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In Vivo Morphological and Inflammatory IVUS Imaging Biomarkers for Coronary Atherosclerotic Lesions

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Collaborators

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Atherosclerosis *- Background -*

Myocardial infarction

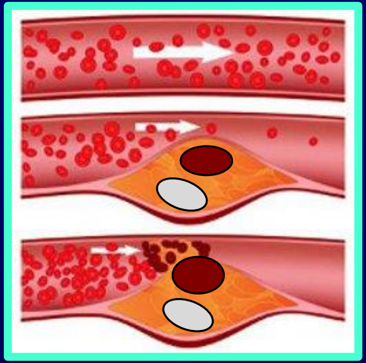
> 1.3 million Americans since 2008

Stroke

Every 45 seconds someone in the United States has a stroke

Atherosclerotic plaque rupture

Depends on mechanical properties



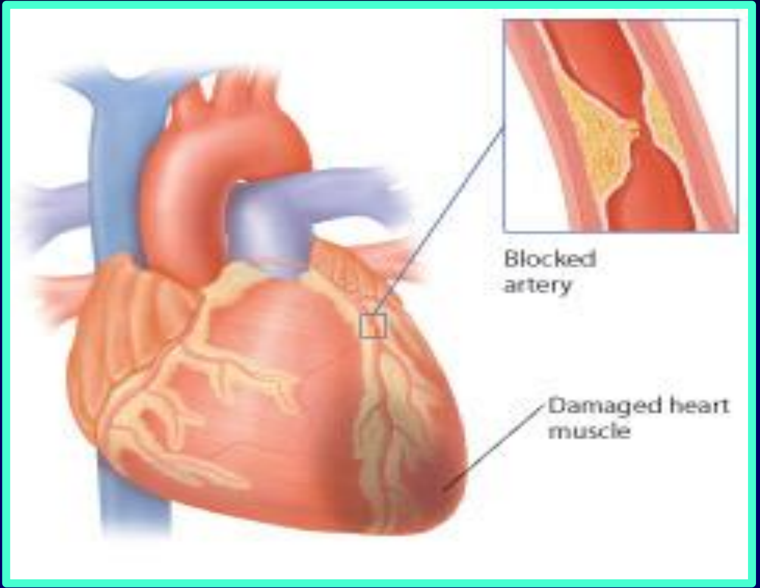
IVUS/OCT Imaging

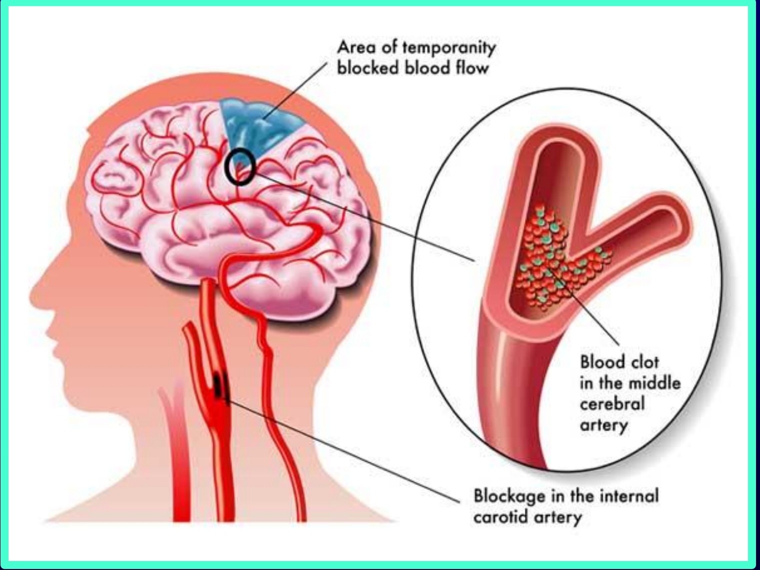
Elasticity map

→Wall stress

→Plaque vulnerability

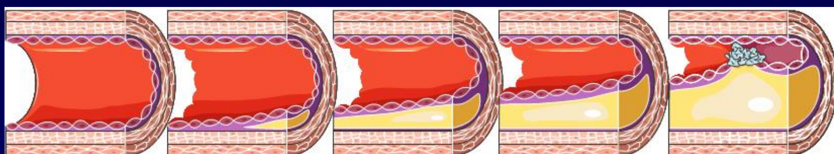
→Diagnosis





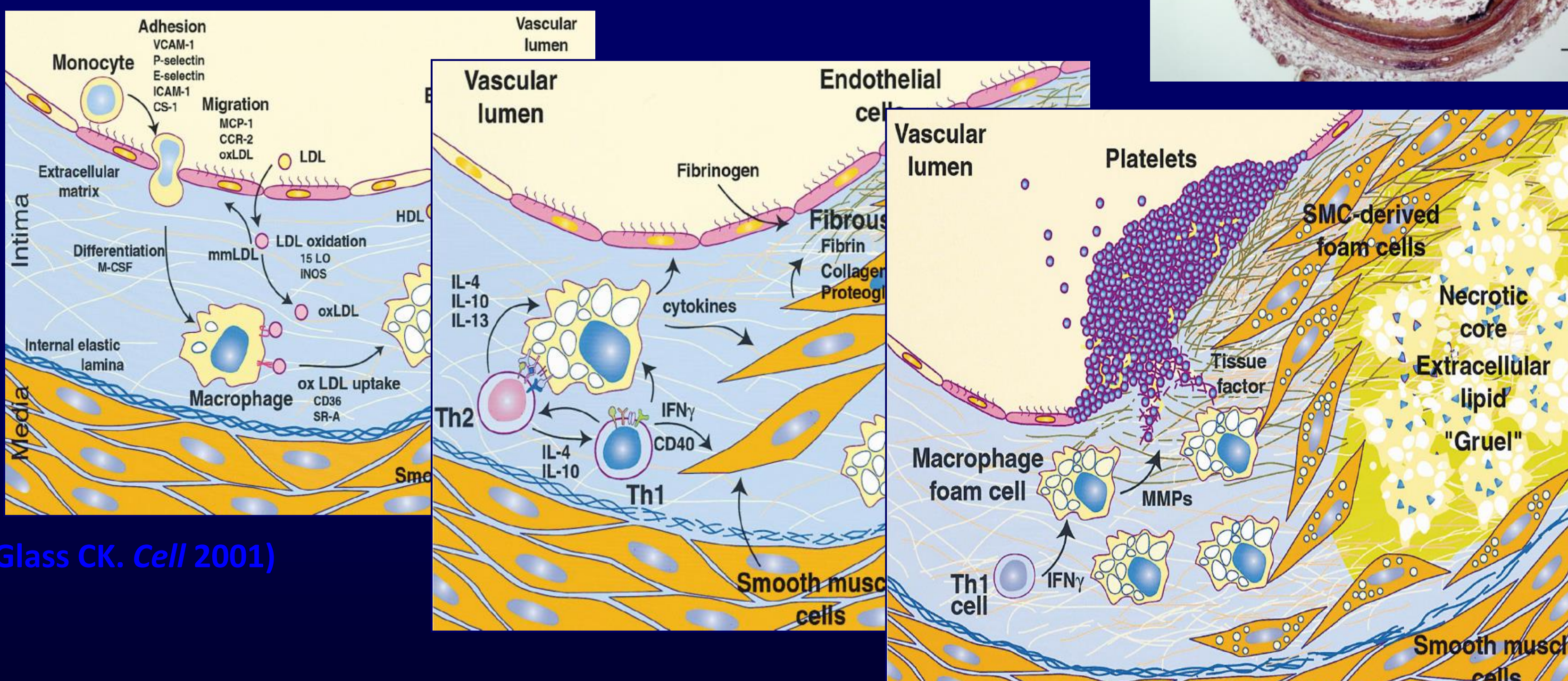
Atherosclerotic Coronary Plaque
- Background -

Plaque growth process & rupture



Courtesy of Dr R. Virmani, CVPath, MD, USA.

Cascade of Biological Events



(Glass CK. *Cell* 2001)

Elasticity Imaging Techniques

Input of the Inverse Problem: Radial Strain Field

Estimation of strain using two successive images
(Optical flow approach – LBUM of Montréal)

Image i

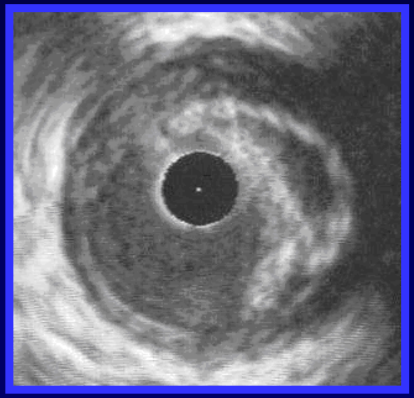
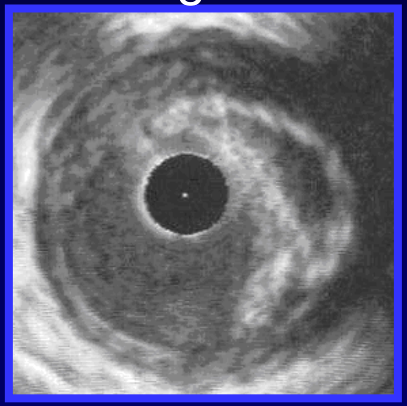
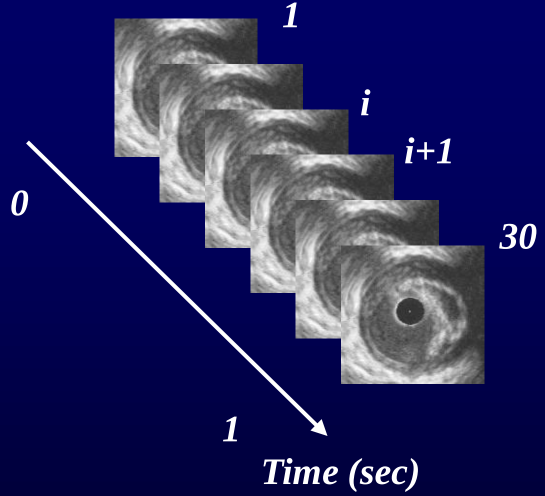
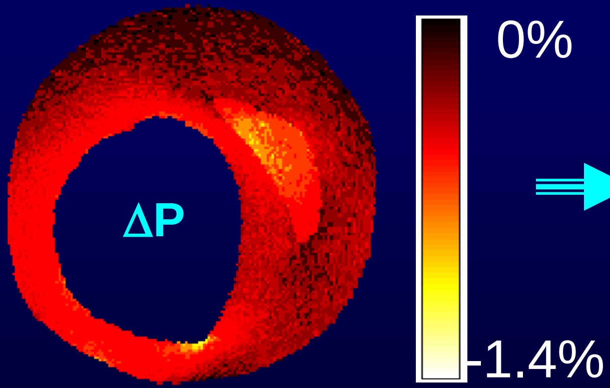


Image i+1



IVUS sequence (30 images/sec)





Radial strain

Palpogram & Plaque Elasticity Map ?

Le Floc'h S et al. IEEE-TMI 2009 - Maurice R, Cloutier G et al., IEEE 2004 – Porée J. et al. IEEE TMI 2016

The Elasticity-Palpography Technique for Vulnerable Plaque Detection

- Theoretical Framework -

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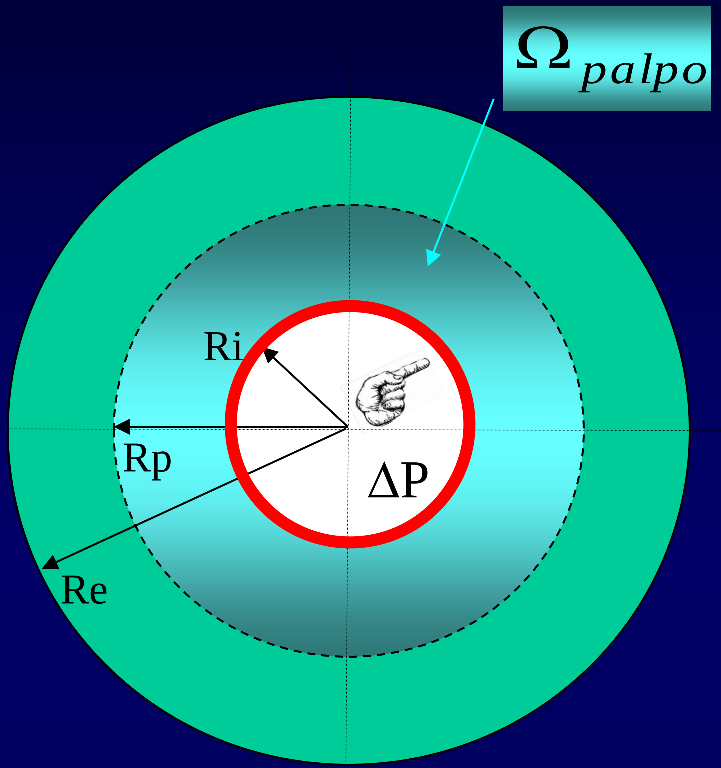


Stress-strain modulus (E_{palpo}) palpogram

$$E_{palpo}(\theta) = \frac{\left| \int_{R_i(\theta)}^{R_p(\theta)} \sigma_{rr}(r,\theta)dr \right|}{\left| \int_{R_i(\theta)}^{R_p(\theta)} \varepsilon_{rr}(r,\theta)dr \right|} = \frac{\text{mean radial stress}(\theta)}{\text{mean radial strain}(\theta)}$$

IVUS

Assuming:

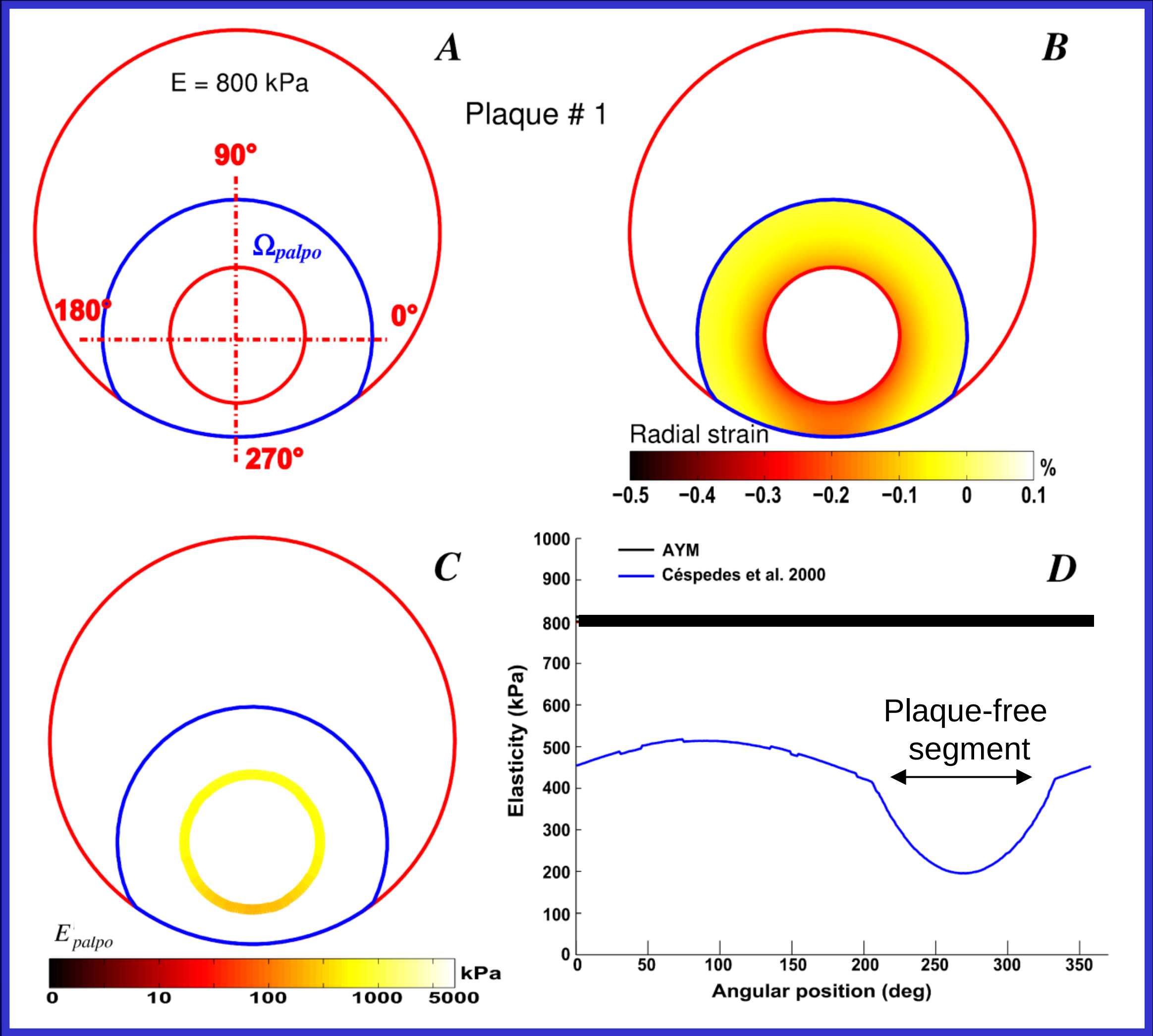
- Concentric plaque
- Specific circular palpography domain ($R_p = 1.8R_i$ if $R_e = 3\,R_i$)
- Isotropic & Incompressible medium

Approximated E_{palpo}

$$E_{palpo}^{\text{Céspedes et al.}}(\theta) = \frac{\Delta P / 2}{\varepsilon(\theta)}$$

Céspedes, de Korte, van der Steen, UMB 2000

The Palpography Technique : *Limitations*



$$E_{palpo}^{Céspedes et al.}(\theta) = \frac{\Delta P/2}{\varepsilon(\theta)}$$

Averaged Young's modulus palpogram

$$AYM(\theta) = \frac{1}{R_p(\theta) - R_i(\theta)} \int_{R_i(\theta)}^{R_p(\theta)} E(r,\theta)\, dr$$

Limitations:

- $\mathbf{E_{palpo}}$ is very sensitive to both plaque and palpography domain geometries.
- The plaque Young's modulus E can not be approximated knowing the $\mathbf{E_{palpo}}$

Céspedes, de Korte, van der Steen, UMB 2000

The Palpography Technique Revisited
-Theoretical Framework -

Redefined stress-strain modulus palpogram

$$E_{palpo}^{revisited}(\theta) = \frac{3}{2}\frac{\left|\int_{R_i(\theta)}^{R_p(\theta)} \sigma_{rr}^{dev}(r,\theta)dr\right|}{\left|\int_{R_i(\theta)}^{R_p(\theta)} \varepsilon_{rr}(r,\theta)dr\right|}$$

Assuming:

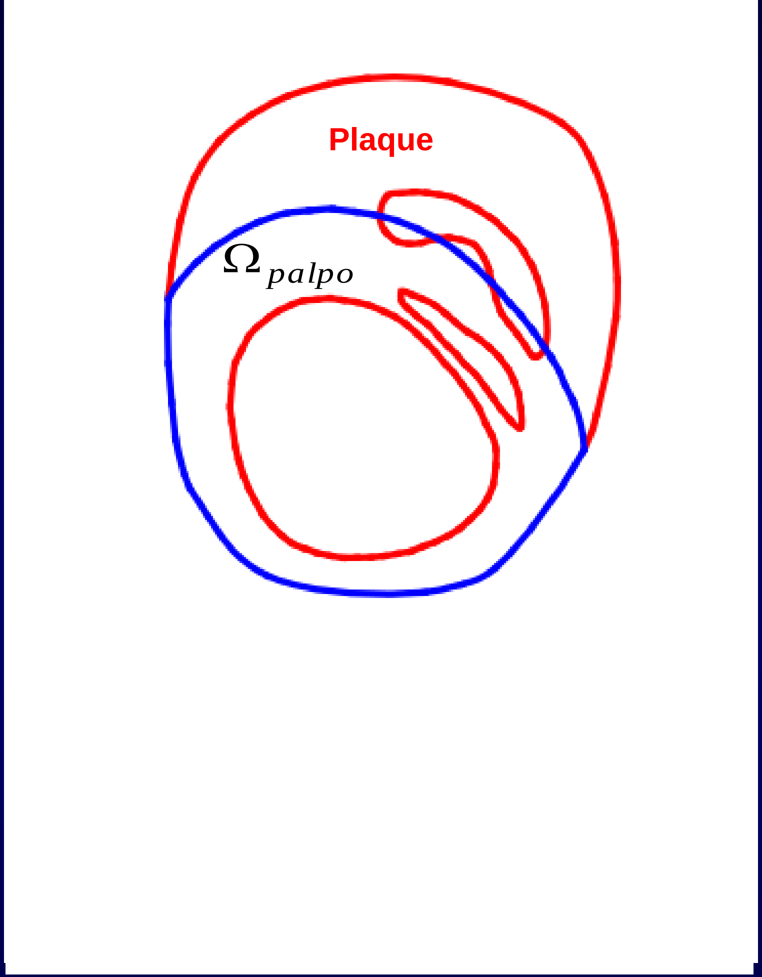
- Isotropic & Incompressible medium

Whatever the geometries of the:

- whole plaque
- palpography domain

Shape function (FEA)

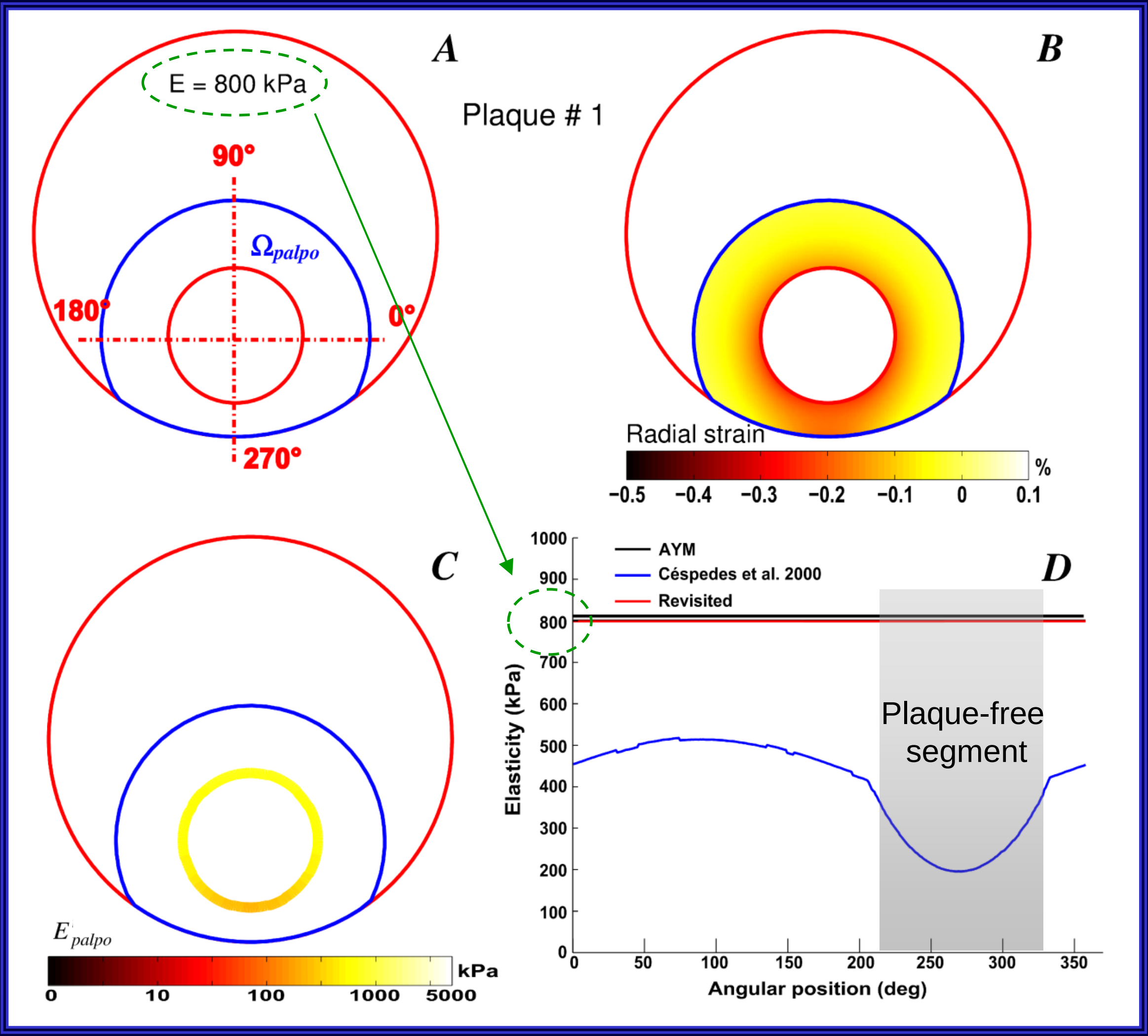
$$E_{palpo}^{revisited}(\theta) = \frac{\Delta P \left|\int_{R_i(\theta)}^{R_p(\theta)} g^{iso}(r,\theta)\ dr\right|}{\left|\int_{R_i(\theta)}^{R_p(\theta)} \varepsilon_{rr}(r,\theta)dr\right|};$$



Revisited approximated E_{palpo} accounts for real plaque and palpography domain geometries.

The Palpography Technique Revisited

- Results -



$$E_{palpo}^{Céspedes et al.}(\theta) = \frac{\Delta P / 2}{\varepsilon(\theta)}$$

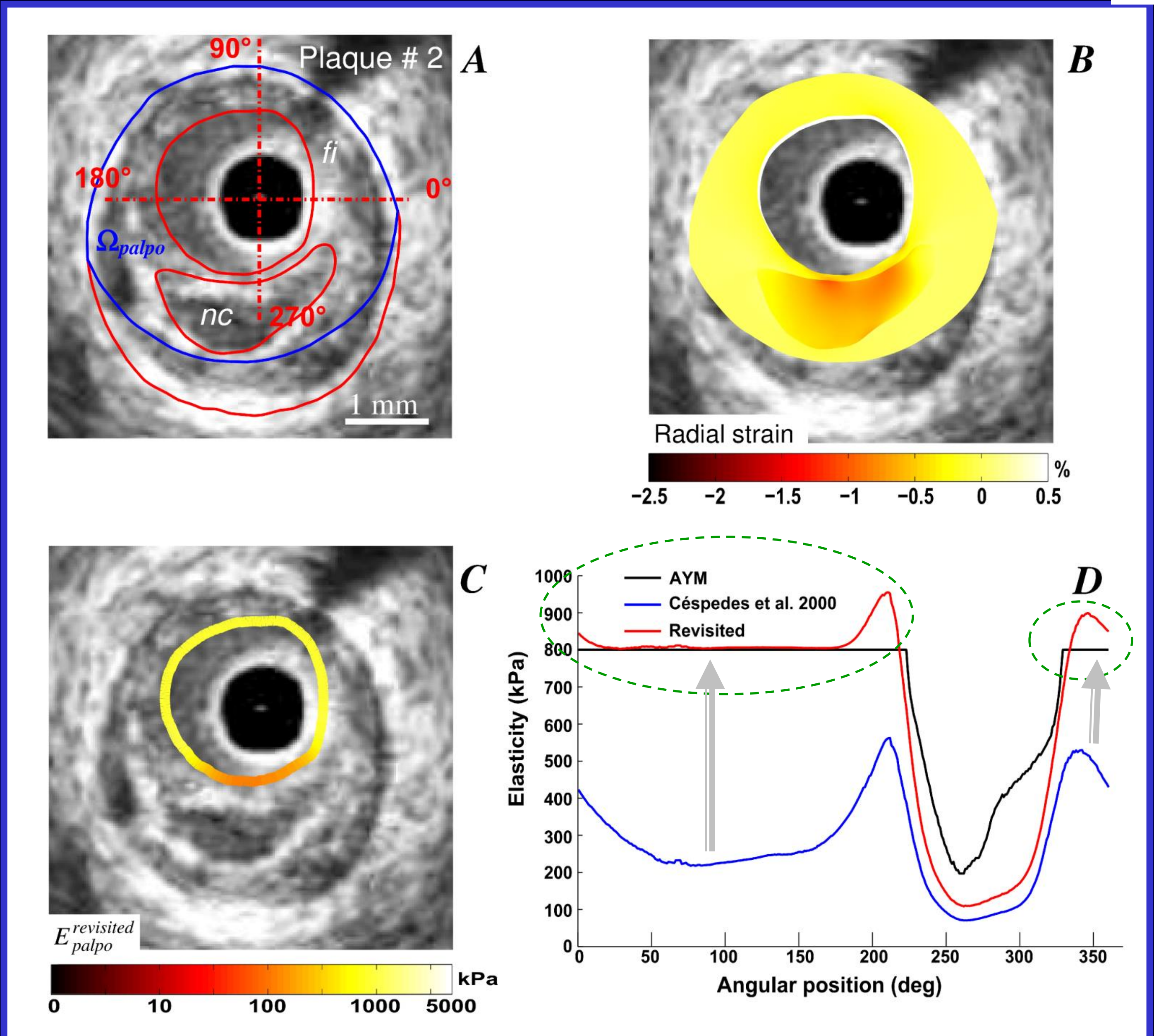
Averaged Young's modulus palpogram

$$AYM(\theta) = \frac{1}{R_p(\theta) - R_i(\theta)} \int_{R_i(\theta)}^{R_p(\theta)} E(r,\theta)\, dr$$

Céspedes, de Korte, van der Steen, UMB 2000

The Palpography Technique Revisited

- Results -



E_{nc}= 5 kPa

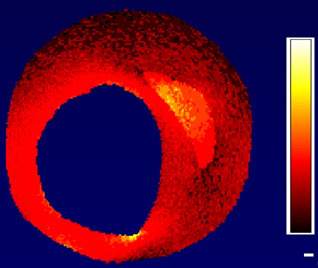
E_{fi}= 800 kPa

Simulated RF data with FieldII

Elasticity Imaging Technique

The Algorithm

Strain elastogram



0%

-1.4%

Optical flow approach (LBUM- Montréal)

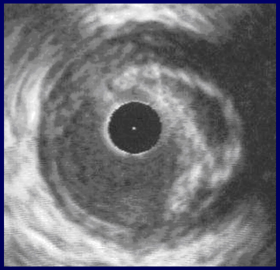


Image i

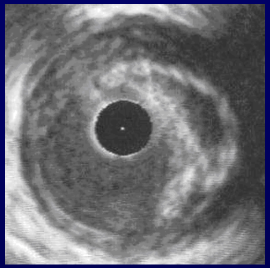


Image i+1

IVUS sequence

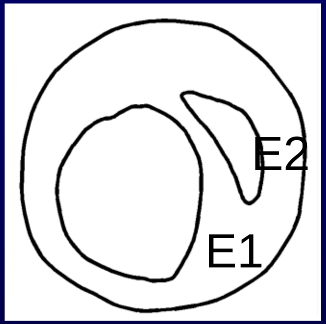
Originality++

Step 1: *Smart* **Automatic segmentation** of plaque heterogeneities based on the **mechanical criterion**

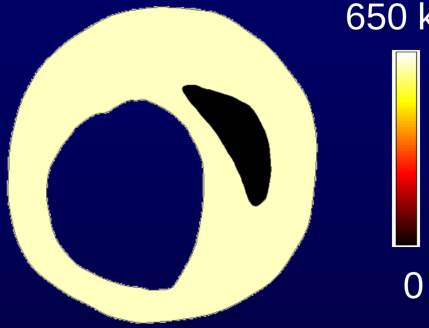
The criterion

$$\vec{H} = -\,[\varepsilon]^{-1}\,\nabla.\,[\varepsilon]$$

Step 2: Optimization



Young's Modulus Map



650 kPa

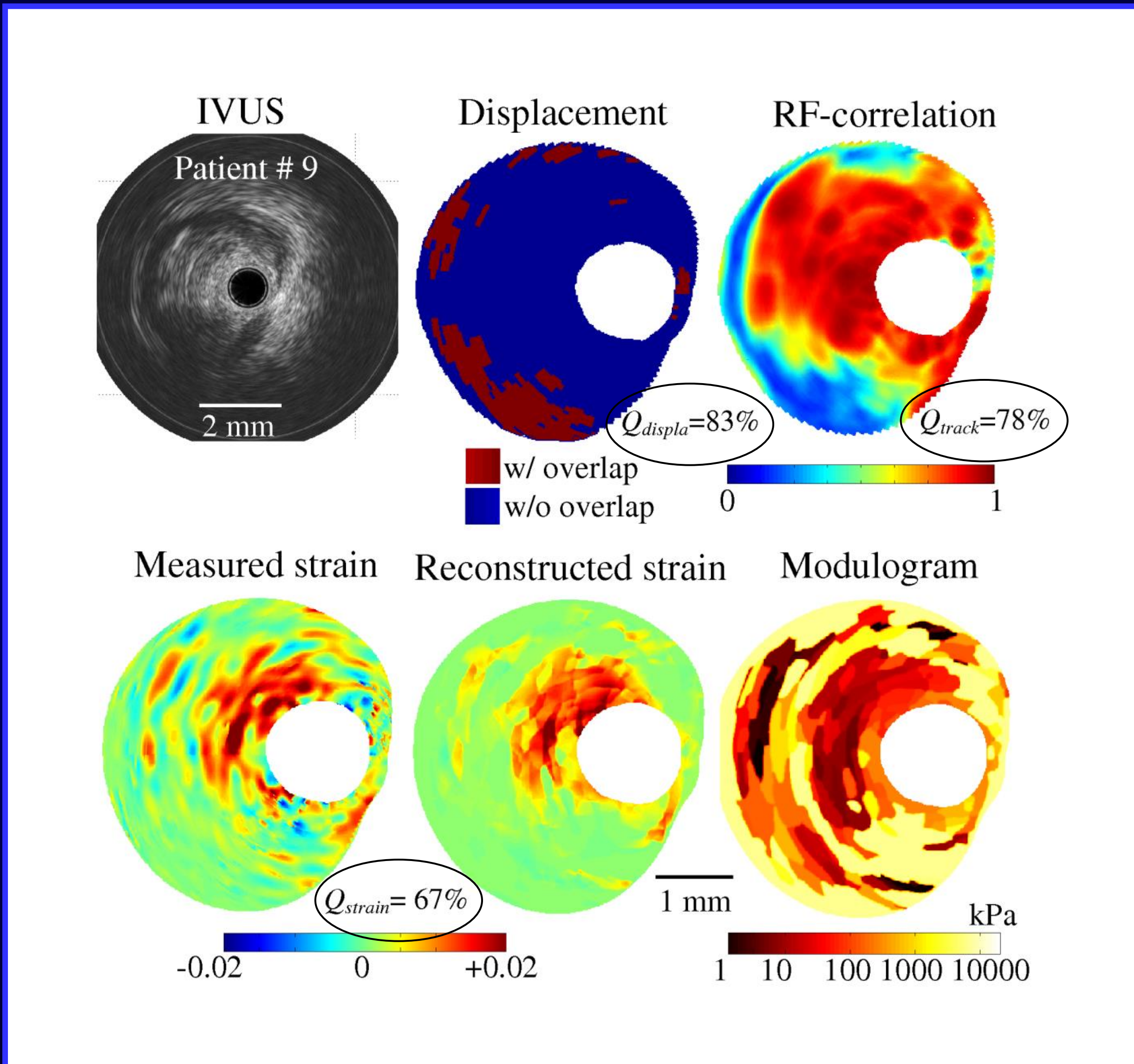
0

++ Approach Based on Continuum Mechanics Theory

Imaging Technique Performance

Inflammatory Process

Population: 12 patients, Directional Coronary Atherectomy (DCA)
(Sendai University Hospital, Japan)



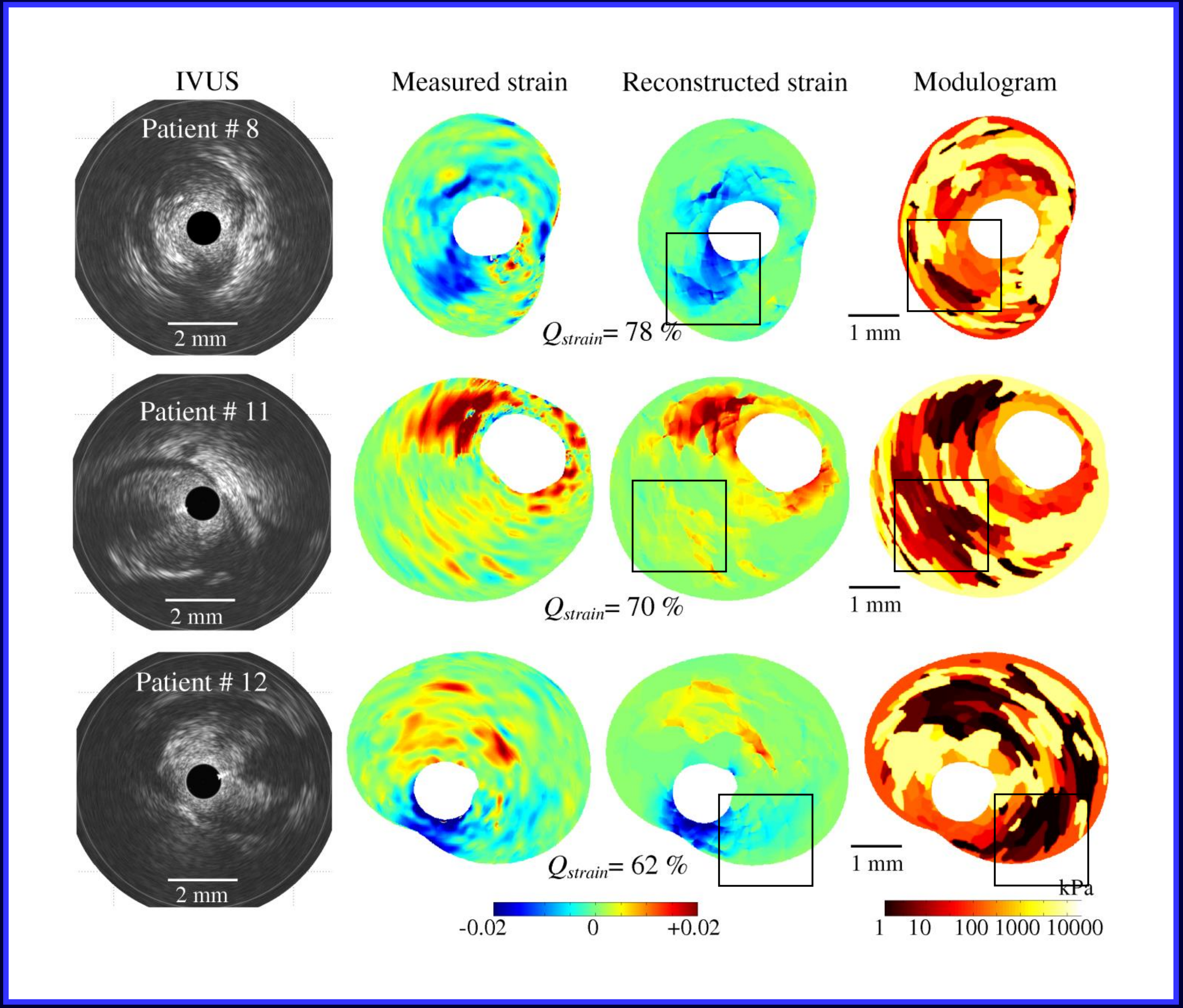
Cap thickness = 290 µm

(kPa)

- [0, 5]
-]5, 30]
-]30, 300]
- > 300

Imaging Technique Performance

Strain Elastograms are not Sufficient to highlight VPs



Perspectives & Works in Progress

Such clinical tool will be used to :

- **detect vulnerable plaques based on OCT (Coronary) and MRI (Carotid, Aorta) sequences**

- **explore *in vivo* the effects of a specific drug therapy (Statins) on the stabilization of vulnerable plaques**

Works in progress :

- **Strengthen the validation study**

  (aorta of Watanabe rabbits: HD-IVUS + Elastography + AFM + Histology)

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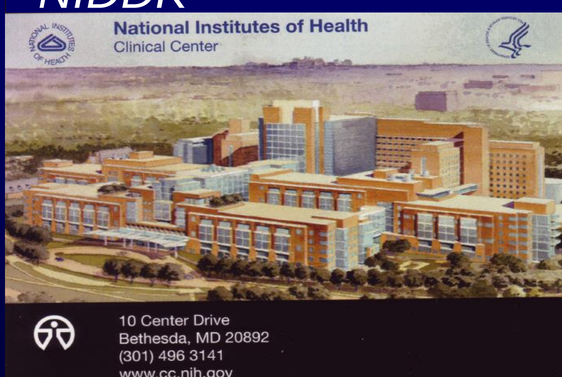

Thank you