Application à la simulation médicale
Identification des paramètres physiques et validation

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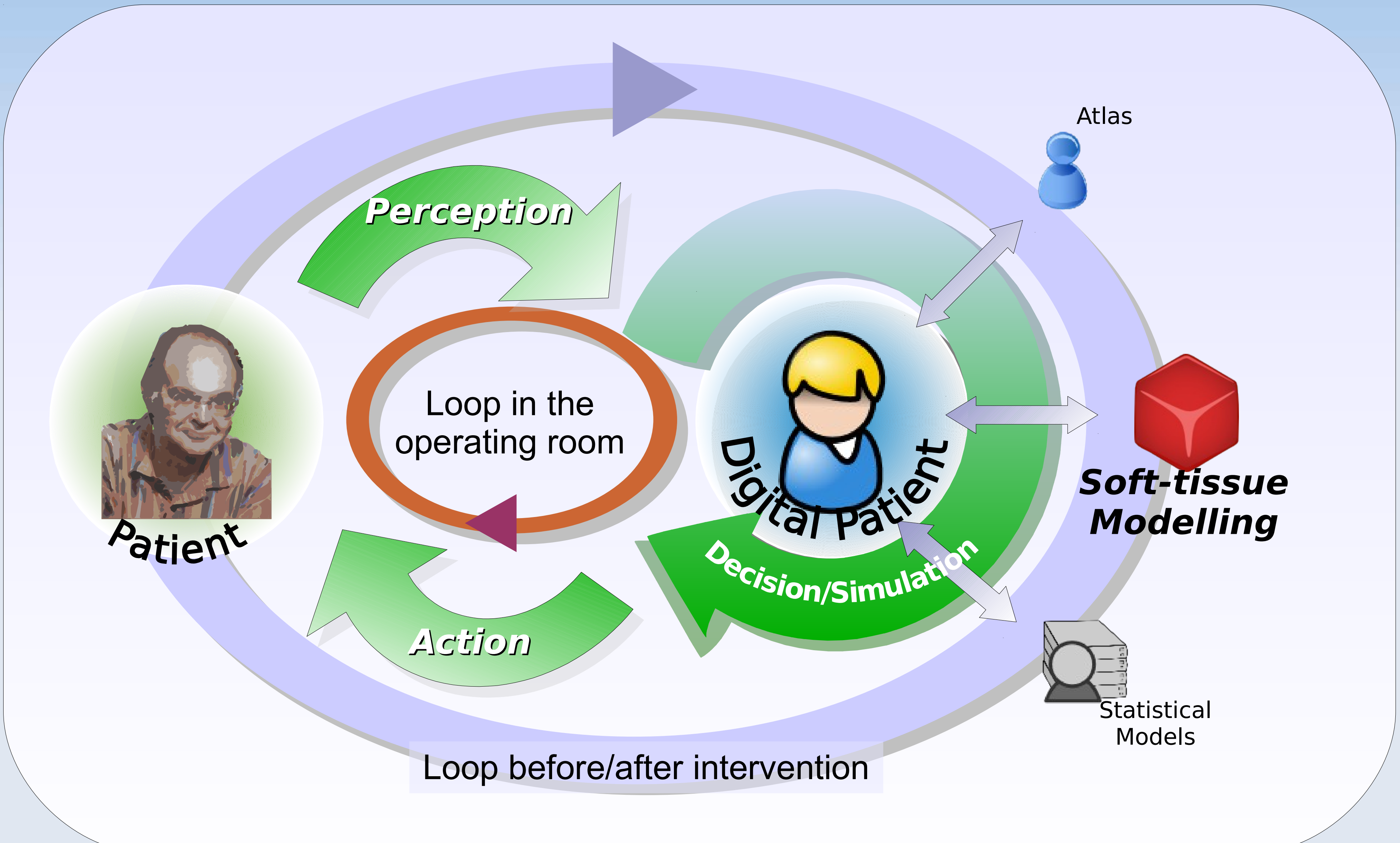
Outline

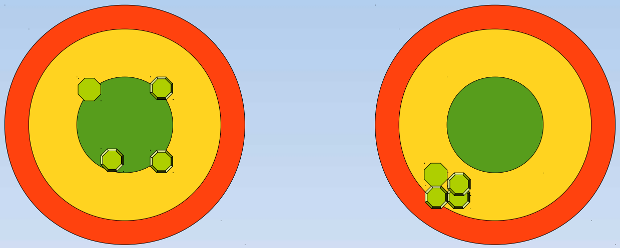
- 1. Introduction
  - Medical Simulator***s***
  - Verification & Validation
- 2. Example
- 3. In vivo measurements

Perception – Decision – Action



Challenge

- Simulation of
  - deformable/soft tissue
  - accurate and precise
  - patient-specific
  - that includes the interaction with the clinician (tools, probe,...) and the surgical navigation system
  - in interactive time



► Build a digital patient as close as possible to the real patient

► Use (and measure) soft-tissue patient-specific constitutive law"

Medical simulator feature list

- Medical simulator have to include
  - Modeling (soft tissue deformations)
  - Interaction (sensors, force feedback)
  - Graphics (medical image simulation / 3D environment)
  - Event recording = trace what happened
    - For usage study, quality control
    - For pedagogy: skill assessment, learning path, exercises, validation of the gesture,...

+ Validation (accuracy/precision of the simulation)

Different types of simulator

- Four types of medical digital simulators should be distinguished
  - Learning simulators
  - Understanding simulators
  - Planning simulators
  - Per-operative simulators

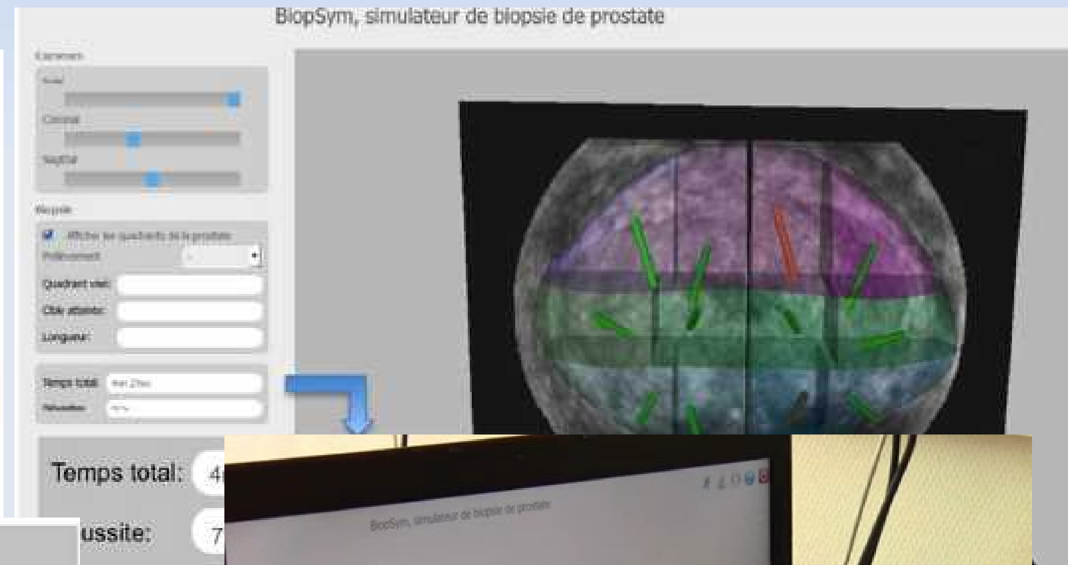
Learning Simulators

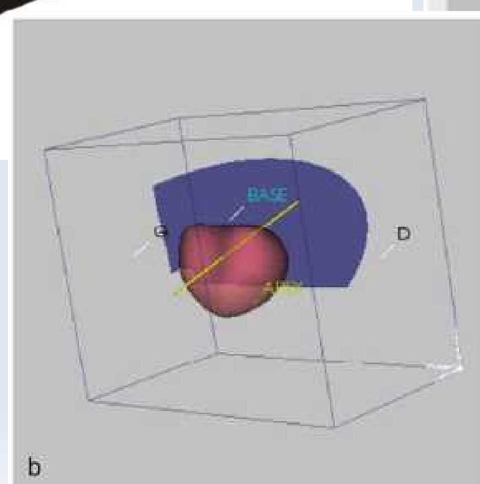
- Aim at
  - Learning an intervention technique or gesture
  - Replacing anatomical specimen and mechanical simulators
- Need to include
  - Force feedback and tissue deformation (“visuo-haptic simulators”)
  - Small subset of generic tissue behaviour

simbionix lap mentor

Learning: virtual prostate biopsy

- Learning Path, user interaction / US imaging + deformation effect





[Fiard et al, 2013]

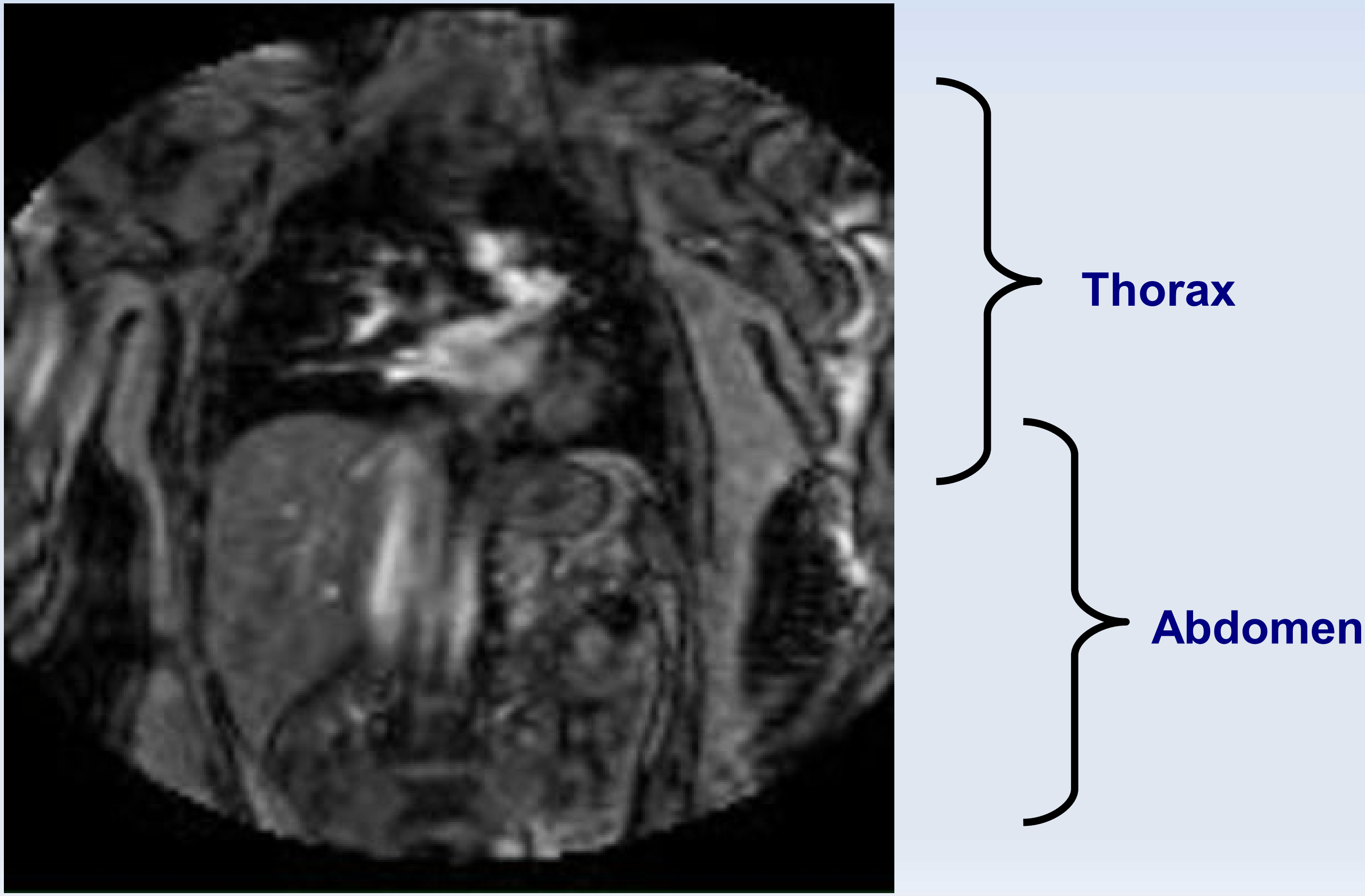
Understanding Simulators

- Also called morpho-dynamic simulator
- Aim at
  - Understanding a phenomenon/pathological case

    → Classical meaning of “model” in science
  - Helping to diagnose a specific patient and to choose a specific treatment
- Need to include
  - 3D deformations and interactions with environments of tissues
  - Some pathological behavior at a “high” level of modeling

Respiratory Motion

- Understand organ displacements and deformations

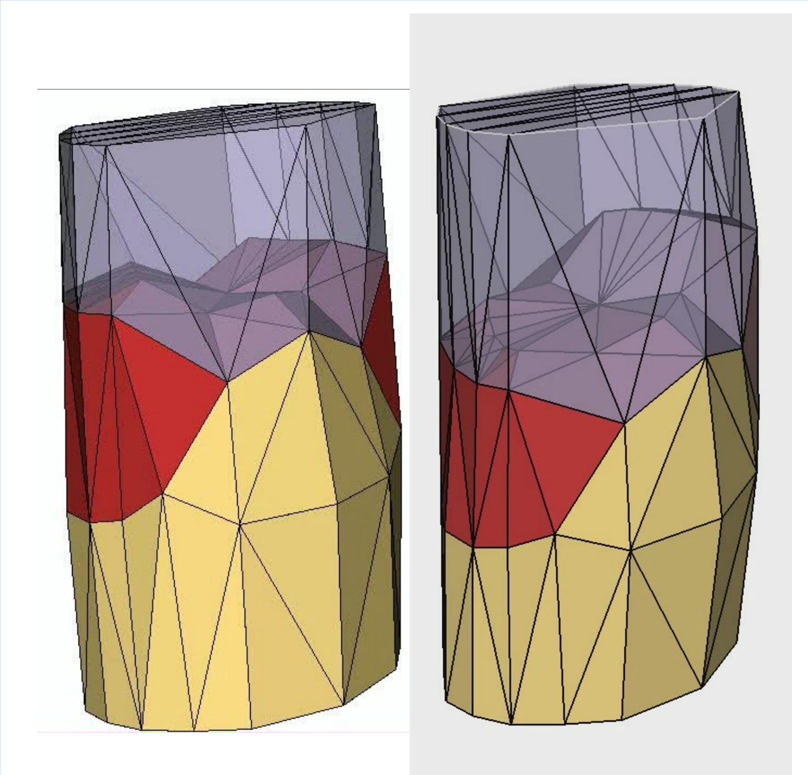


[Craighero et al, 2005]

Understanding hemidiaphragm

- Aim: understanding raised hemi-diaphragm
- Half the diaphragm is paralyzed
- Paradoxical movements
  - Very small volume intake

imagingpathways.health.wa.gov.au

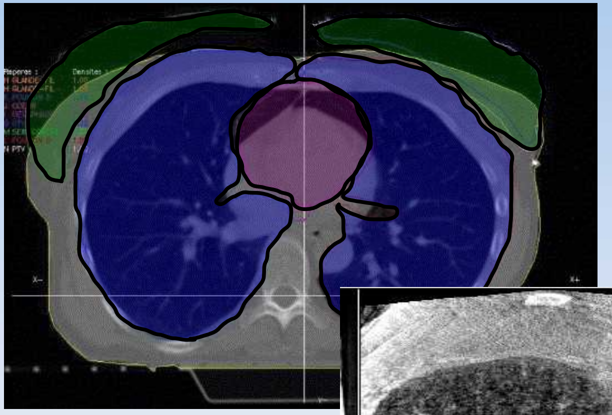


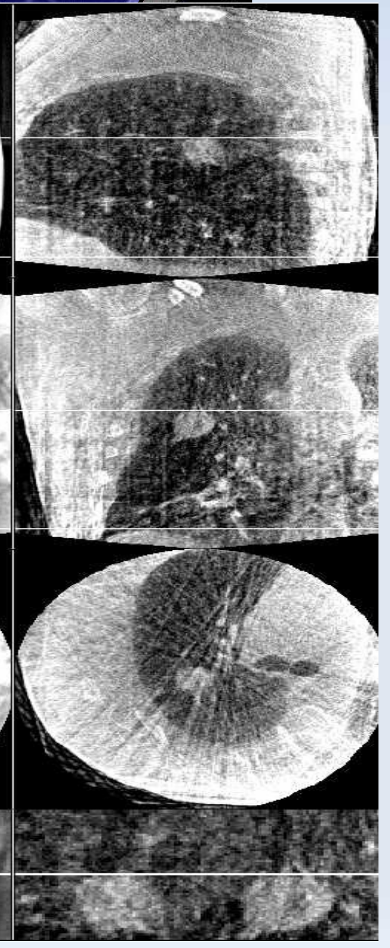
[Promayon Baconnier, 2008]

Planning Simulators

- Aim at
  - Define the operative strategy
  - Plan an intervention
    → anticipate a functional/anatomical effect
- Need to include
  - Patient specific data (tissue properties, disease)
  - Medical level validation

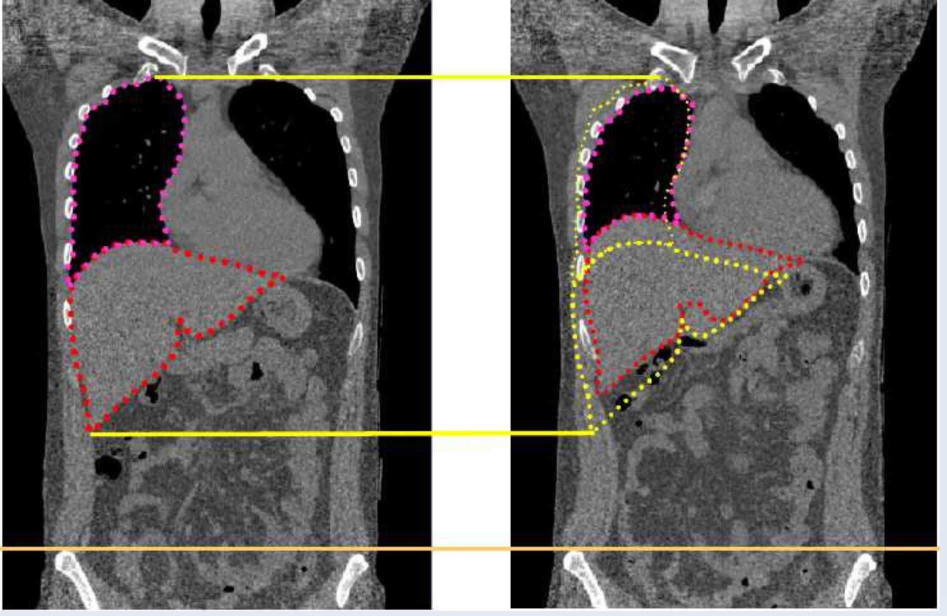
Issues of Respiratory Motions





- Dose planning and control
- Interventional Radiology, puncture, biopsy

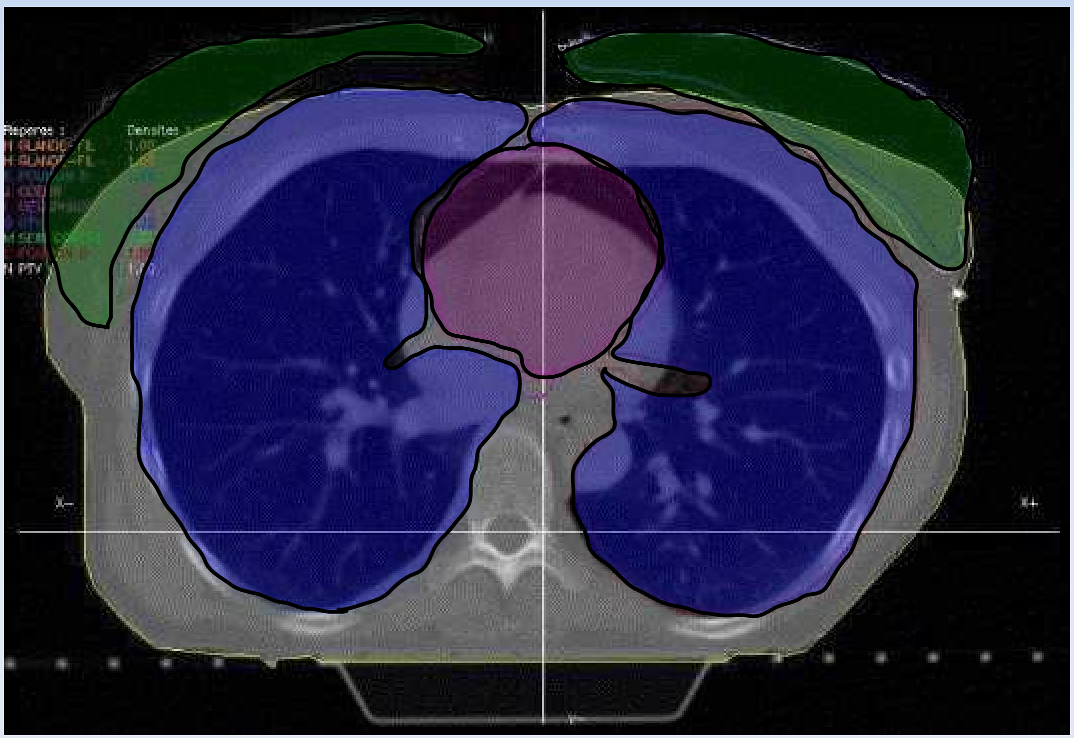
  → Reaching target organ



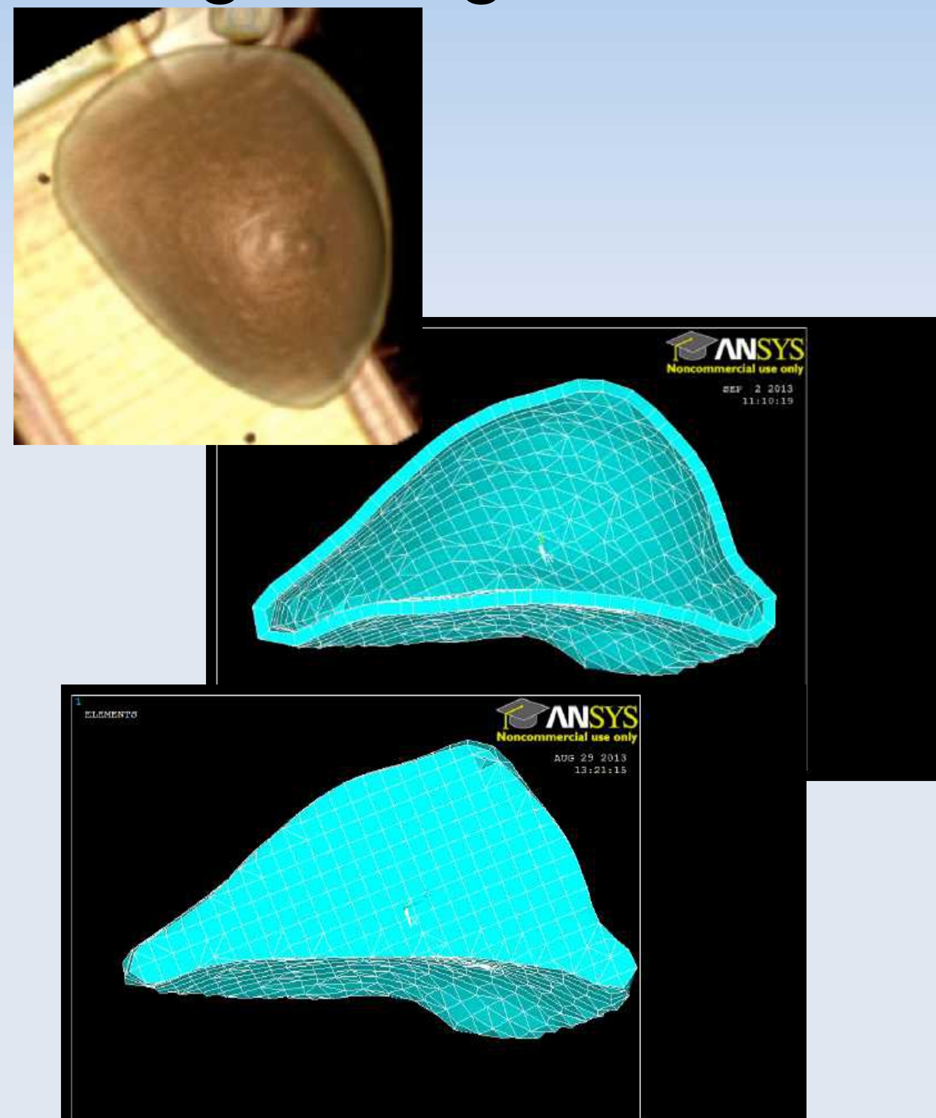
[Hostettler, 08]

Biomechanical breast modelling

- Aim: improve patient positioning during breast cancer radiotherapy



modified from [Saliou 2005]



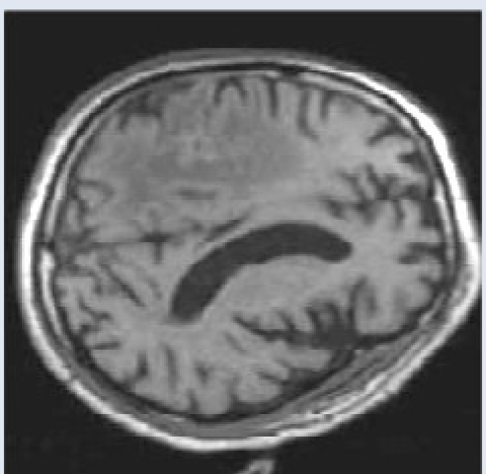
[Vallier et al, 2013]

Per-operative simulators

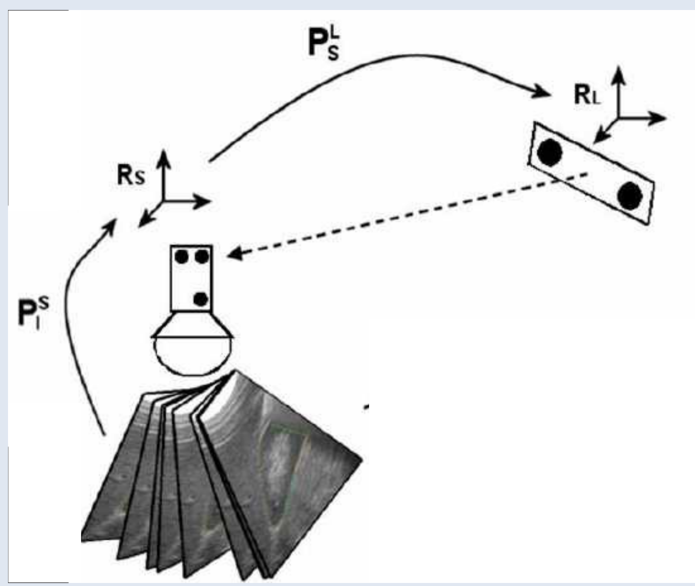
- Also called «the grail»
- Aim at
  - Simulating the complete environment and intervention
  - Unity of place
  - Unity of time
- Need to include...
  - ...everything!

Per-Operative: Low-cost brain shift compensation

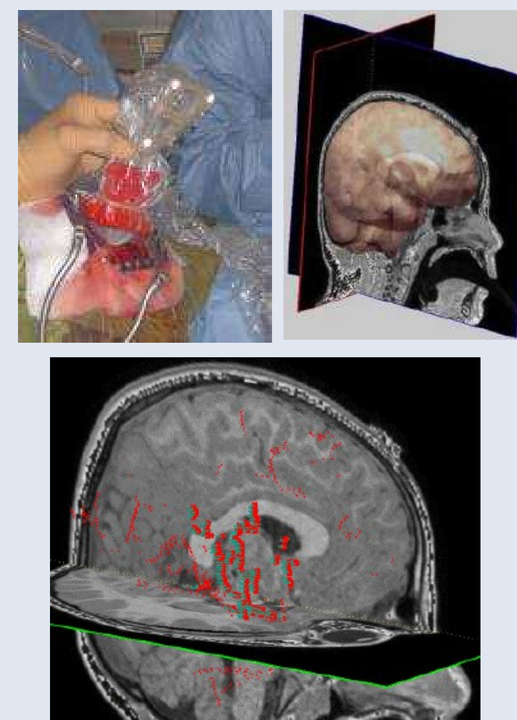
- Aim: replacing the high cost intra-operative MRI by 2.5D US images + biomechanical model.
- Grail: estimate brain shift deformations from 2.5D localized US images + model



[Ferrant 2002]



2.5D localized US
→ Doppler effect

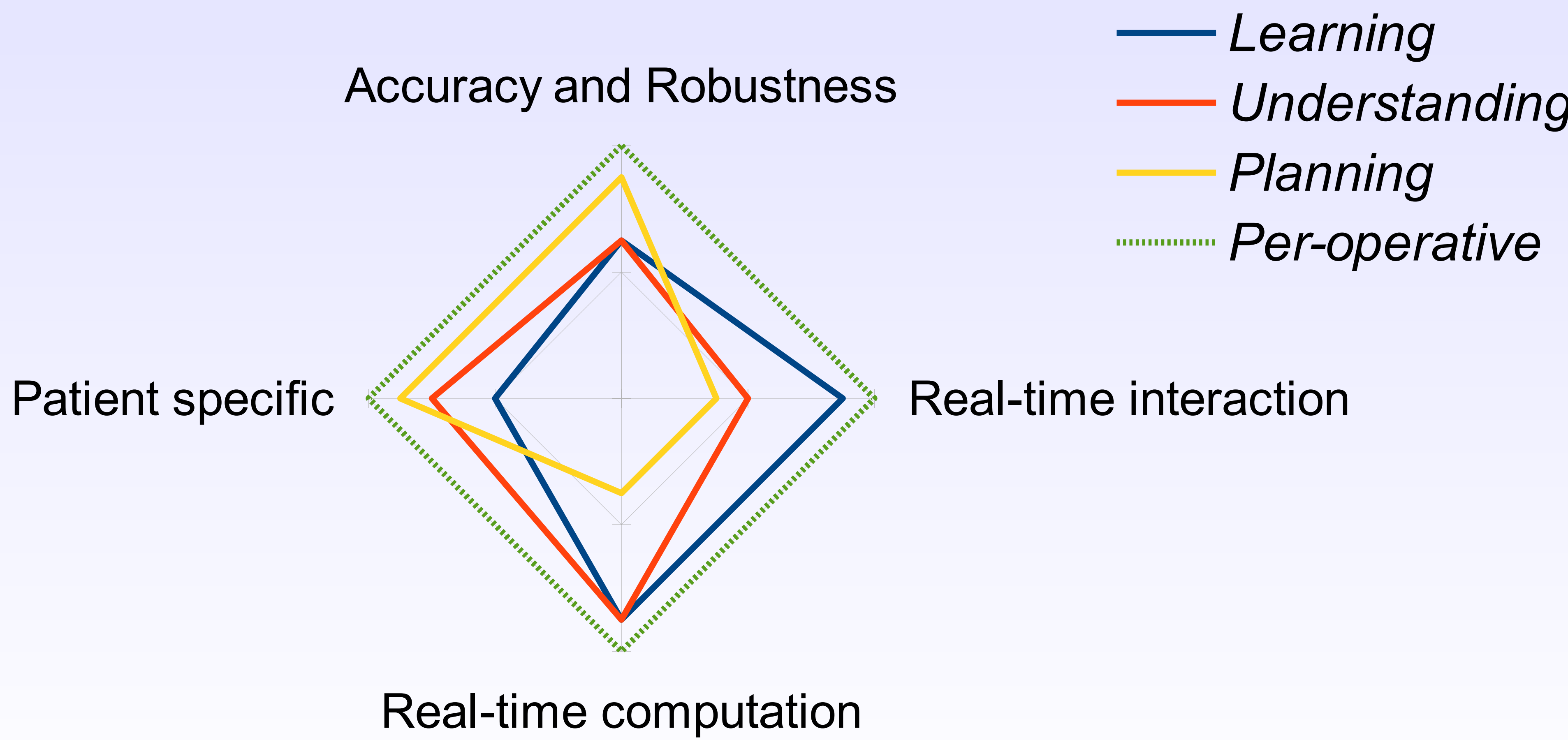


[Bucki et al, 2007]

Different types of challenges

- Real-time interaction with the user
- Real-time computation of tissues
- Accuracy and robustness
- Patient-specific fidelity

Needed features



- Different types ► different approaches!

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Validation

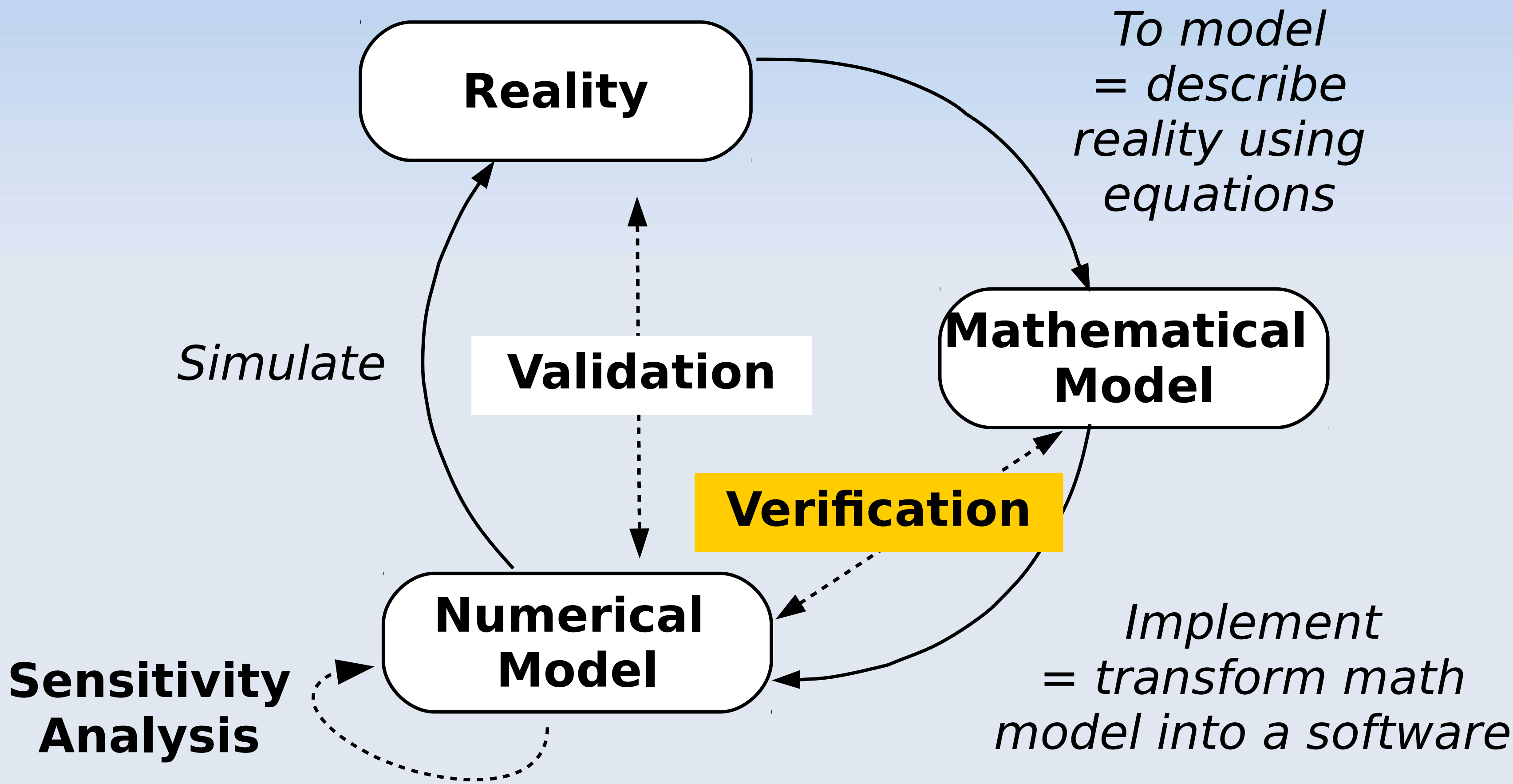
- 4 types of simulators
  - Learning

    - interaction is more important
    - simulation does not have to be exact or patient-specific
  - Others
    as the clinician will base his decisions on the simulator results, validation is essential
- Validation of the
  - Physical realism
  - Parameters (even for continuous model)

Validation

- In medical literature, validation is nearly always the main point
- Elsewhere
  - It is too often in the “to do” / “future works”
  - Or reduced to one image/video comparison
- Why?
  - Not so easy to do or organize
  - Can show negative results! (not easy to publish a paper finishing by “the validation section proved that the simulation are not accurate enough!”)

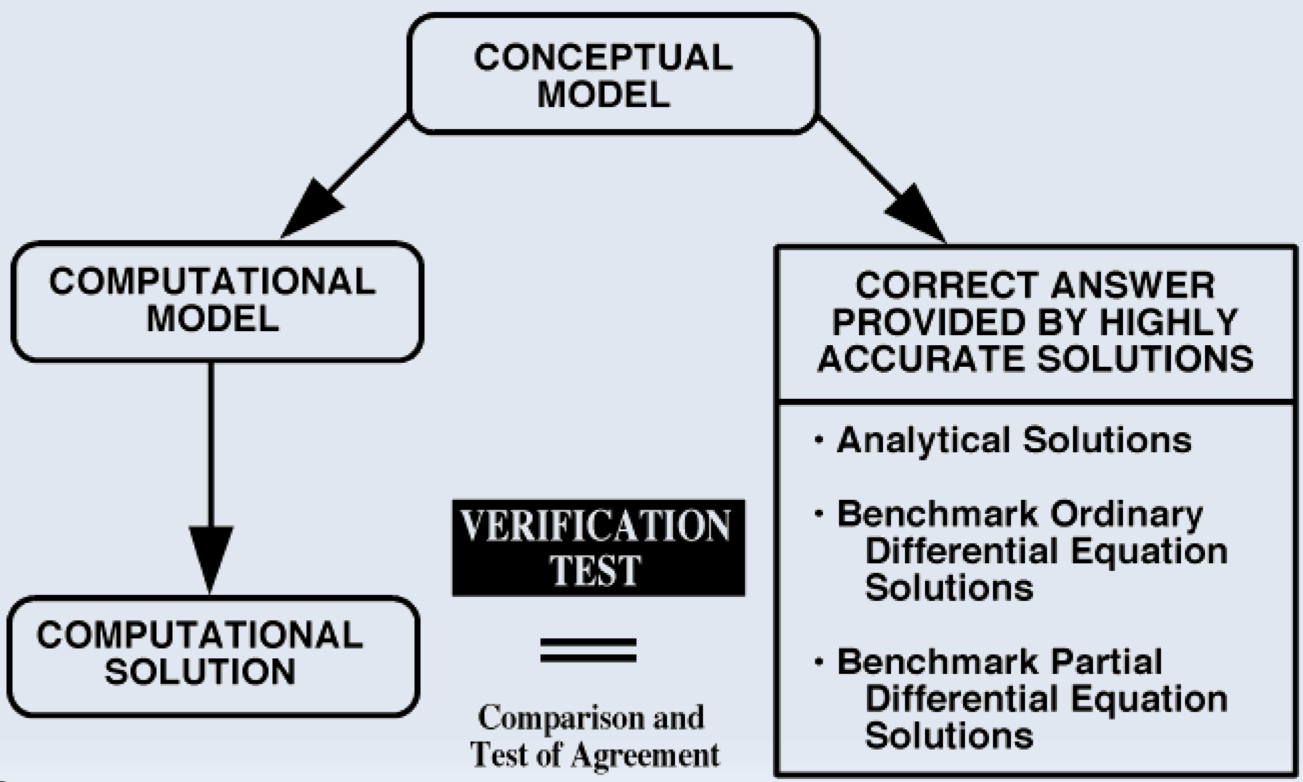
V&V



[Deram 2012]

Verification of soft tissue models

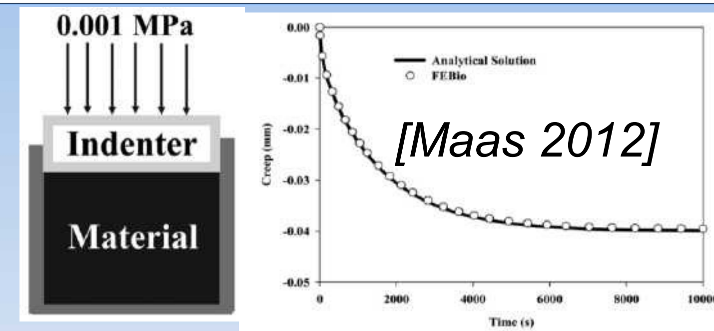
- Verification
  - Mathematical point of view
  - Ensure that the mathematical model solve the mathematical problem with enough precision / accuracy



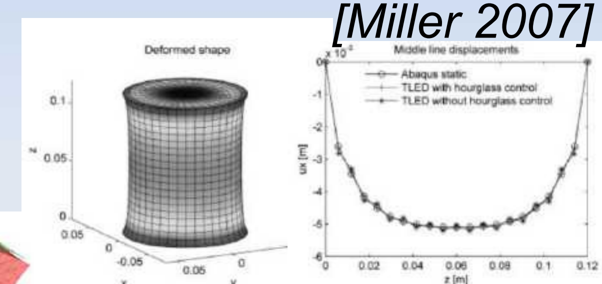
Oberkampf
Sandia Nat. Labs

Verification of soft tissue models

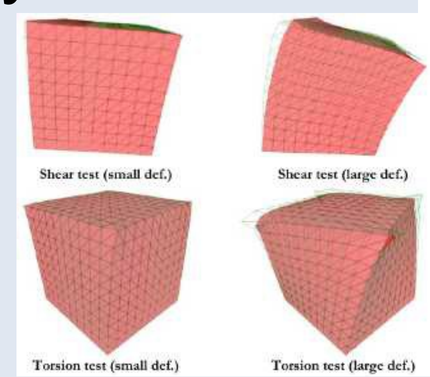
- Code validation
  - Comparison with analytical solution of known problems
  - Comparison with previously verified numerical implementation
- Computation validation
  - Ex: refined mesh convergence



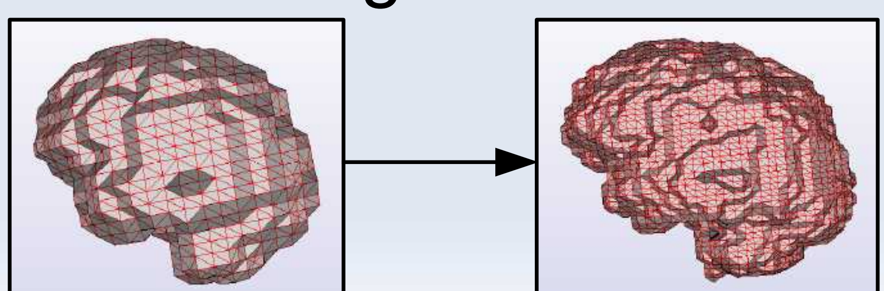
[Maas 2012]



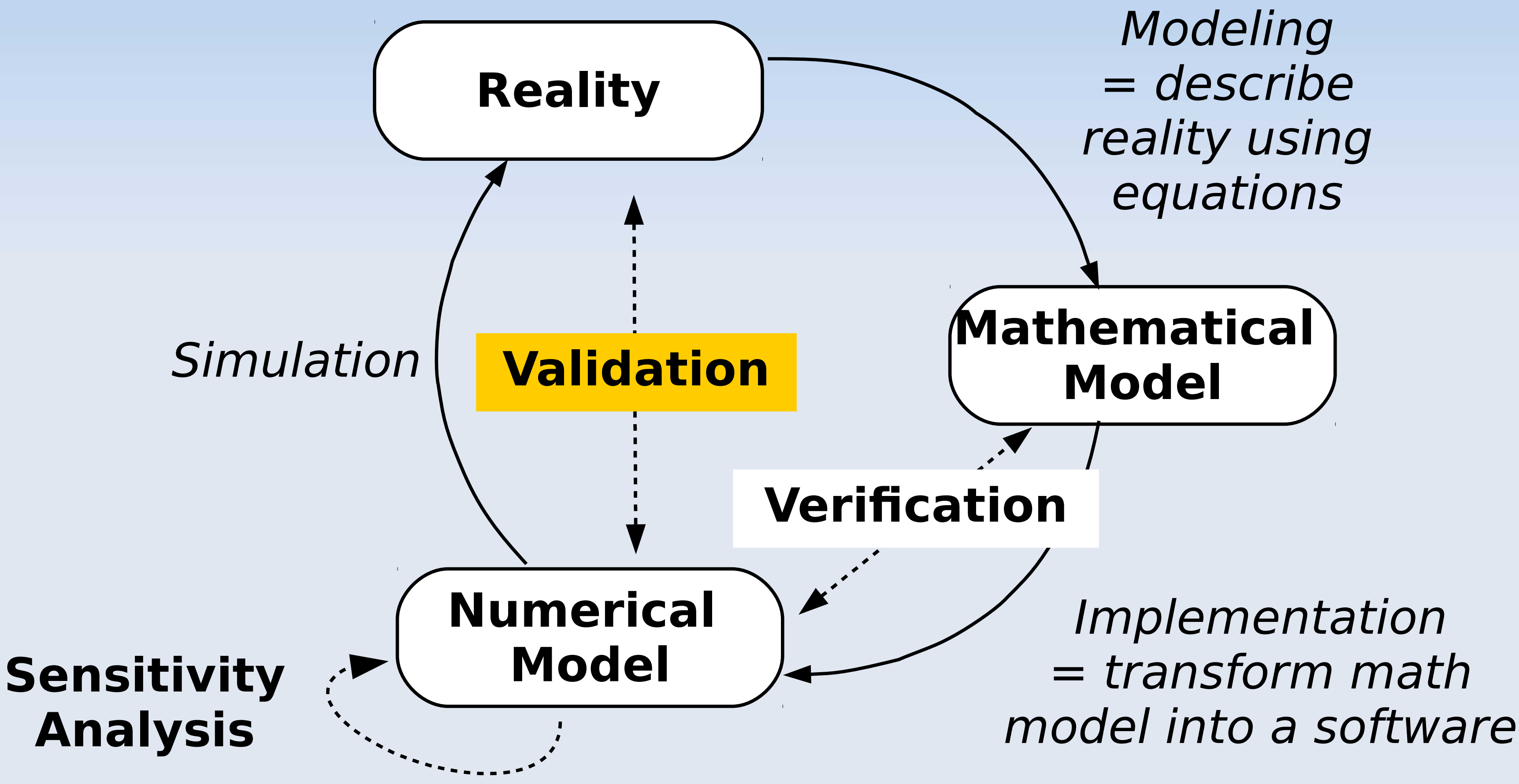
[Miller 2007]



[Otamendi 2006]

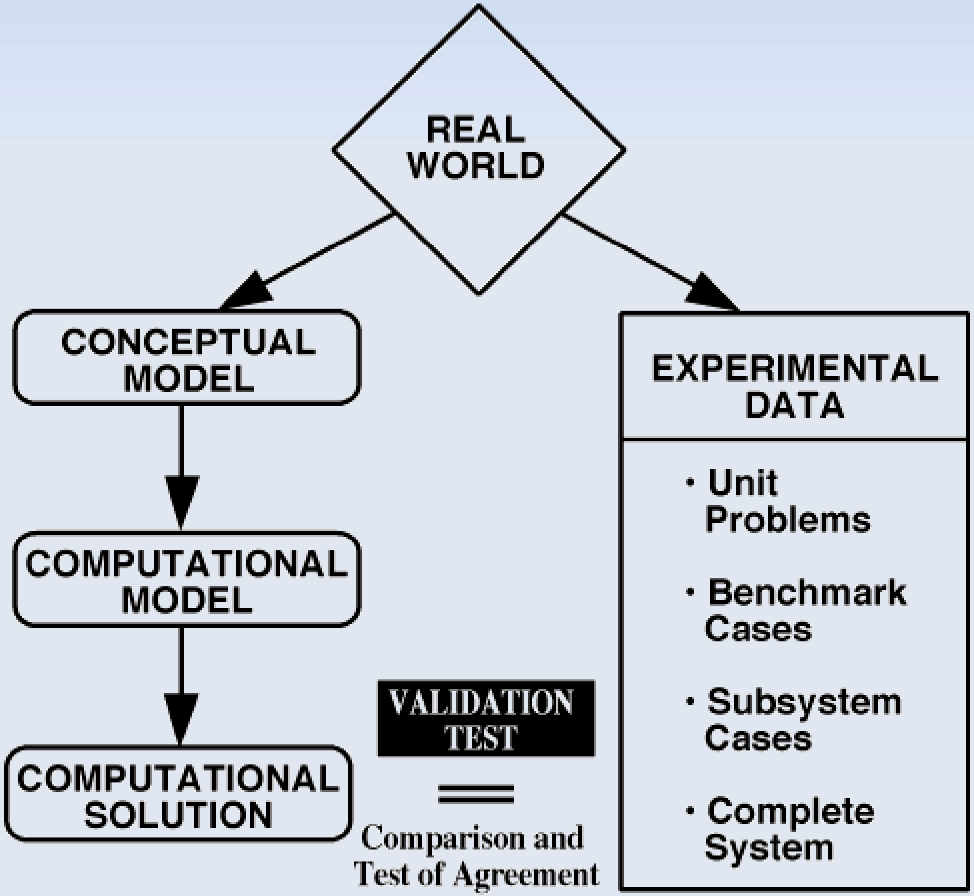


V&V


Reality
Modeling
= describe
reality using
equations
Mathematical
Model
Simulation
Validation
Verification
Numerical
Model
Implementation
= transform math
model into a software
Sensitivity
Analysis

Validation of soft tissue models

- Aim
  - Ensure the numerical solution can be used for medical decision



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V&V of soft tissue models

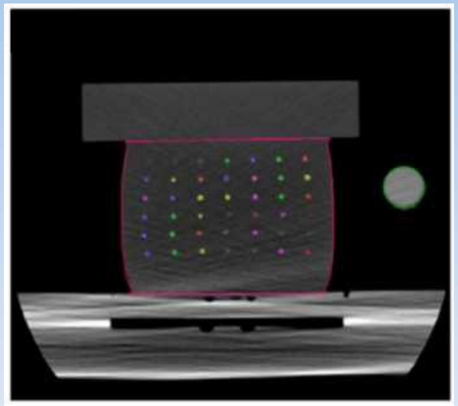
- How easy is it?
- Beside theoretical comparison, the most popular way is by **comparison with data**
- Four types of comparisons

1. *comparison with in silico* data
    - Comparison with other validated numerical simulations

    = Verification

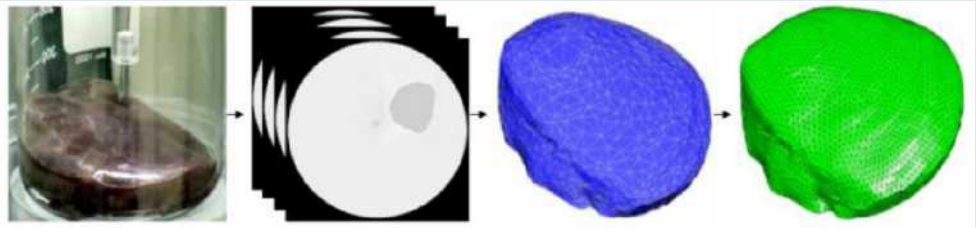
Four different types of comparisons

2. *In vitro* experiments



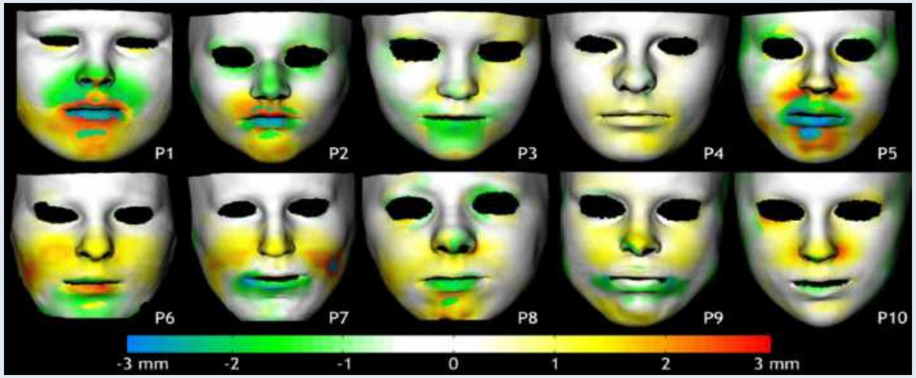
[Kerdok 2003]

3. *Ex vivo* experiments



[Shi 2005]

4. *In vivo*

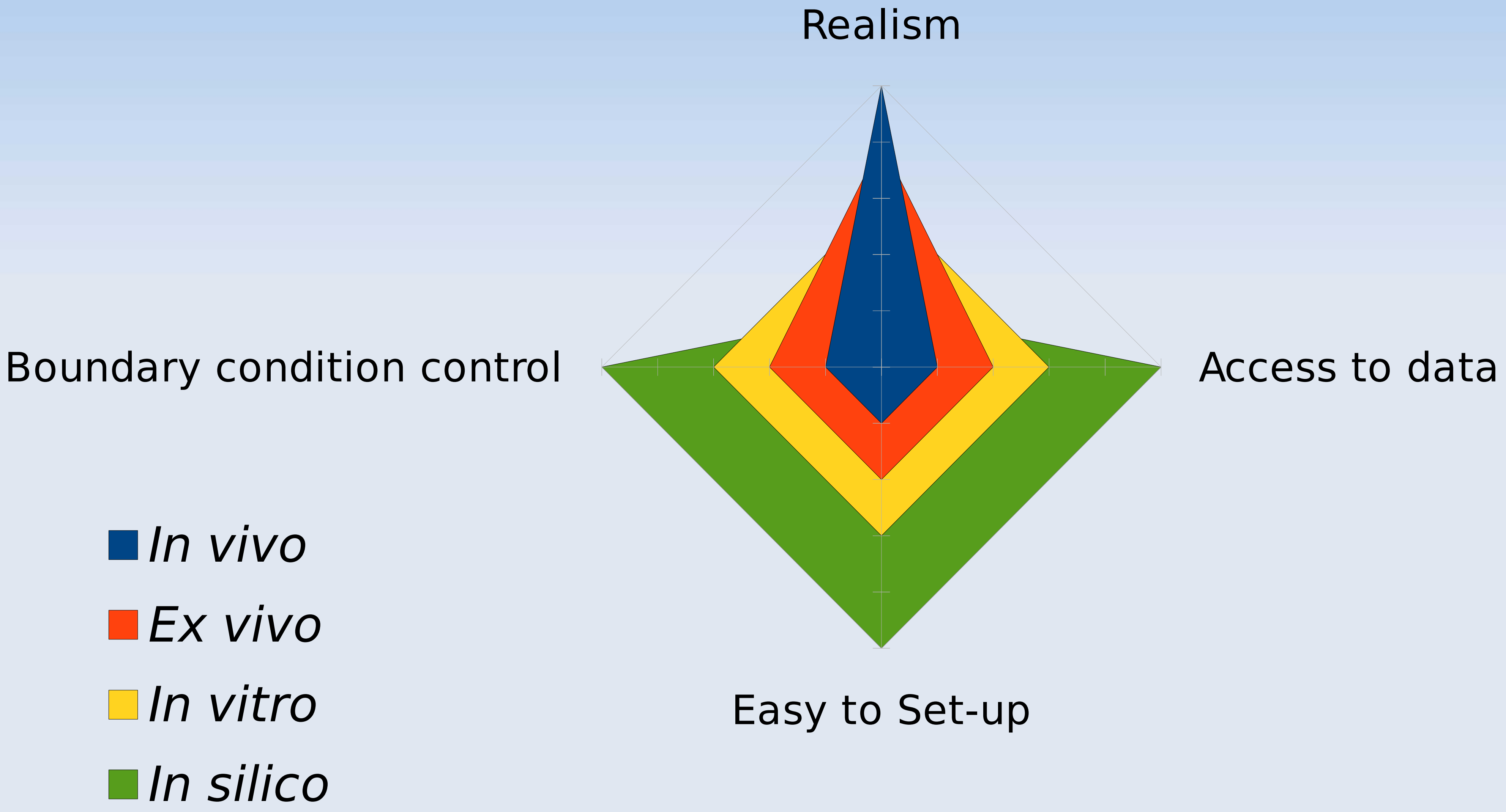


[Mollemans 2007]

How easy is it?

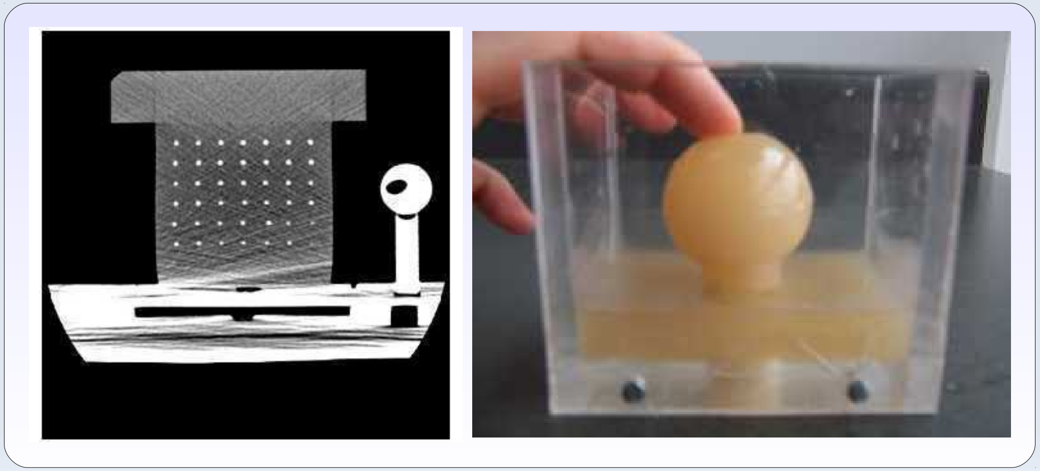
- 4 criteria (Deram 2012)
  - **Access to data/parameters**
    how easy it is to access data/parameters
  - **Boundary condition control**
    how easy it is to known/control the boundary conditions
  - **Set-up**
    how easy is it to organize/set up the validation (acquisition chain, data analysis...)
  - **Realism**
    how close to reality is the experiment? How close is it to comparing with reality ?

Validation levels



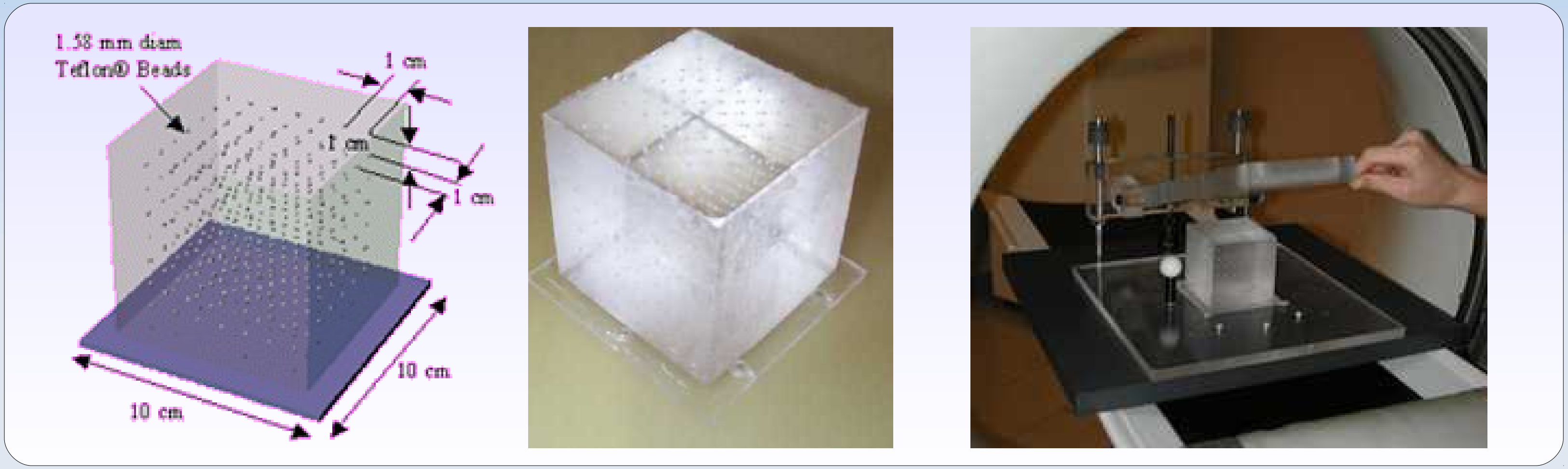
Example: *in vitro* comparison

- Experimental validation
  - Needs a real physical model
    → difficult to control the material properties of a build object
  - Needs a control of experimental condition
    → difficult to be really precise (error in building or assembling, position or force control, friction condition...)
- Examples
  - Truth Cube
  - Ad hoc phantoms



Example: truth-cube design

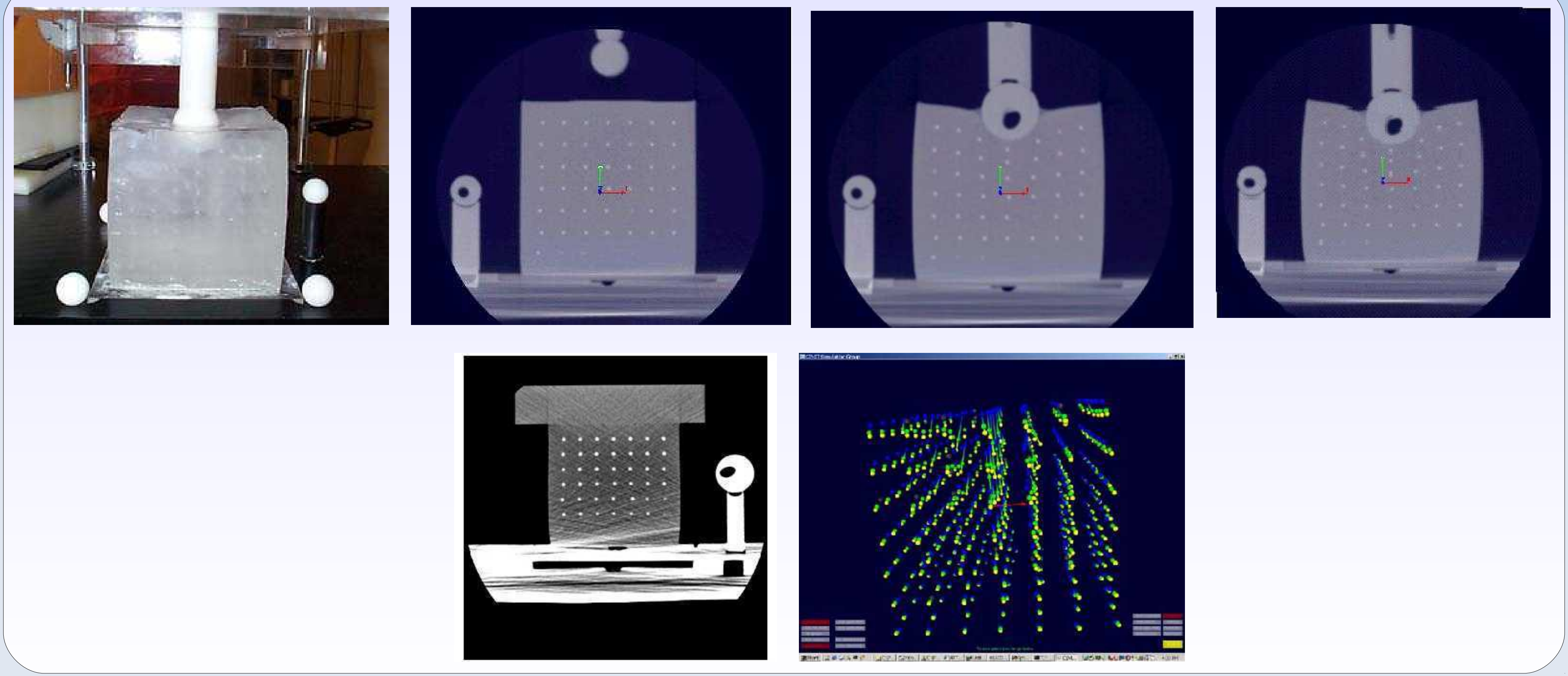
- Truth Cube (Kerdok and al., 2003)



- Silicon cube of supposedly known mechanical properties (elasticity, contractility)
- Build layer by layer
- Each layer has 7x7 Teflon beads

Example: truth-cube experiments

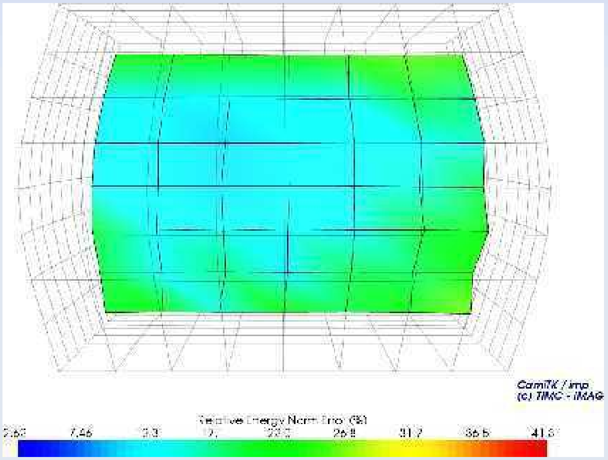
- Indentation/compression controlled by CT scan

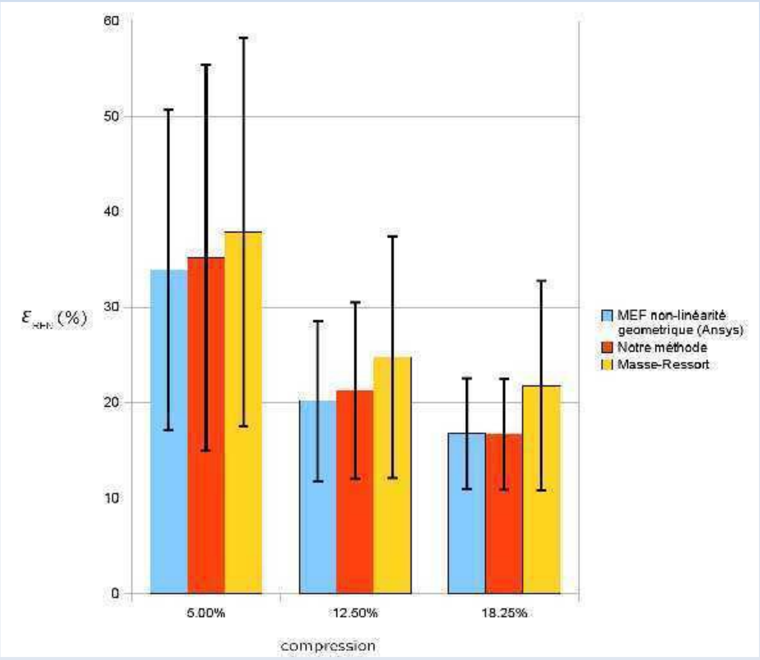


- Bead positions segmented
  → local displacement/deformation in the cube

Example: truth-cube simulations

- Simulation of the experiments and comparisons of the real displacements with simulated ones



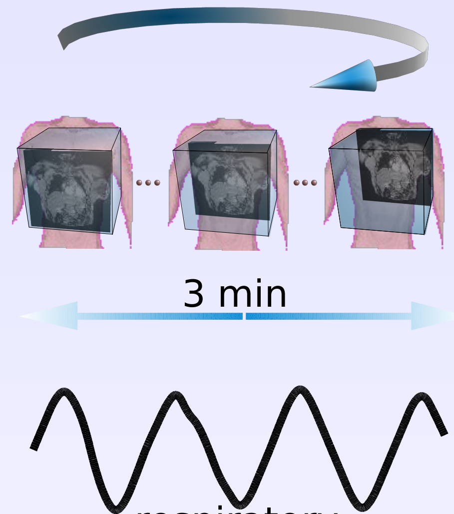


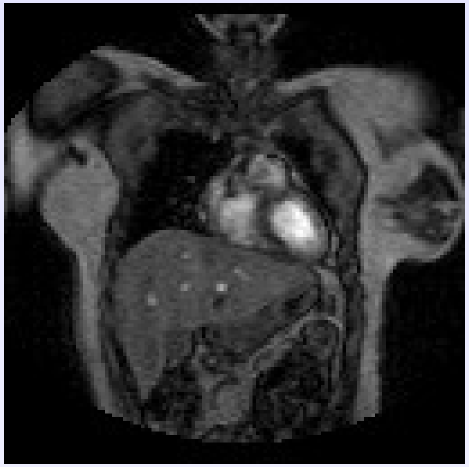
- Possible comparison of different models

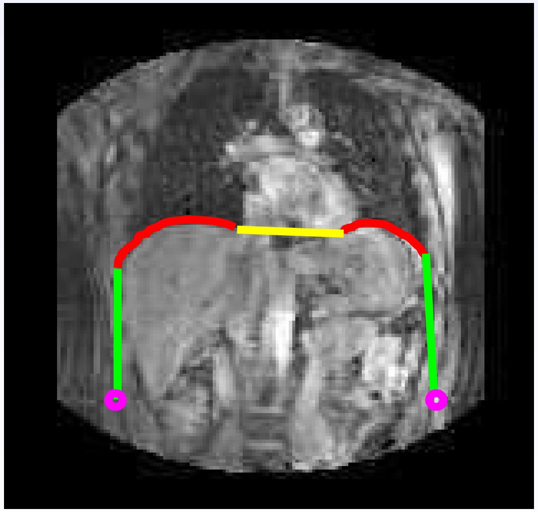
Example: *In vivo* comparison

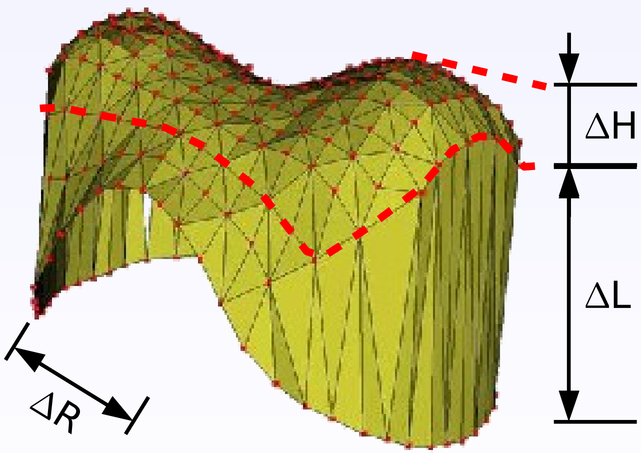
- Comparison with medical data are not easy
- Possible if
  - Clinicians need control exams (you cannot ask for a post-operative CT scan if there is no clinical needs!)
    e.g. maxillofacial surgery (CT scan)
  - Non-invasive data acquisition
    e.g. respiratory movements (dynamic MRI)

Example: dynamic MRI









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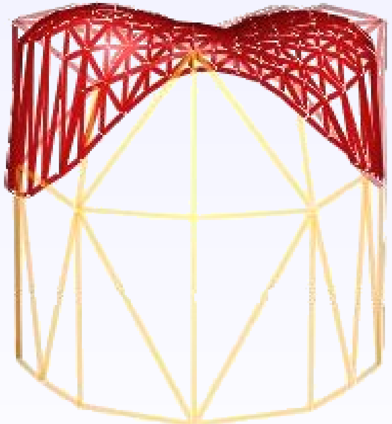

End of inspiration
model ≈ real data

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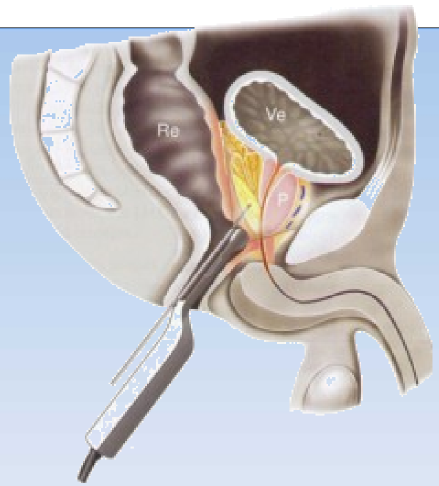
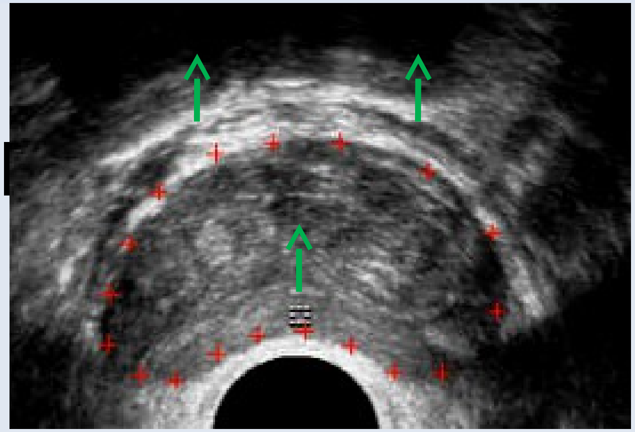
Prostate Cancer detection



- Biopsy and TRUS echography
  - Images with low resolution
  - Prostate *is* deforming
  - 2D / 3D projection
  - Usually pre-operative MRI

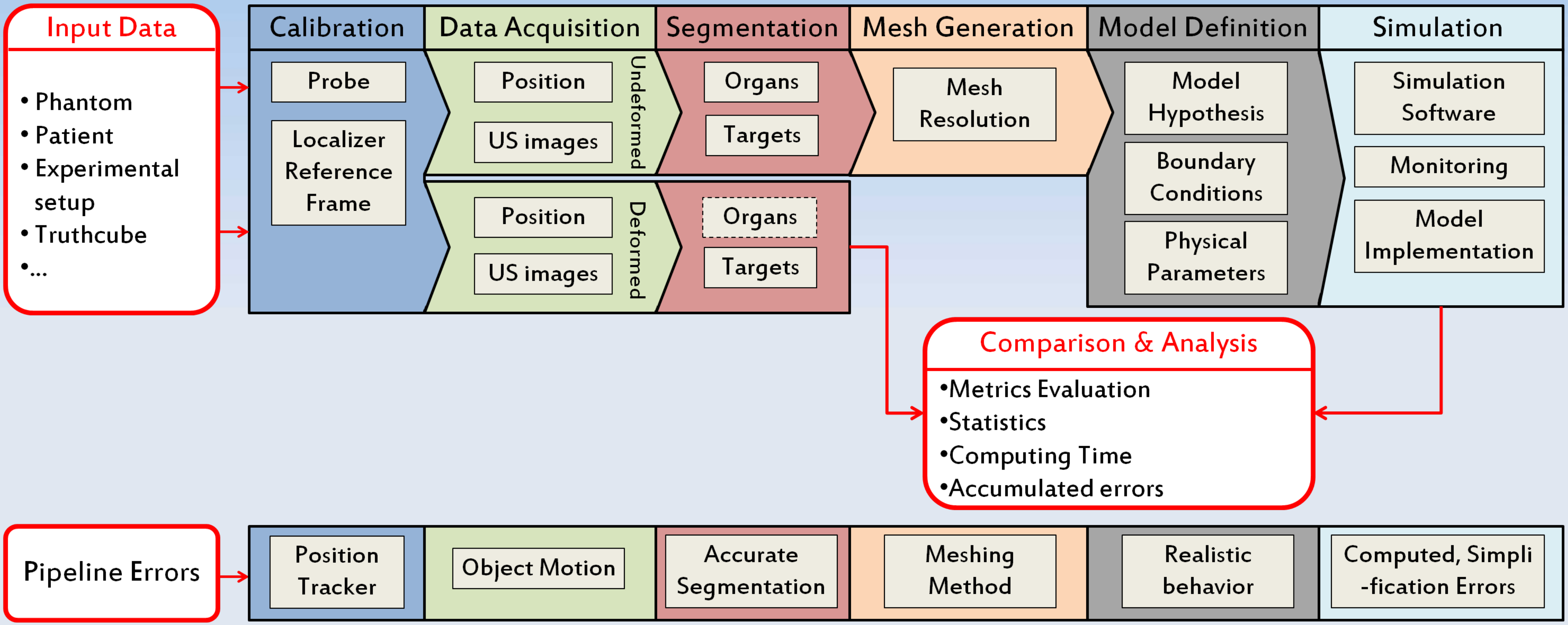


- Koelis
  - Planning
    Mapping
    Localization
  - ANR ProsBot

Aim of the simulator

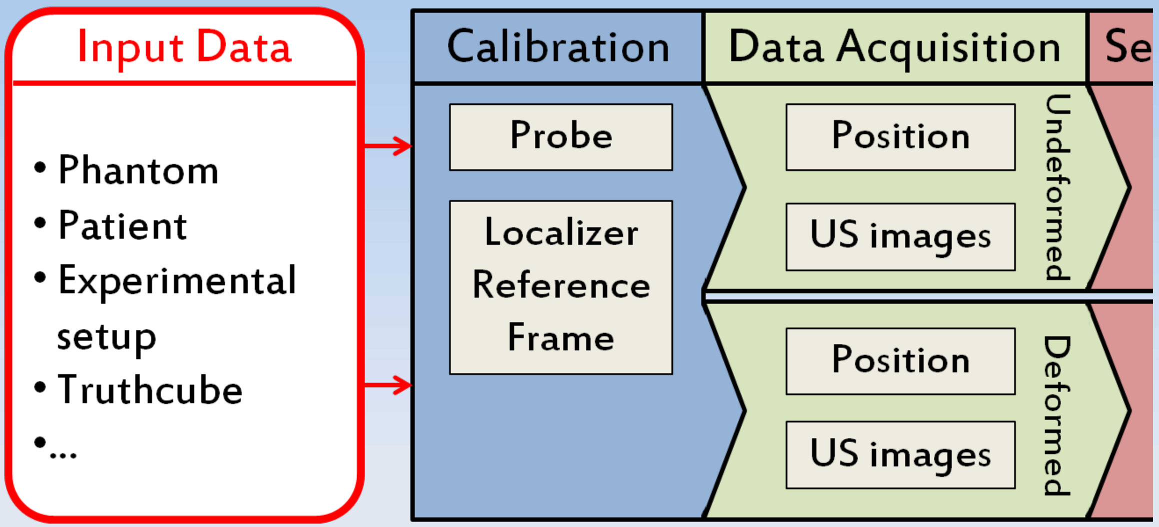
- Create a patient-specific biomechanical model
- Interaction TRUS probe / prostate
- Simulation of the deformations
- Per-operative simulator
- Interaction between US images and model
- V & V needed before including it in the final medical device

Validation Workflow



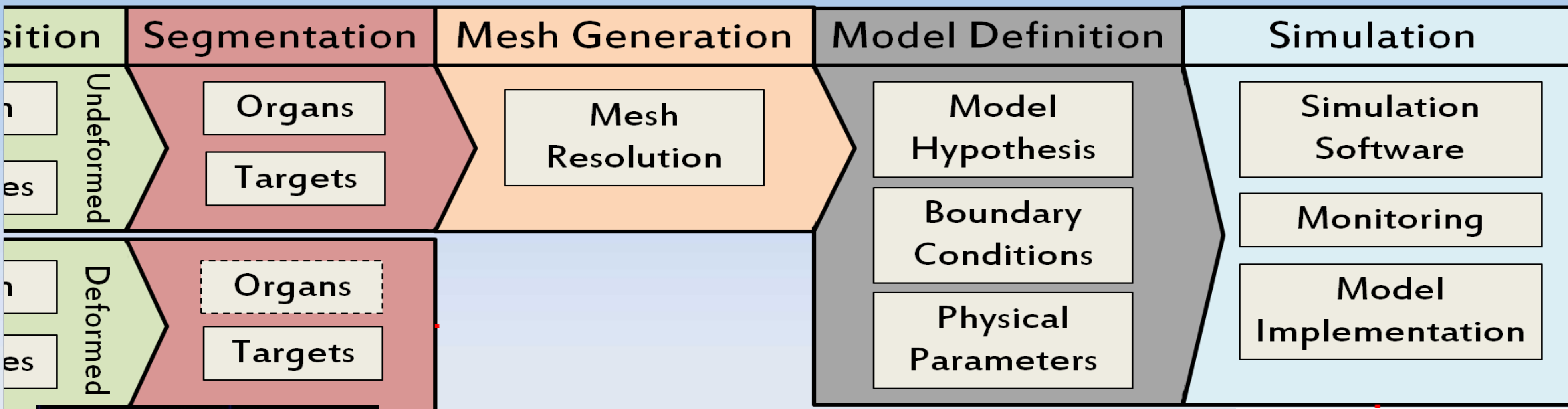
- Be as close as possible to the real physical object
- Everything can be directly used in clinical conditions

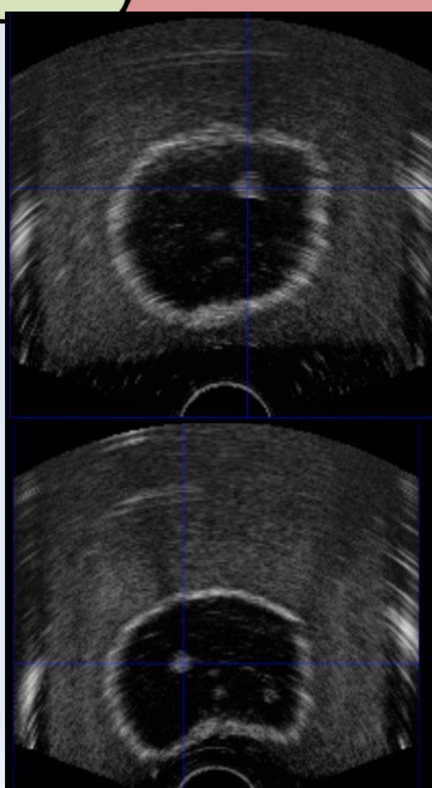
Acquisition



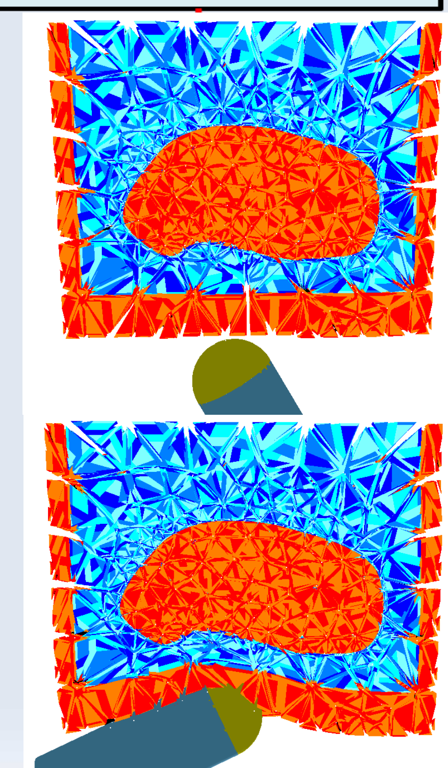
- US volume acquisition
  - With deformation
  - Without deformation (with displacements)
  - Trajectory are recorded for V&V (3D tracker)
- Realistic phantom

Simulation

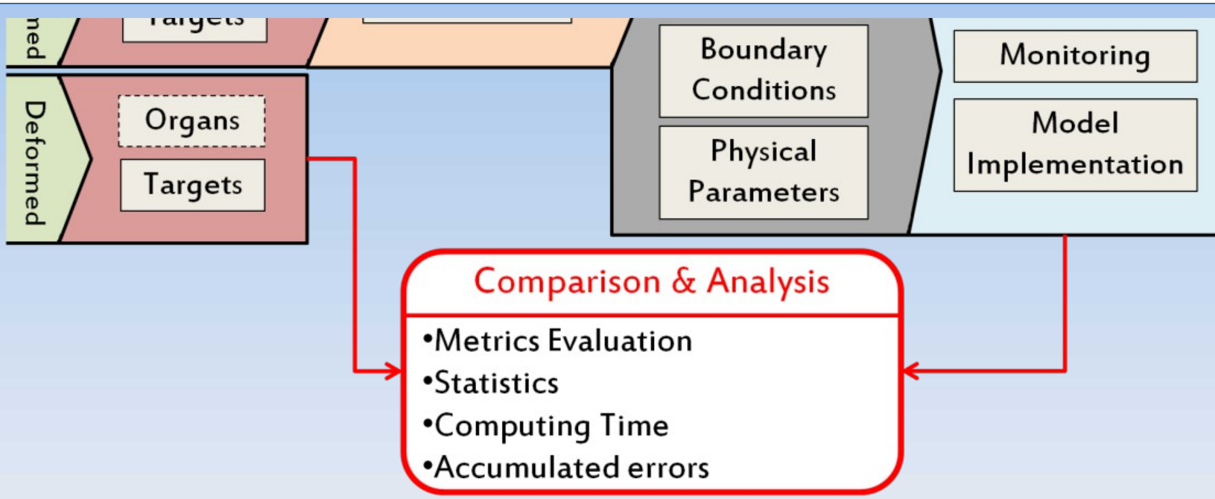


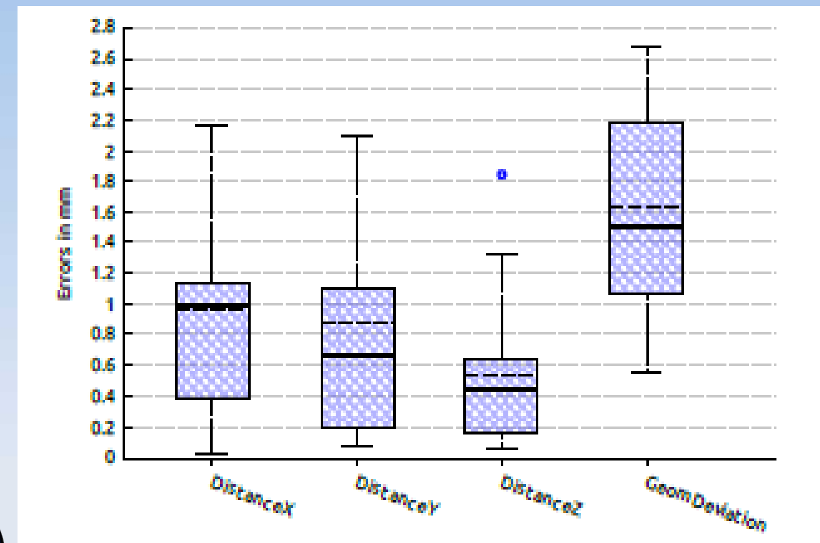


- Manual Segmentation
- 4 targets
- Two mesh
  - 13k tet
  - 26k tet
- Linear FEM
- Parameters + BC

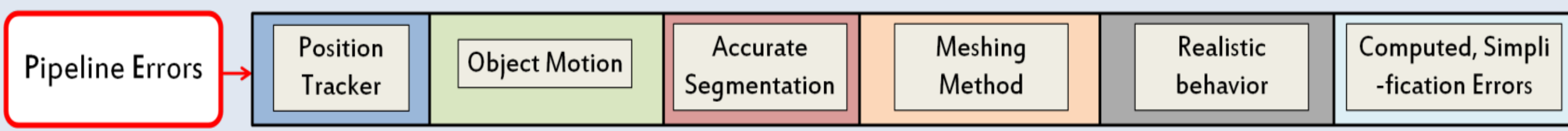


Comparison and analysis





- Using MML and CamiTK
- Comparison of many different metrics



0.33mm **0.57mm** **X** ⟷ **X**

X = Error accumulated in the final error

Test on 120 simulation

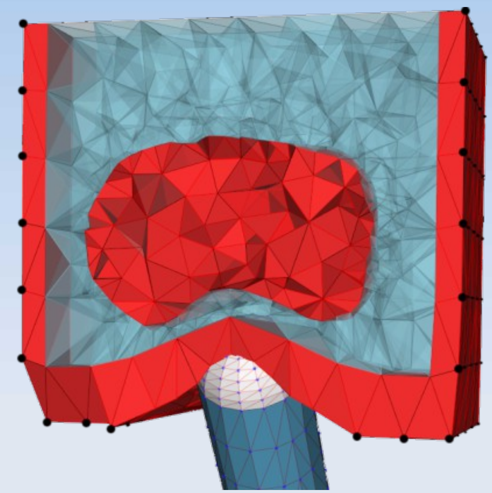
- Estimation of required precision in the model

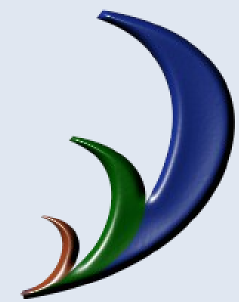
Workflow Step	Parameter	Value Prostate	Value Surroundings	Value Walls
Mesh Generation	Mesh Resolutions (number of tetrahedra)	4,202 18,083	6,781 21,419	1,912 1,912
Model Definition	Young Modulus (kPa)	50 100	13 50	50 100
	Poisson Ratio		0.45 0.40	
Simulation	SOFA FEM implementation (method name)		Small Large Polar SVD	

X4 Acquisition

Initial Results

- 3 Linear FEM method (SOFA)
  - 2 mesh
  - Parameter study
  - 4 experiments (lots of displacement)
  - 1.74 +/- 0.66 mm





- Accumulated errors
  - Potentially 50% comes from the simulation

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In vivo measurements

- *Ex vivo* measurements are important for building simulators but are different to *in vivo* measurements (Kerdok et al. 2006)
  - Vascularization
  - Temperature
  - Elasticity..

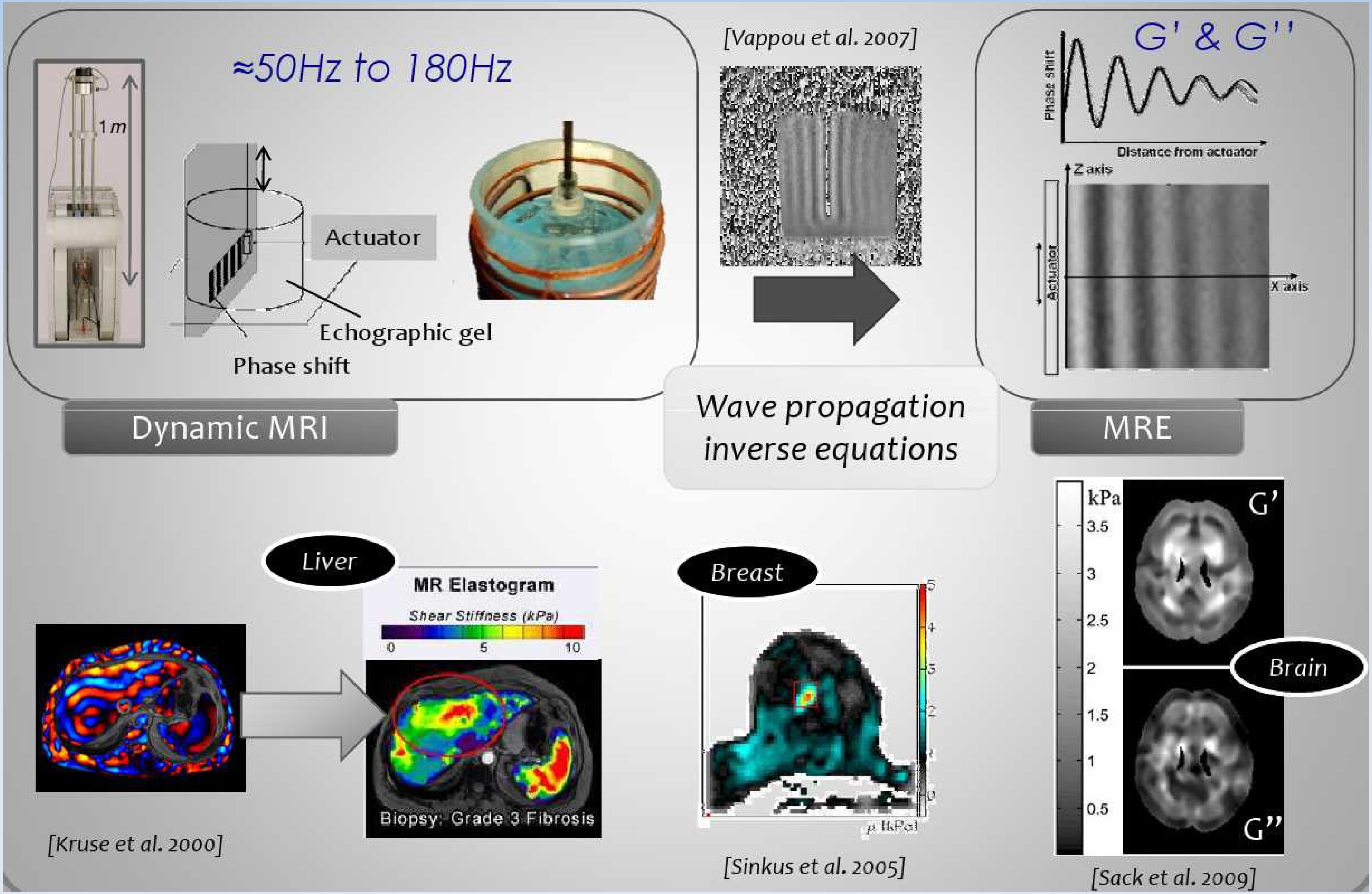
- To be patient-specific
  → measure the properties *in vivo* and *in situ*

Two main approaches

- Elastography: imaging deformation (MR or US)
  - Image of the organ before and after a controlled stress → deformation (generally ultrasound)
  - Measure the tissue local displacement
- Direct mechanical test (indentation or aspiration)
  - Direct mechanical stress/probing
  - Measure of the tissue deformation or response using force sensors (identation) or camera (aspiration)

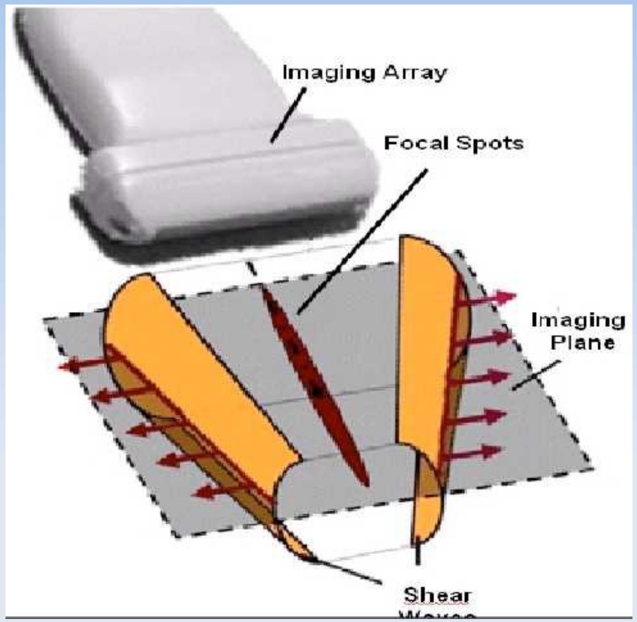
→ Inverse problem gives the model parameters

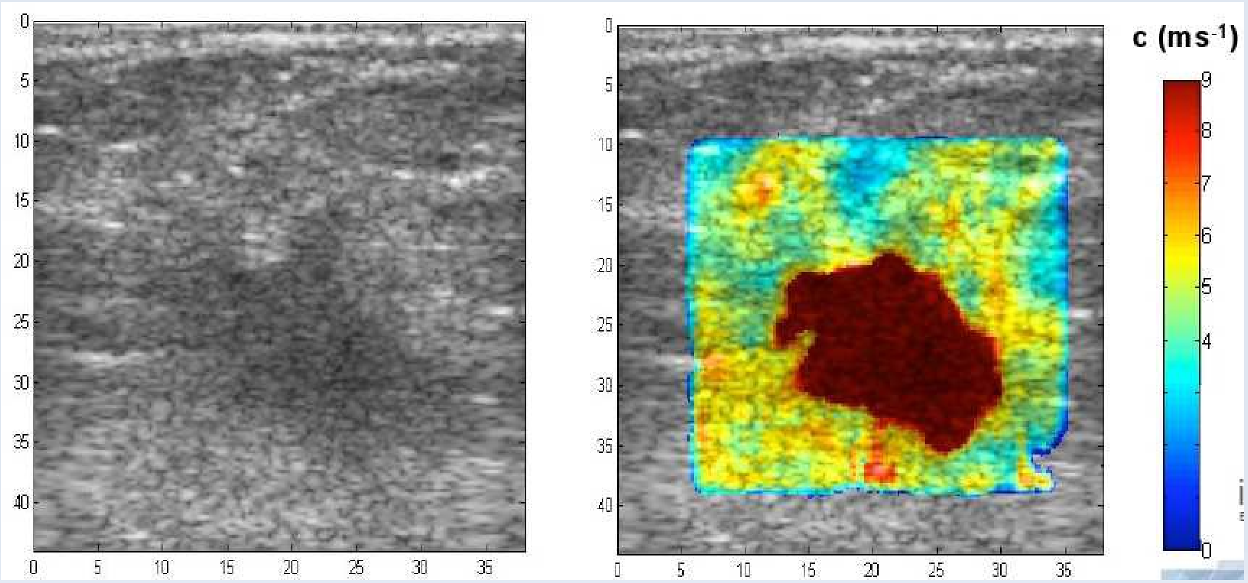
Magnetic Resonance Elastography



(from R. Willinger, Univ. Strasbourg)

Ultrasonic Imaging Elastography





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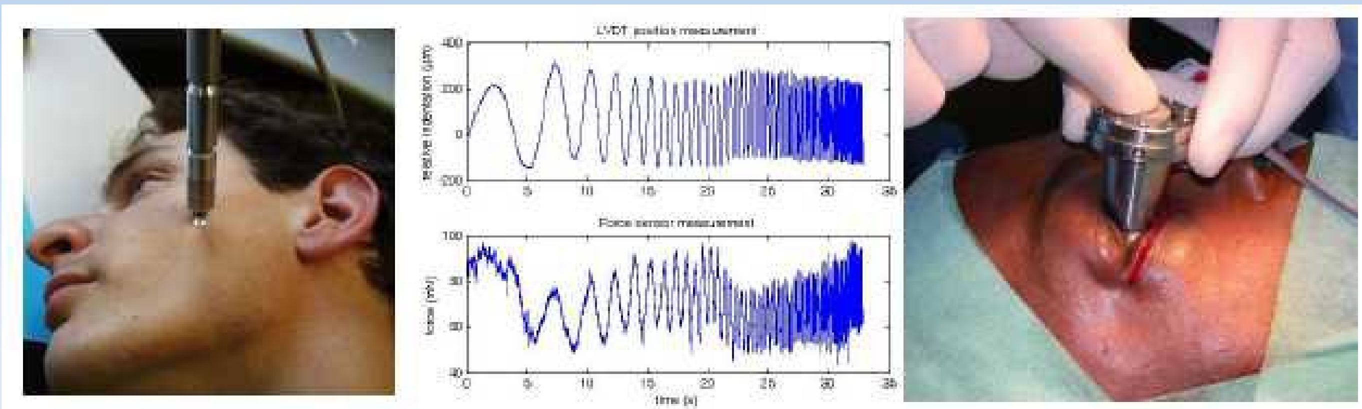
Mechanical Probing

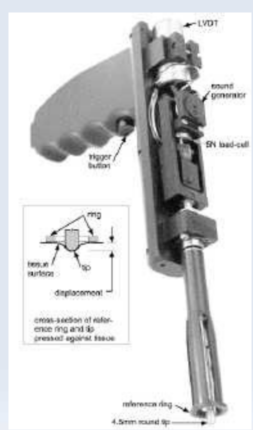
- External measurements



Payan et al., 2005 Luboz et al., 2007

commercial

- Internal tissue/organ measurements
  - Indentation
  - Aspiration

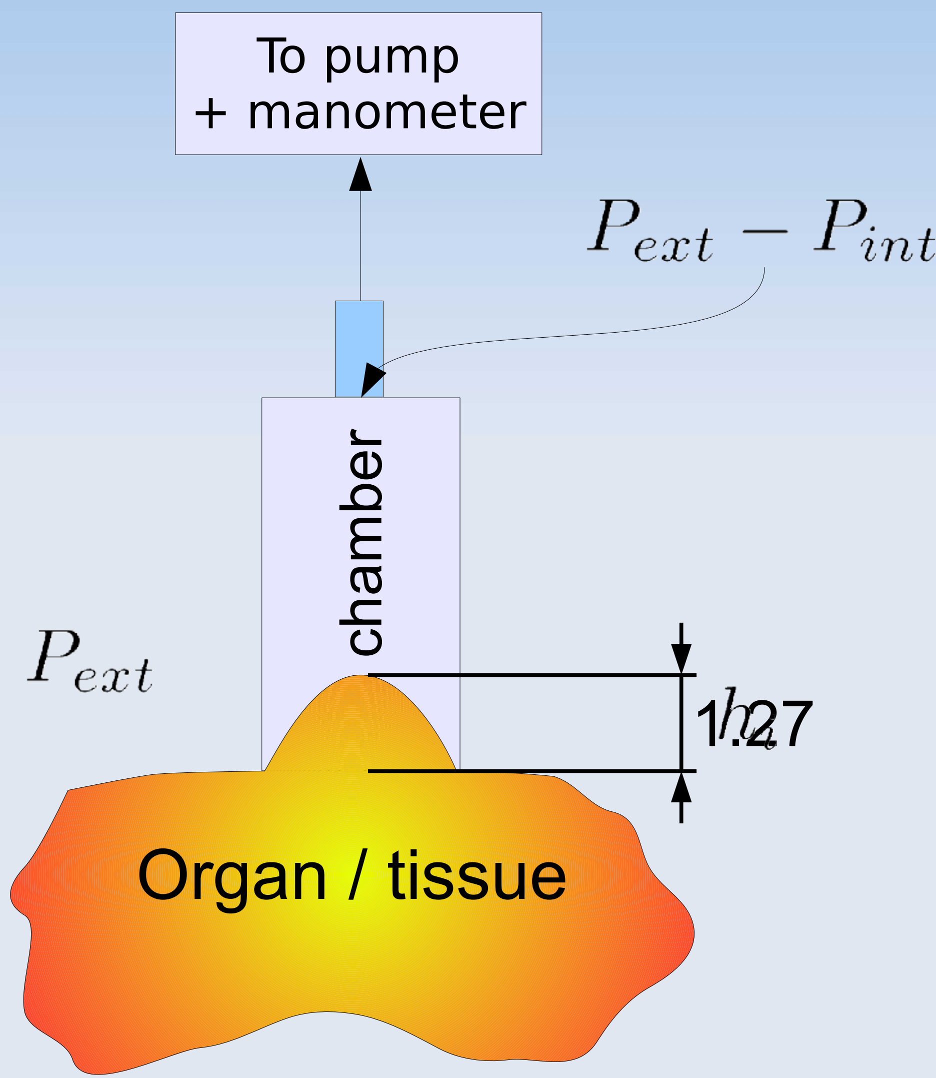


Carter et al. (2001) (liver)

In vivo is difficult

- Cannot create tissue damage
- Per-operative use implies
  - Sterilization
  - Ergonomics and functional (bulk, time,...)
- Most difficult: sterilization
  - Aggressive process : T140° for 20min, steam, high-pressure, heat, chemicals (liquid, gaz, plasma...)
  - Fragile parts (electronics, sensor) could easily be dammaged
  - Everything has to be sterile (even parts not in the field, because of projection risks)

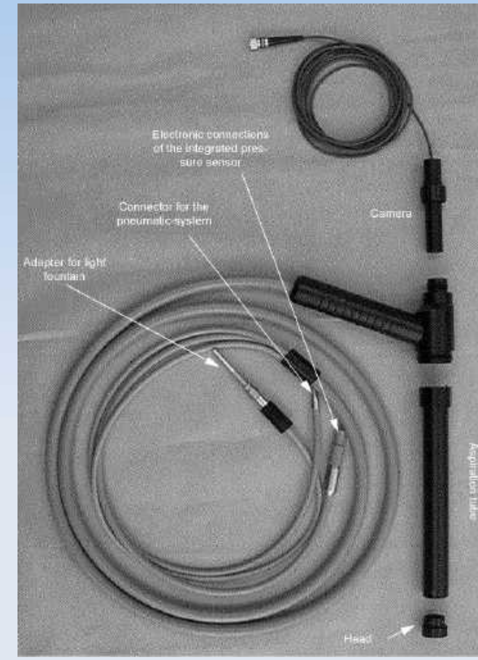
Aspiration/suction : principles



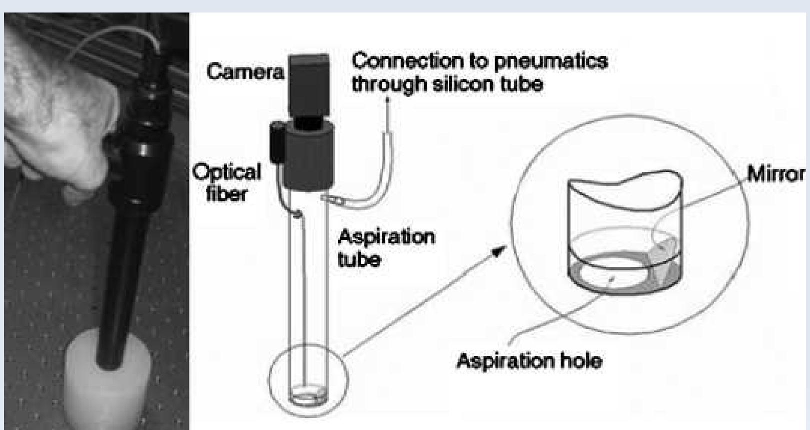
- In contact
- Negative pressure P_{int} applied in the chamber $\rightarrow$ tissue is "aspired"
- Aspired height h_i is measured (mirror)
- As the device is fixed by suction, measurements are independent of the natural movements (beathing, heart beat...)

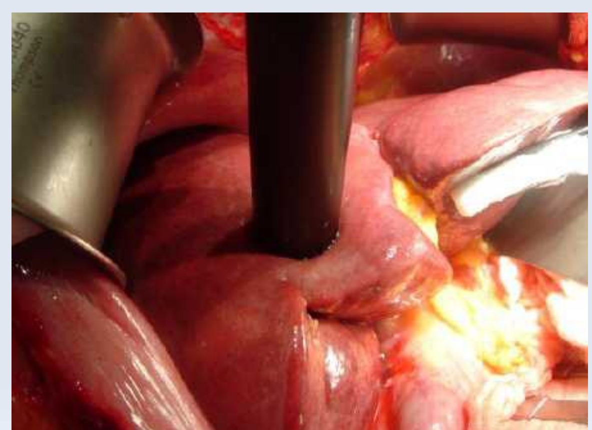
Per-operative measurements: aspiration

- Vuskovic (2001) Kauer et al. (2002) : uterus



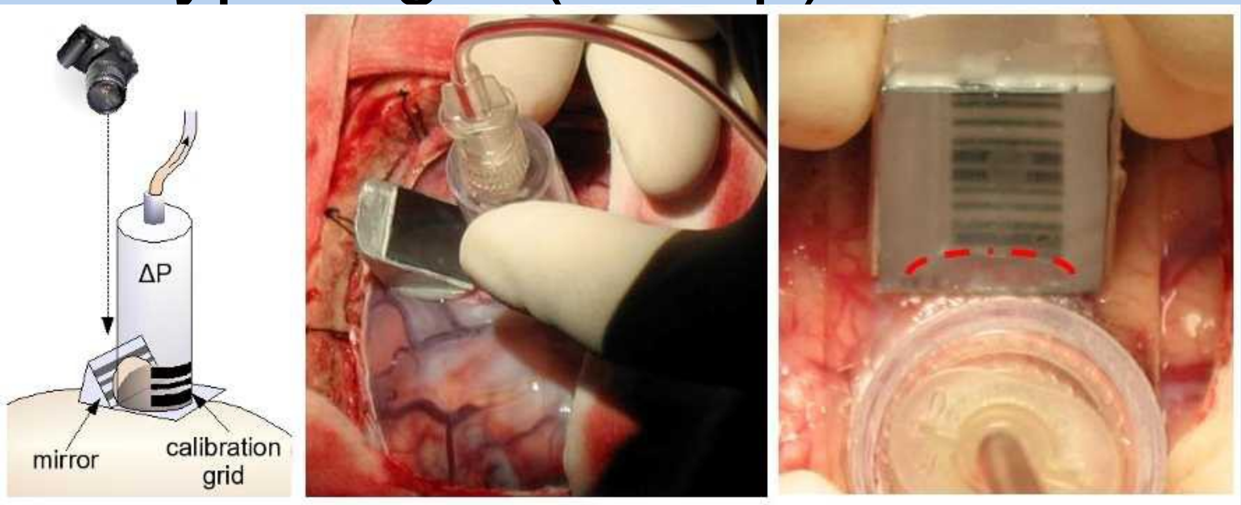
- Nava et al. (2008) :liver



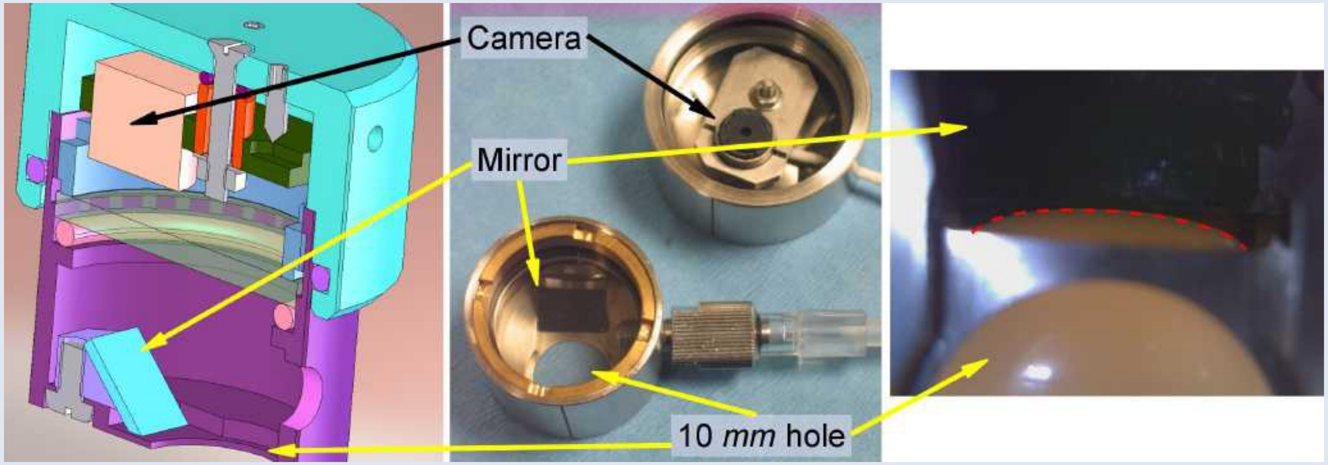


LASTIC (TIMC-IMAG)

- First prototype: light (cheap)



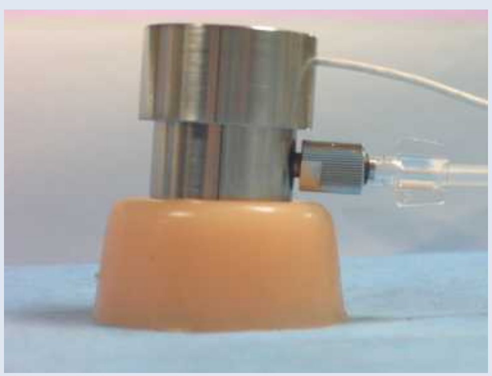
- Second prototype: integrated camera/mirror

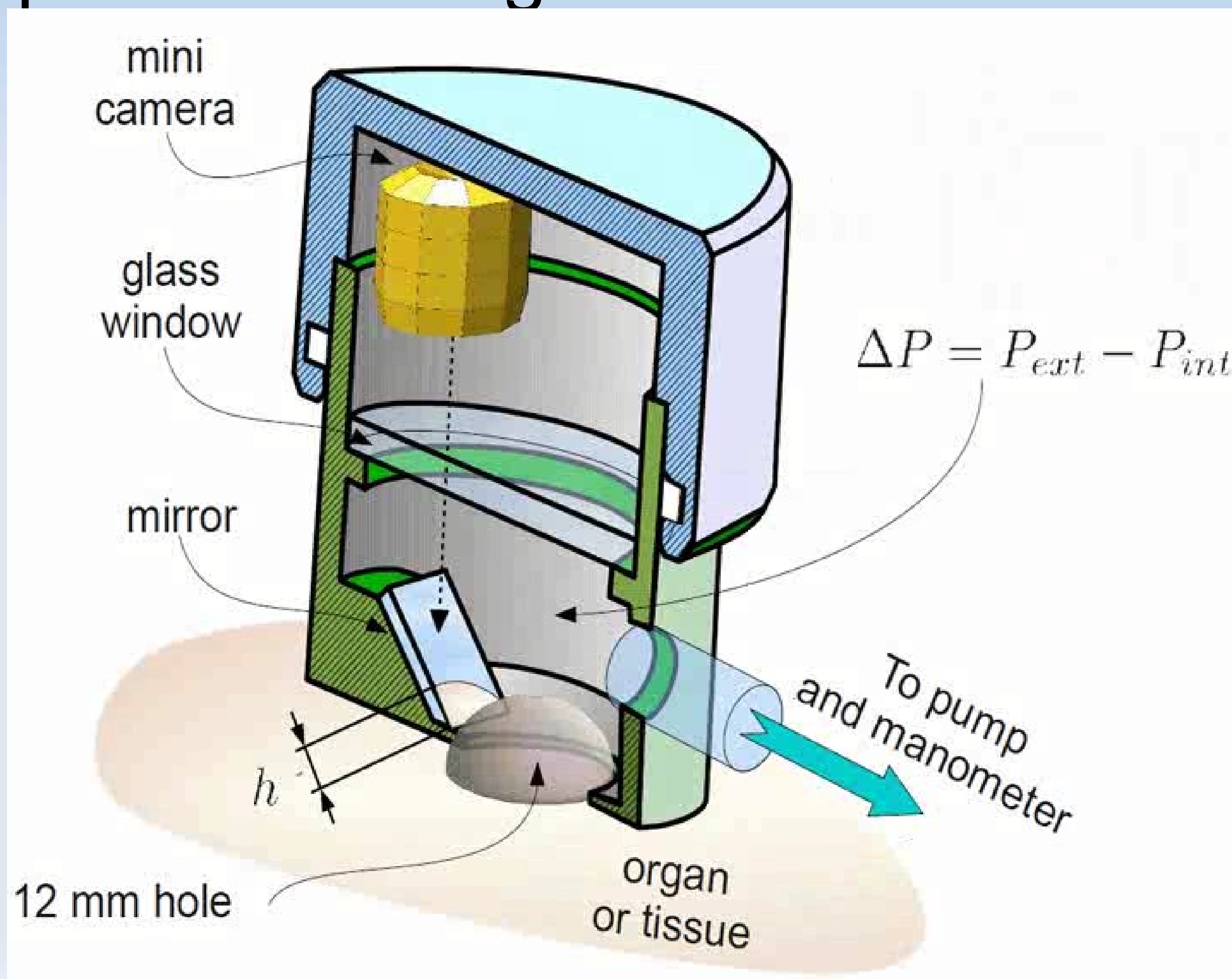


(Schiavone et al, 2009)

Capture and segmentation

- The image of the tissue deformed by the applied pressure is captured and segmented

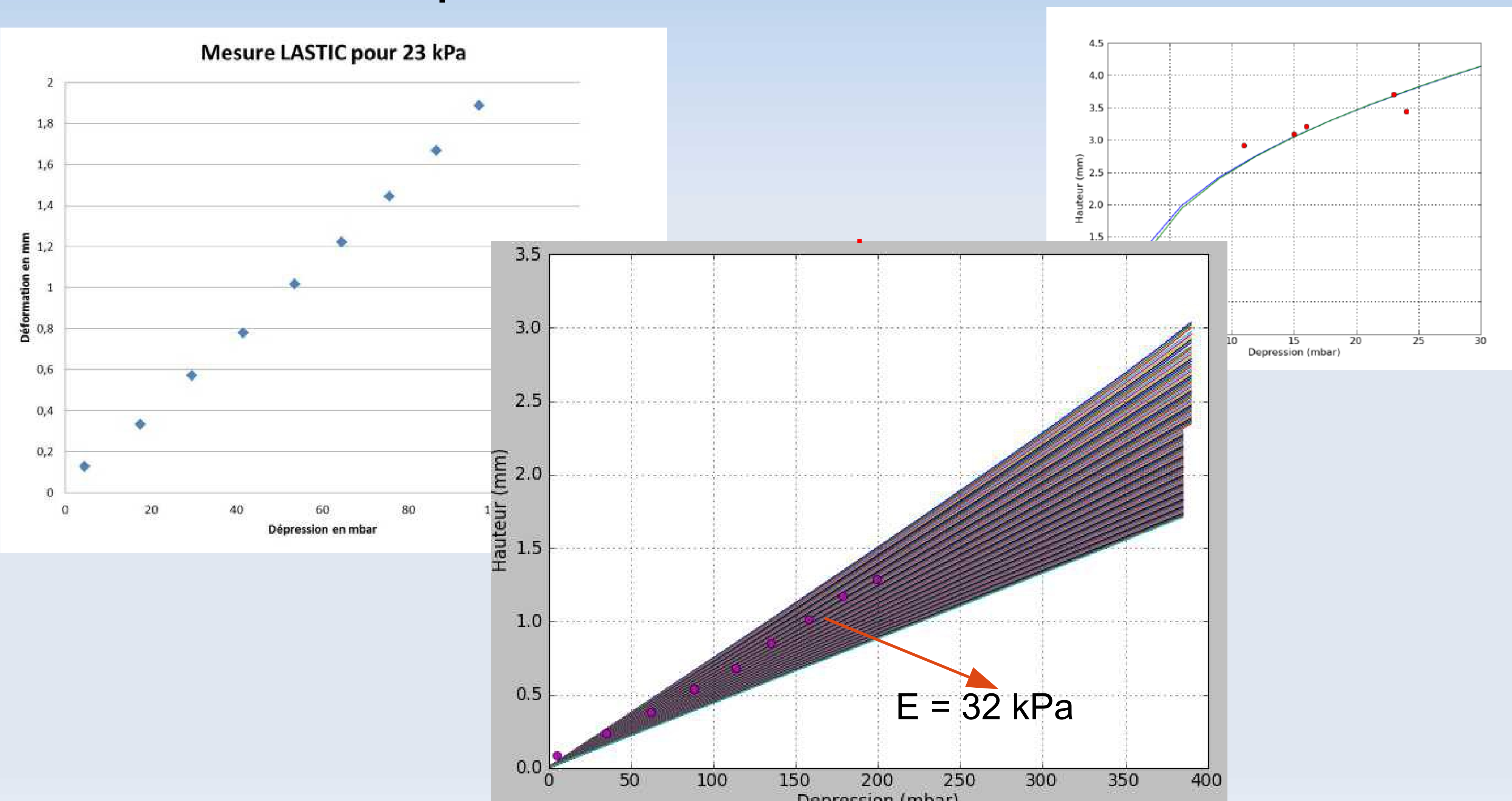




+VIDEO

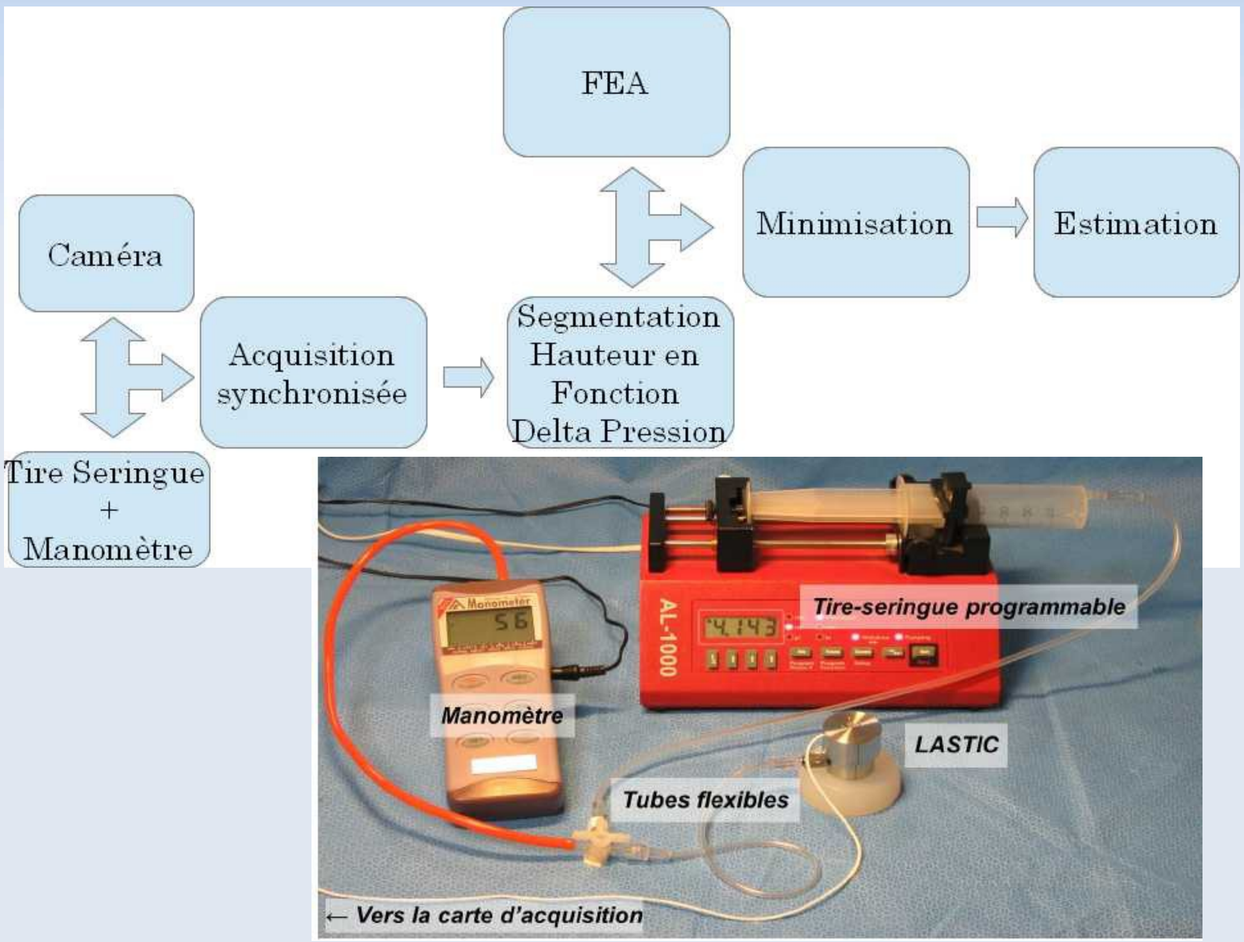
Inverse problem: optimization

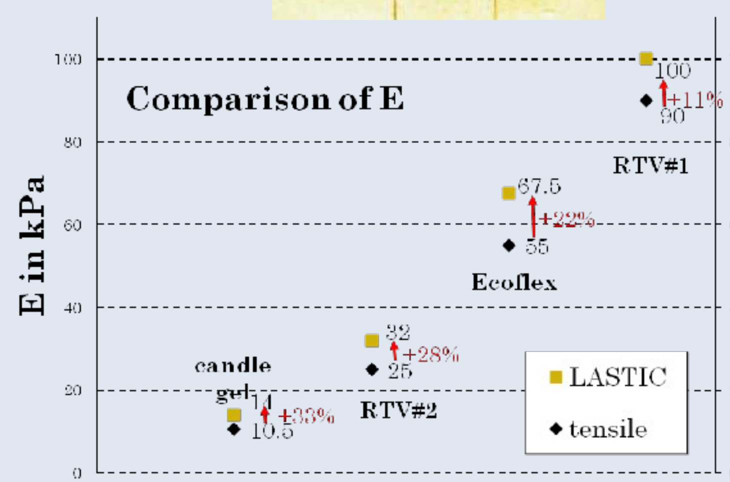
- A FEM is optimized to fit the measurements



Validation of the validation tool...

- Is the measurement accurate/precise?





Conclusion

Medical simulation is a quest...

"The Achievement of the Grail" (1891-4) Tapestry by Edward Burne-Jones, Museum and Art Gallery of Birmingham

Acknowledgements

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  - J. Sarrazin, S.Y Selmi, A. Deram, M. Marchal
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- And more...