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INVERSE IDENTIFICATION OF REGIONAL MATERIAL PROPERTIES IN A MOUSE MODEL OF SUPRARENAL AORTIC DISSECTIONS

Matthew R. Bersi, Víctor Acosta Santamaría, Paolo Di Achille, Evan H. Phillips, Craig J. Goergen, Jay D. Humphrey, Stéphane Avril

CHALLENGES AND OBJECTIVES

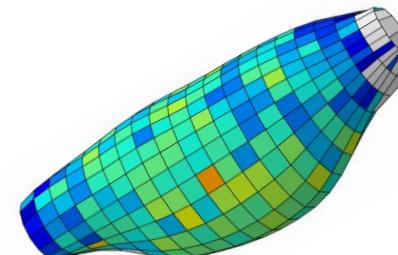
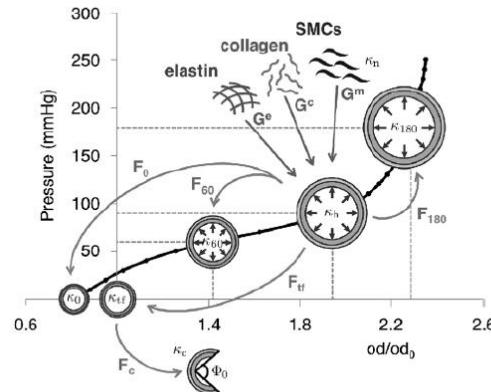
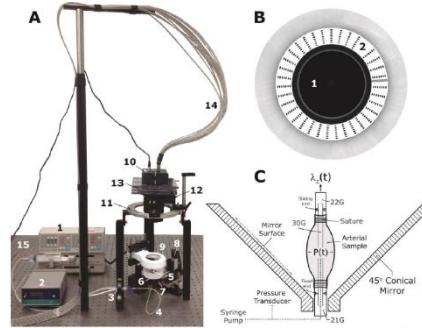
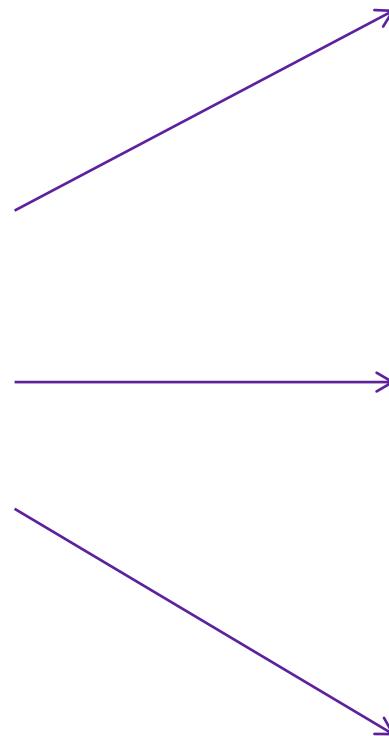
Fundamentally understand local structure–function relationships in aortic dissections.

This requires an approach permitting:

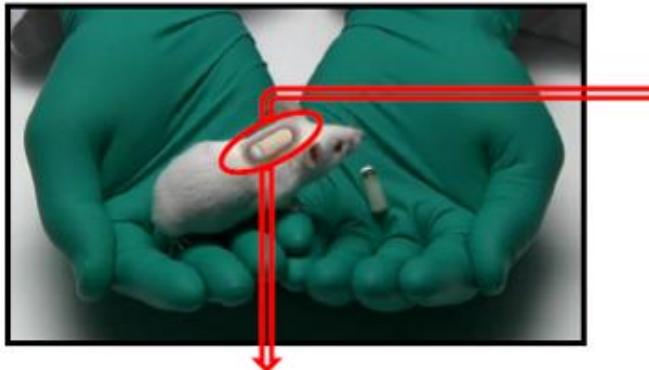
- 1. To reconstruct the regional distribution of mechanical properties of the aortic dissection.**
- 2. To investigate their correlation with the underlying microstructure and its evolutions.**

APPROACH

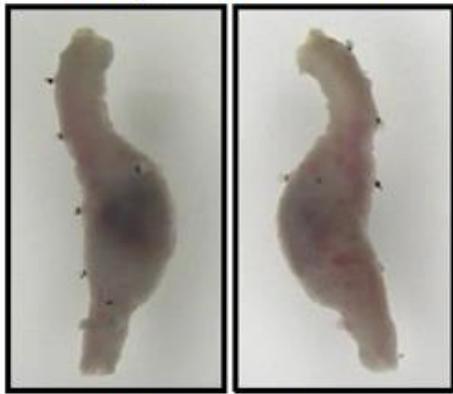
1. Experiments
2. Material model
3. Inverse method



Dissected suprarenal aortas in the ANGII infused mice

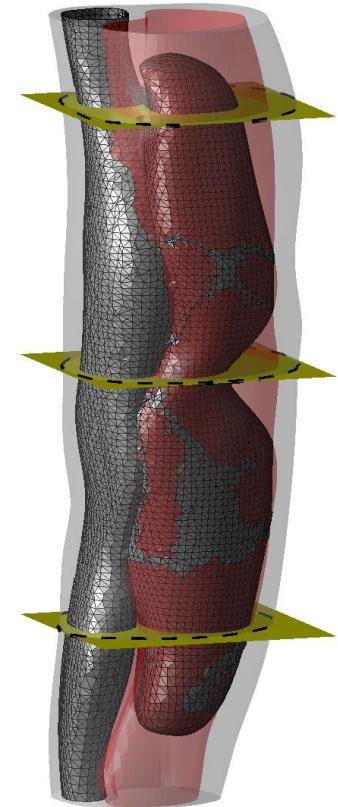
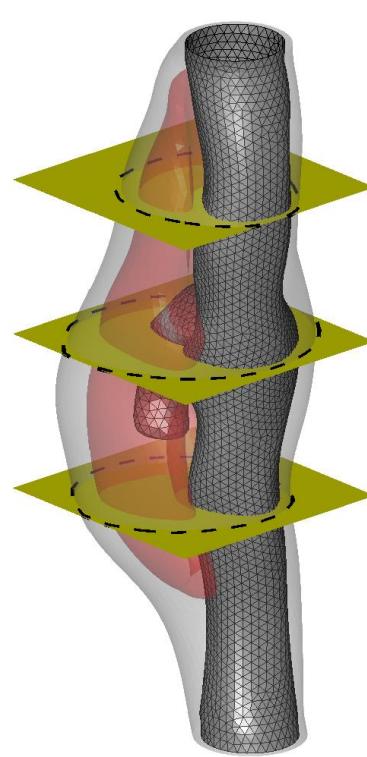


Dissecting Aortic Aneurysm



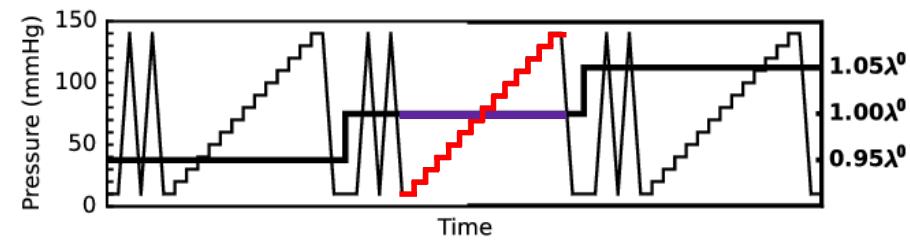
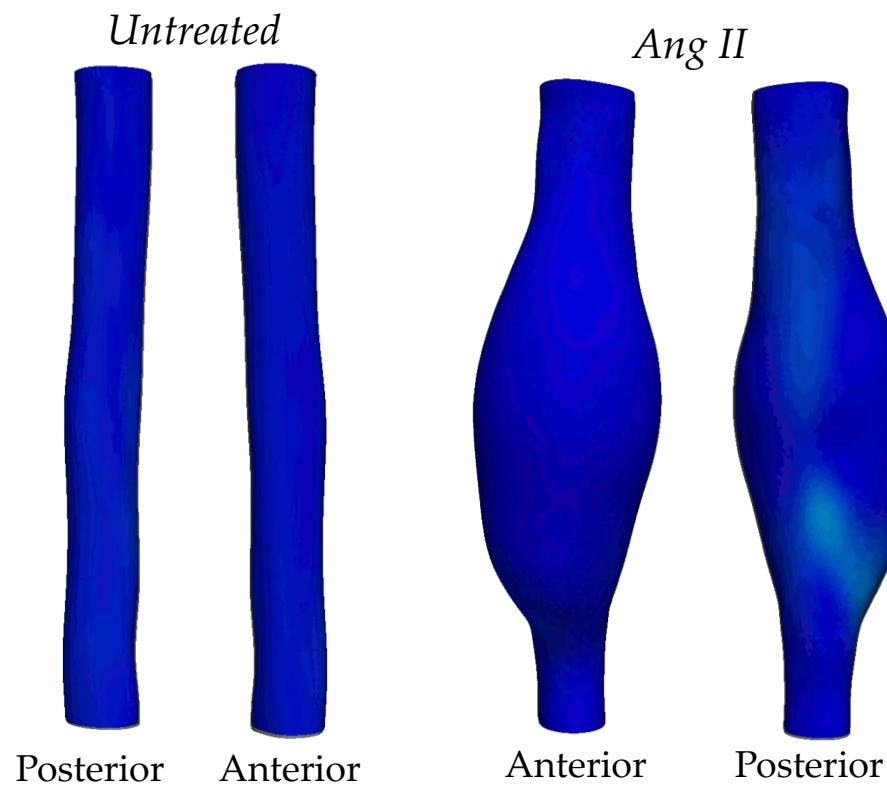
Anterior

Posterior

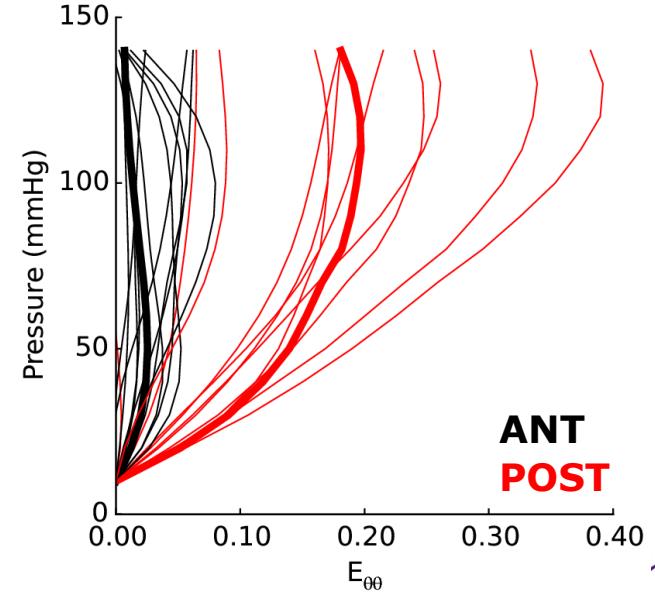


Measurement of surface deformation fields using Panoramic Digital Image Correlation (pDIC)

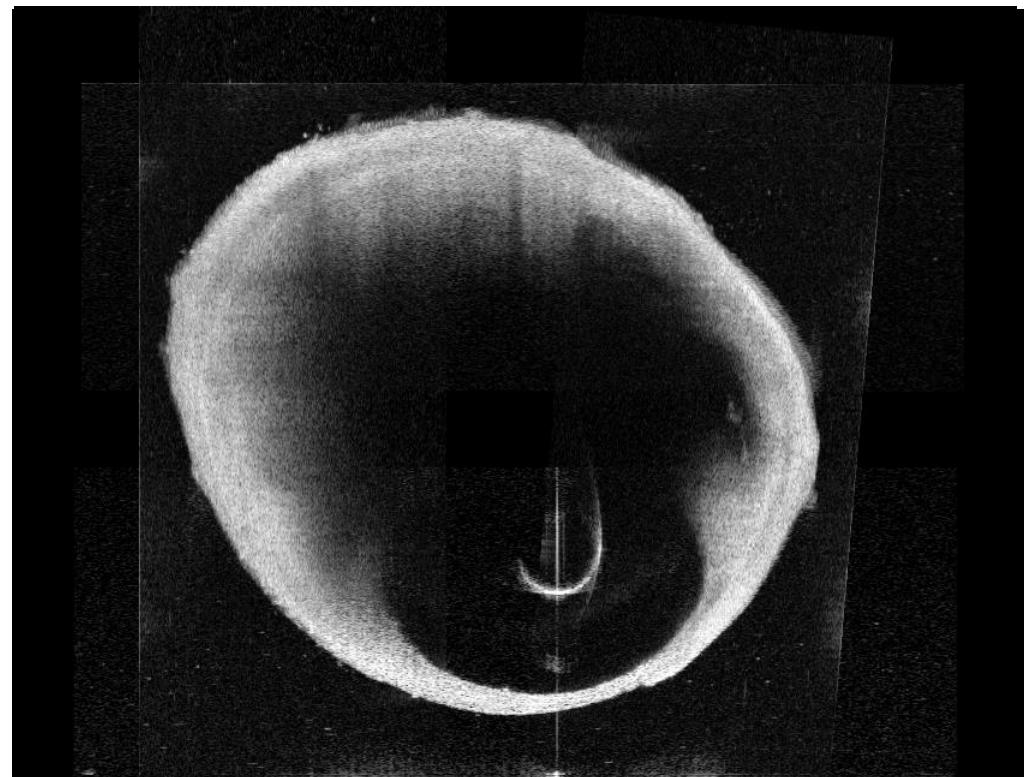
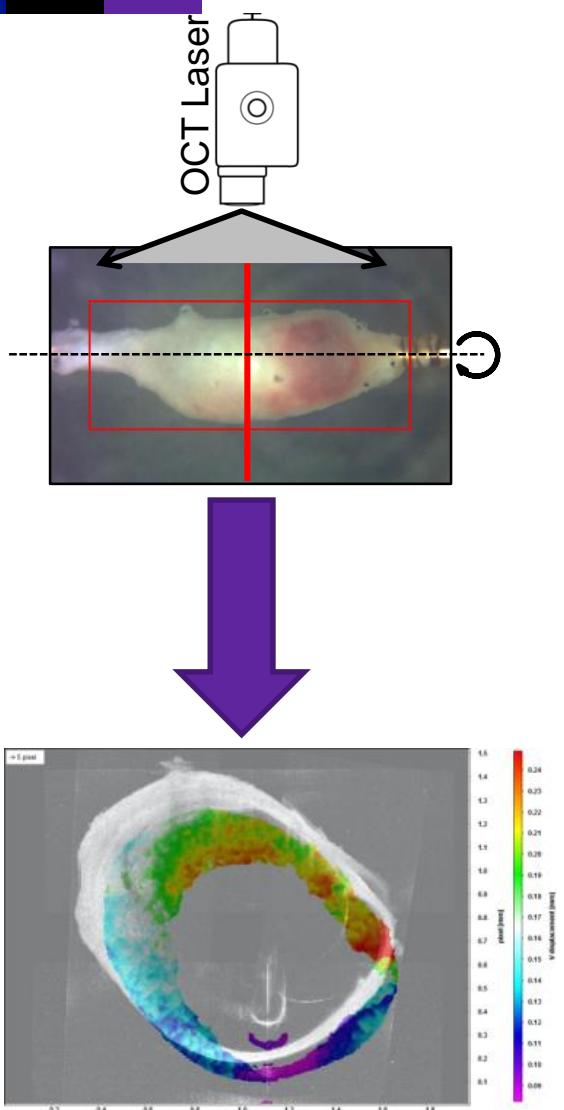
Suprarenal Abdominal Aorta (SAA)



Circumferential Green Strain

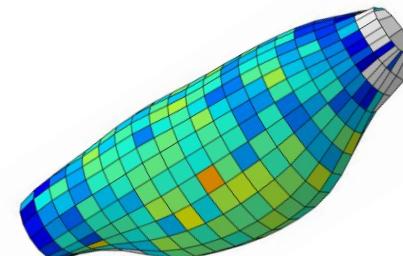
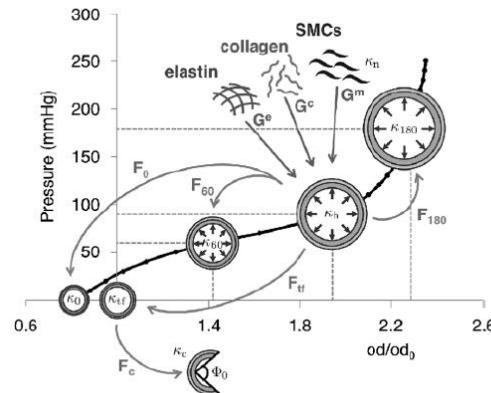
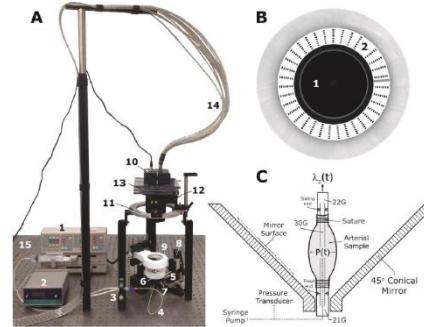
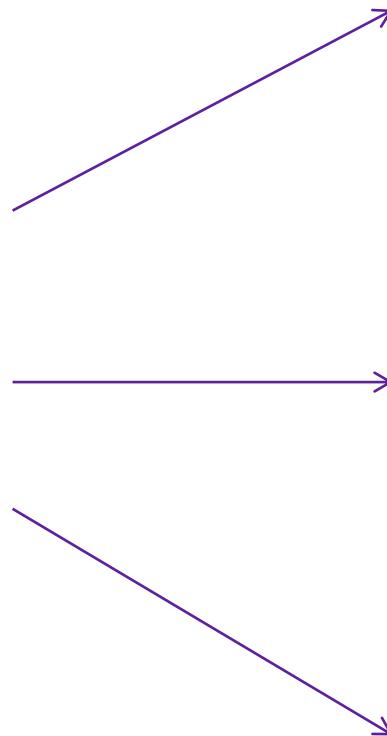


Measurement of bulk deformation fields by Digital Volume Correlation on OCT images



APPROACH

1. Experiments
2. Material model
3. Inverse method



CONSTITUTIVE MODEL

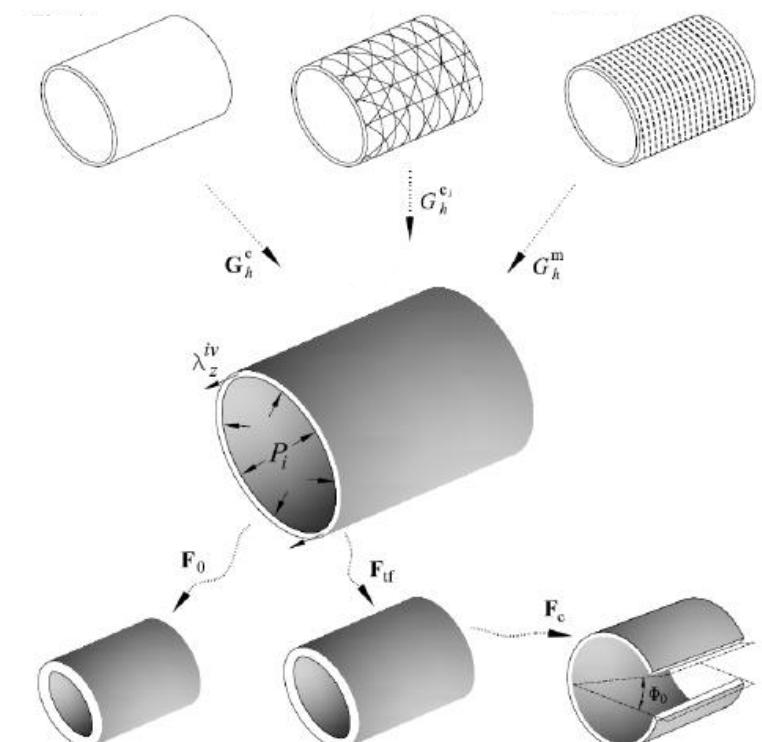
Strain energy functions:

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

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

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

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



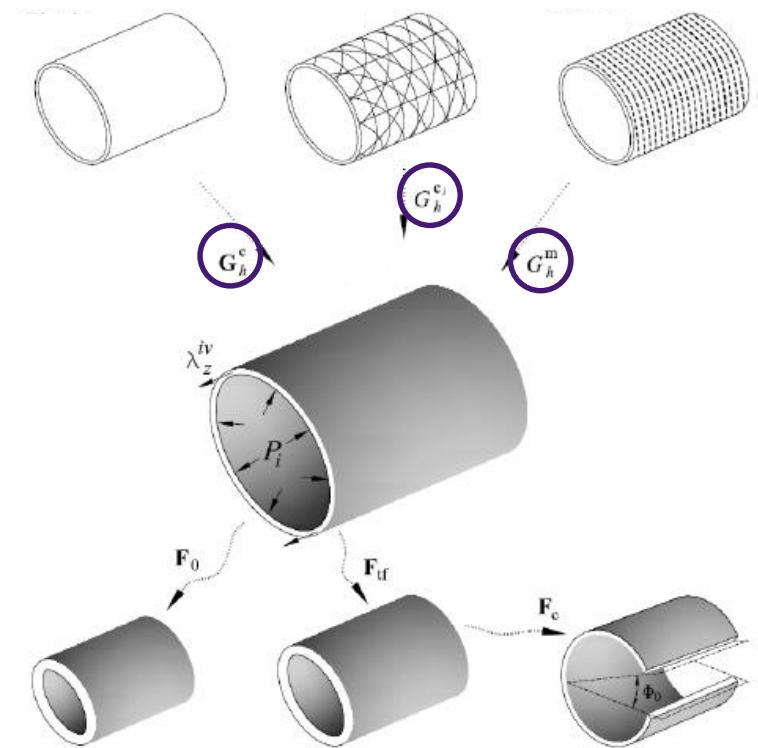
PARAMETERS TO BE IDENTIFIED

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

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

$$W^m(\lambda^m) = \frac{c^m_2}{4c^m_3} \left[e^{\frac{c^m_2}{c^m_3}((\lambda^m)^2 - 1)} - 1 \right]$$

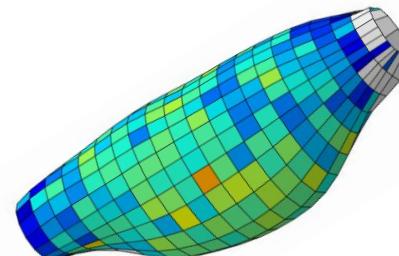
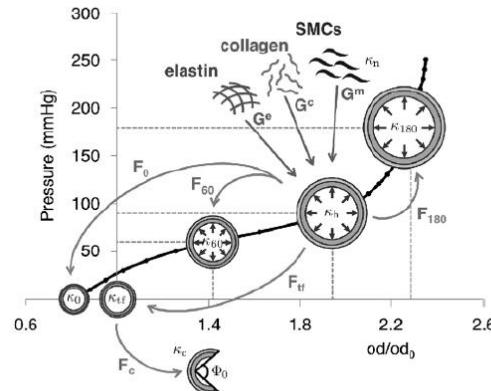
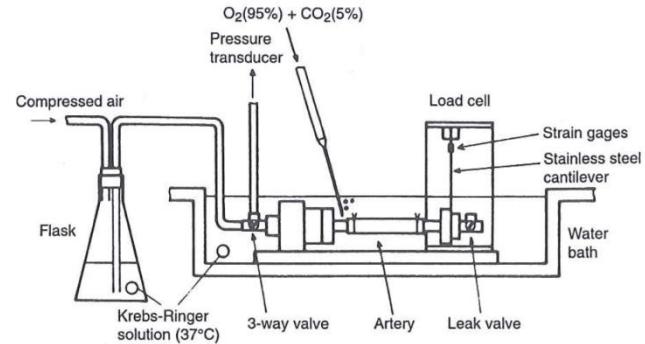
$$W^{c_j}(\lambda^{c_j}) = \frac{c^c_2}{4c^c_3} \left[e^{\frac{c^c_2}{c^c_3}((\lambda^{c_j})^2 - 1)} - 1 \right]$$



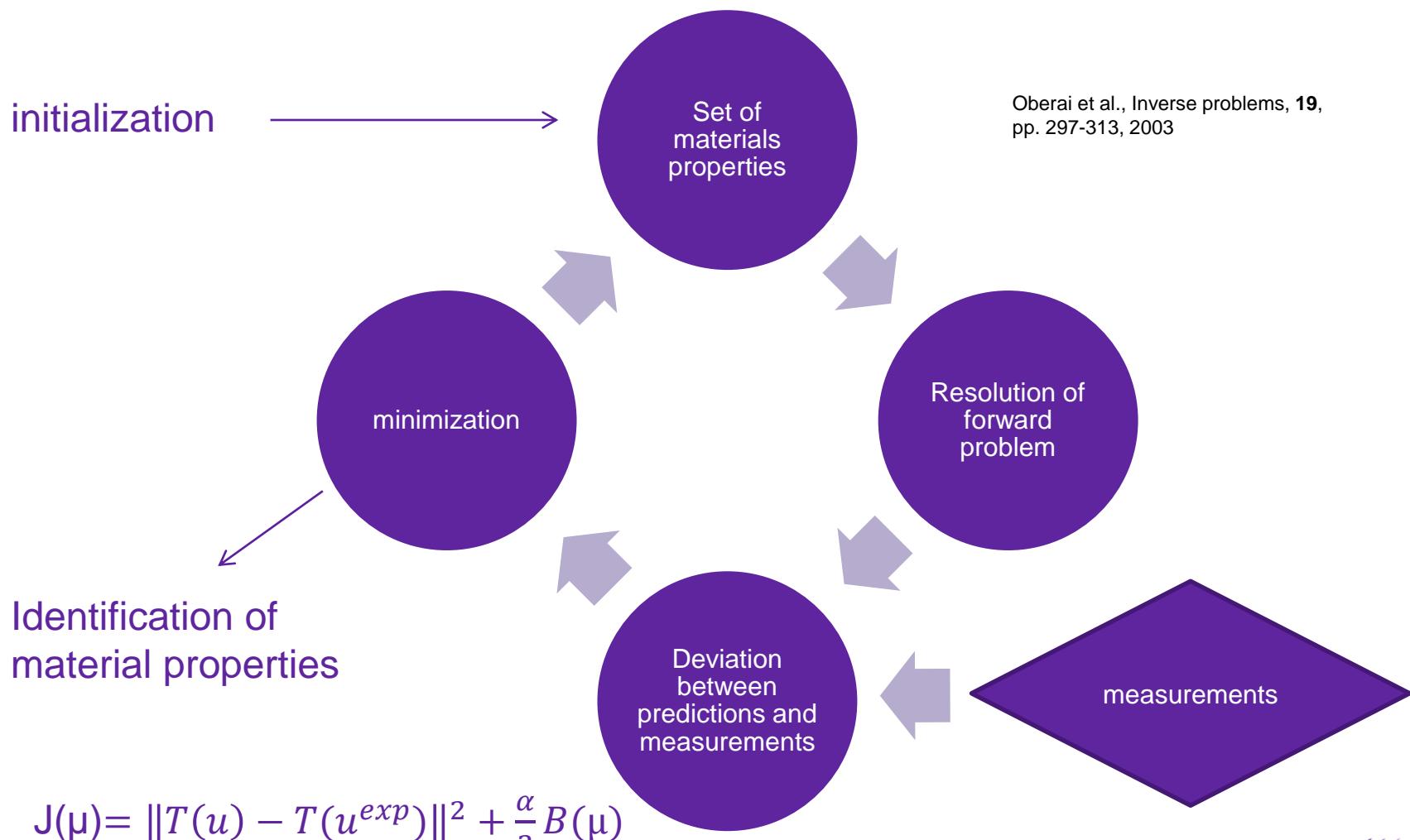
Bersi et al., BMMB, 2018

APPROACH

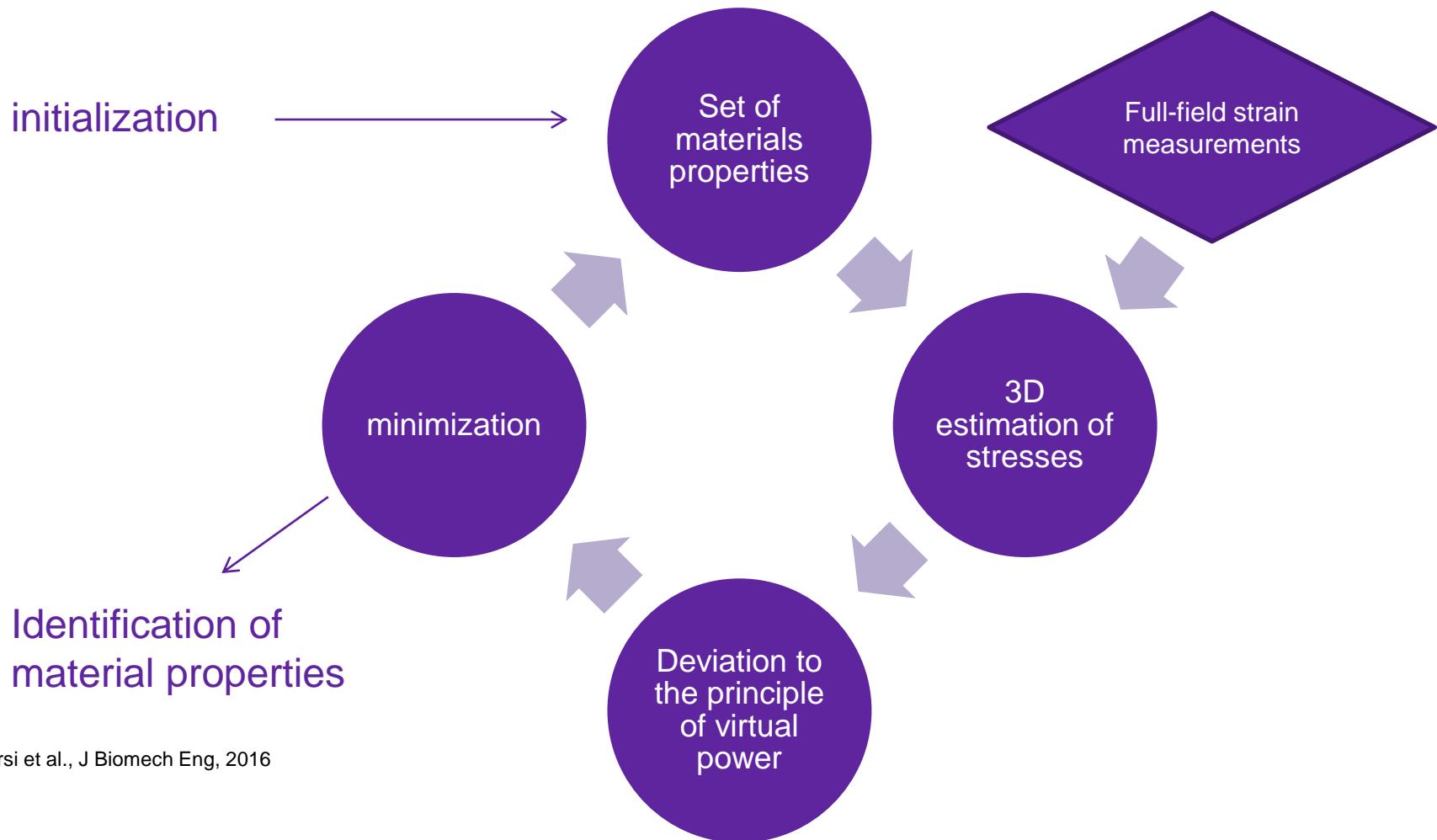
1. Experiments
2. Material model
3. Inverse method



Inverse approach – traditional approach



Alternative inverse approach: the virtual fields method



Bersi et al., J Biomech Eng, 2016

Minimization of the equilibrium gap using the principle of virtual power

minimization

$$J = \sum_p \sum_{\lambda} \left(\underbrace{- \int_{\omega(t)} \underline{\sigma} : (\nabla \otimes \underline{\xi}^*) d\omega}_{P_{int}^*} + \underbrace{\oint_{\partial\omega(t)} T : \underline{\xi}^* ds}_{P_{ext}^*} \right)^2$$

Bersi et al., J Biomech Eng, 2016

Resolution:

$$\min_{c_3^1, c_3^{2,3}, c_3^4, \alpha, \beta} \left[\min_{c^e, c_2^1, c_2^{2,3}, c_2^4} \left[\frac{J(u)}{A} + \frac{J(v)}{B} \right] \right]$$

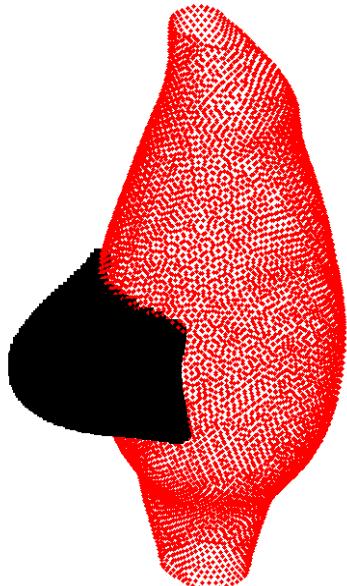
Linear least-squares

Genetic algorithm

Example of virtual field

1. A local virtual radial “bulge”: $\mathbf{u}(\mathbf{x}) = [f(\mathbf{x}-\mathbf{x}_0) / r^2] \mathbf{e}_r$

$$\underbrace{- \int_{\omega(t)} \underline{\underline{\sigma}} : (\underline{\nabla} \otimes \underline{\xi}^*) d\omega}_{P_{int}^*} + \underbrace{\oint_{\partial\omega(t)} \underline{T} : \underline{\xi}^* ds}_{P_{ext}^*} = 0$$



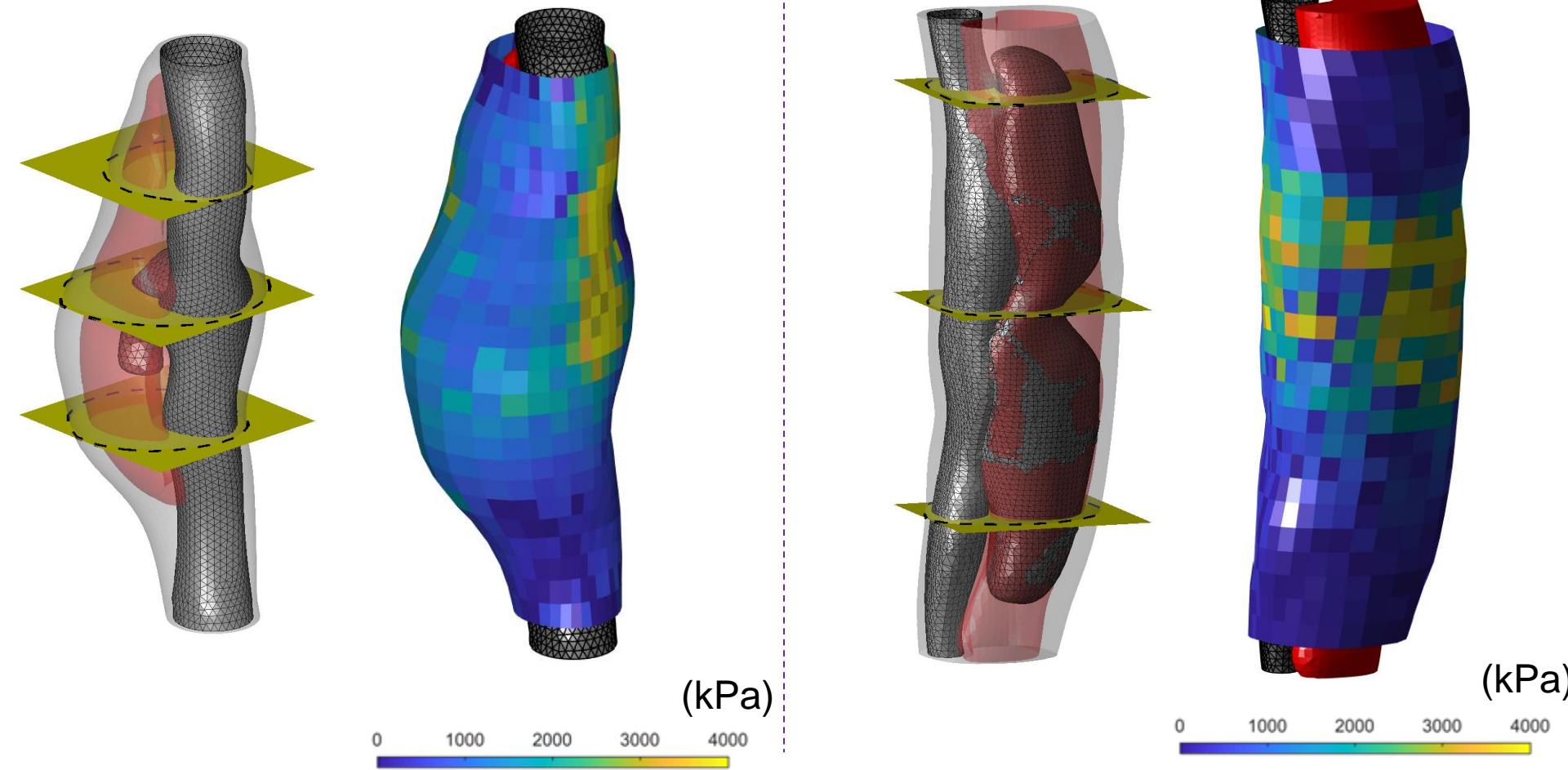
After deriving virtual strains (infinitesimal) local internal virtual work is derived at every Gauss point and integrated across the volume

The virtual field is normalized such as the external virtual work equals P.



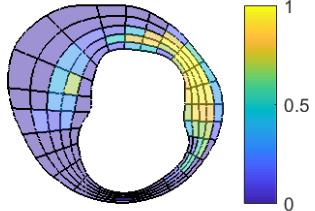
Results - Highlights

Obtained linearized circumferential stiffness

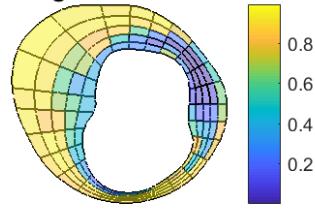


Cross sectional structure – function analysis

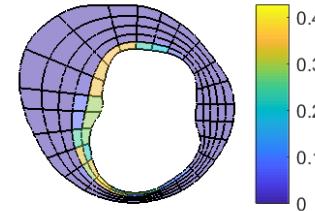
Fibrin fraction area



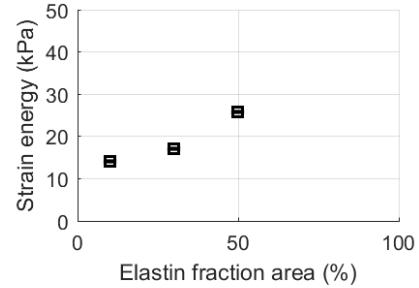
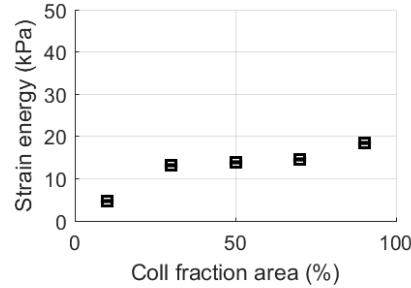
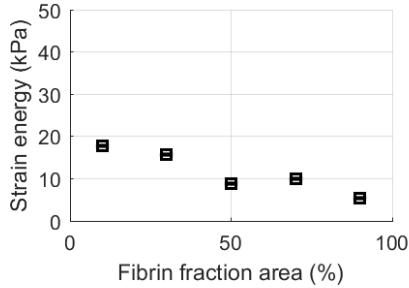
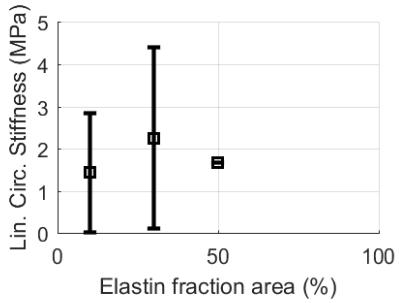
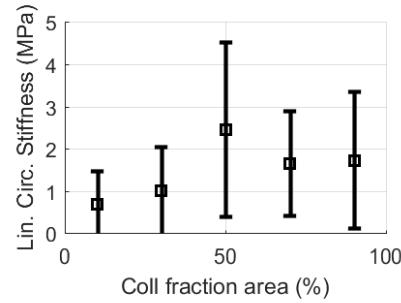
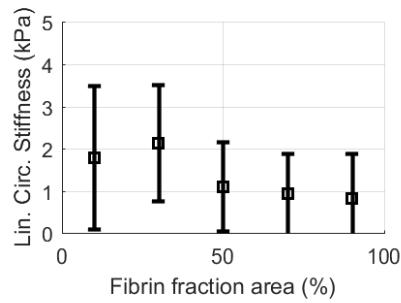
Collagen fraction area



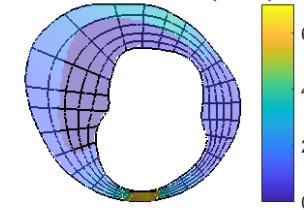
Elastin fraction area



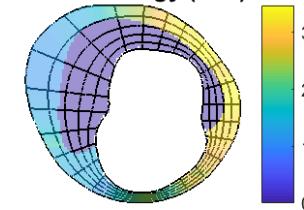
Histological cross section



Lin. Circ. Stiffness (MPa)



Elastic energy (kPa)



SUMMARY

- Inverse approach permitting to reconstruct the regional distribution of mechanical properties of the aorta.
- Towards correlations between mechanical properties and underlying microstructures during aneurysm growth.
- 100 to 1000 independent local responses which could be used to set up statistical mechanobiological models using Bayesian inference and machine learning.

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