Presented at the COMSOL Conference 2010 Paris

COMSOL CONFERENCE 2010

NOVEMBER 17-19 2010, PARIS, FRANCE

Finite Element Simulation of Shear Wave Propagation Induced by a VCTE Probe

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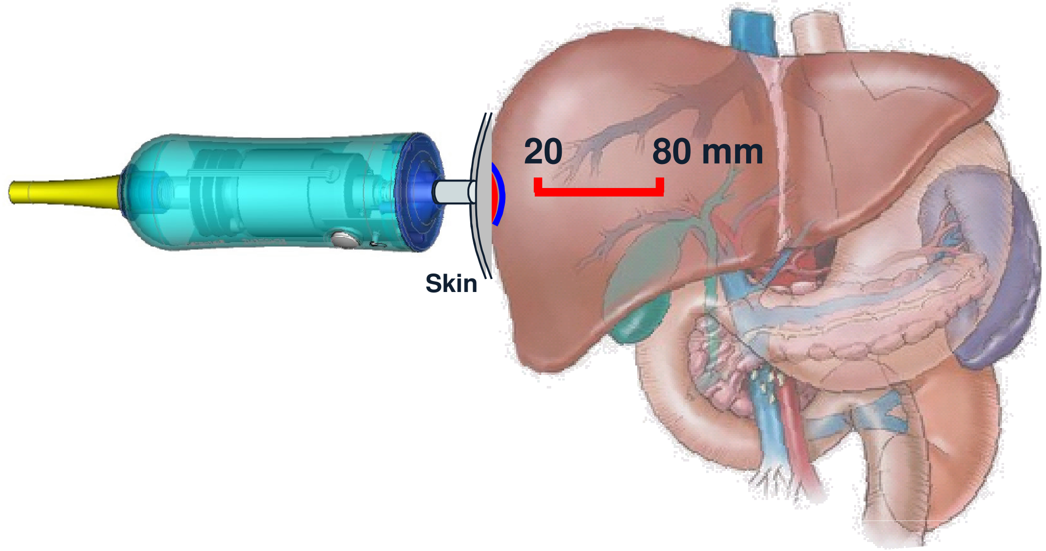
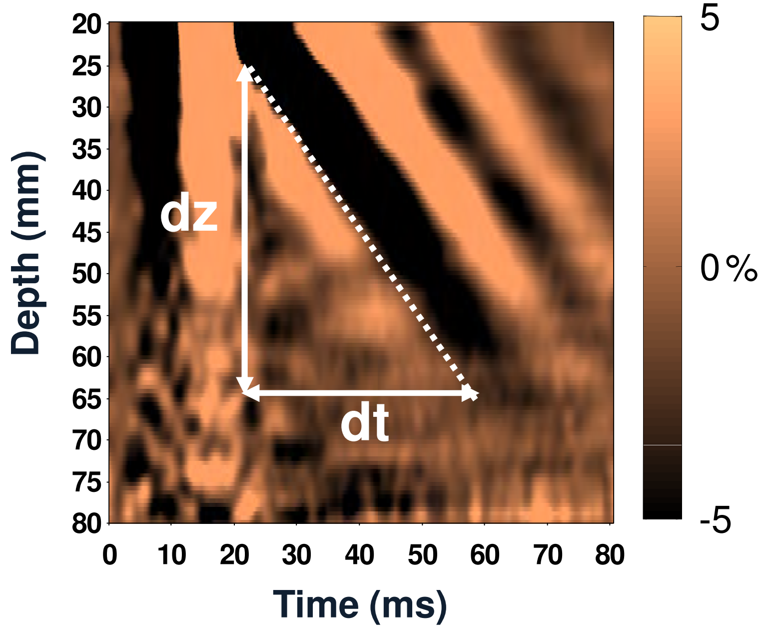
Vibration-Controlled Transient Elastography

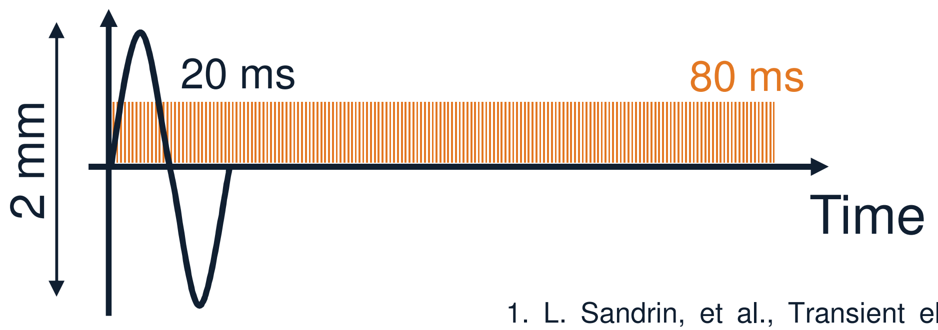
Liver stiffness measurement using VCTE



Strain image or « Elastogram »



1. 50Hz mechanical vibration
2. 3.5 MHz ultrasound acquisition (PRF=6kHz)



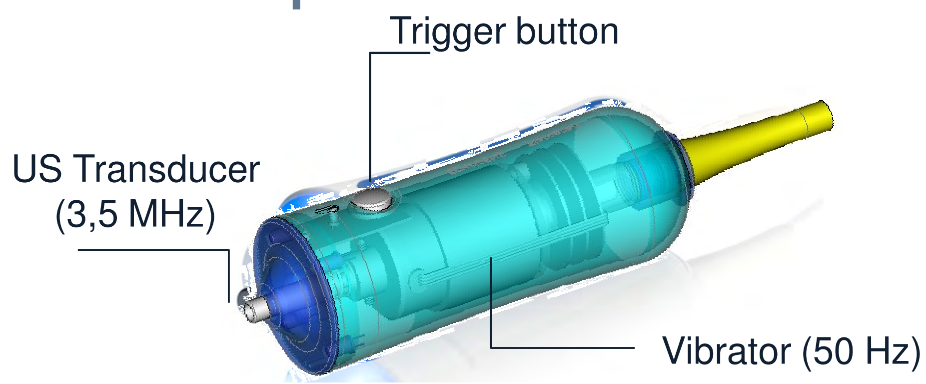
$$\left\{ V_s = \frac{dz}{dt} \right.$$

1. L. Sandrin, et al., Transient elastography: a new noninvasive method for assessment of hepatic fibrosis, *Ultrasound in Medicine & Biology*, ***29*, *pp. 1705-1713*, *(2003).***

Fibroscan

900 devices used worldwide

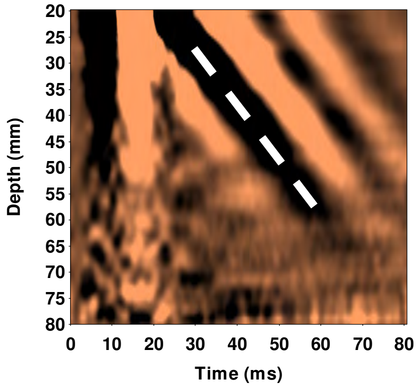
- **Based on VCTE [1]**
- **Used to assess liver stiffness**
- **>300 independent peer-reviewed medical publications**
- **Dedicated electronics**
  - Generation of a mechanical vibration
  - Ultra-fast ultrasonic RF signal acquisition
- **Integrated computer**
  - RF processing
  - Tissue stiffness measurement
- **Fibroscan probe**



[1] Sandrin *UMB* 2003

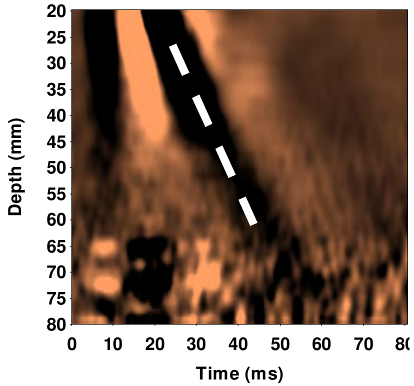
Hepatic fibrosis stage evaluation

Healthy



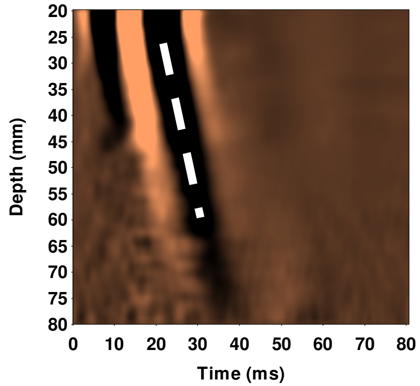
E ~ 3 kPa

Moderate Fibrosis



E ~ 9 kPa

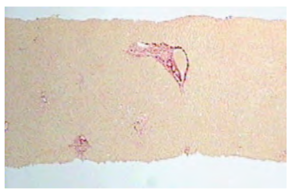
Cirrhosis



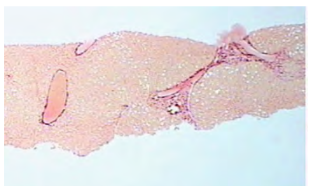
E ~ 40 kPa

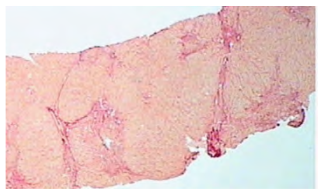
Metavir score (biopsy)

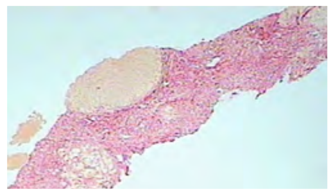
F0	F1	F2	F3	F4
No fibrosis	Few	Significant	Extensive	Cirrhosis



10mm

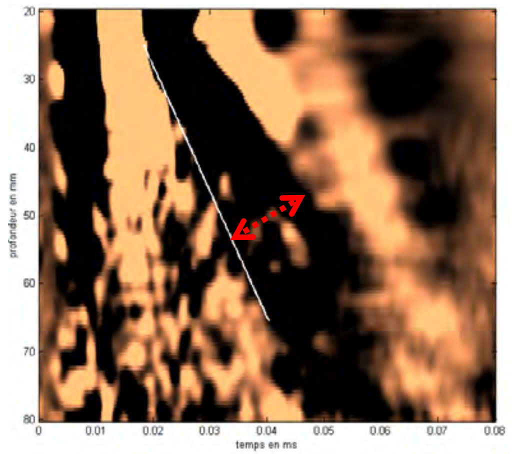


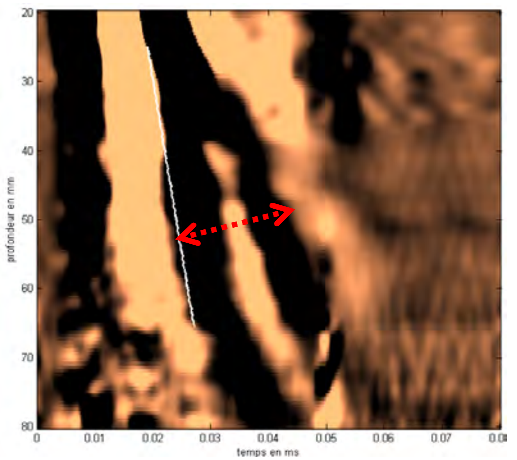




Motivation for simulation studies

Motivations for simulation studies

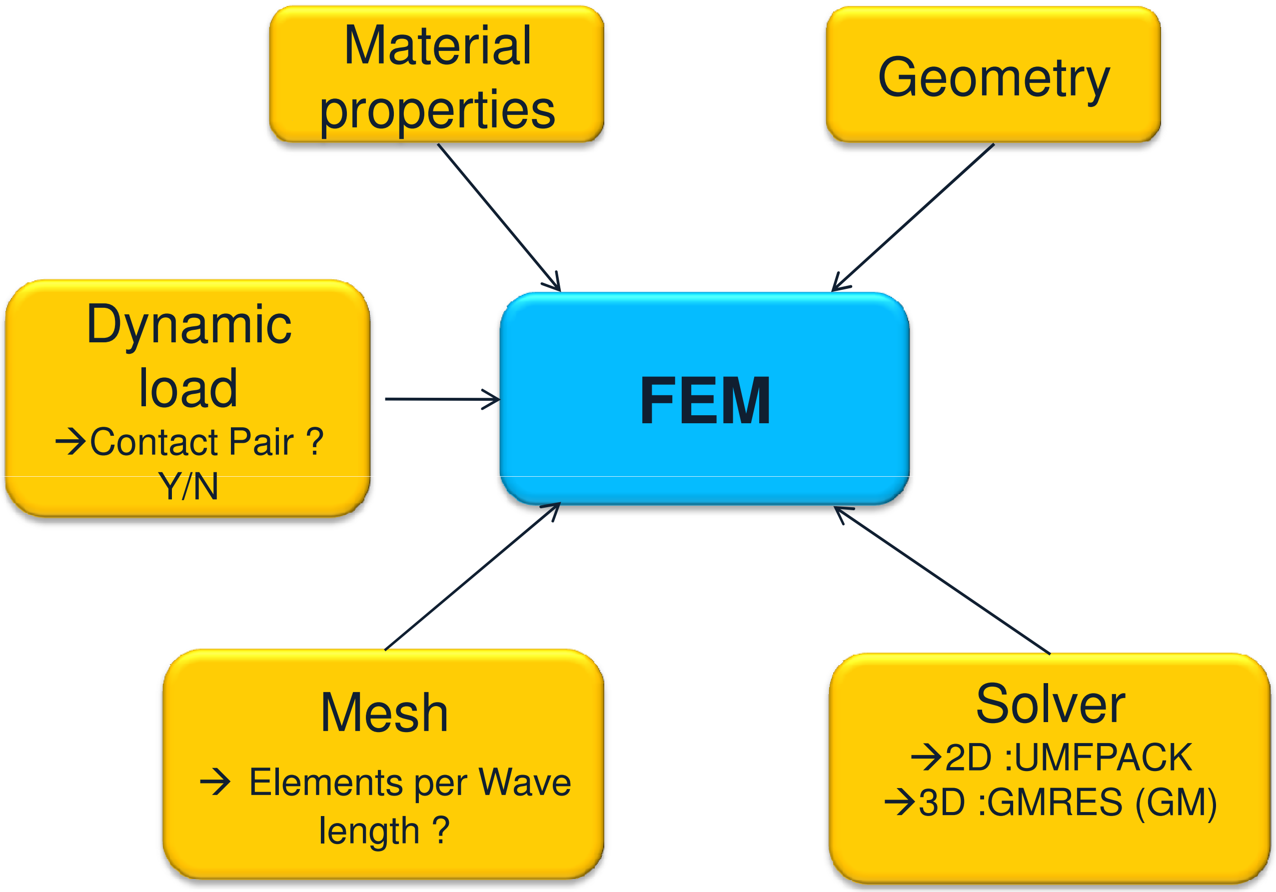


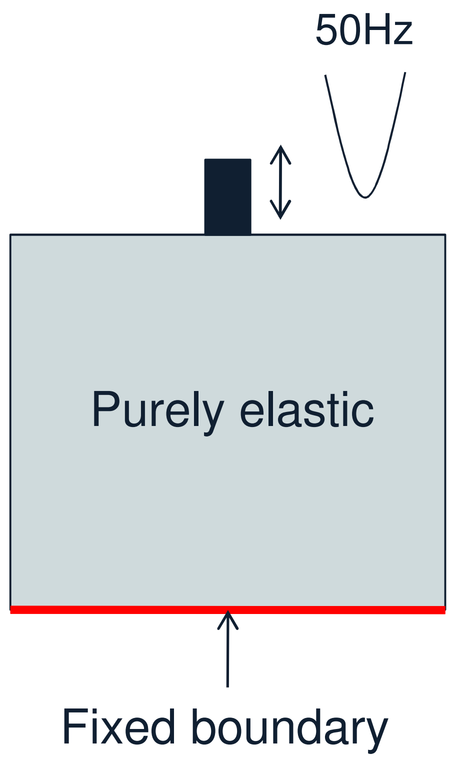


- **Non-exploitable elastograms:**
  - ➔ Possible origins of artefacts:
    - Ribs vibration?
    - Thick subcutaneaous fat layer?
    - Others?
- **Experiments:**
  - ➔ In vivo database with ground truth cannot be acquired.
  - ➔ Phantoms are complex to build and calibrate.
- **Create a virtual experiment**
  - ➔ With a finite element modeling software

FEM Simulation of a VCTE experiment

Simulation Method





Evaluation of the simulation accuracy:

Goodness of Fit

Analytical model (1)

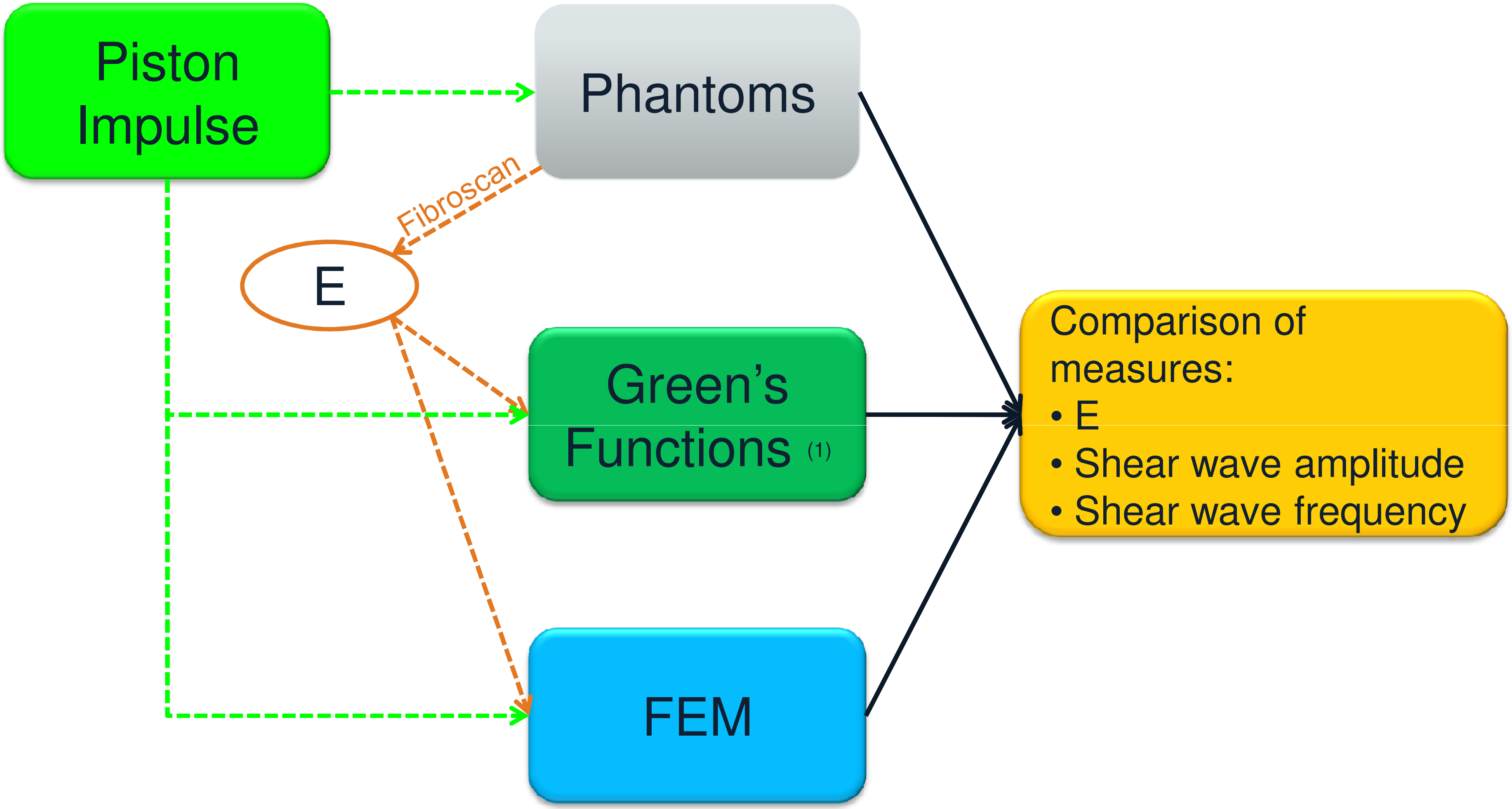
Experiment on Phantom

➔ Green's functions
➔ Numerical precision is satisfactory under the physical conditions of the experiment

➔ Our goal is to dispose of a virtual experimental environment.
➔ To highlight sources of measurement uncertainties from the Fibroscan

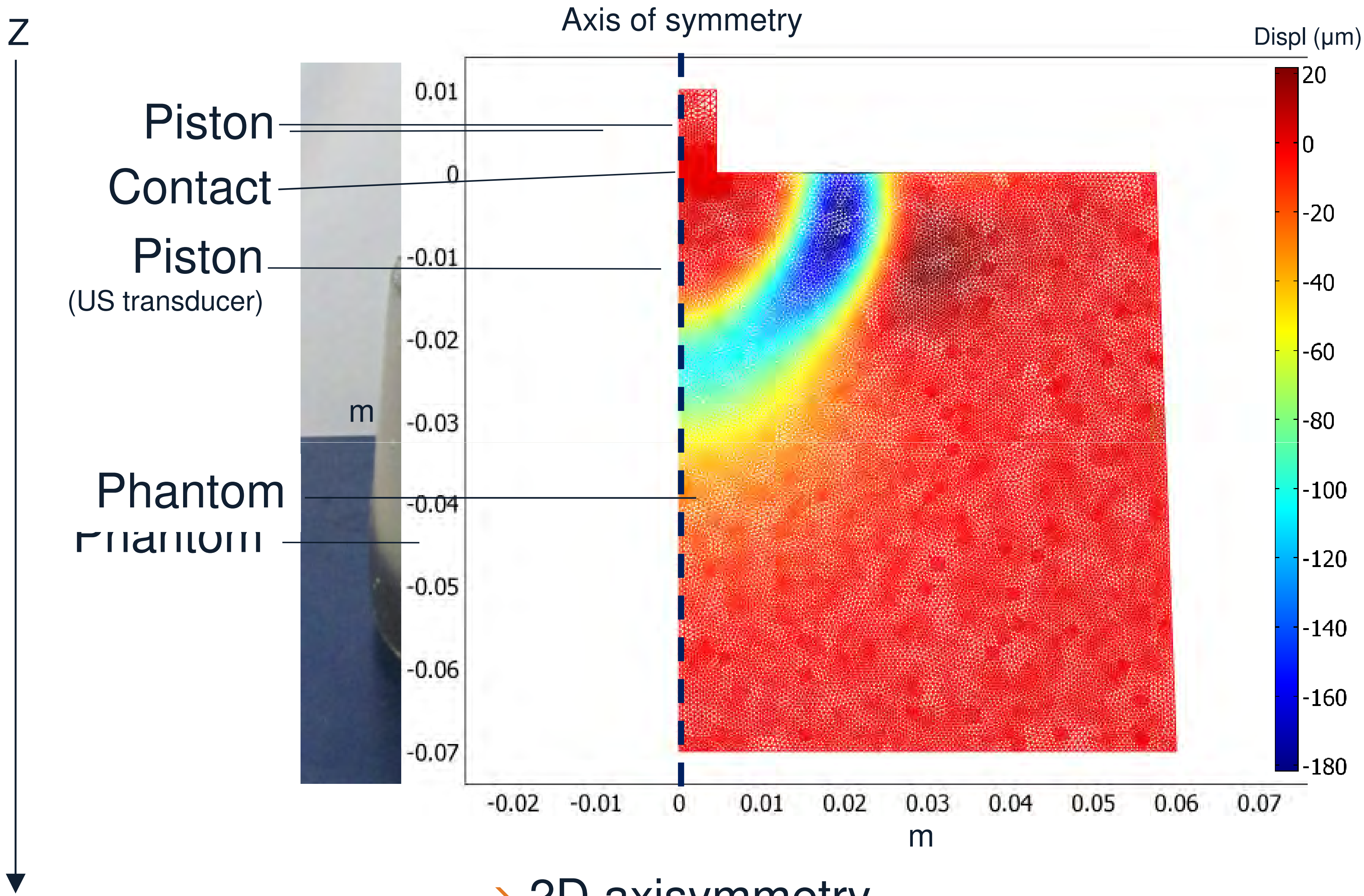
(1) L. Sandrin, et al., The role of the coupling term in transient elastography, *J. Acoust. Soc. Am.* ***115, 73 (2004)***

Simulation Framework



(1) L. Sandrin, et al., The role of the coupling term in transient elastography, *J. Acoust. Soc. Am.* ***115, 73 (2004)***

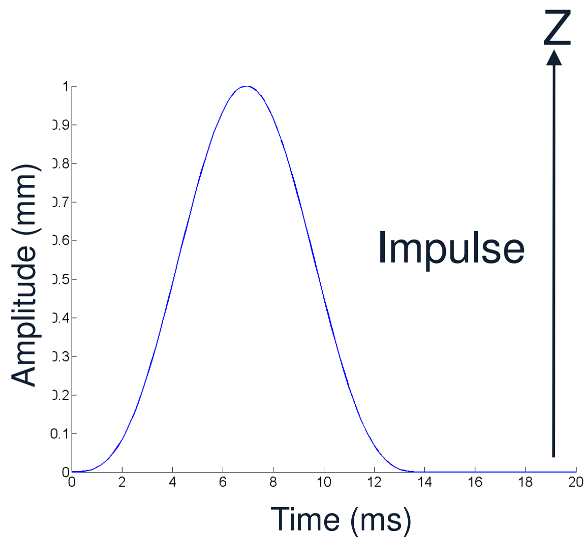
FEM simulation with Comsol™



→ 2D axisymmetry

FEM simulation with Comsol™

- **E = 6 KPa, σ = 0.4999**
- **size$_{element}$ < 2 mm** (1/20 λ_{shear})
- **18 000 elements, 36000 dof**
- **Solver: UMFPACK**
- **Tstep : 1/10000 sec**



- **Computation error:**

➔ $| \varepsilon | \leq \max(\varepsilon_r \times |\text{Displ}|, \varepsilon_a)$

  - Relative error: ε_r = 0.1 %
  - Absolute error: ε_a = 10 nm (displacement min ≈ 1µm)

- **Computational time for 55 ms propagation:**

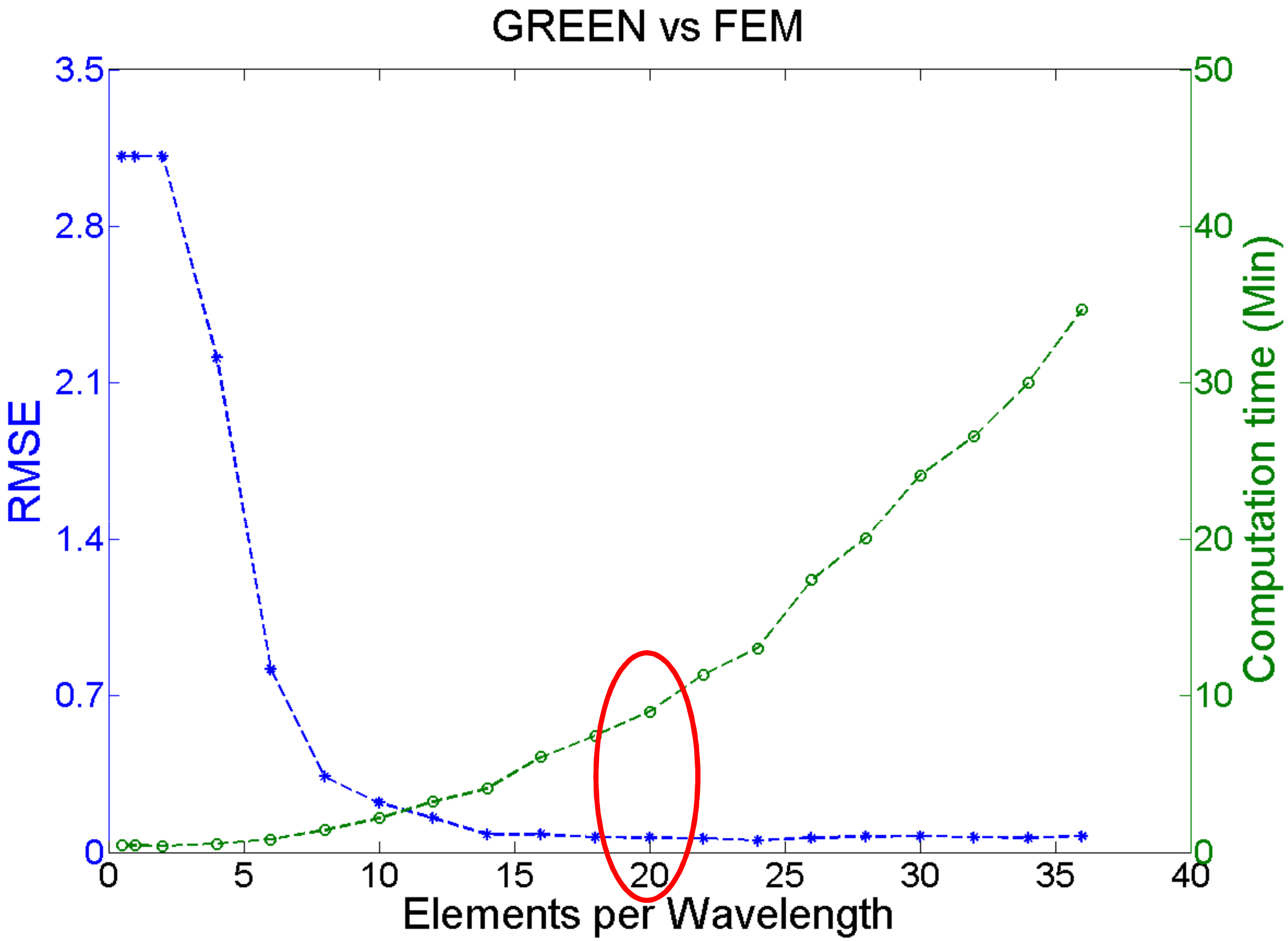
On Intel Core2Quad Q6700 @ 2.67 GHz and 16Go of RAM

➔ Piston adhering with phantom surface → 10 min

➔ Piston **not** adhering with phantom surface → 80 min

Results

Influence of mesh density

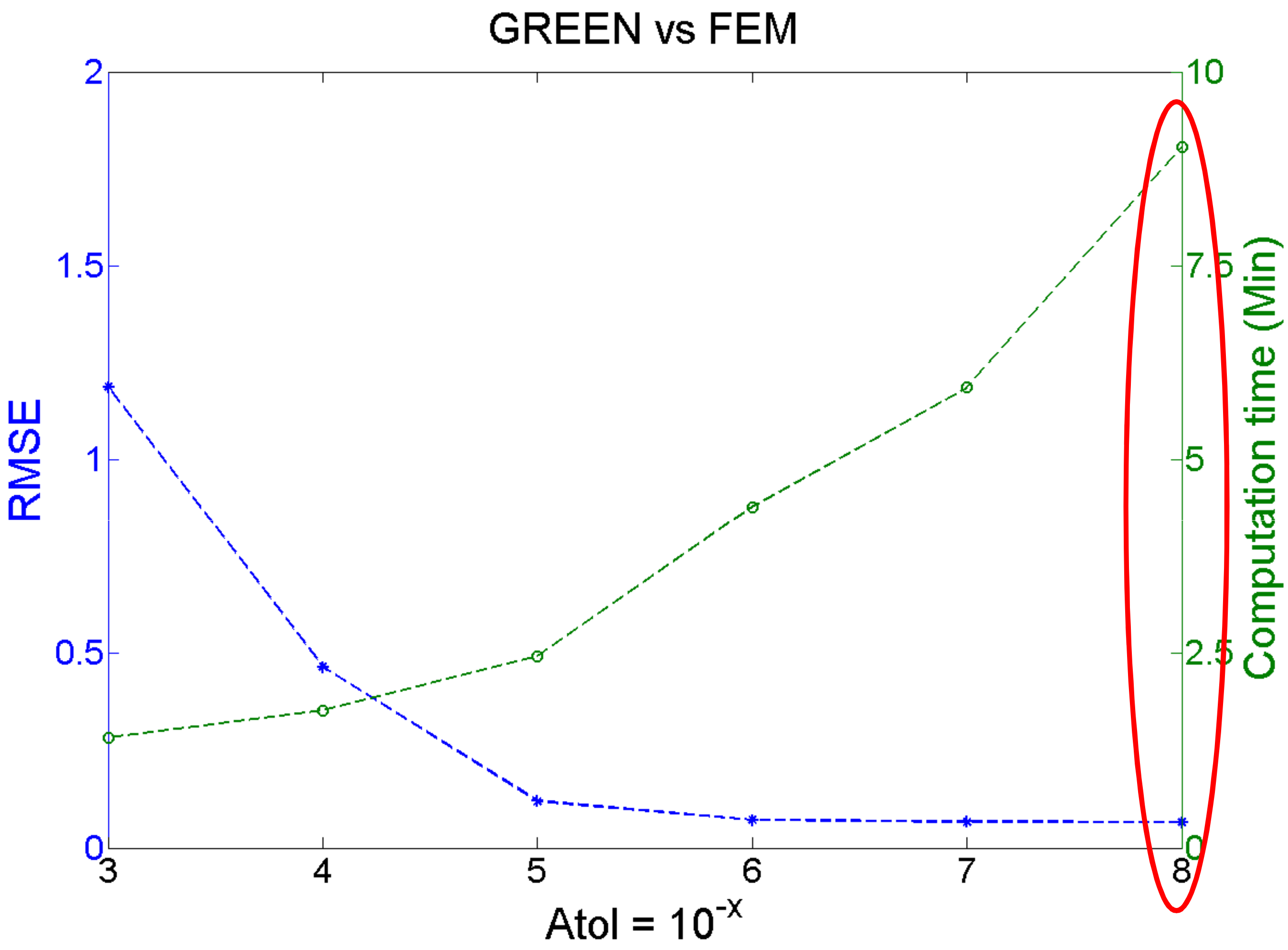


➔ Corresponding to the results found in literature (1)

(1) S. Roth et al., Influence of mesh density on a finite element model's response under dynamic loading, *J. Biol Phys Chem* . ***9, 210-219 (2009)***

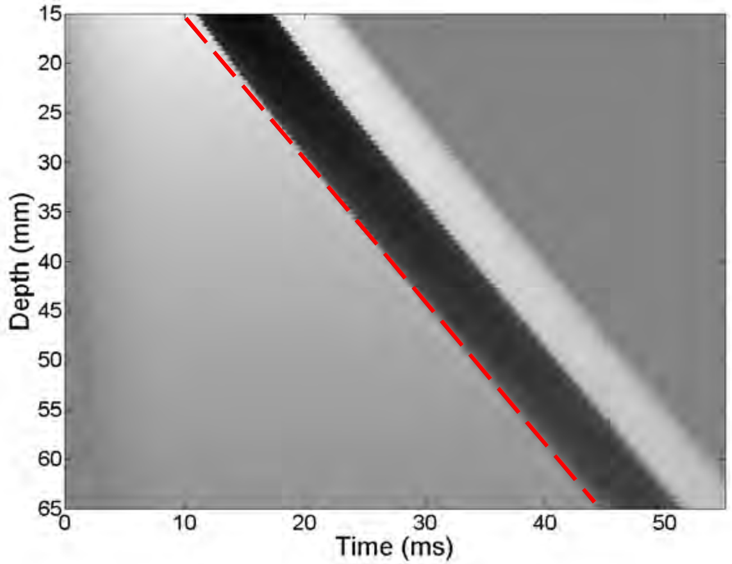
Simulation Method

Influence of Atol

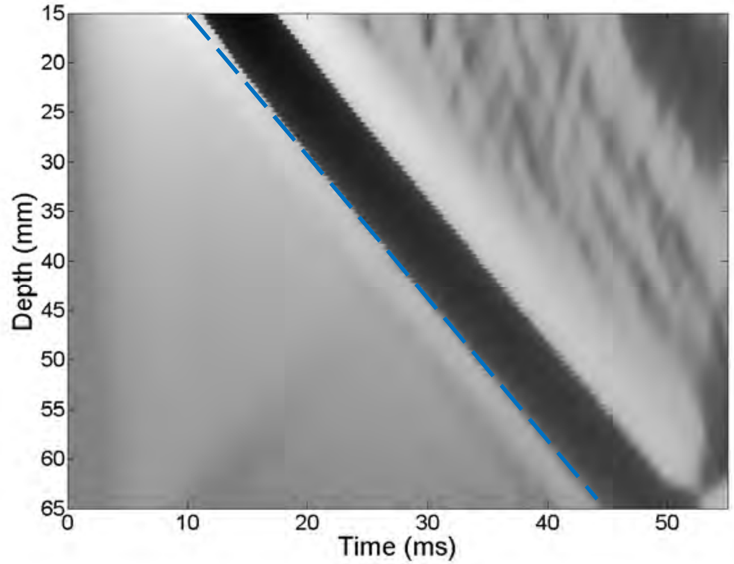


→ Atol = 10^{-8}

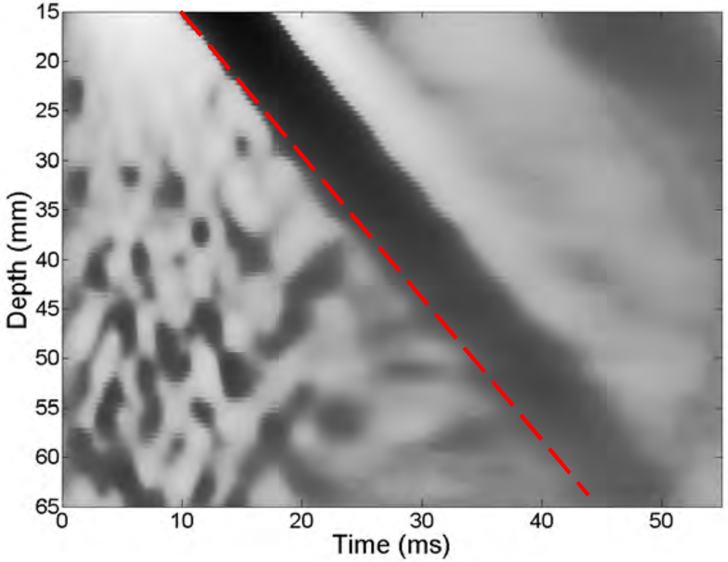
FEM simulation results : Elastogram



Green's Functions



FEM



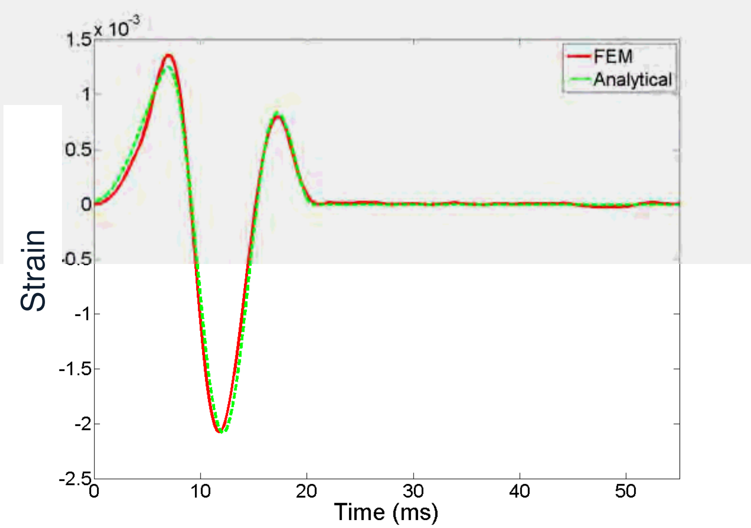
Phantom

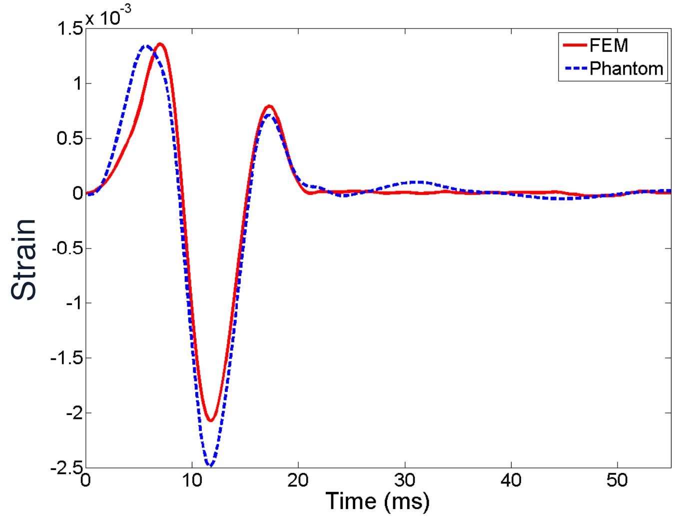
Results : amplitude & frequency

FEM vs GREEN's Functions

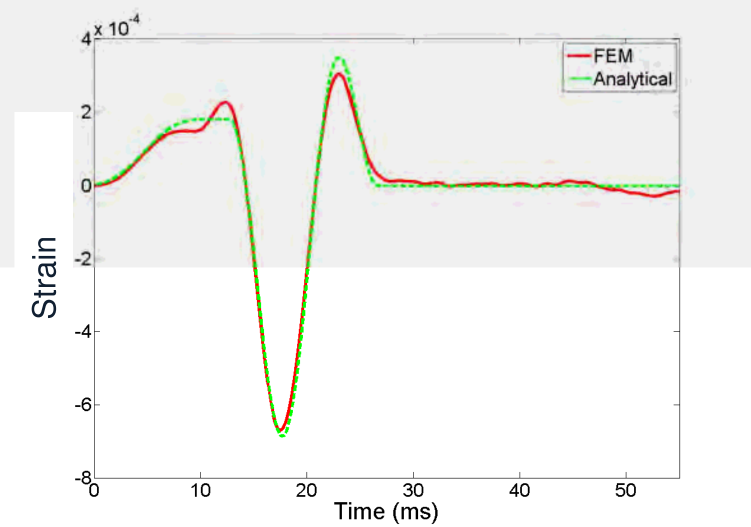
FEM vs Phantom

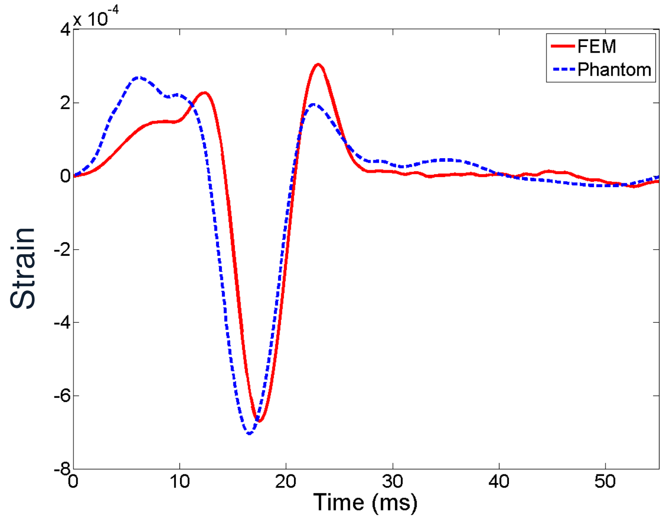
15 mm





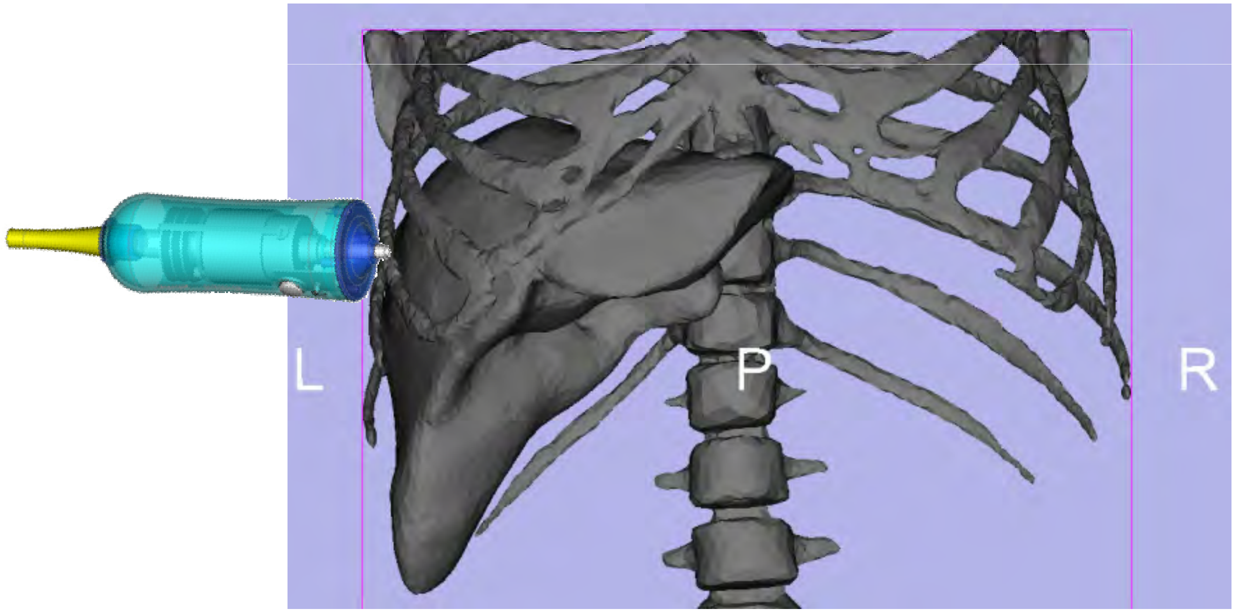
20 mm





3D simulation: Anatomical model

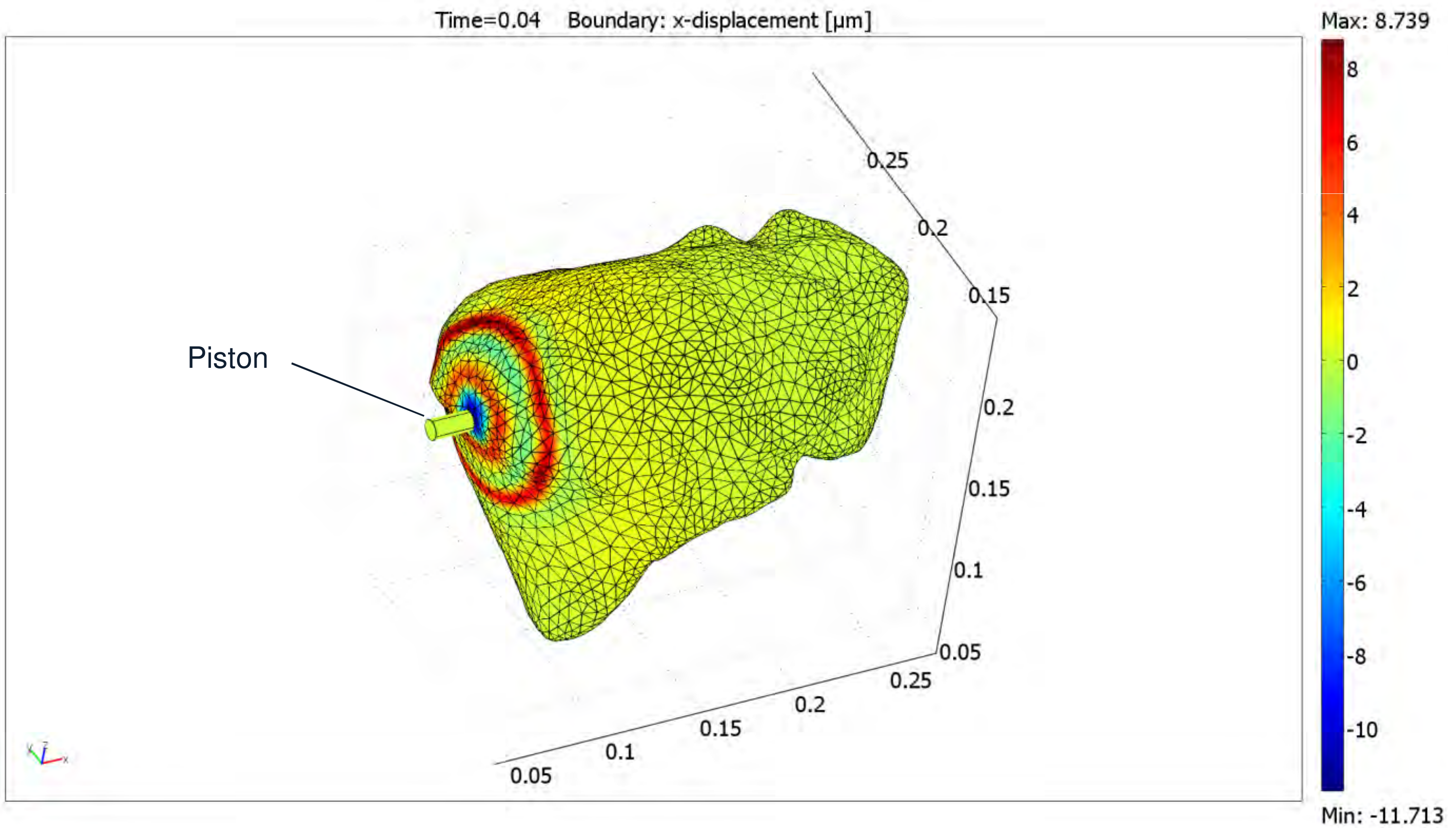
- **High fidelity of simulation:**
  - ➔ Generating the shear wave and the propagation induced by a piston hitting a 3D liver model
  - ➔ A liver 3D mesh was created from the surface mesh distributed by the IRCAD (Strasbourg, France)



3D simulation: preliminary results

- Computational time:
  - ε_a = 10 µm → ≈ 12 hours
  - ε_a = 1 µm → ≈ 15 days
  - ε_a = 100 nm → > 1 month ?
  - ε_a = 10 nm → ∞

- Piston **cannot** adhere to the liver's surface
- E = 20 KPa, σ = 0.4999
- $size_{element}$ < 5 mm (1/10 λ_{shear})
- >400 000 elements, 1.7 M dof
- Solver: GMRES, Geometric Multigrid



Conclusion

- **Promising FEM simulation results**
  - ➔ To understand the behavior of different tissue types for Fibroscan scanning
  - ➔ Capabilities to accurately simulate a shear wave propagation in transient elastography on 2D geometries with liver tissue properties
  - ➔ High agreement of displacement measures comparing with analytical solutions and experimental data
  - ➔ By including the measurement uncertainties, the shear wave arrival time and frequency content are agreed with experimental data.

Perspectives

- **2D FEM simulations setup**
  - ➔ Models more complex: Viscoelastic, Multi layers, hard inhomogeneity, etc…
- **3D FEM simulations setup**
  - ➔ High fidelity of simulation:
    - Requires the use of a complete thoracic and abdominal anatomical model
  - ➔ Experiments in 3D cannot be performed using the 2D setup:
    - Need to use 3D models with 2D symmetries.
    - Need for dedicated high-performance implementation.

Thank you for your attention…

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