

$$W^{m}(\lambda^{m}) = \frac{c_2^{m}}{4c_3^{m}}\left[e^{c_3^{m}((\lambda^{m})^2-1)^2} - 1\right]$$

$$W^{c}(\lambda^{c_j}) = \frac{c_2^{c}}{4c_3^{c}}\left[e^{c_3^{c}((\lambda^{c_j})^2-1)^2} - 1\right]$$



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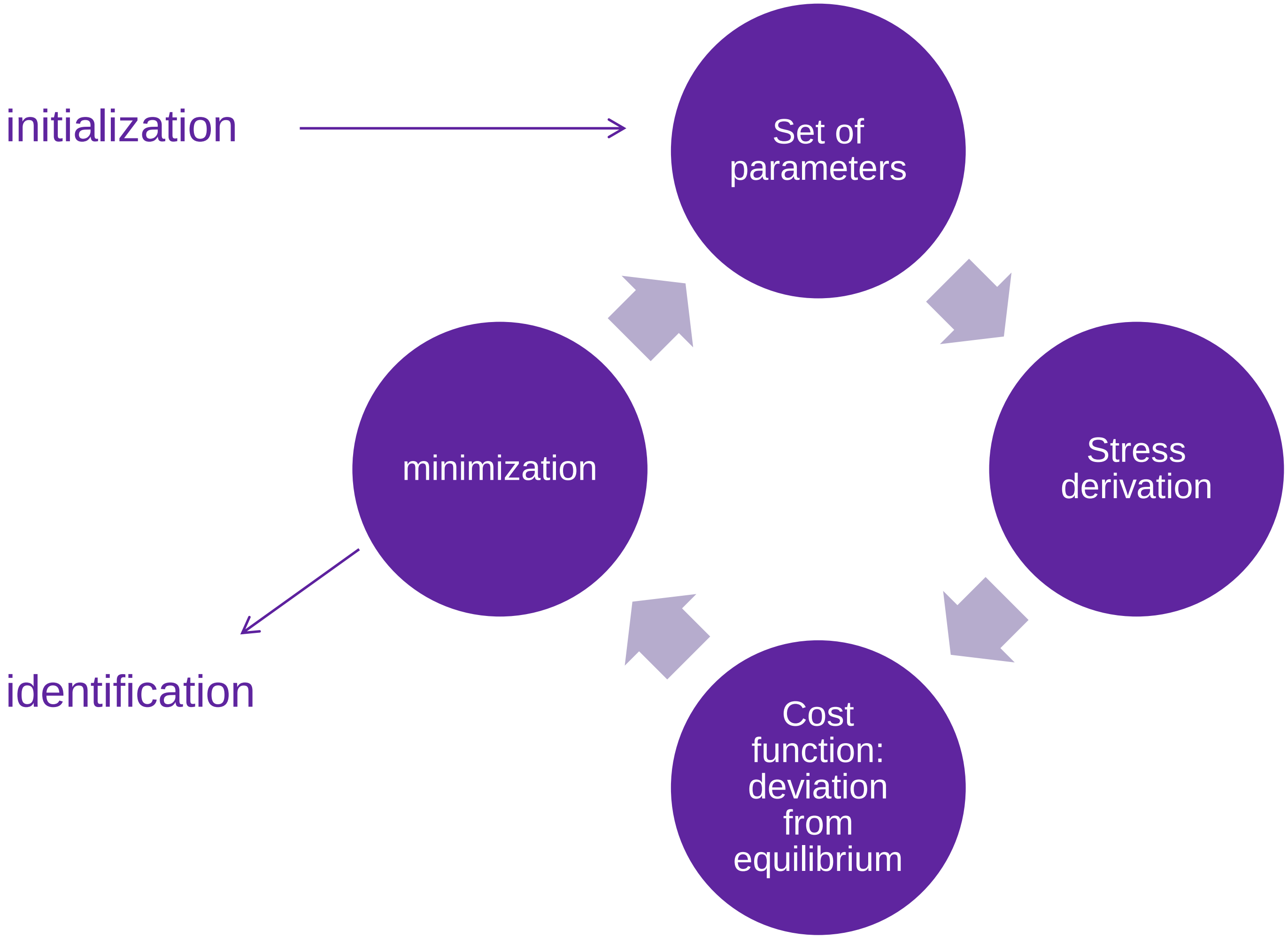
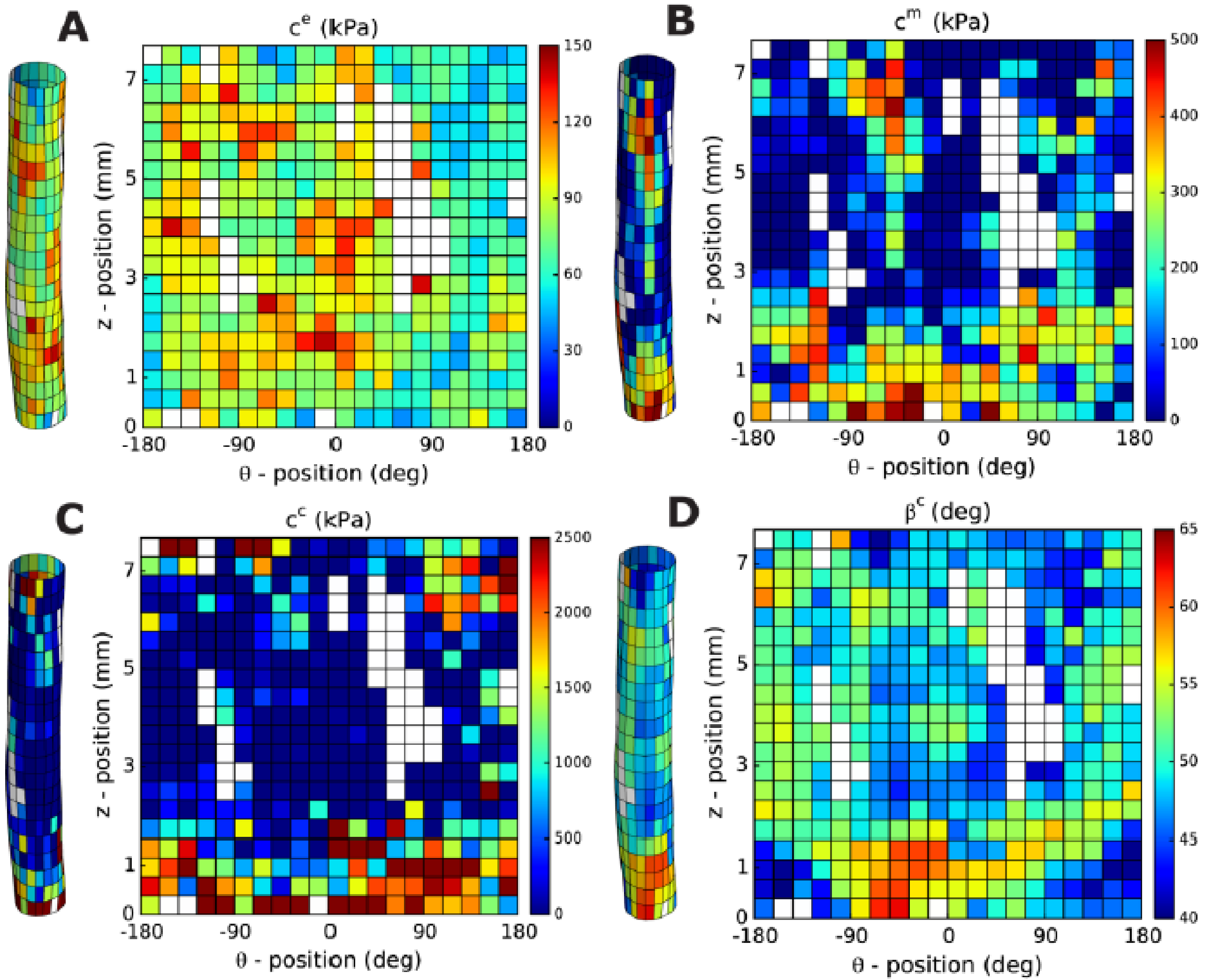
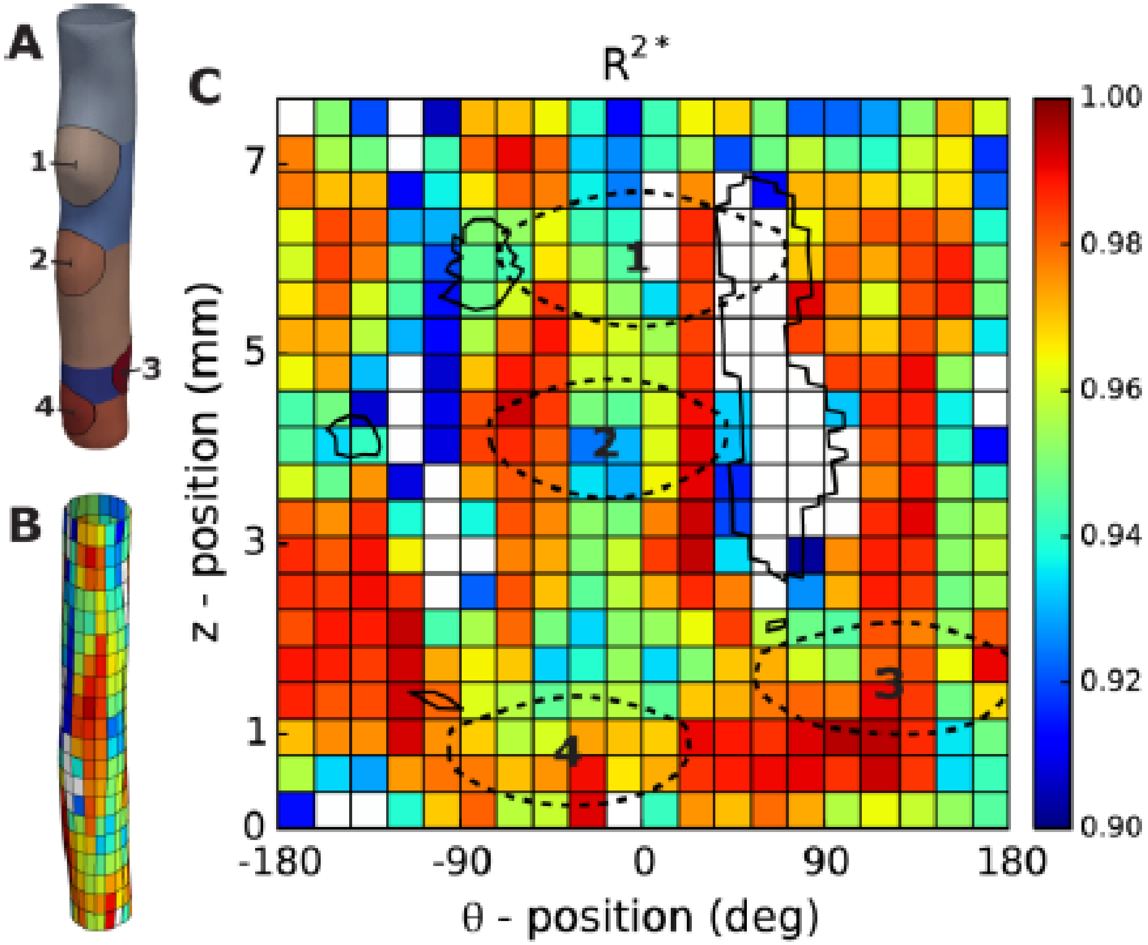
IDENTIFICATION OF CONSTITUTIVE PROPERTIES



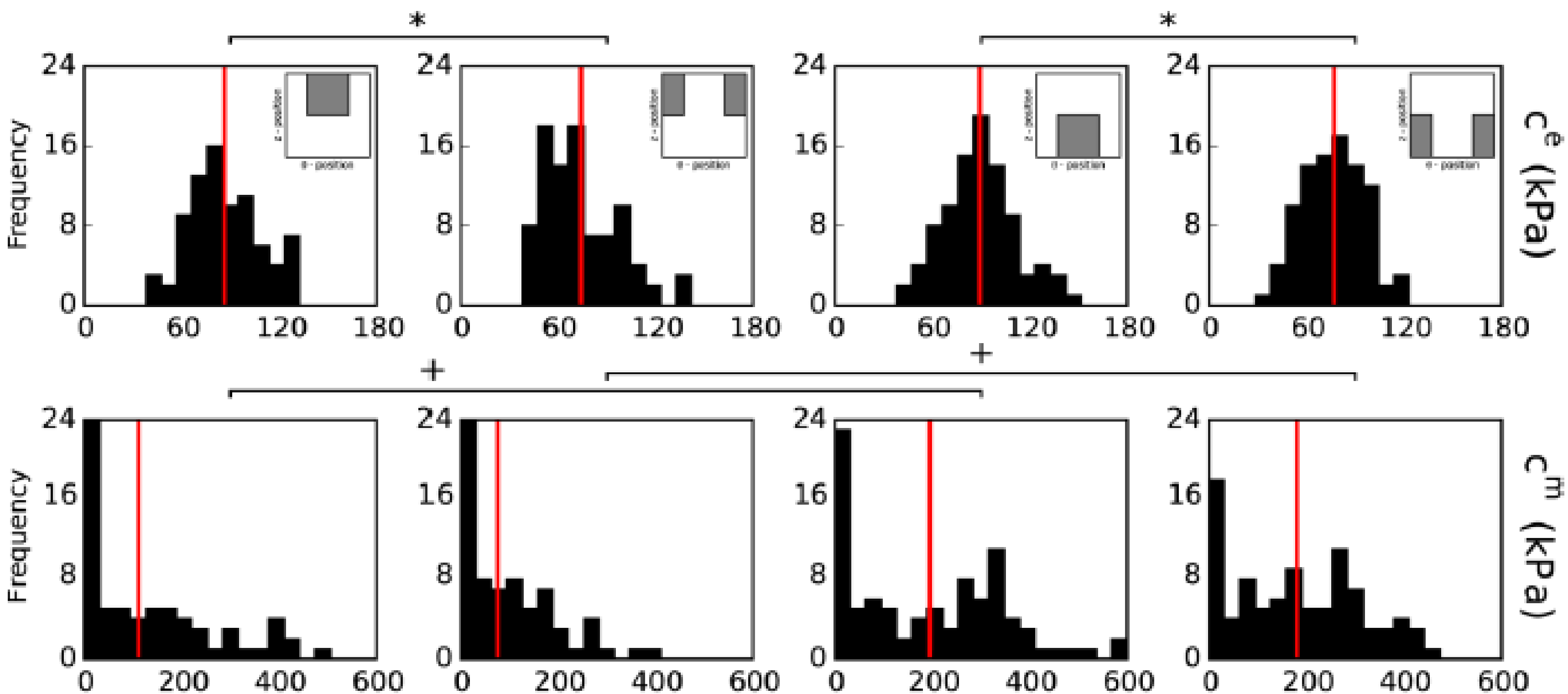
EXAMPLE DE RESULTS



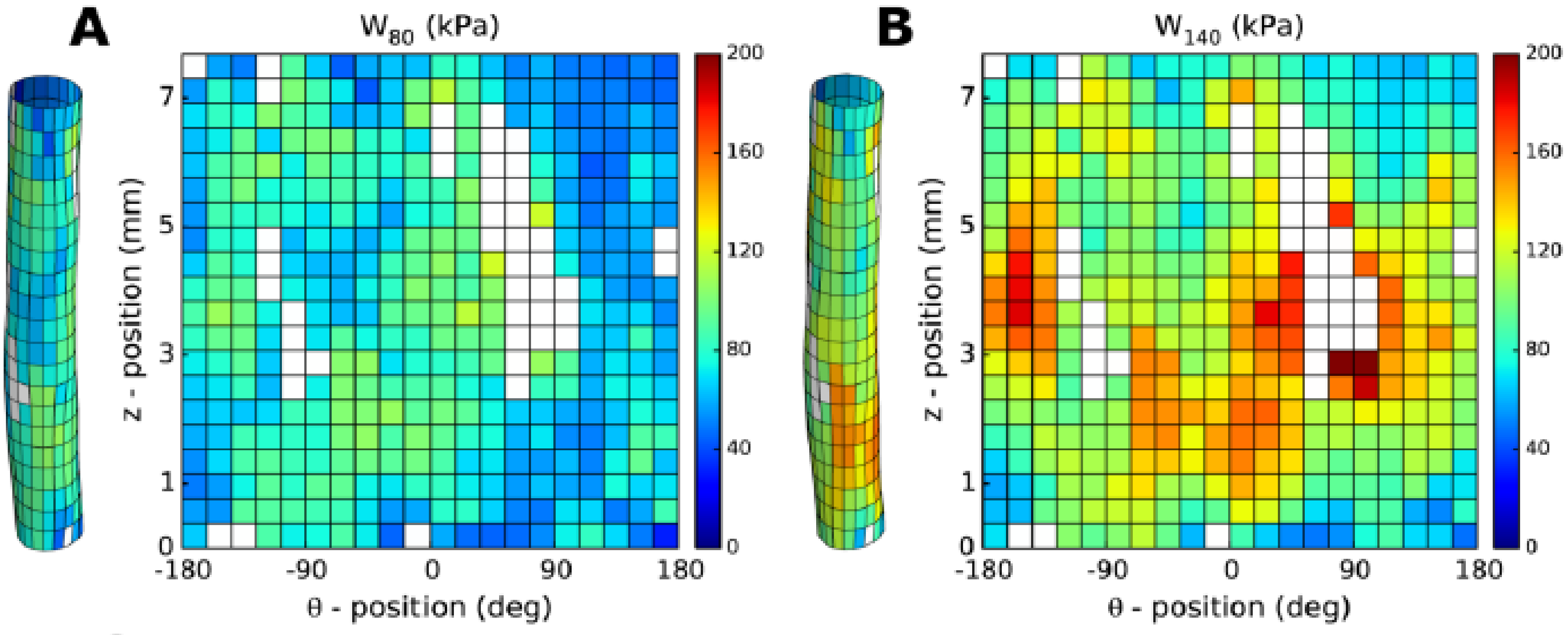
EXAMPLE DE RESULTS



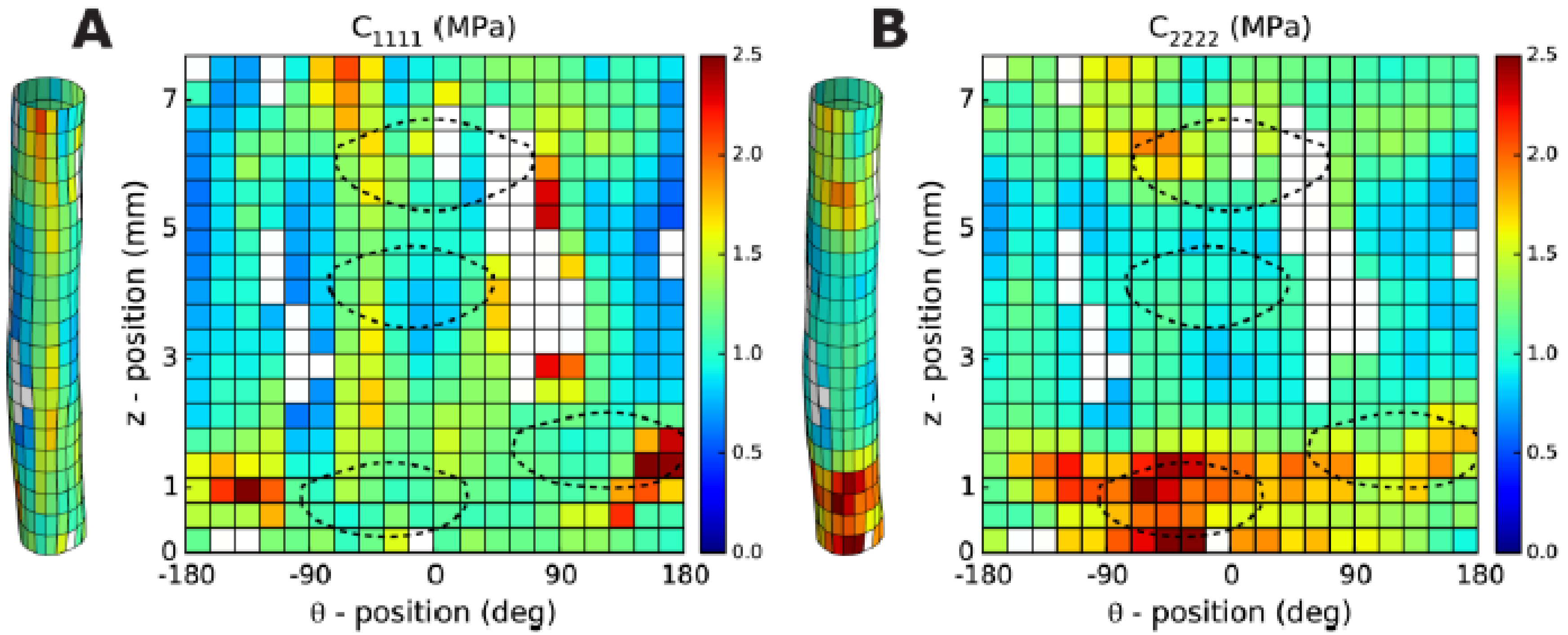
EXAMPLE DE RESULTS



EXAMPLE DE RESULTS



EXAMPLE DE RESULTS



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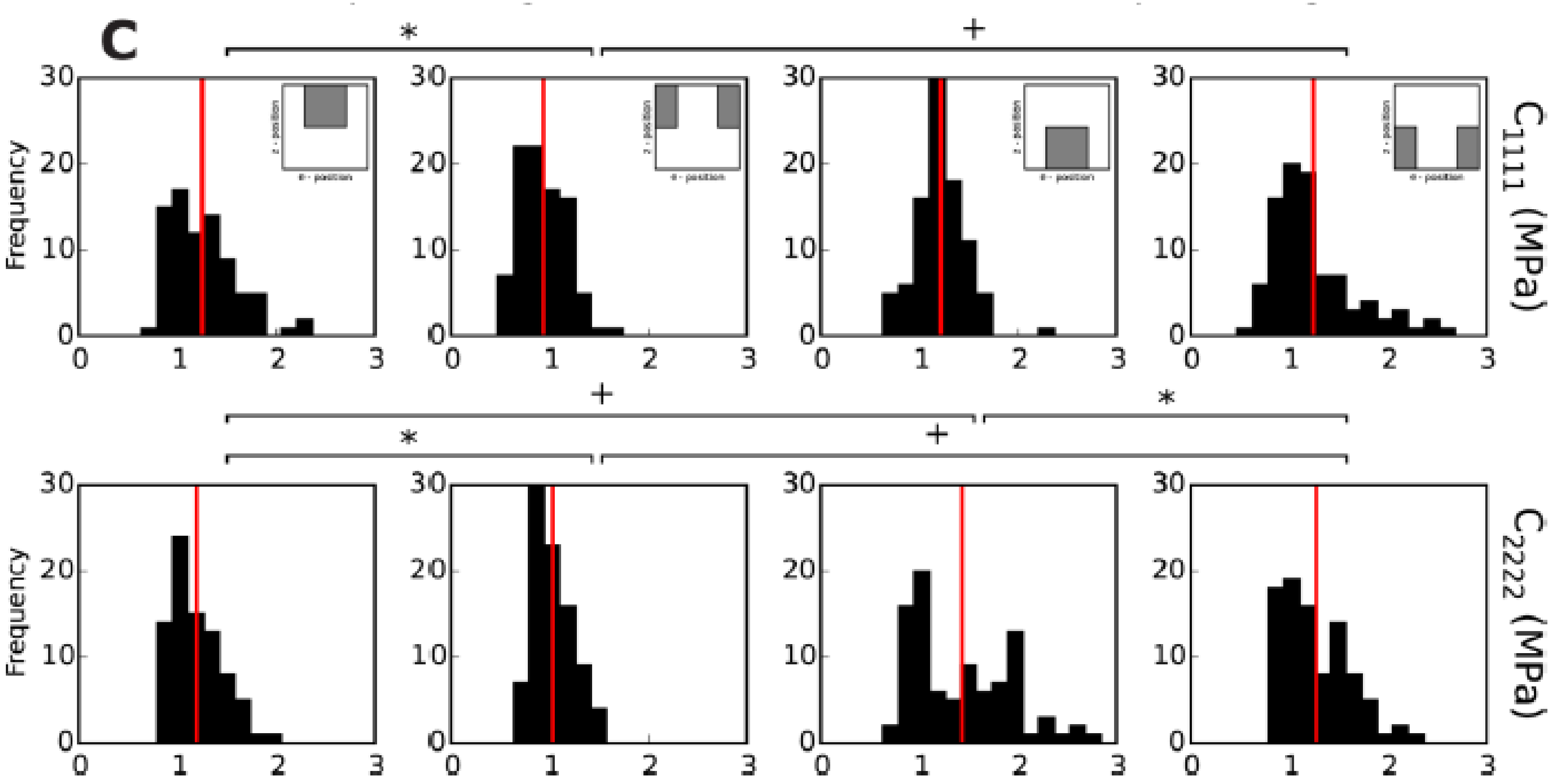
EXAMPLE DE RESULTS



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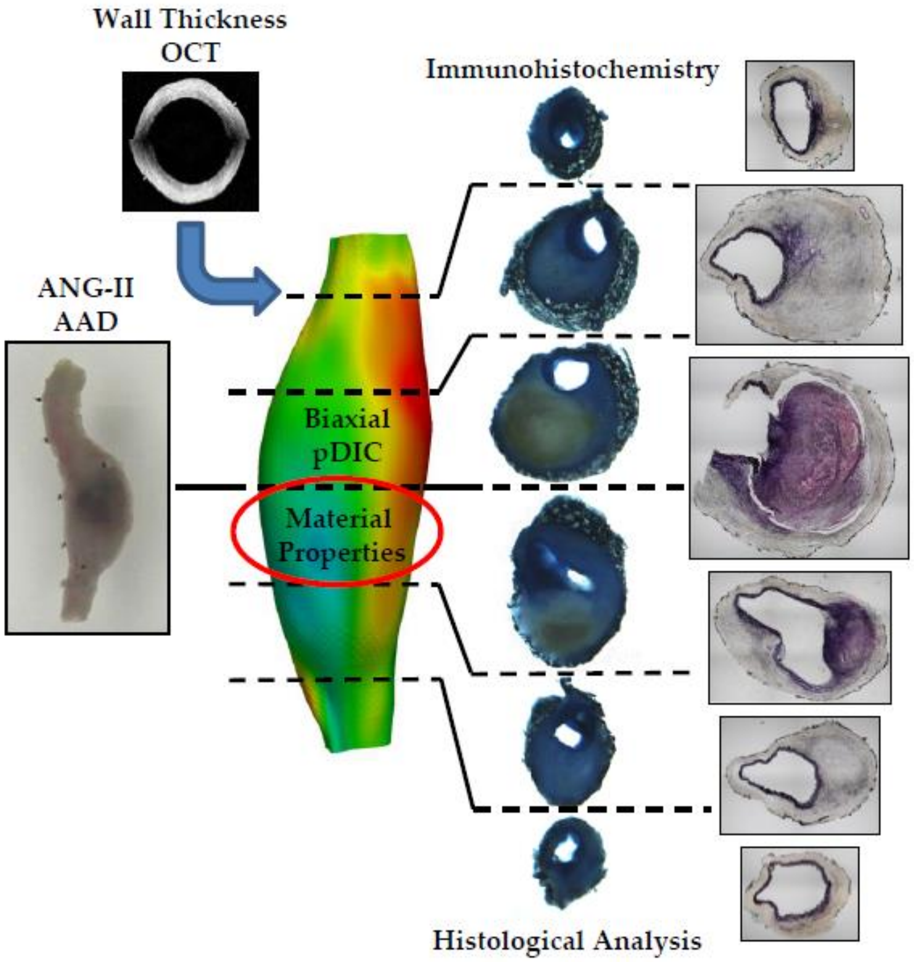
CONCLUSIONS - PERSPECTIVES



We can now begin to establish a correlation between regional mechanical properties and the underlying biological expression in murine models of aneurysms.

ACKNOWLEDGEMENT

ANSYS
Inserm
AGENCE NATIONALE DE LA RECHERCHE ANR
Whitaker International Program
cnrs dépasser les frontières
CONACYT
European Commission
erc European Research Council
Région RhôneAlpes

INVITATION


ESB 2016
JULY 10-13 2016
CITÉ DES CONGRÈS, LYON, FRANCE
European Society of Biomechanics
Société de Biomécanique