

The logo for LIRIS (Laboratoire d'InfoRmatique en Image et Systèmes d'information) features the word "LIRIS" in a bold, blue, sans-serif font. The letter "I" is stylized with a vertical bar and a red dot above it. The logo is partially enclosed by an orange circle on the left side.

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UNIVERSITE DE LYON



Centro Nazionale di Adroterapia Oncologica per il trattamento dei tumori  
**Hadrontherapy school**  
Conference Room CNAO

# Modeling of Moving organs

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Pavia 23/09/2016

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09/11/2018



# Outline

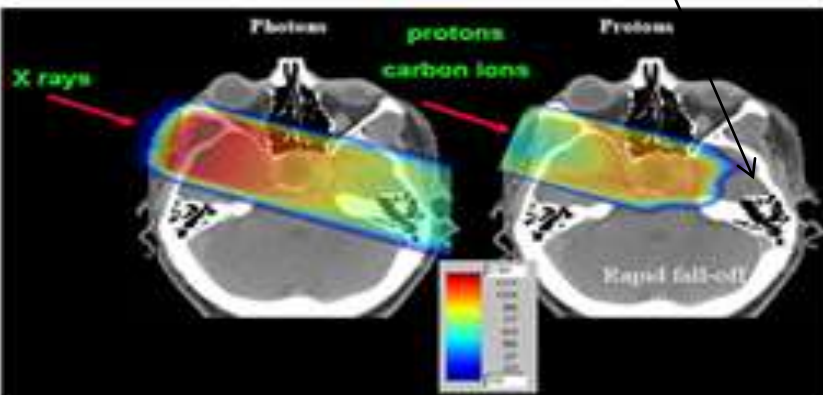
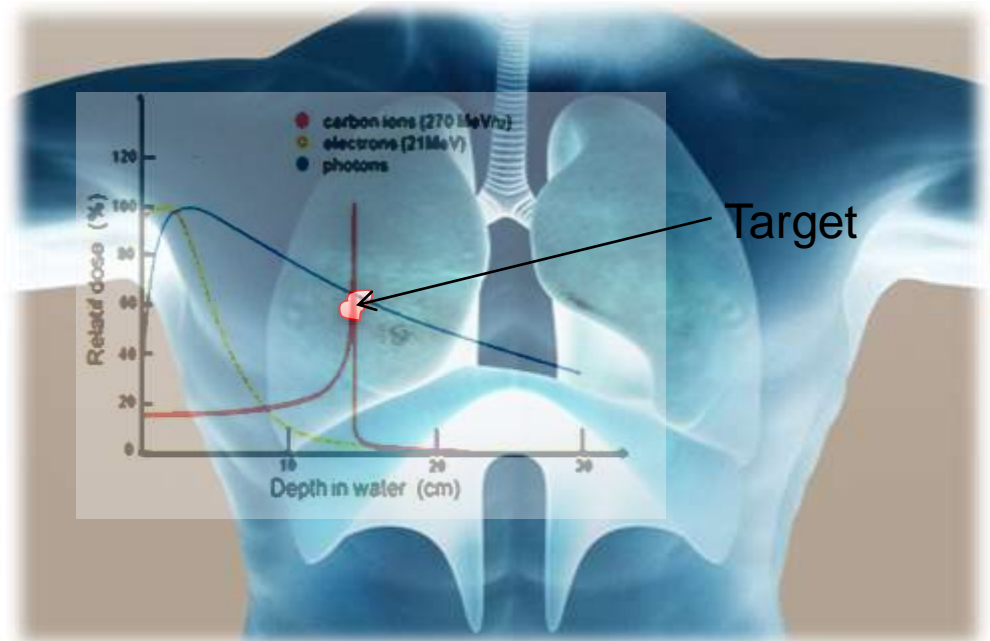
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- Context: moving organs
- Challenge and Objective
- Methodology and why the biomechanical modeling patient specific can help?
- Results and validation
- Conclusion and futur work

# Context: Hadron therapy:

- Advanced radiotherapy technique for cancer treatment that uses charged particles like light ions or protons instead of photons.
- Requires some appropriate quality assurance procedures.

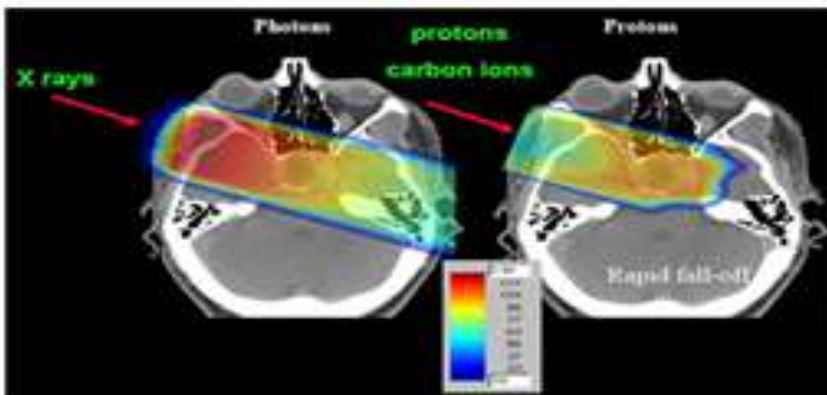
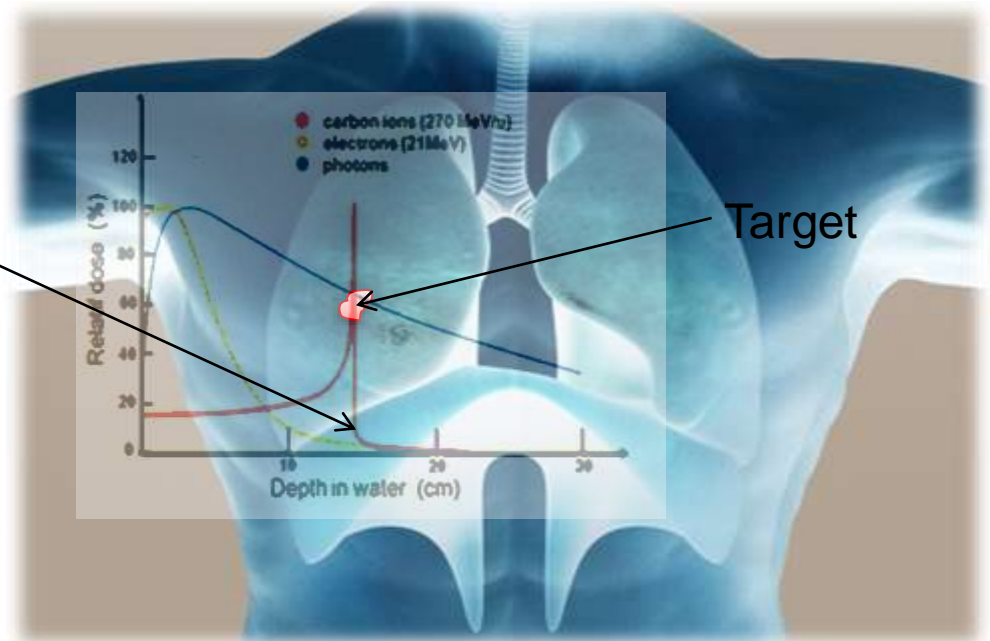
The delivered dose can be limited to the target, hence sparing the healthy tissues surrounding the tumor.



# Context: Hadron therapy:

- Advanced radiotherapy technique for cancer treatment that uses charged particles like light ions or protons instead of photons.
- Requires an appropriate quality assurance procedures.

The position of the Bragg peak depends on the density of the matter traversed by the beam



# Context: moving organs

## Ballistics problem:

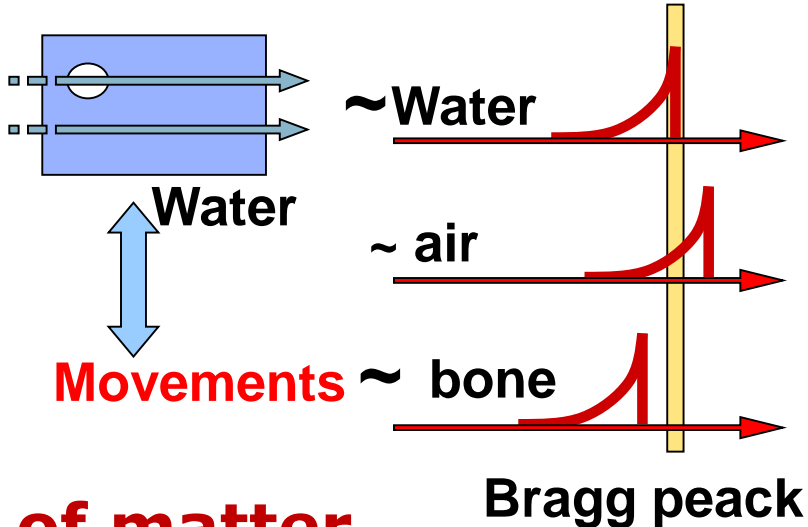
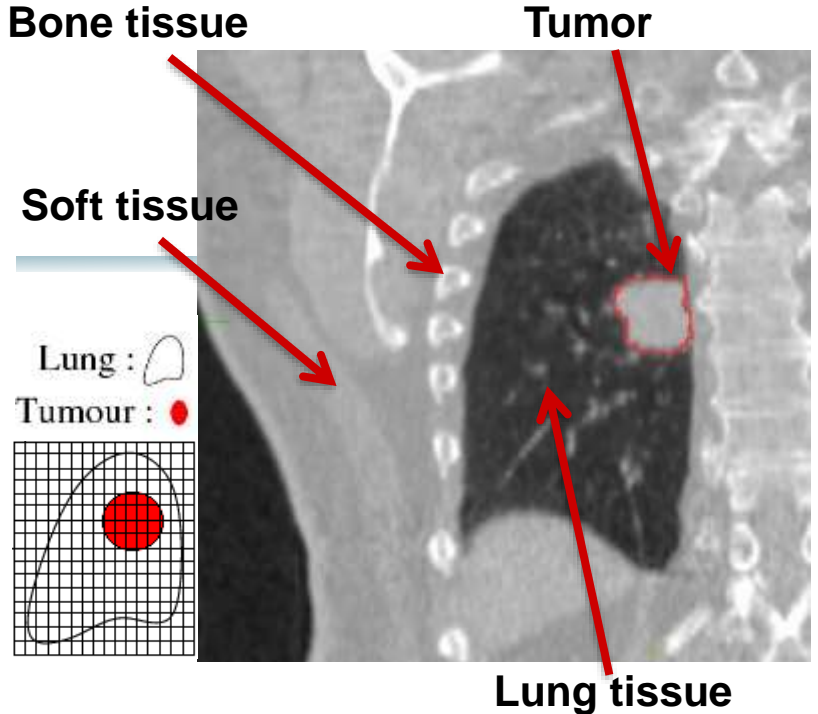
- The position of the lung tumor
- Calculate and optimize the dose delivery

**➡ Geometric data**

## Specific problem of Hadrontherapy:

- Knowledge about the organs traversed by the beam
- The position of the Bragg peak depends on the density of the matter traversed by the beam
- Geometric data = insufficient !!!

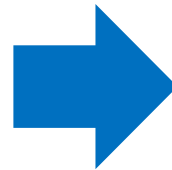
**➡ Density of matter**



# 1- Imaging techniques: Target localisation techniques

- Imaging the tumour, if possible !!!
- Imaging of anatomical structures rigidly bound to the tumour (ex. bony landmarks)
- Detecting artificial fiducials implanted in or near the tumour (invasive, infection risk, pneumothorax...)

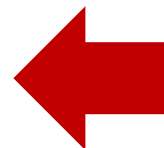
**Techniques based on imaging**



**assume a reproducible motion of the respiratory system.**

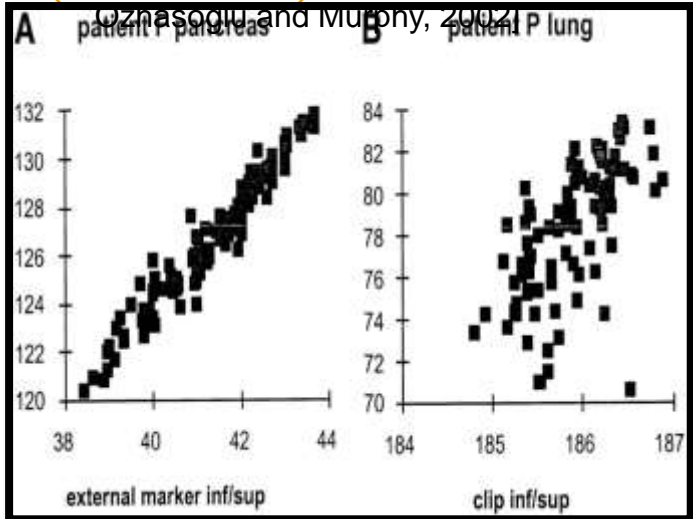
**Existing solutions on tracking:**

- Fiducial Markers
- CyberKnife system
- Online Pet Scan

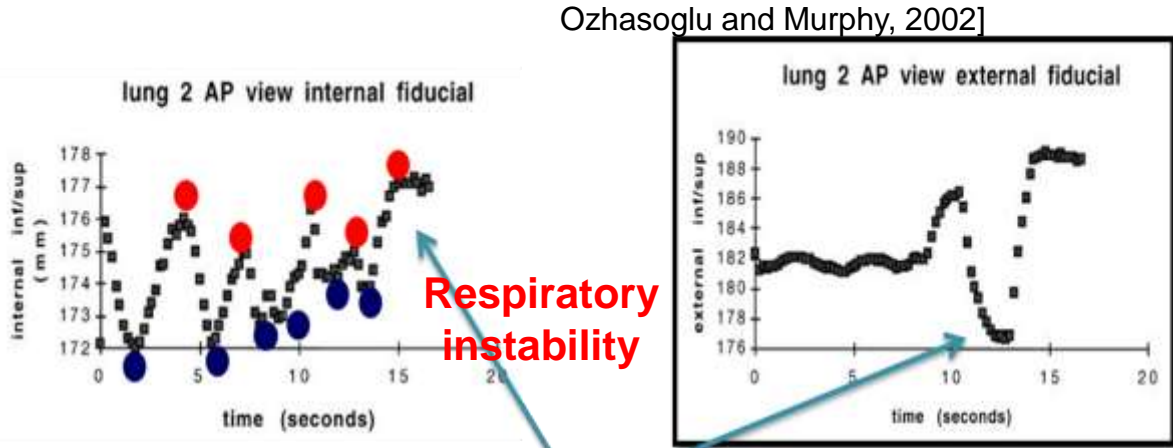


**intrusive or invasive the irradiation of the patient**

## 2- Monitoring surrogate organs moving in synchronism with the lung tumour.



**Correlation diaphragm movement vs pancreas and lung tumour**



Tumor

Thorax

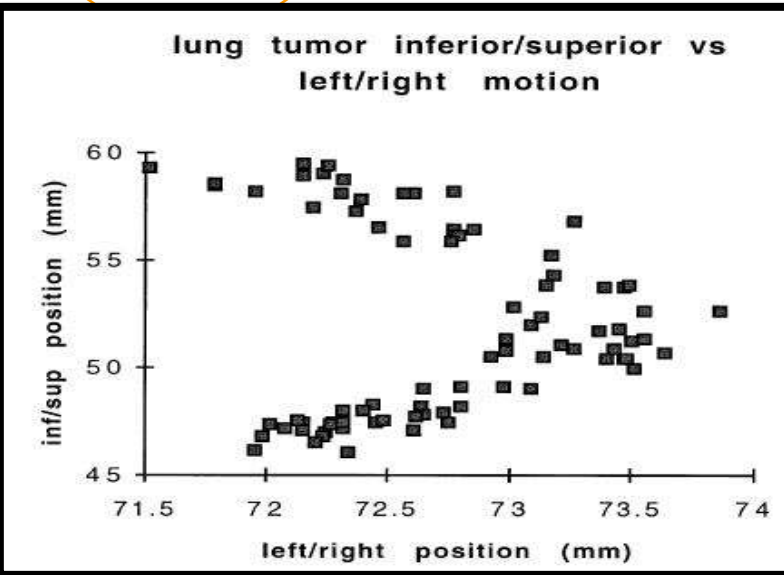
$$E_{\text{Resp}}(t) = F(\phi(t))$$

**Correlation between internal motion lungs and external motion thorax**

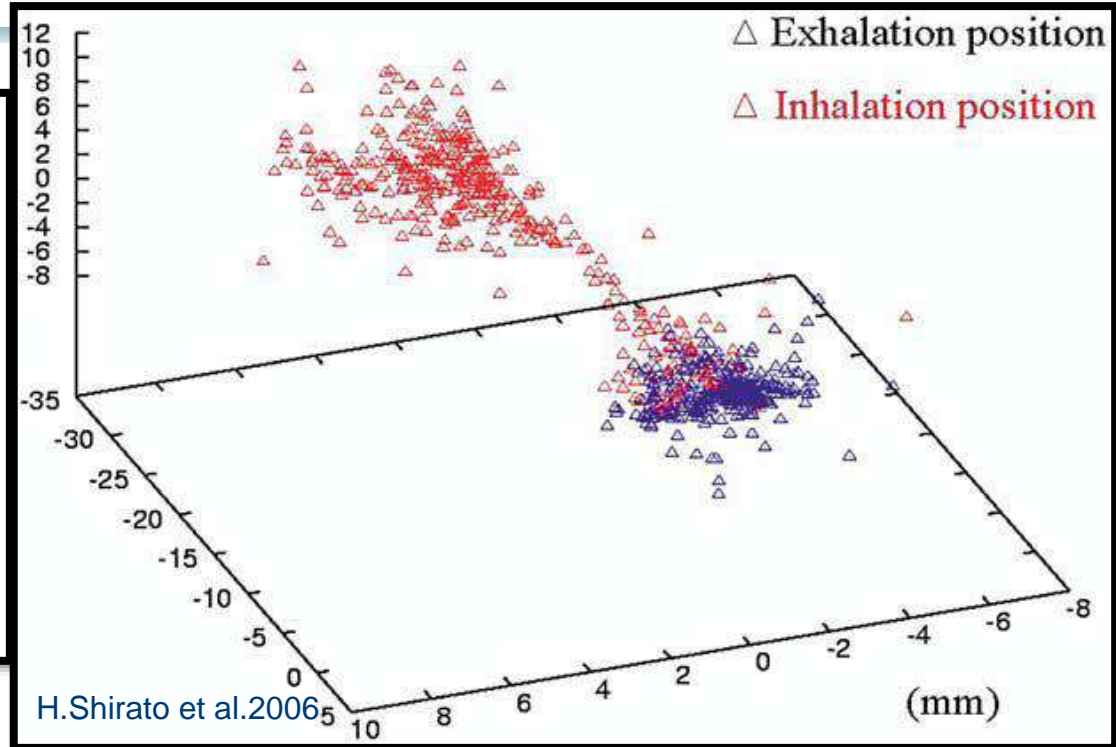


**Respiratory instability**

# Non-reproducibility of the movements



**Lung tumor  
inferior/superior  
vs left/right motion**



**Internal marker : exhalation &  
inhalation positions**

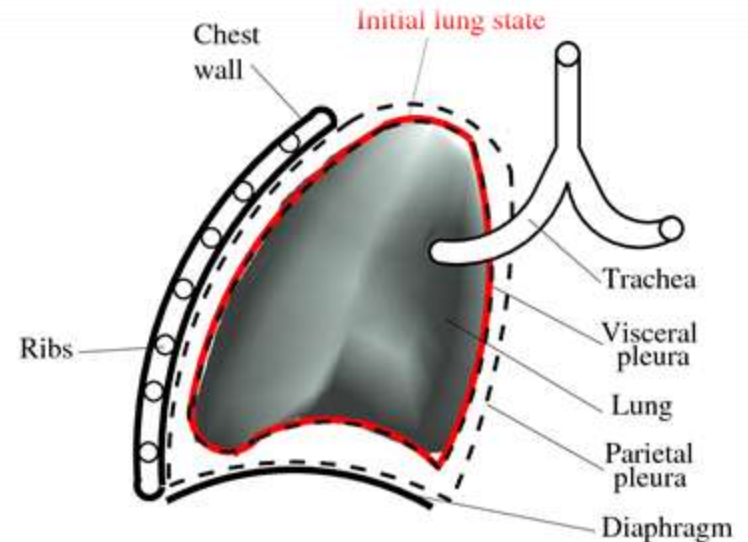
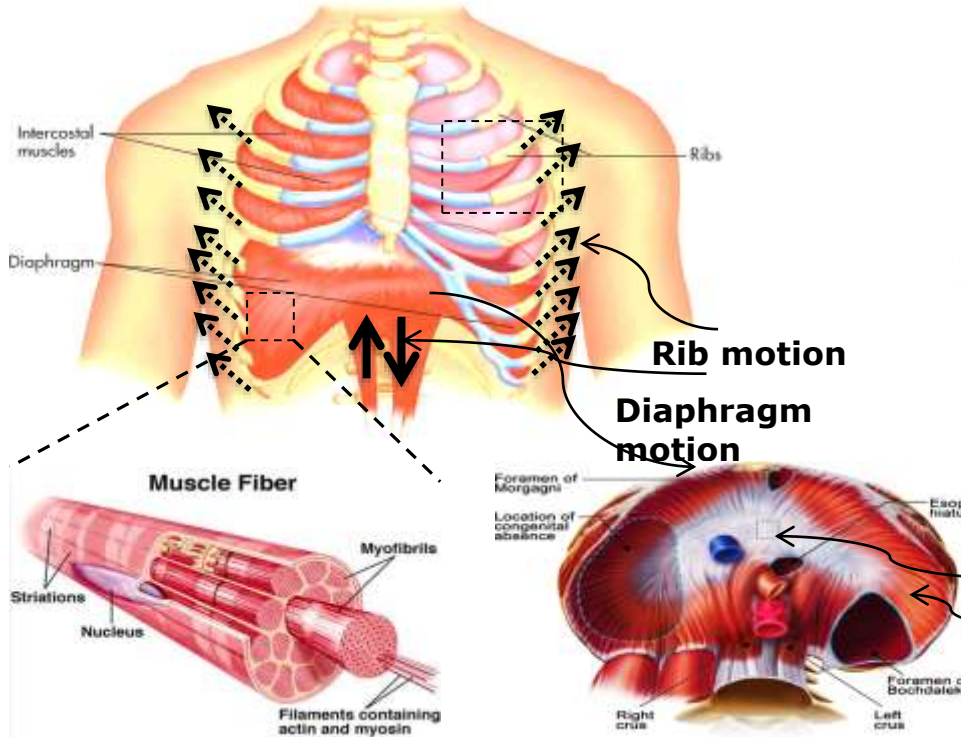
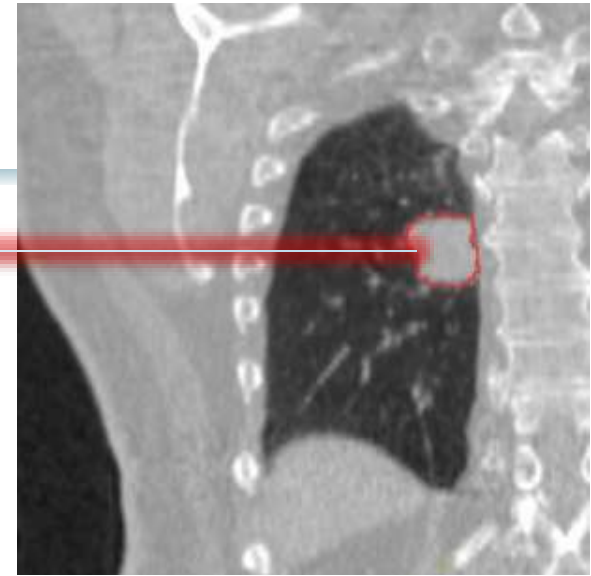
**Non-reproducibility  
of the movements (chaotic?)**



# Anatomy of the respiratory system.

## Breathing is non-reproducible

- Contraction of the diaphragm muscle.
- Intercostal muscles of the ribcage.

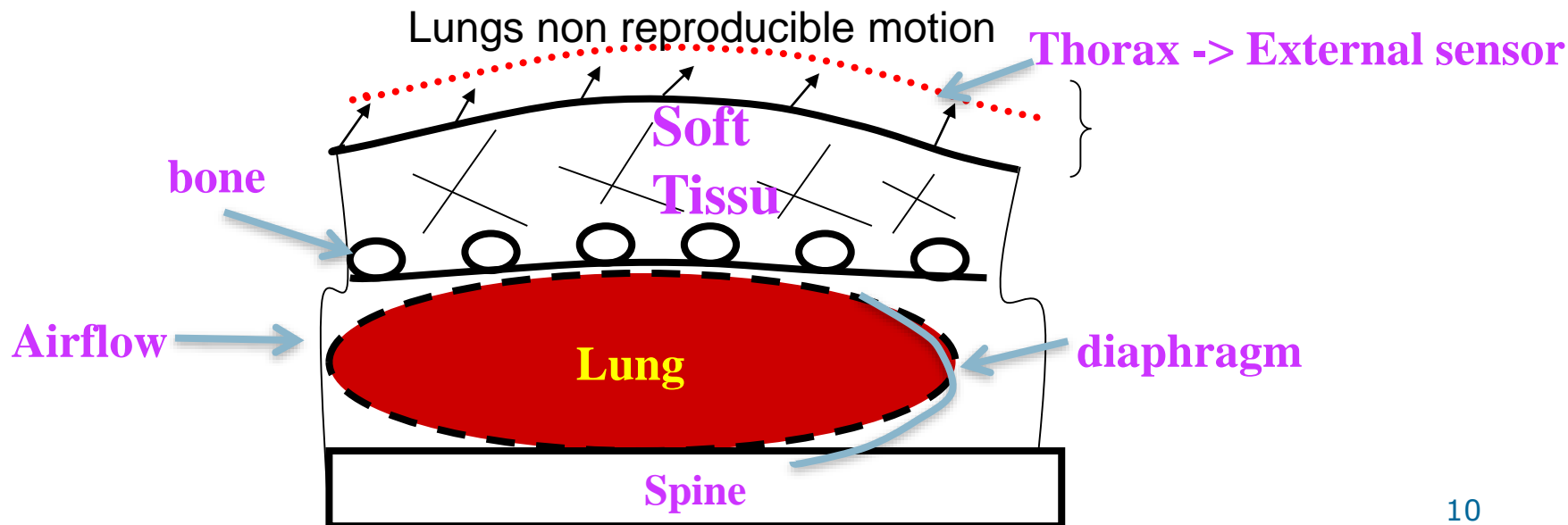


The breathing cycle is not regular,  
Varies in amplitude and in phase from  
one cycle to another

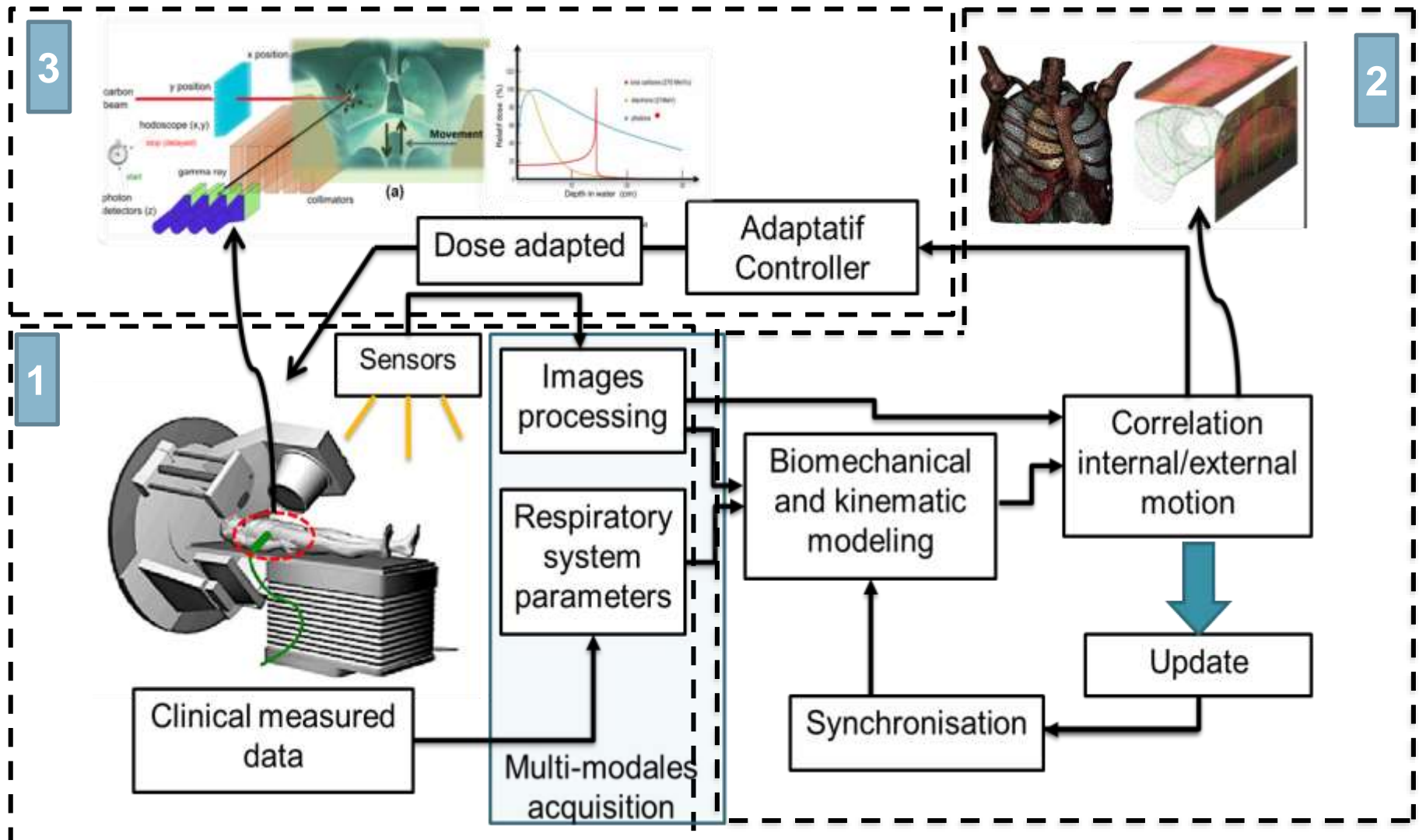
Diaphragm and Thorax

# A biophysical approach

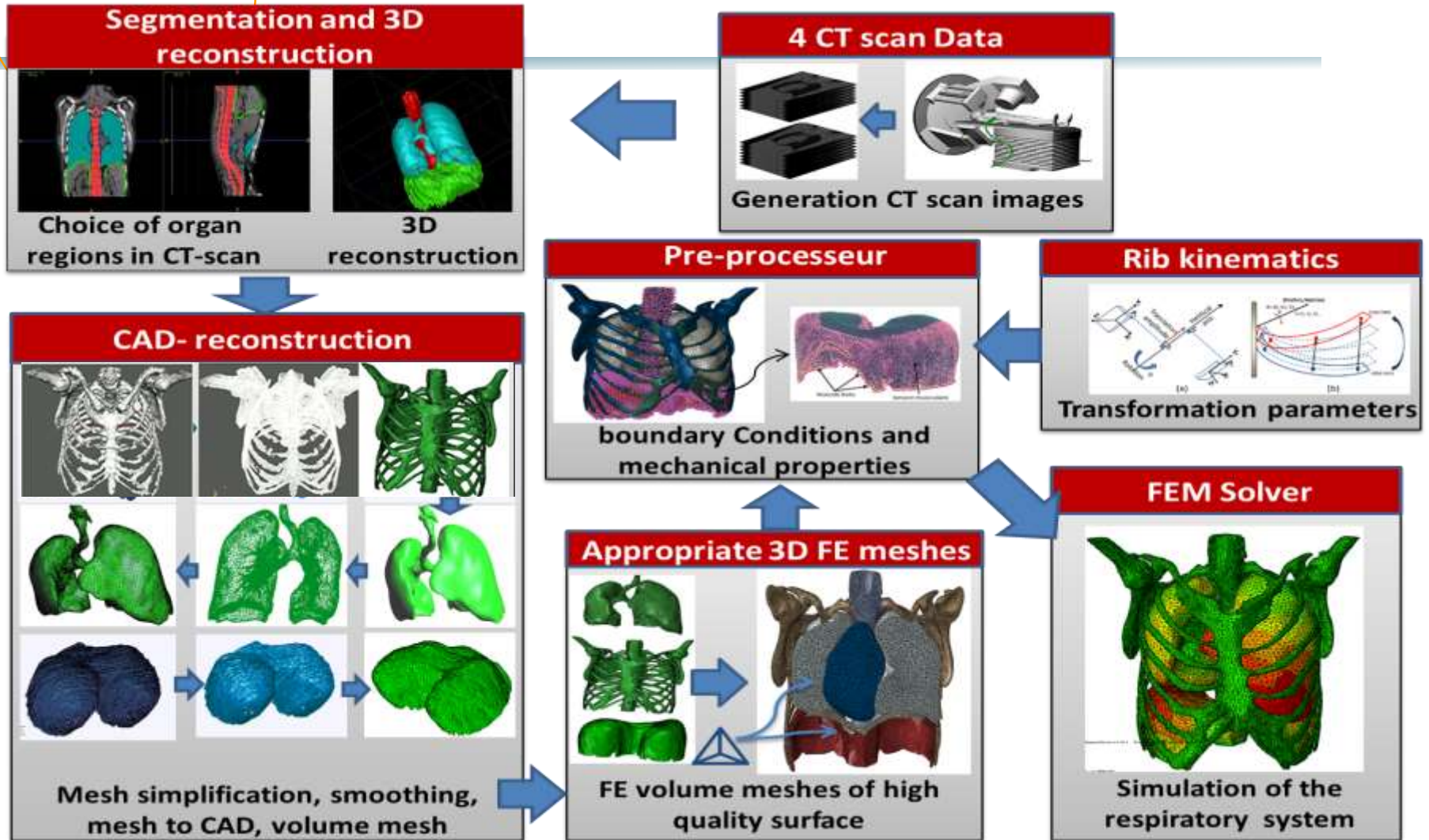
- Approach based on the Biomechanical modeling of respiratory system allowing to:
  1. Take non reproducible aspects of lung motions into account
  2. Establish the biomechanical model from patients' geometrical and physical data
  3. Be monitored by external sensors during the treatment
  4. Simulate a "virtual 4D-Scan"
  5. 4D dose distribution and online imaging control



# External surrogates and sensors track internal organs motion based biomechanical model during treatment.

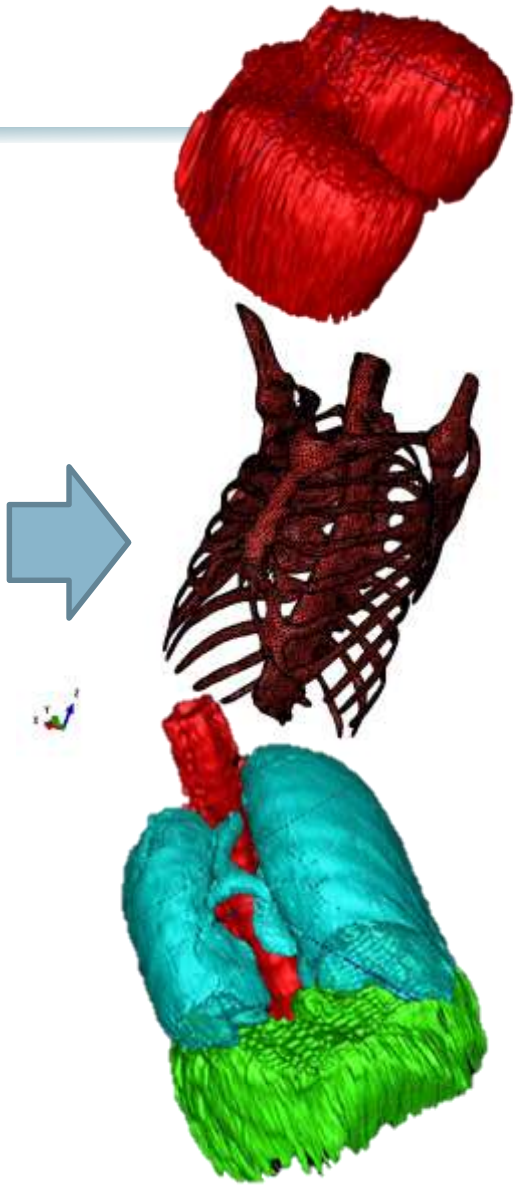
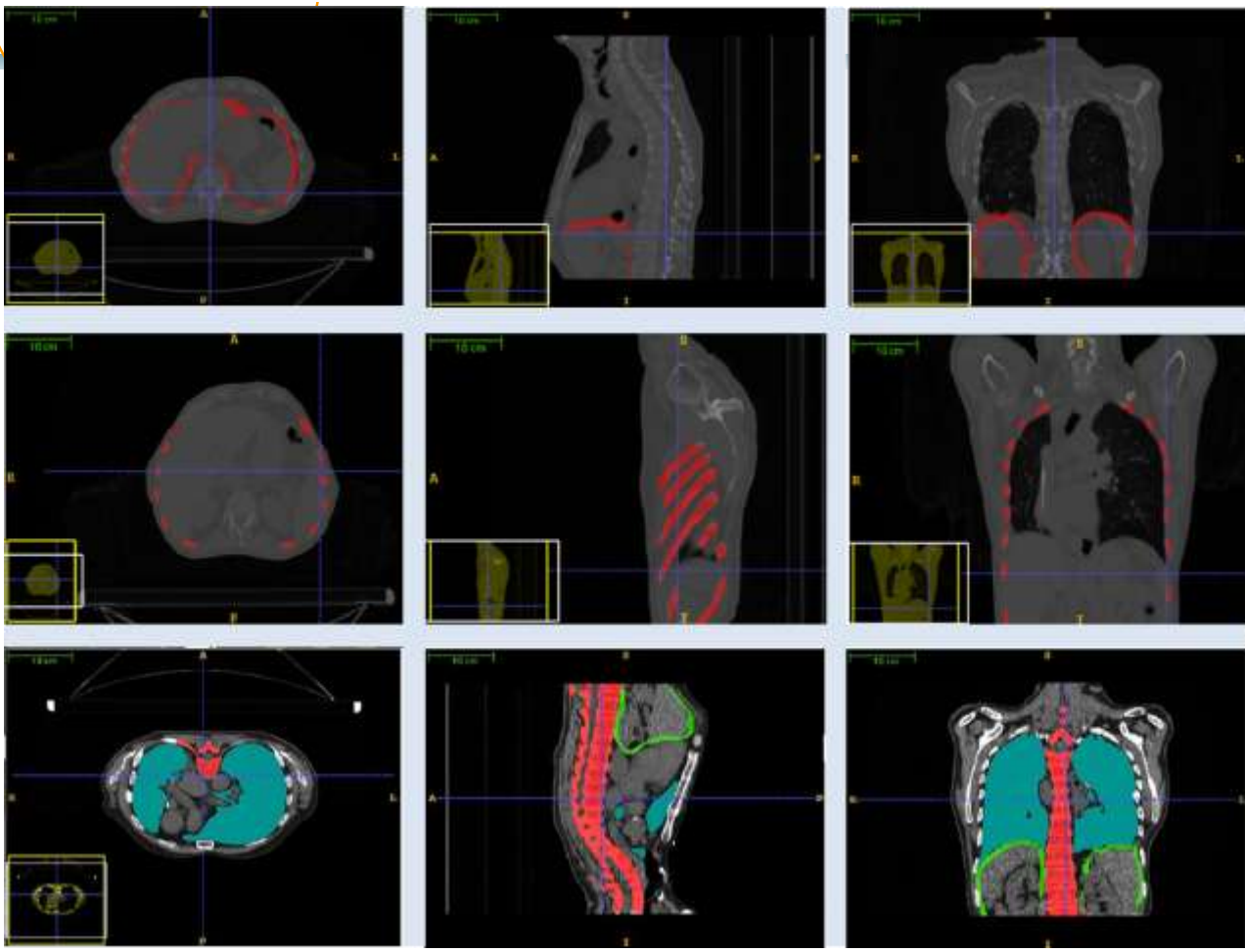


# From CT scan images to Biomechanical Simulation



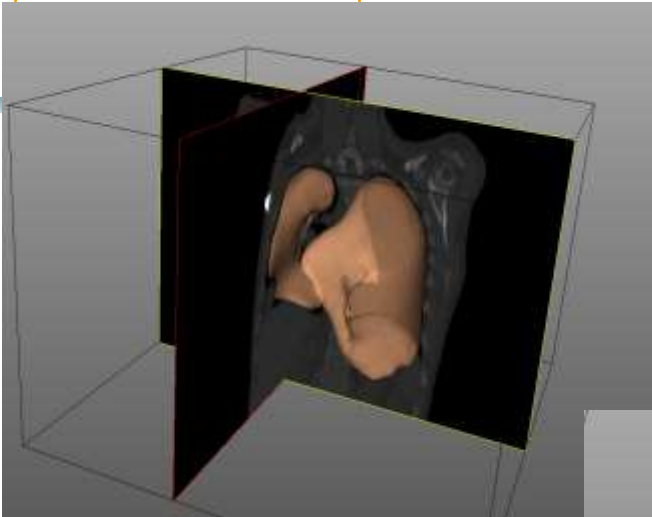
**Pipeline Modeling based CAD modeling for FEM simulation**

# Semi-Automatic Segmentation of multi organs

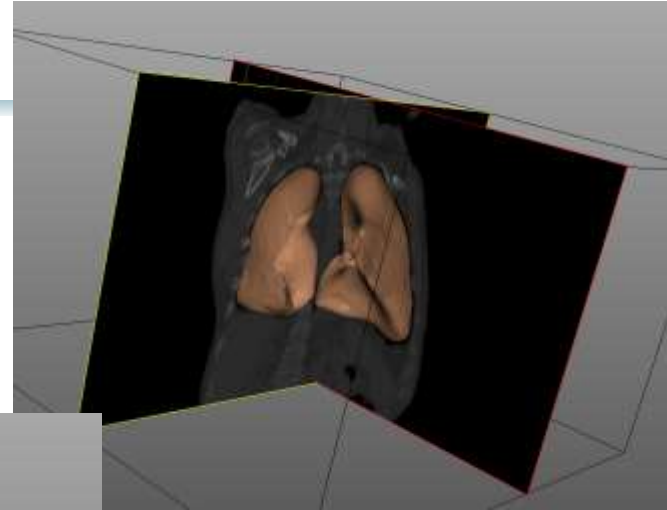


Automatic and semi-automatic Segmentation of multi organs (respiratory system)

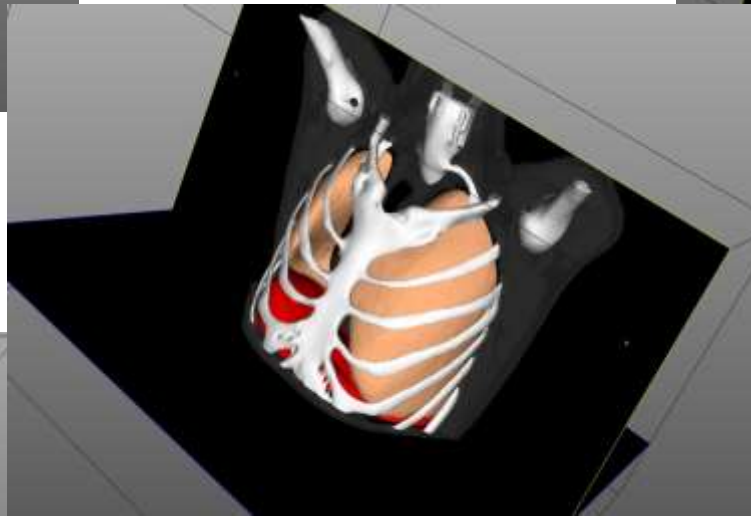
# CAD reconstruction



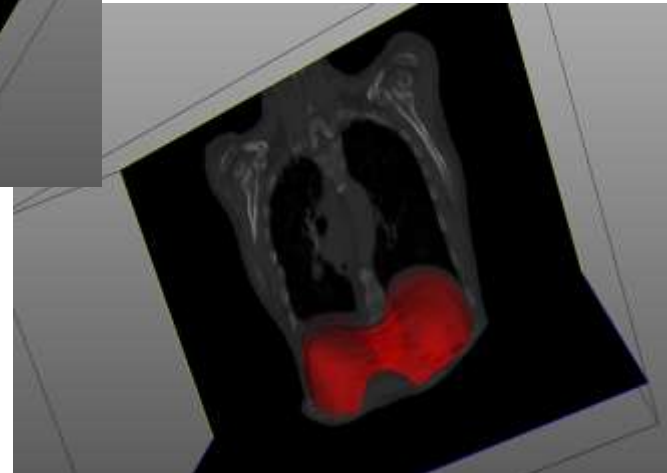
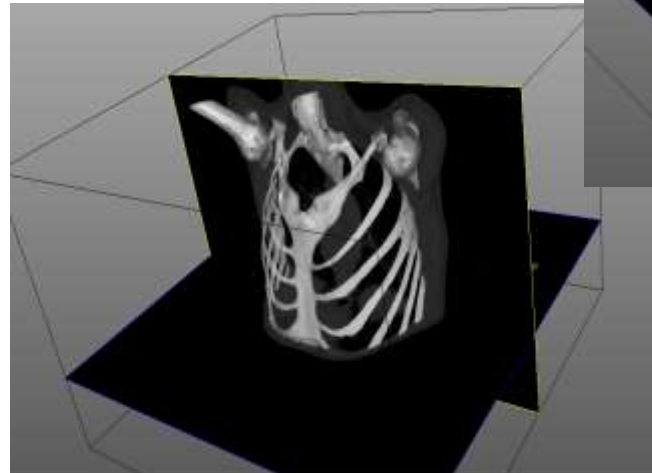
Lungs  
Thorax



Lungs  
Diaphragm



Respiratory sytem  
CAD



# Mesh quality

Mesh generation is a critical and important step in the finite element analysis. The mesh affects the accuracy, convergence and speed of the computational process.

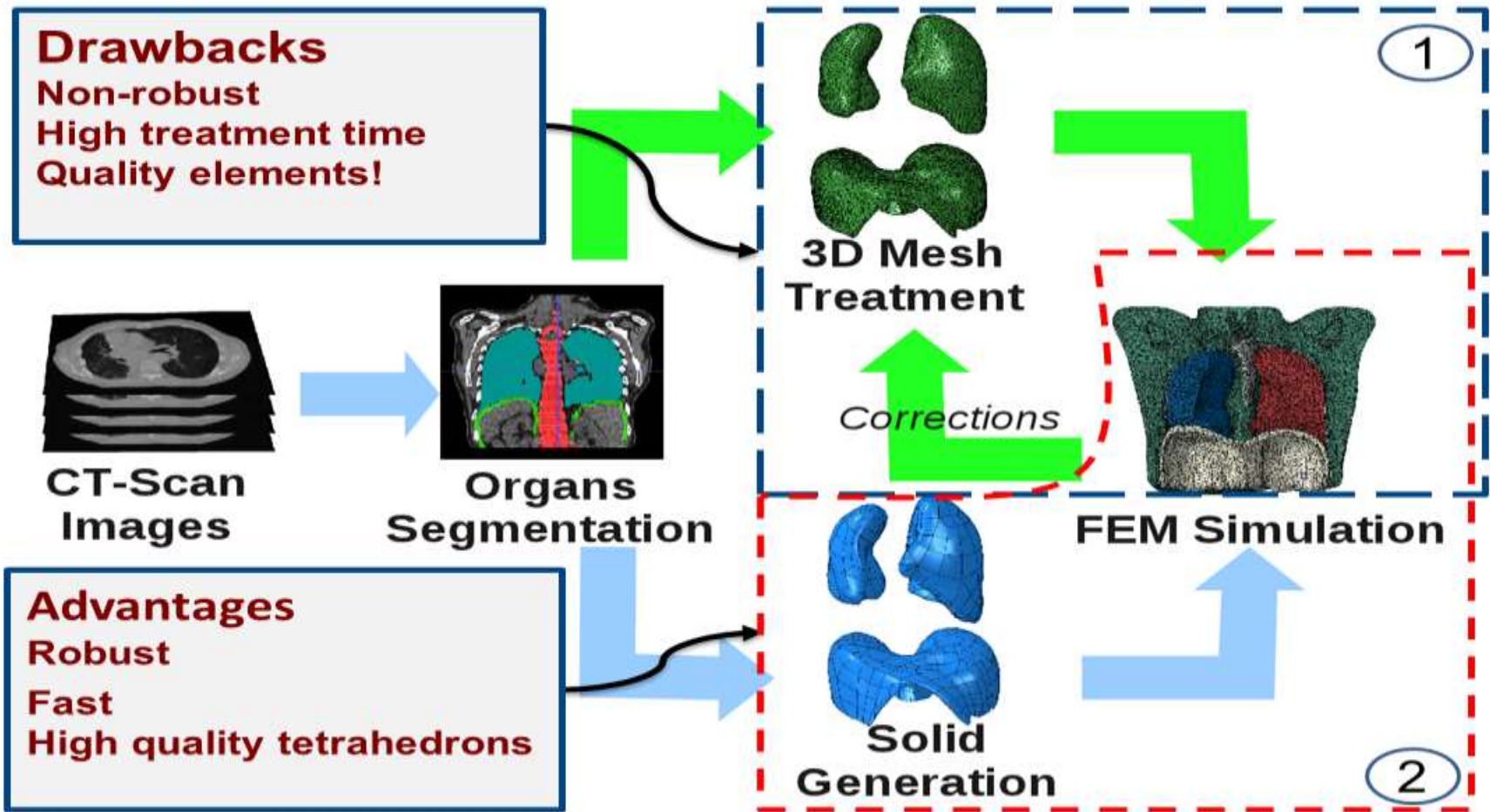
## ■ Criteria

- Geometry : Distortion , aspect ratio, minimum angle, maximum angle, ...
- FE-based: jacobian

## ■ Influence:

- Low quality = bad mesh convergence
- Large stress field discontinuities
- Some elements may « lock » for high aspect ratio
- round-off errors & singularities
- if jacobian is negative !

# Mesh quality



**Pipeline Modeling for finite element simulation  
Mesh treatment vs CAD modeling**



# CAD & Meshing:


## ■ In CAD:

### ○ Create CLEAN parts for FEA:

- **Avoid** creating **small surfaces & edges**
- **Avoid** « **tangent** » connections (very **small angles**)
- Try to **minimize** the **number of faces** present in the model

### ○ Remove insignificant geometric details:

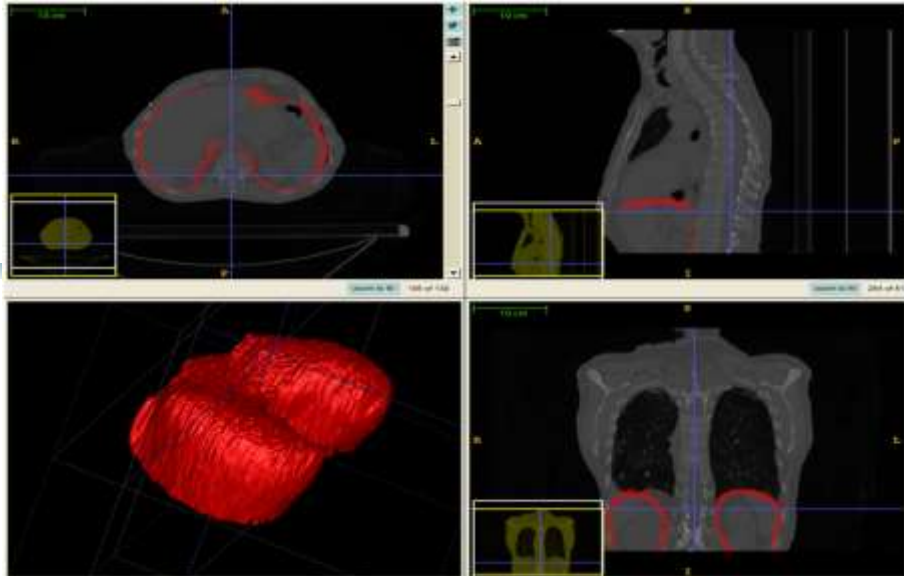
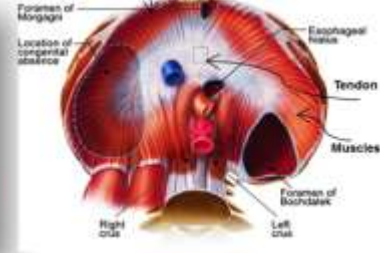
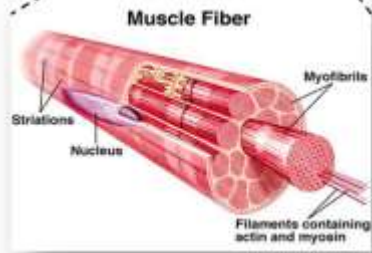
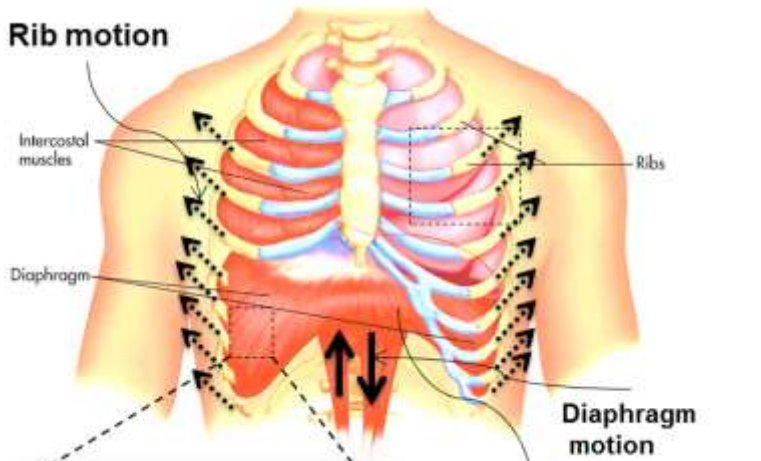
- Typical details: fillets / chamfers, small holes, insignificant components (bolts & nuts, rivets)



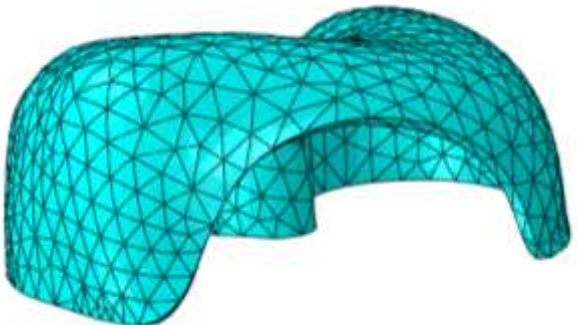
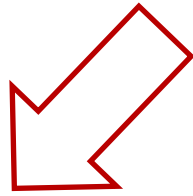
Biomechanical modeling  
of the diaphragm  
and thorax

# Diaphragm modeling

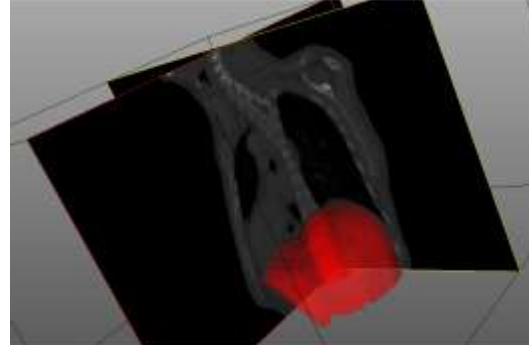
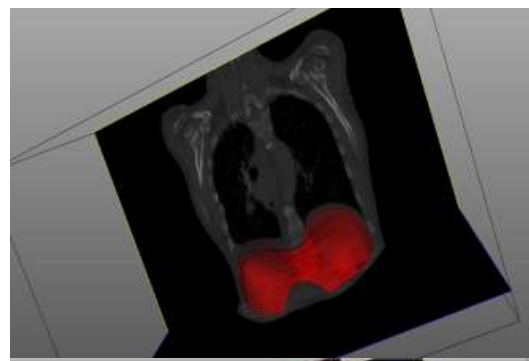
## Rib motion



Semi-automatic Segmentation of the diaphragm

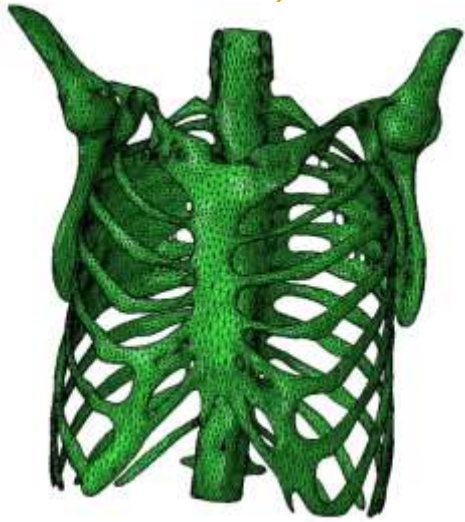


Segmentation and 3D mesh generation



# Biomechanical modeling:

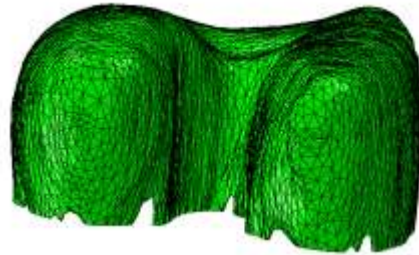
Elastic linear



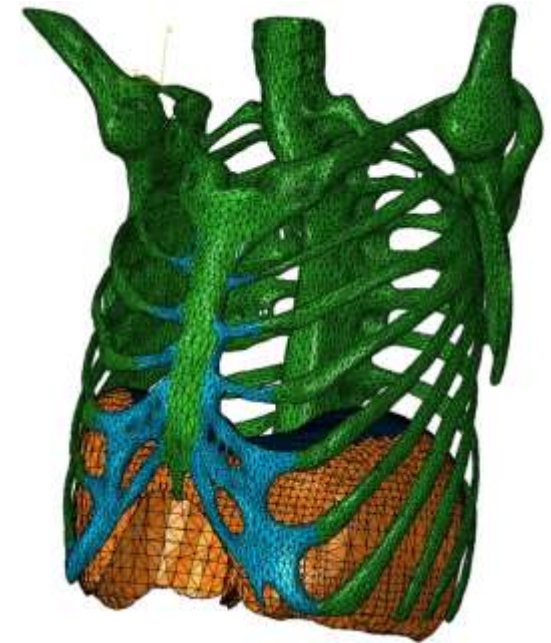
Thorax

+

Hyper-elastic models



Diaphragm



Thorax+ diaphragm

- Type of the nonlinearities (geometric or material nonlinearities)?

Two nonlinear hyperelastic models:

The Saint-Venant Kirchhoff and MooneyRivlin models.

# Biomechanical modeling of the diaphragm

We chose two simple hyperelastic models, Saint-Venant Kirchhoff and Mooney-Rivlin hyperelastic

For an isotropic elastic or hyperelastic material the elastic energy, noted  $W$ , can be written as:

$$W(\mathbf{E}) = \frac{\lambda}{2} (\text{tr } \mathbf{E})^2 + \mu (\text{tr } \mathbf{E}^2) \quad (1)$$

where  $\mathbf{E}$  is the Green-Lagrange strain tensor  $\lambda$  and  $\mu$  are the Lamé's coefficients

$$\begin{aligned} \mathbf{E} &= \frac{1}{2} (\mathbf{F}^T \cdot \mathbf{F} - \mathbf{I}) \\ &= \frac{1}{2} \left( \text{grad } \underline{U} + \text{grad}^T \underline{U} + \text{grad}^T \underline{U} \cdot \text{grad } \underline{U} \right) \end{aligned} \quad (2)$$

# Biomechanical modeling of the diaphragm

For small deformations, the Green-Lagrange strain tensor is linearized into the infinitesimal strain tensor:

$$\boldsymbol{\epsilon} = \frac{1}{2}(\text{grad } \underline{U} + \text{grad}^T \underline{U})$$

The relation between the stress tensor and the strain tensor (Hooke's law), for isotropic material and for linear deformation, can be written:

$$\boldsymbol{\varepsilon} = \frac{1 + \nu}{E} \boldsymbol{\sigma} - \frac{\nu}{E} \text{tr}(\boldsymbol{\sigma}) \text{Id}$$

$$\mu = \frac{E}{2(1 + \nu)} \quad \lambda = \nu \frac{E}{(1 - 2\nu)(1 + \nu)}$$

# Biomechanical modeling of the diaphragm

The Saint-Venant Kirchhoff law extends the Hooke's law for large displacement. the Green-Lagrange:

$$\mathbf{S} = (\lambda (\text{tr } \mathbf{E}) \mathbf{I} + 2\mu \mathbf{E}) + \eta \left( \lambda (\text{tr } \dot{\mathbf{E}}) \mathbf{I} + 2\mu \dot{\mathbf{E}} \right)$$

The strain energy of the second hyperelastic Mooney Rivlin model can be written as:

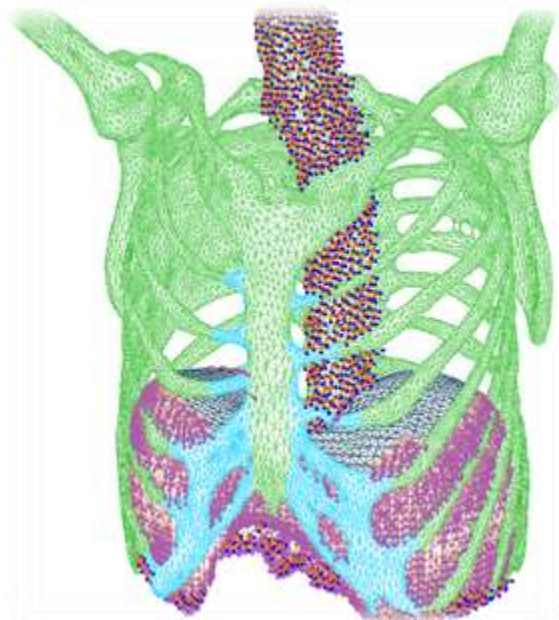
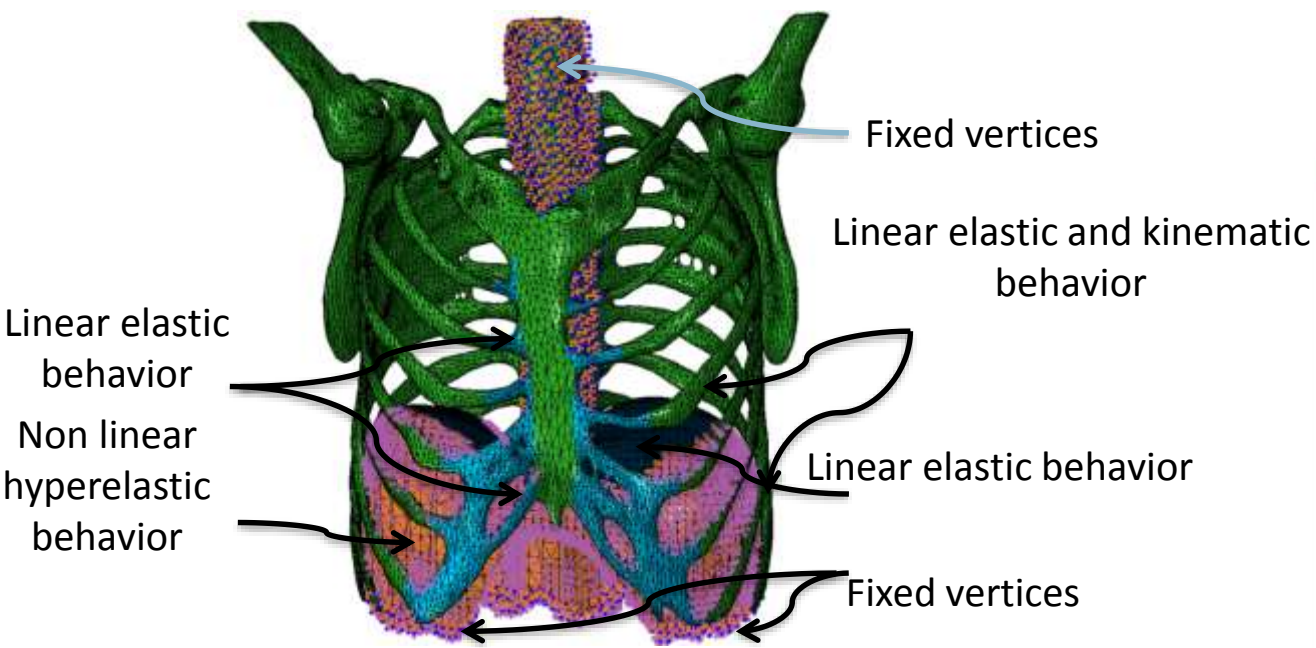
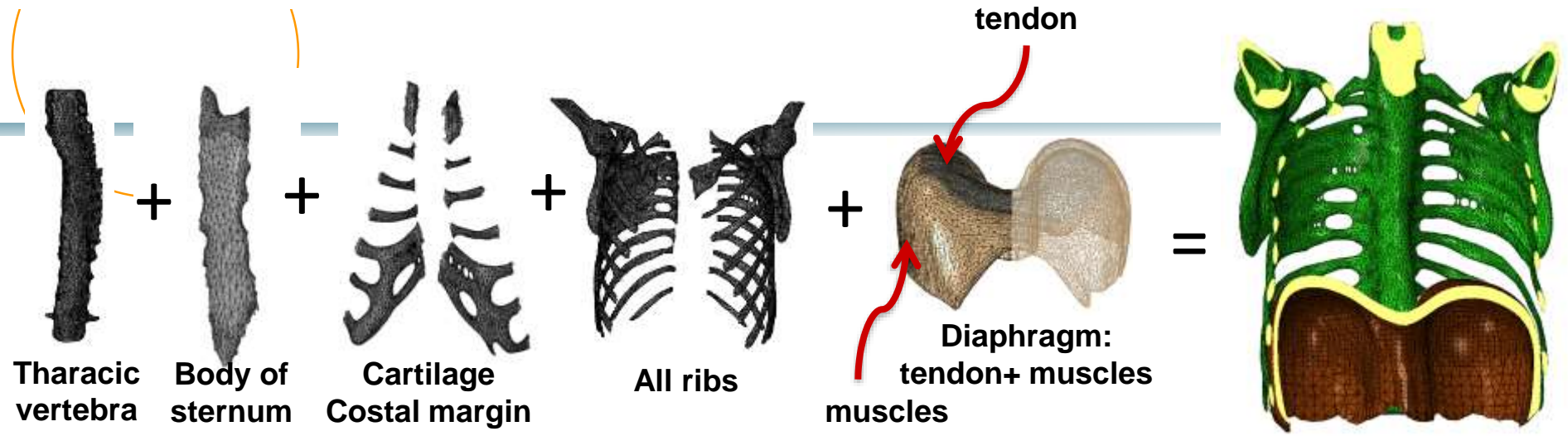
$$W(\mathbf{C}) = c_1 (\bar{I}_1(\mathbf{C}) - 3) + c_2 (\bar{I}_2(\mathbf{C}) - 3) + \frac{K}{2} (J(\mathbf{C}) - 1)^2 \quad (4)$$

where  $c_1$ ,  $c_2$  are material parameters and  $K$  is the Bulk modulus. The quantities  $\bar{I}_1$  and  $\bar{I}_2$  are the isochoric invariants of the Cauchy-deformation tensor  $\mathbf{C}$  :  $\bar{I}_1(\mathbf{C}) = J(\mathbf{C})^{-2/3} I_1(\mathbf{C})$ ,  $\bar{I}_2(\mathbf{C}) = J(\mathbf{C})^{-4/3} I_2(\mathbf{C})$  where  $I_1(\mathbf{C}) = \text{tr} \mathbf{C}$ ,  $I_2(\mathbf{C}) = \frac{1}{2} ((\text{tr} \mathbf{C})^2 - \text{tr} \mathbf{C}^2)$  and  $J$  is the Jacobian:  $J(\mathbf{C}) = \det \mathbf{F}$ .

- 1) **The diaphragm behavior** is considered as a compressible solid with a non-linear elastic, and as a heterogeneous material with the muscles in its peripheral part converging into a central tendon.
- 2) **The complete thorax behavior** with musculoskeletal structure is modeled as incompressible solid with an elastic linear behavior including the ribcage kinematics model using the finite helical axis method.



# 3D Reconstruction of the Thorax

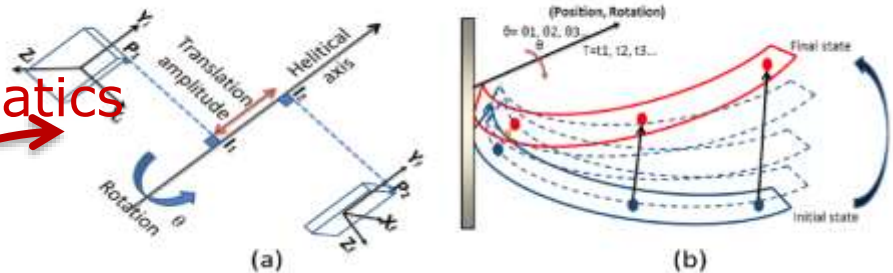


# Boundary conditions

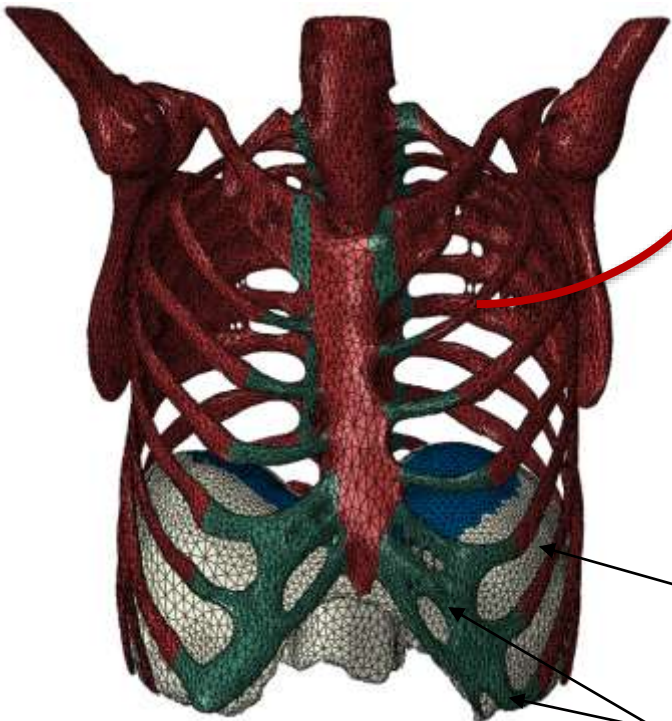
## Enhancement of diaphragm model

- Based on rib kinematics & muscle tension
- Heterogeneous modeling of diaphragm (tendon & muscles) and ribcage kinematic

rib kinematics



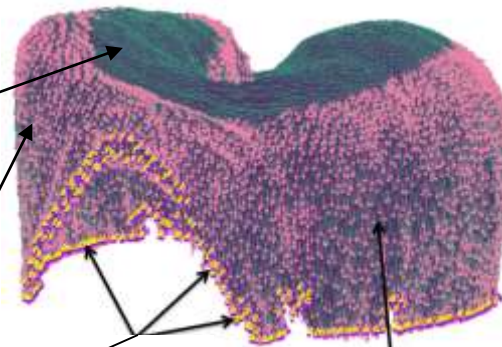
Finite helical axis method principle



Tendon

Muscles

Attachment to ribs



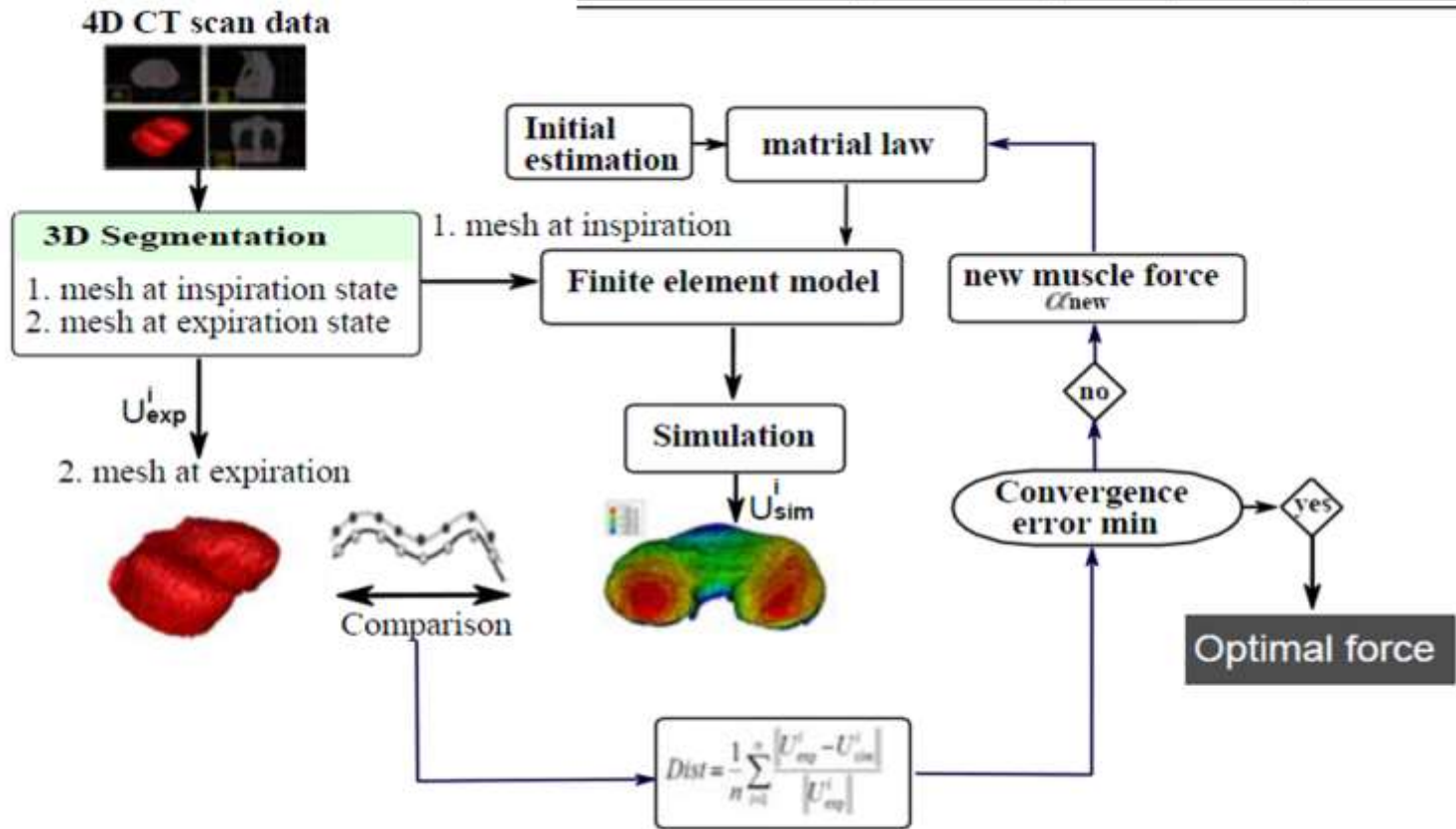
Tension

The boundary conditions

# Diaphragm simulation

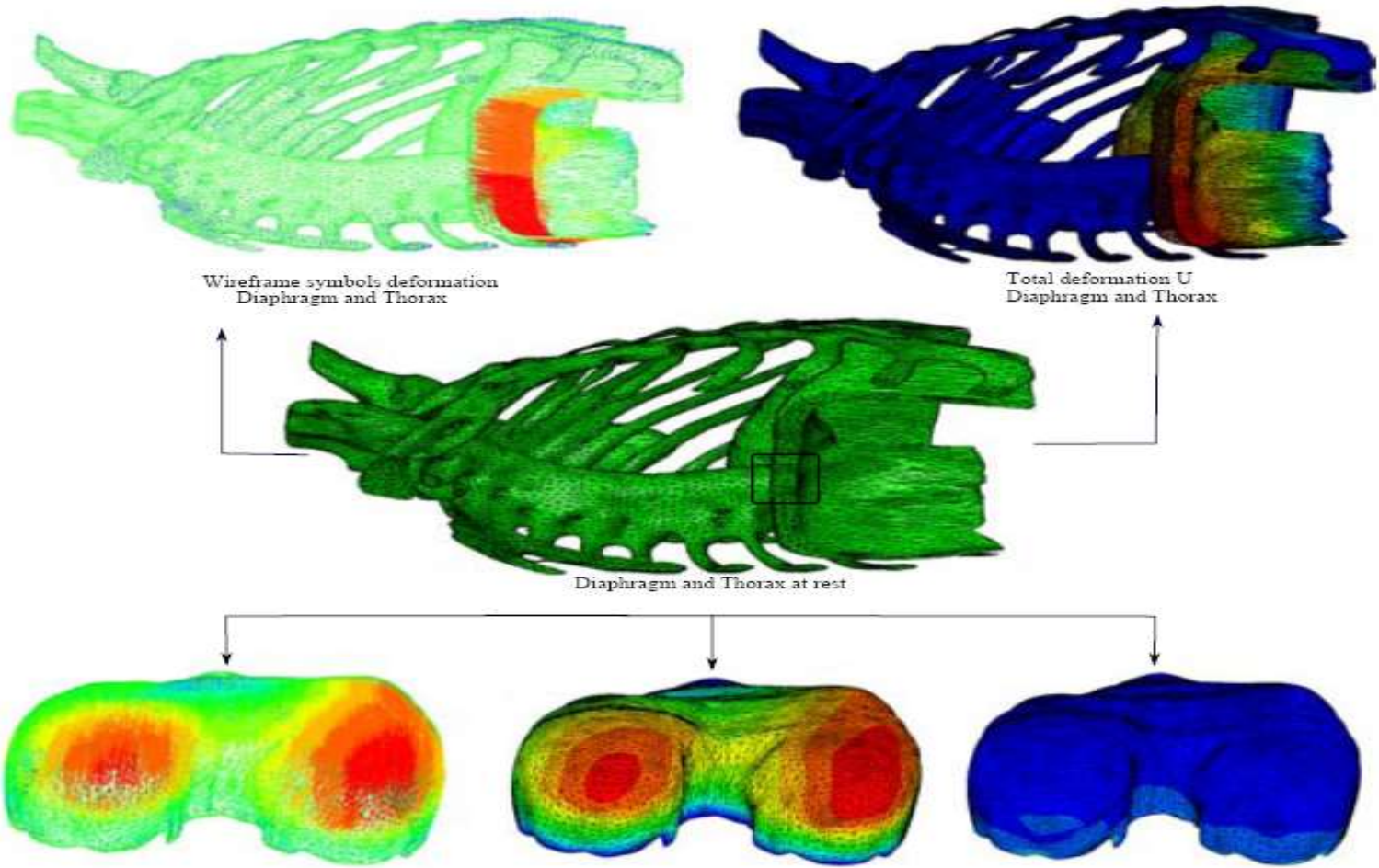
**Table 1** Mechanical properties of the human diaphragm and thorax, where  $E$ : Young's modulus,  $\nu$ : Poisson's coefficient.

Tissues	Young modulus (MPa)	Poisson's coefficient	References
Diaphragm muscle	5.32	0.33	Behr et al.2006,Pato et al. 2011
Diaphragm tendon	33	0.33	Behr et al.2006,Pato et al. 2011
Ribs	5000	0.3	Kimpara et al. 2005
Cartilage costal margin	49	0.4	Abe et al.1996,Yamada.1970
Body of sternum	11500	0.3	Kimpara et al.2005
Thoracic vertebra	9860	0.3	Kimpara et al.2005



Iterative process to minimize the displacement errors between simulation  $U_{sim}$  and initial mesh  $U_{exp}$ .

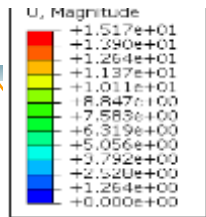
# Diaphragm simulation: quantitative and qualitative analysis



Displacement (U) and Stress (S) for the diaphragm  
Maximum displacement Right Posterior (RP) and Left-Posterior (LP) sides,  
Slightly larger (RP) side motion than the (LP) side motion

**➔ This corresponds to the anatomical reality.**

# Simulation results

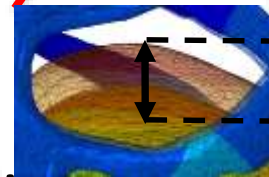
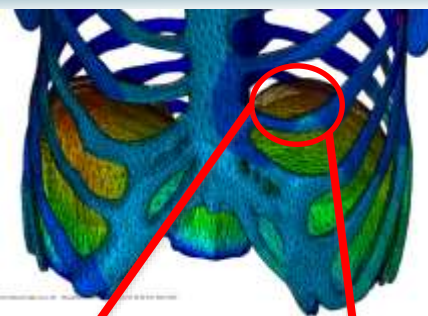


Ribs motion

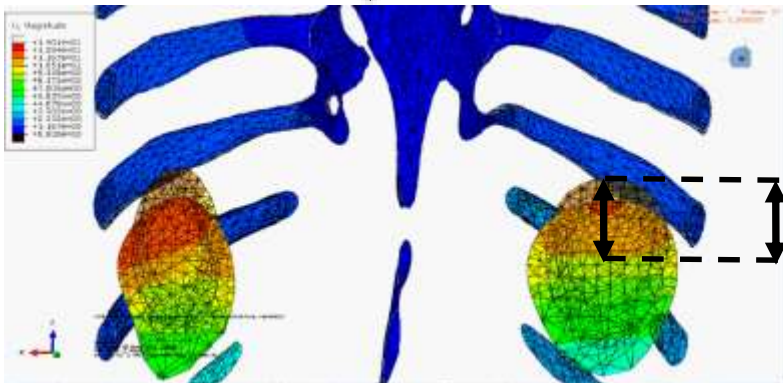
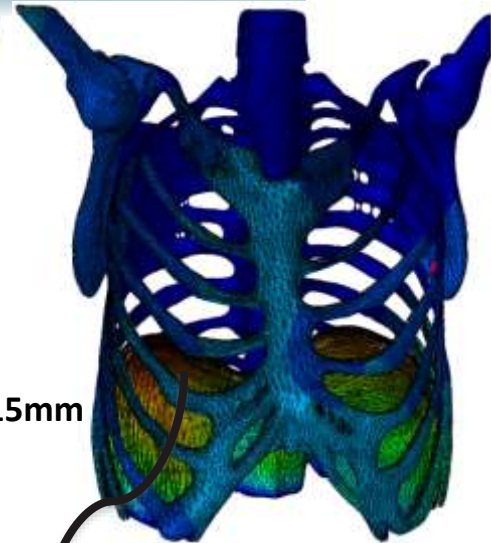


Diaphragm motion

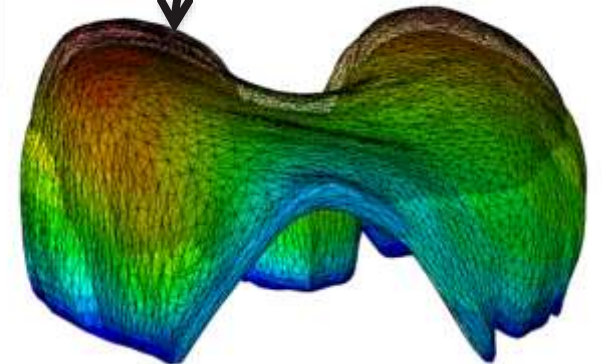
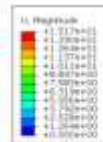
Inspiration Expiration



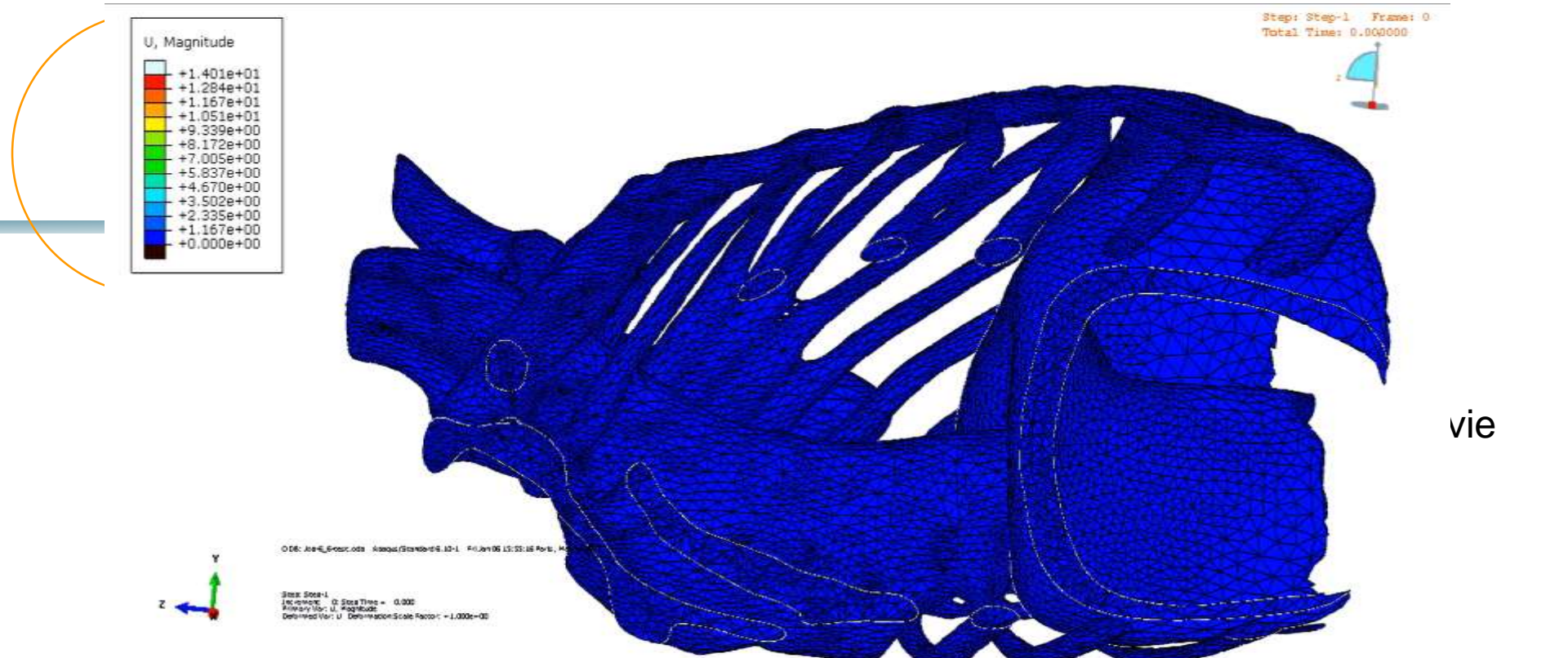
~15mm



View cut of the diaphragm and ribs



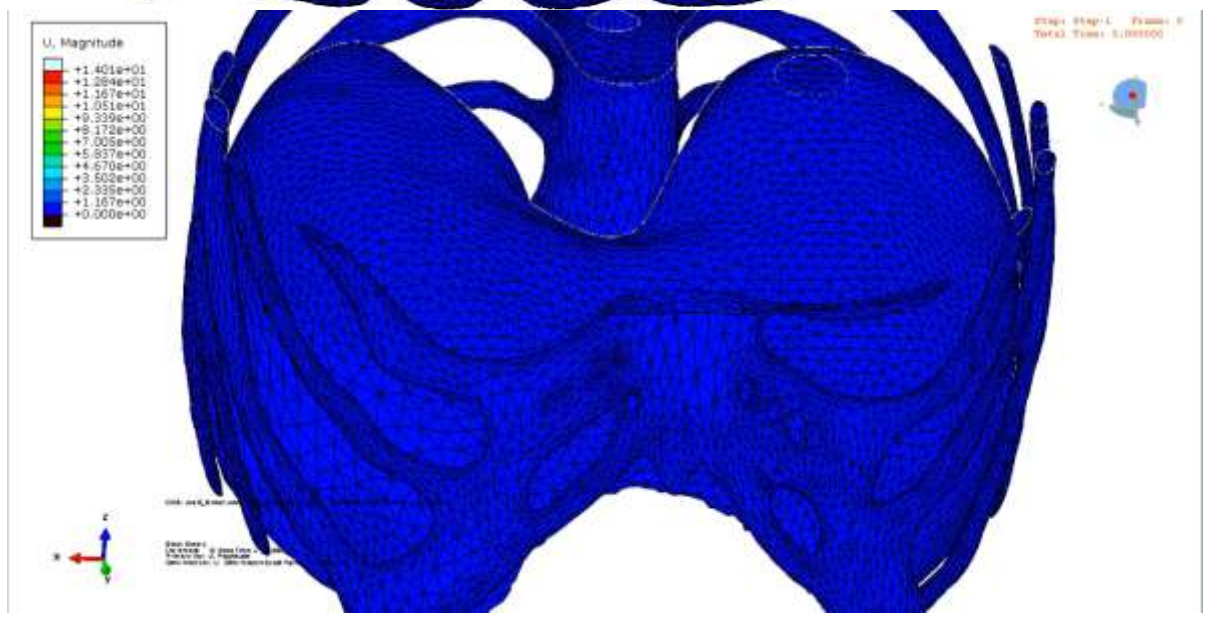
Diaphragm behavior



vie

# 4D Biomechanical & Kinematical modeling

Movie



# Simulation comparison

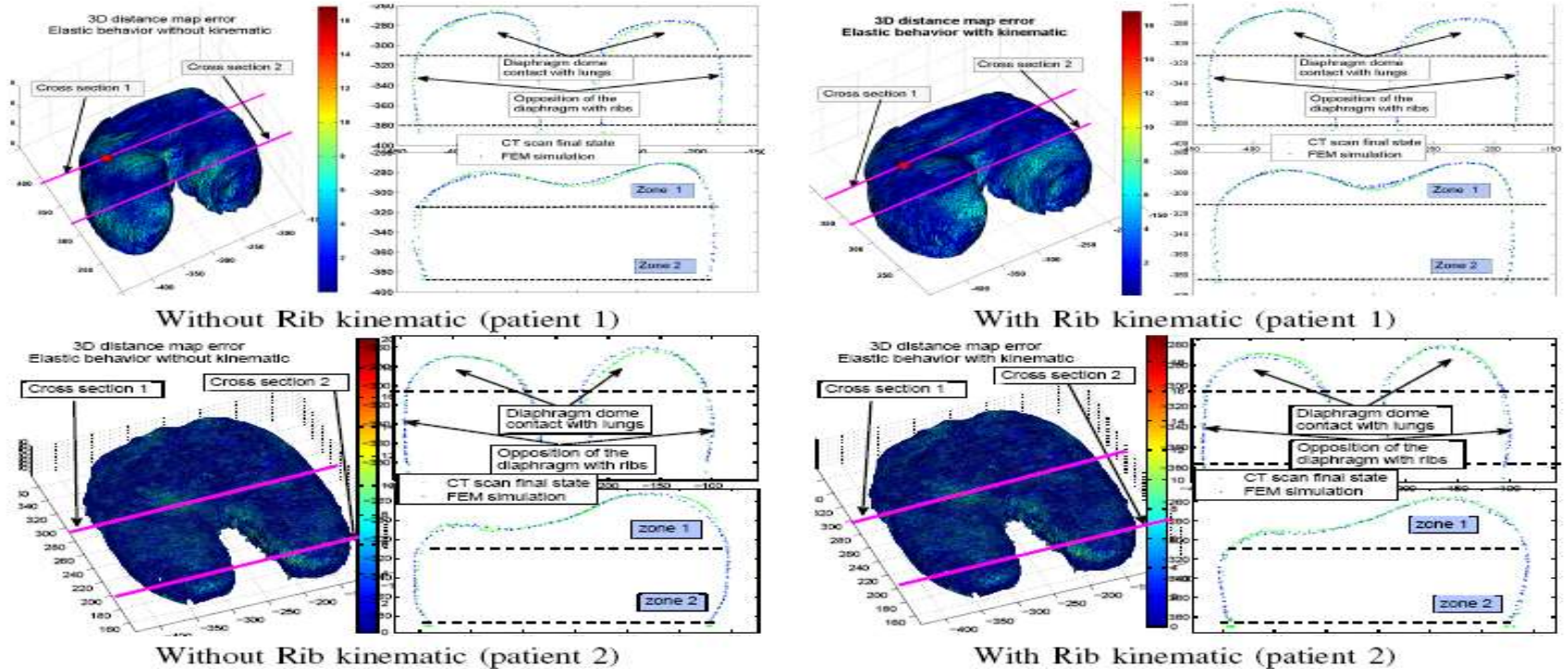


Fig. 9. 3D distance map error between the FE simulation and the reference real mesh at inspiration including or no rib kinematics. Color coding ranges from 0.0mm (blue) to 16.0mm (red), the vertical slices (showing the view from the cross sections) between the reference mesh and FE at expiration. Zone 1 presents the cross sections of interest region (contact with lungs). Zone 2 presents the peripheral contact between the diaphragm and ribcage.

Average error measurement  $\epsilon$  and standard deviation (SD): applied to different scenarios.

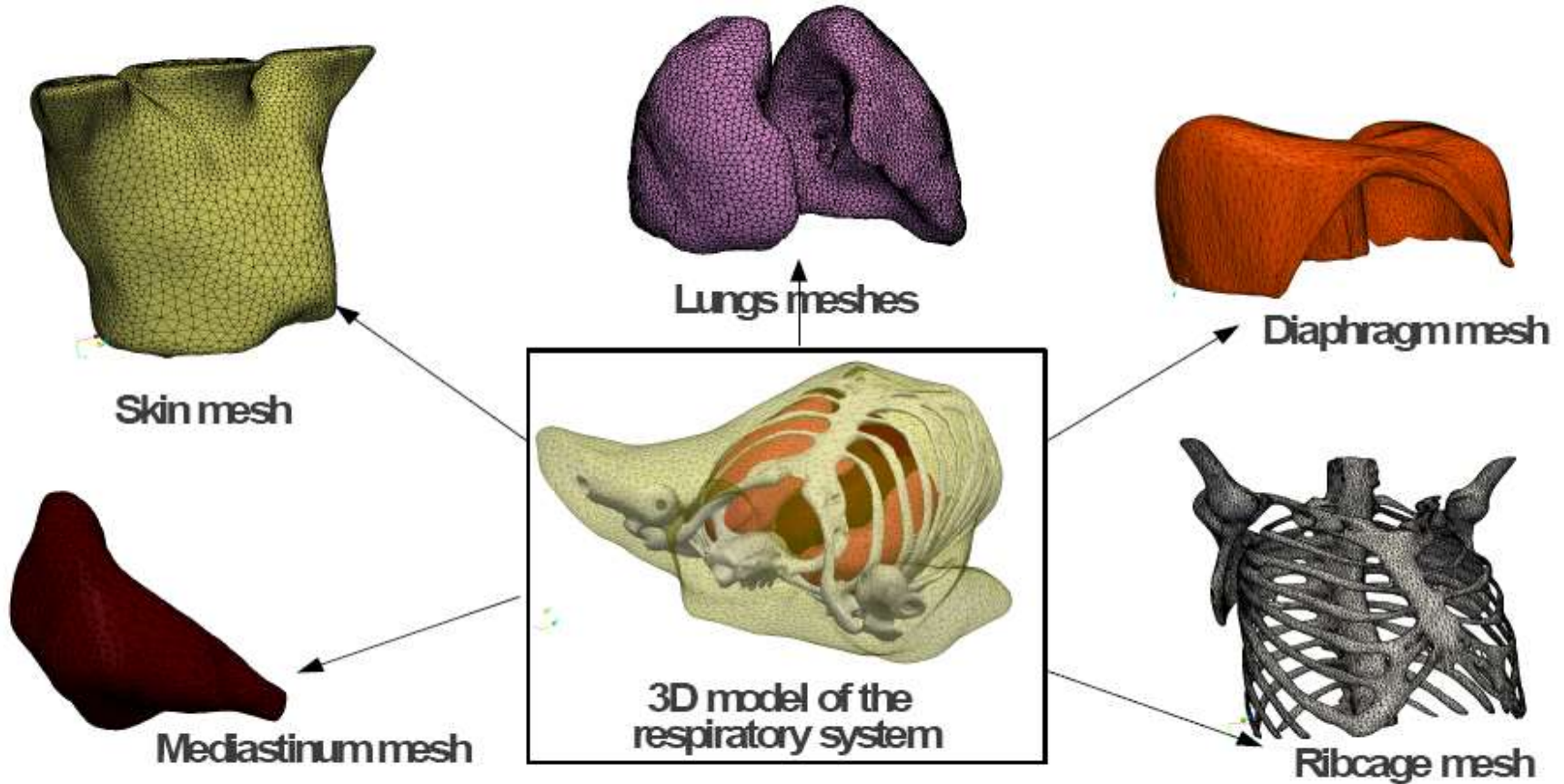
	Patients			
	St-Venant Kirchhoff		Mooney-Rivlin	
	$S_1$ (Without RK)	$S_2$ (With RK)	$S_3$ (Without RK)	$S_4$ (With RK)
mean $\pm$ SD (mm)	2.1 $\pm$ 2.3	2.0 $\pm$ 2.2	2.2 $\pm$ 2.3	1.9 $\pm$ 2.1



# Biomechanical modeling patient specific

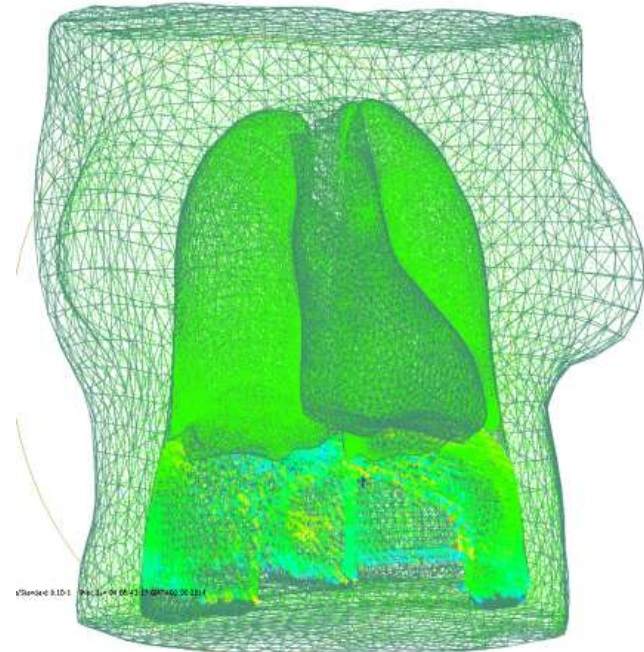
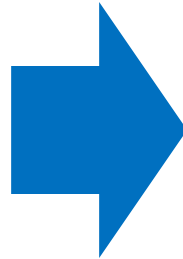
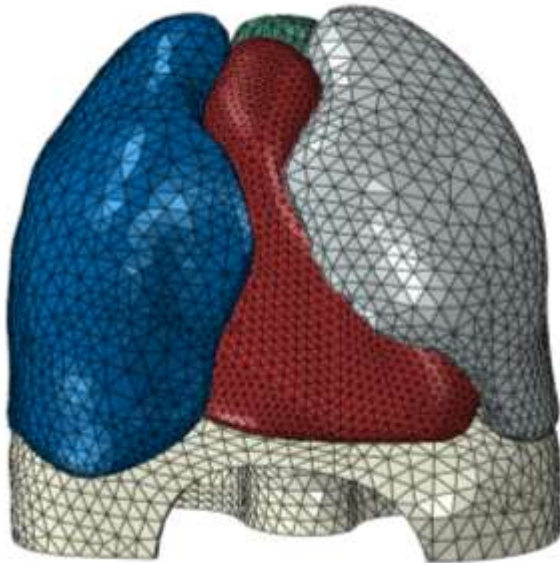
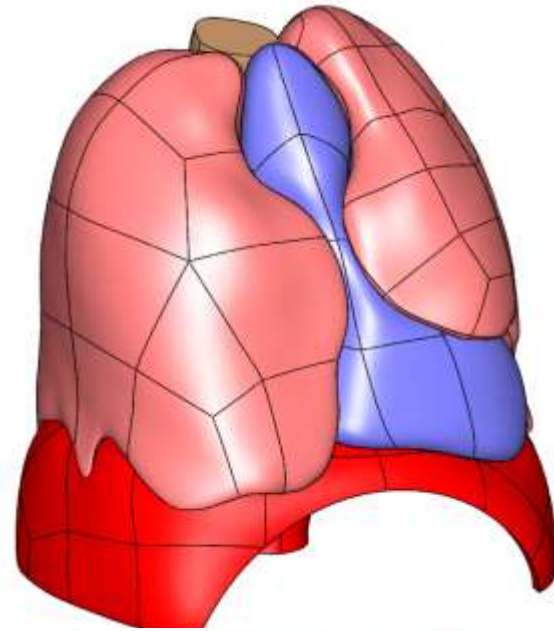
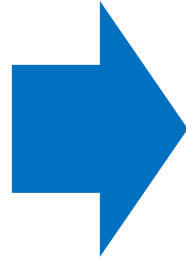
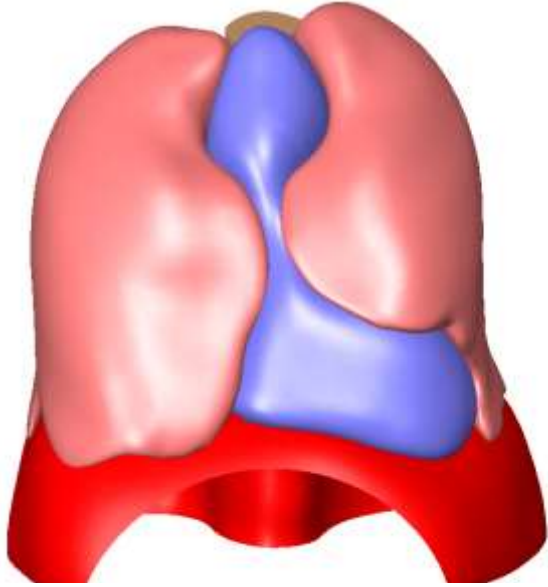


# Biomechanical Patient Specific



**Patient specific of the respiratory system**

# 3D reconstruction

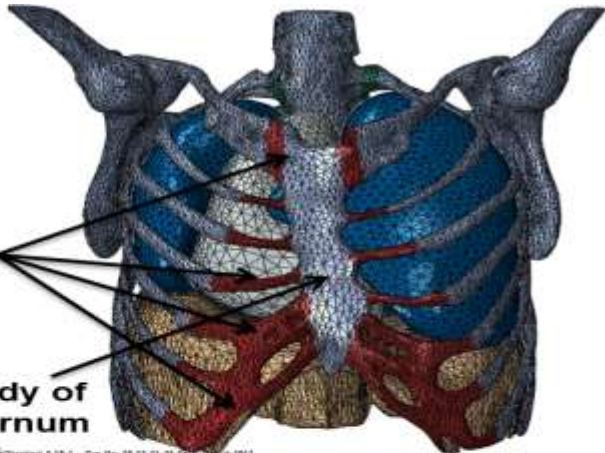
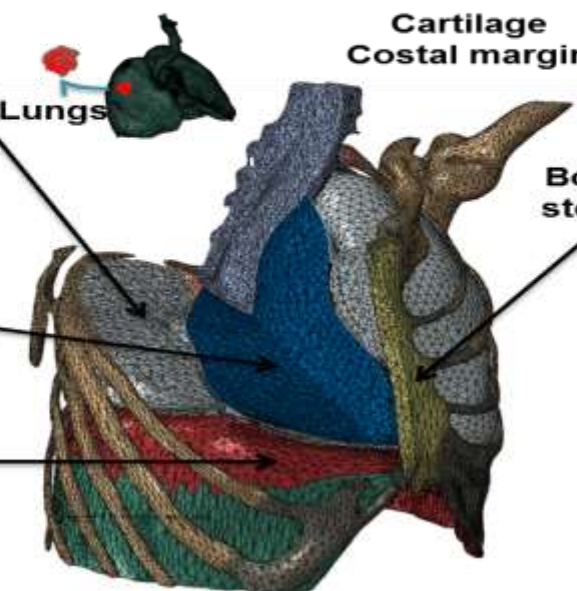
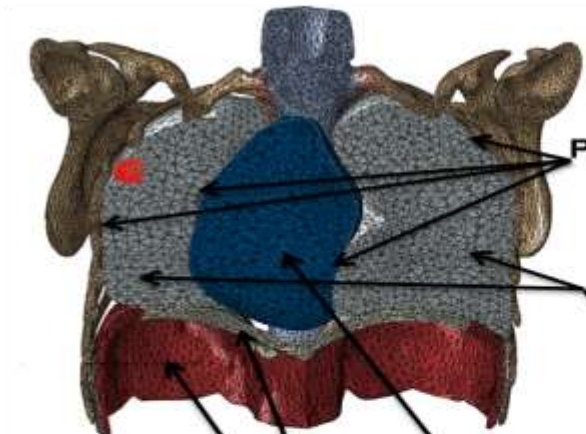
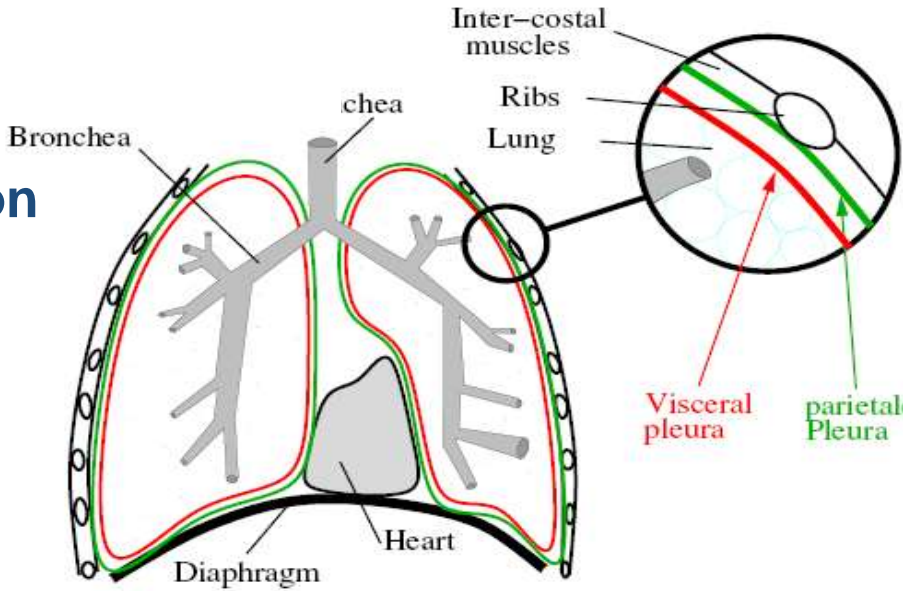


# 3D mesh

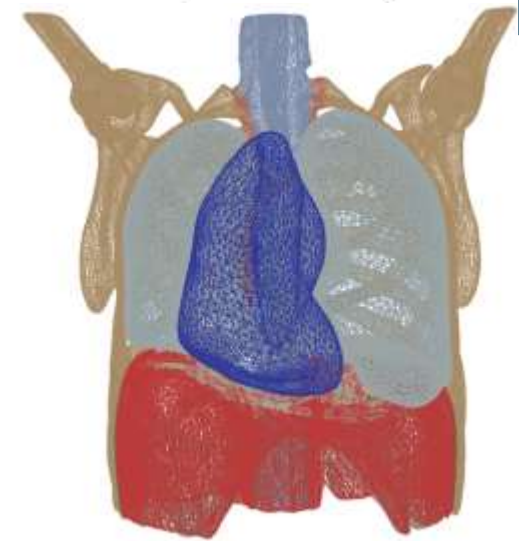
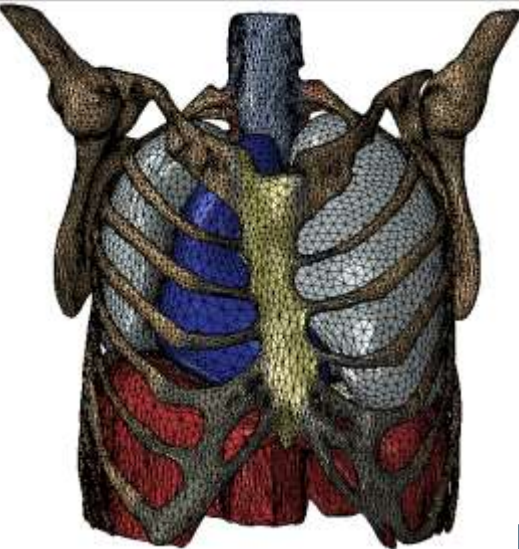
- Intercostal muscles action
- Diaphragm action



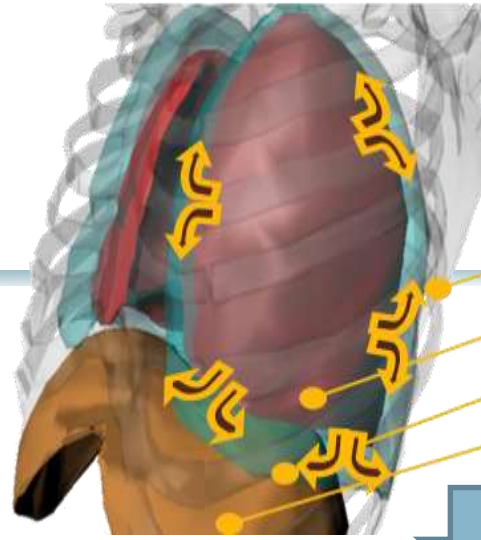
## Two independent actions



# Boundary conditions

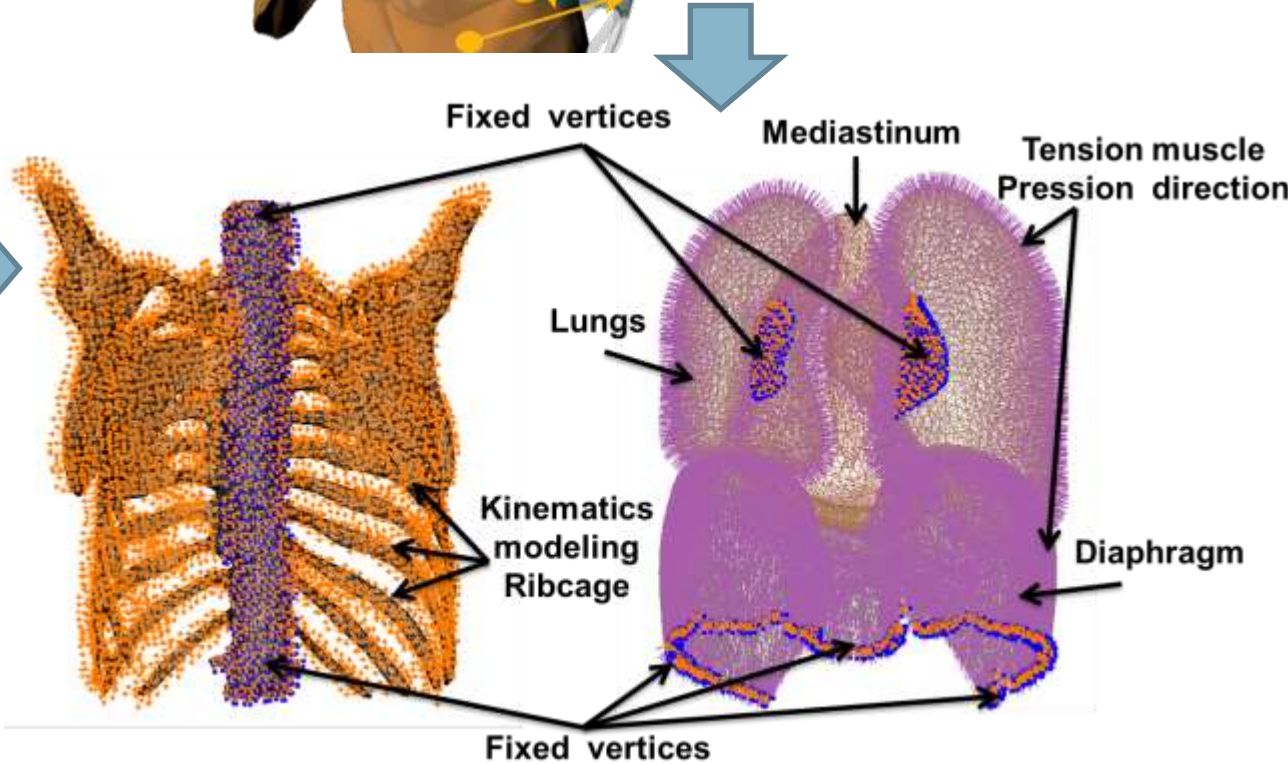


Respiratory System



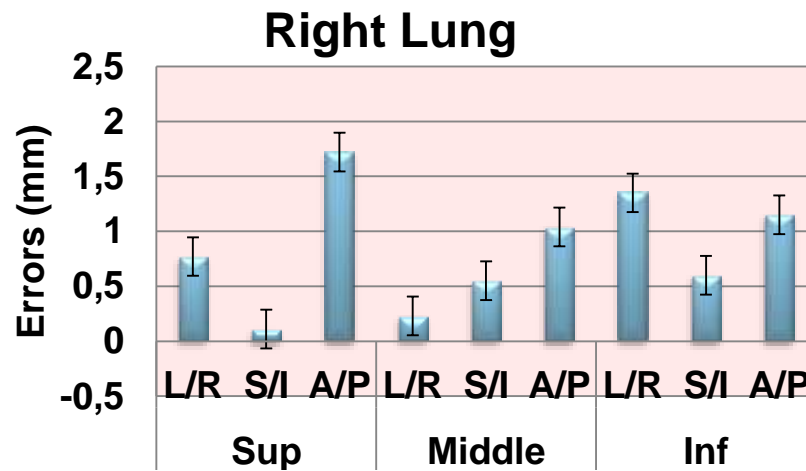
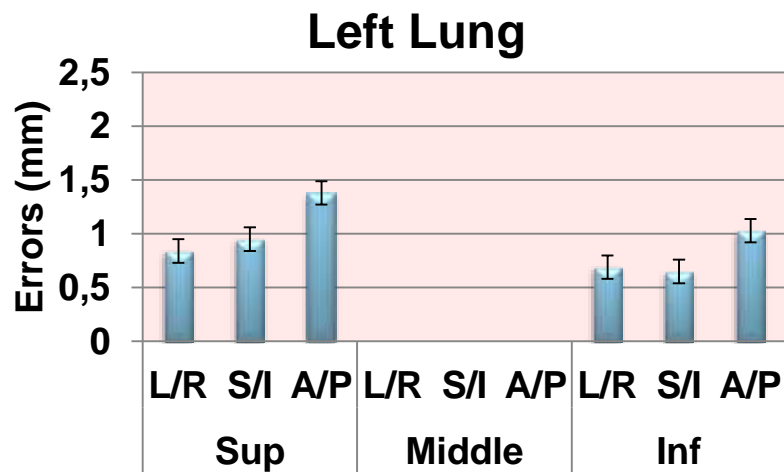
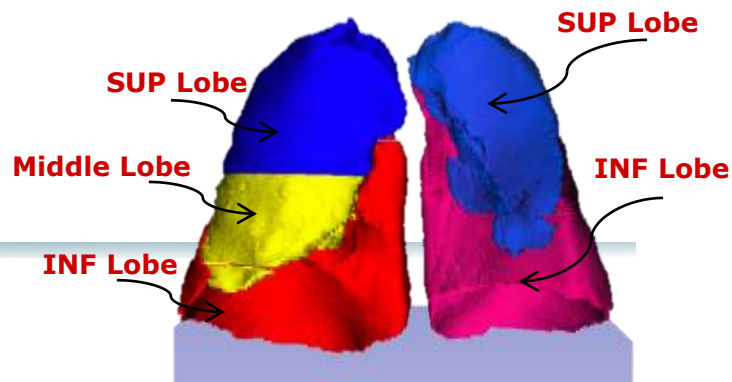
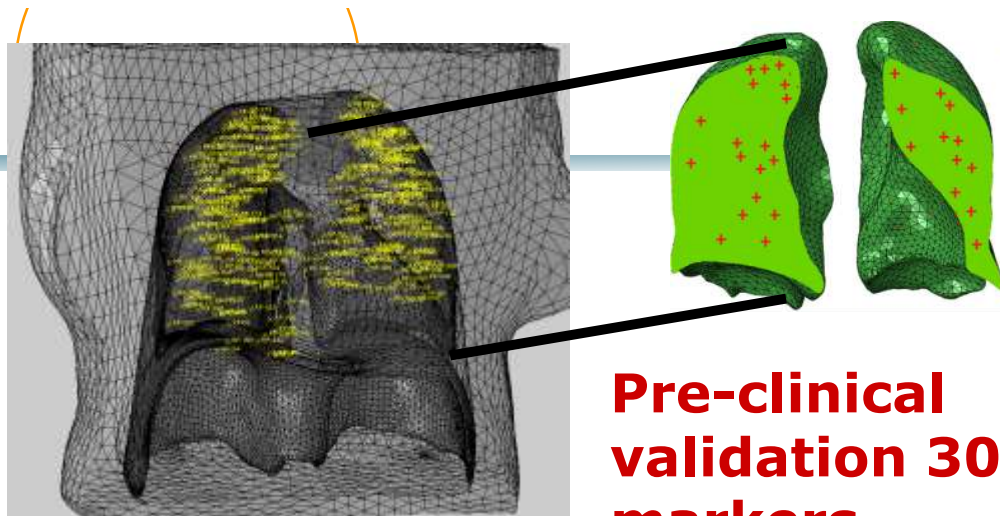
Motion with sliding

- Thorax
- Lung at exhalation
- Lung at inhalation
- Diaphragm

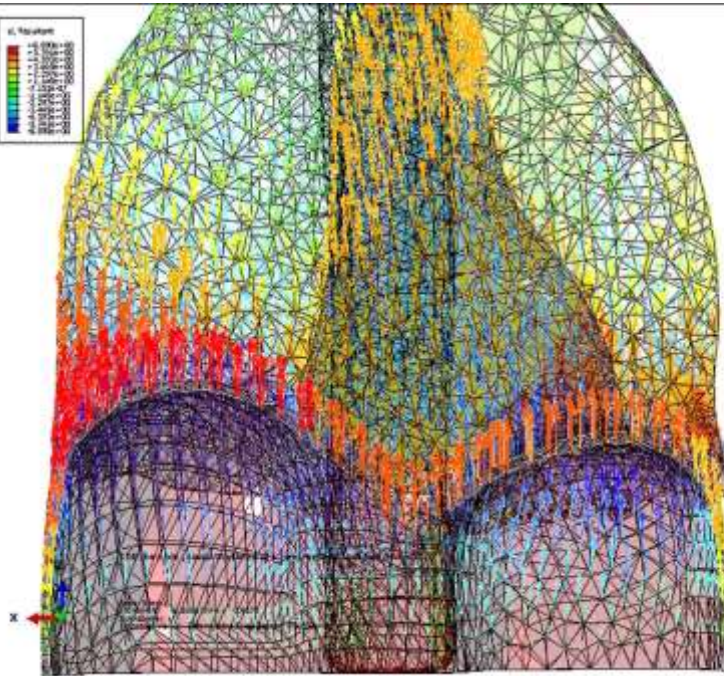
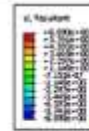
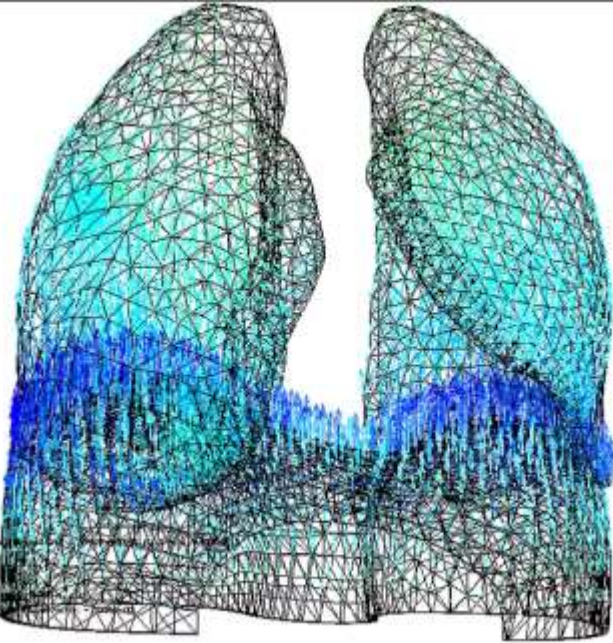
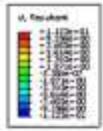


boundary conditions are inferred from the anatomy

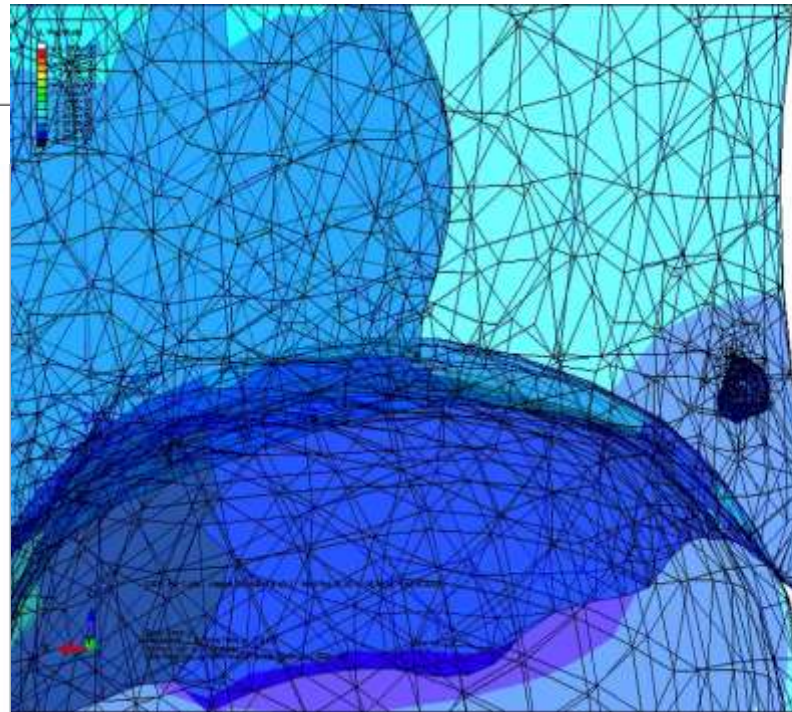
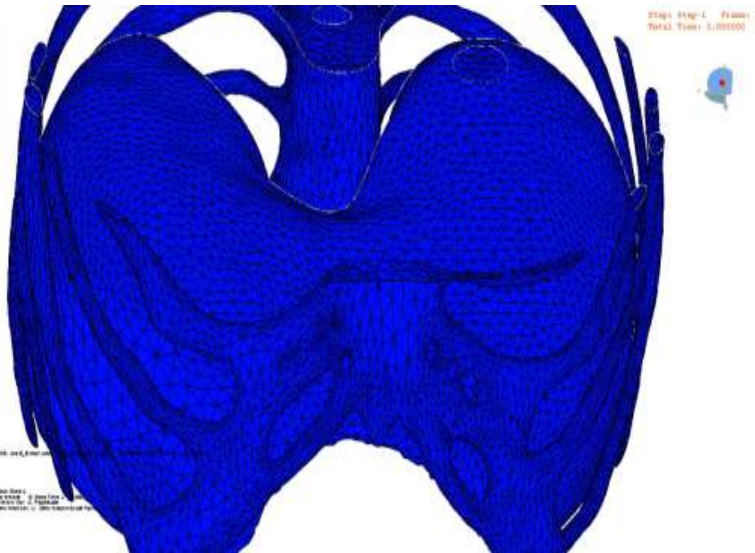
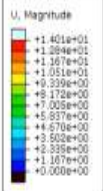
# Experimental Validation



# 4D Biomechanical simulation

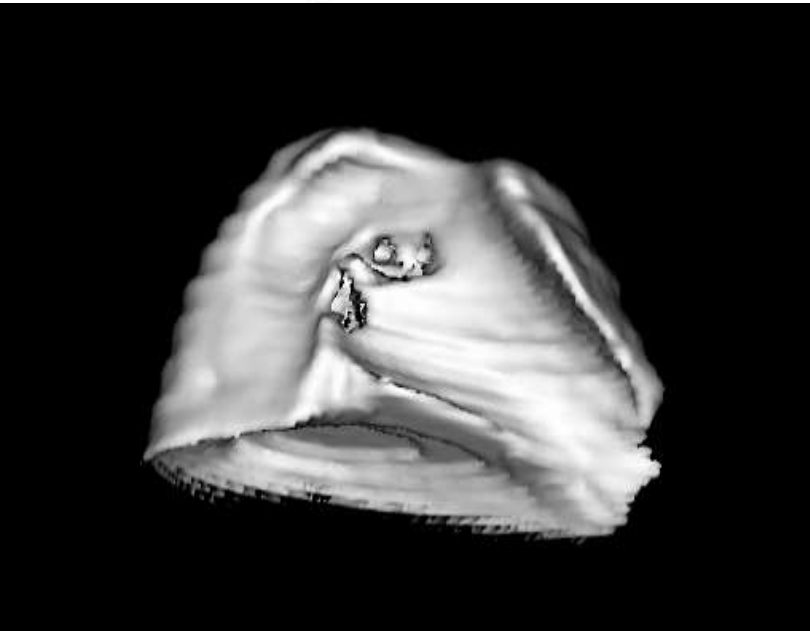
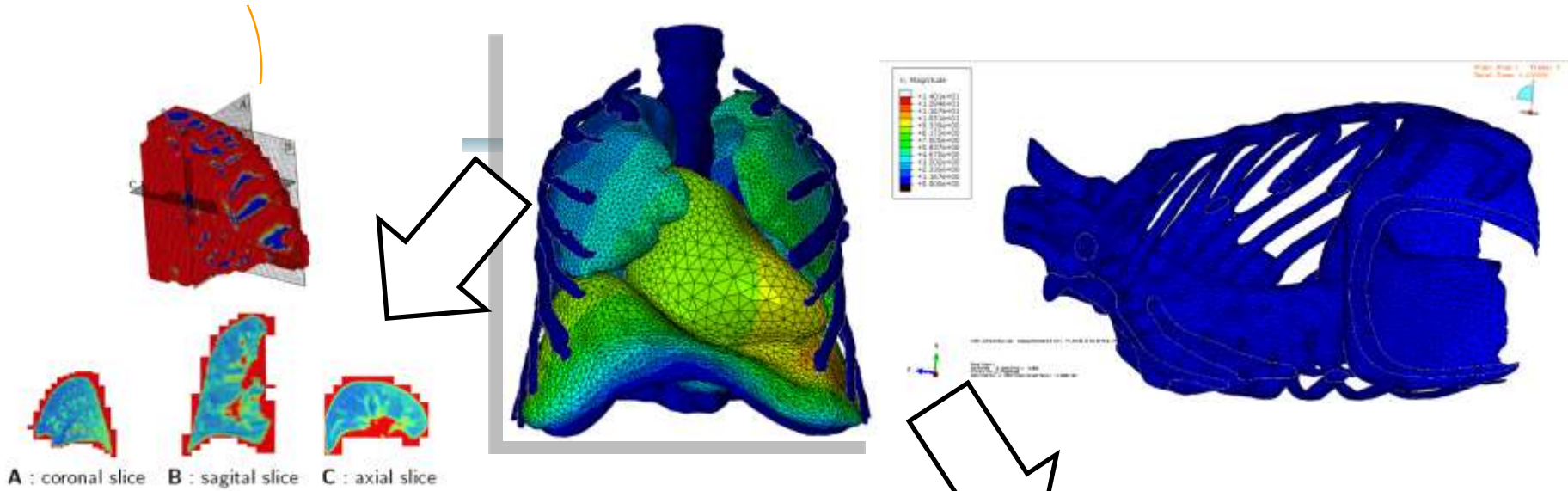


Scale Factor

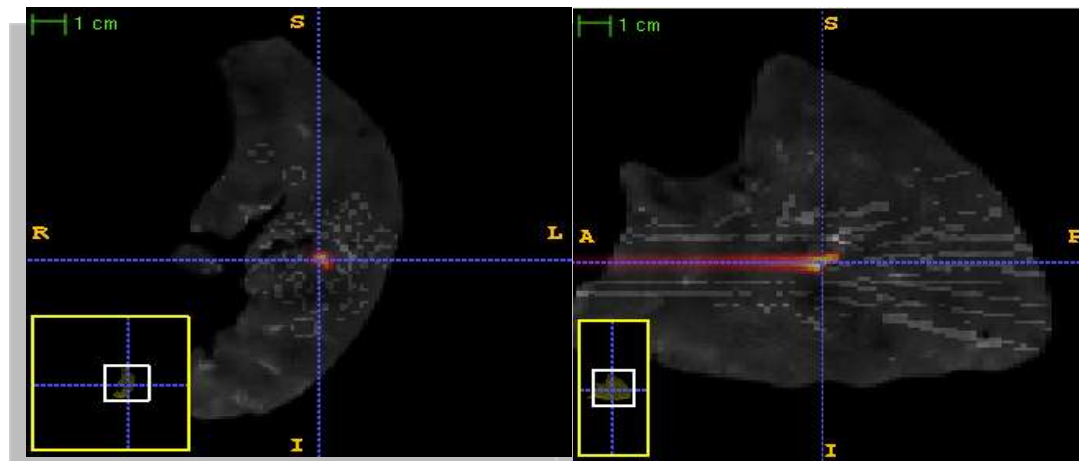


Scale Factor : 1.00

# Virtual 4D CT scan reconstruction & dose simulation



Conversion of displacement simulation into CT scan

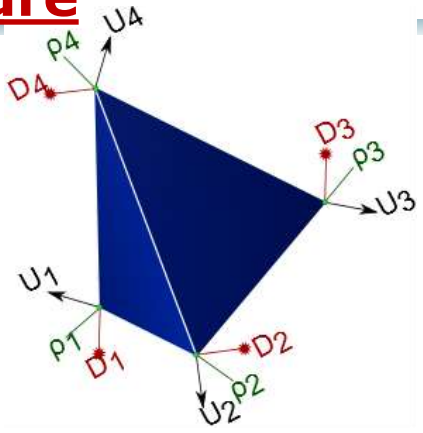


Dose simulations on the density map

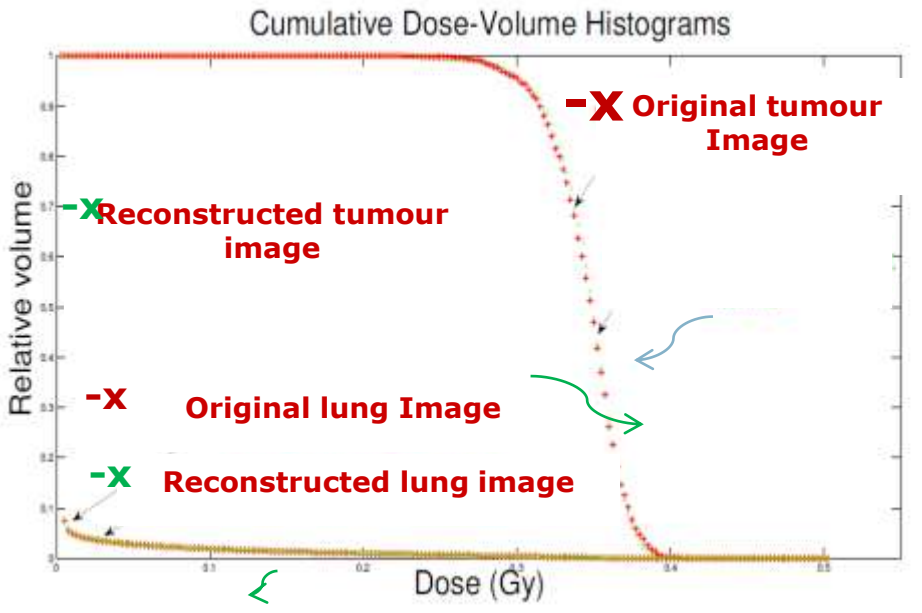
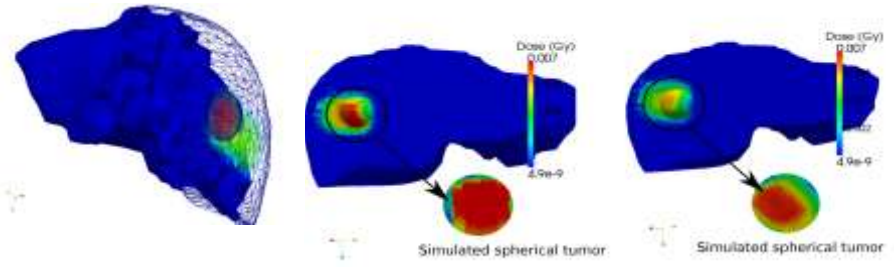
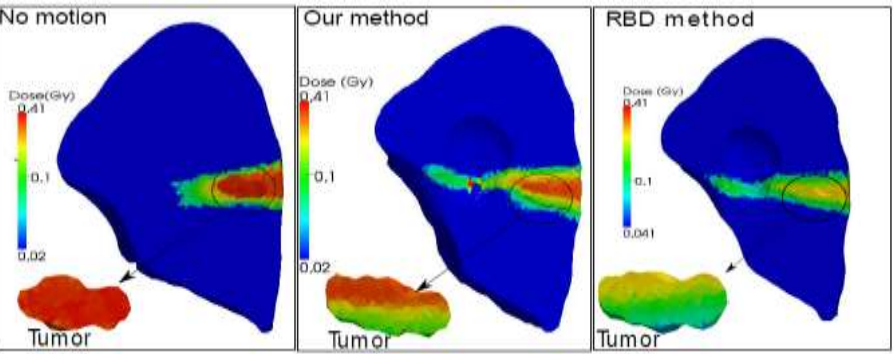
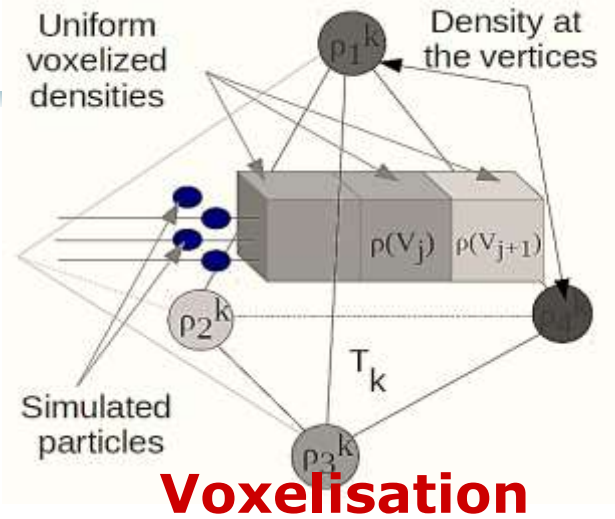
# Multiphysics continuous representation

## Tetrahedral structure

- Density
- Masse
- Displacements
- Dose



IEEE ISBI 2014 ,JCARS 2014

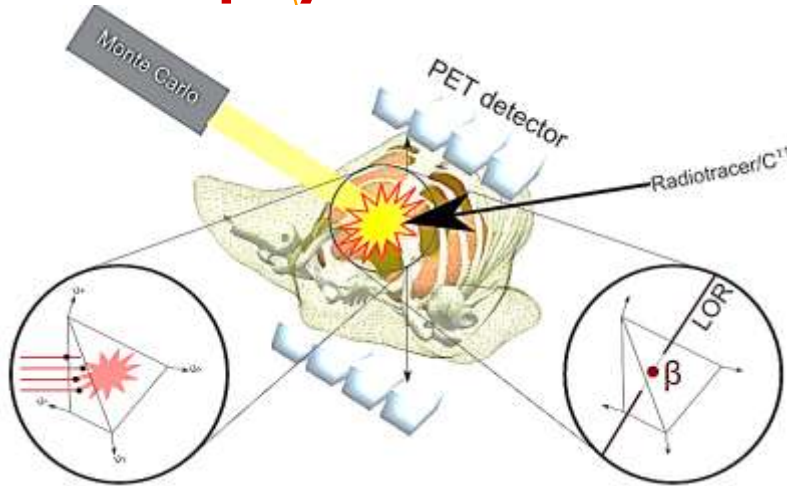


Cartography of dose deposit

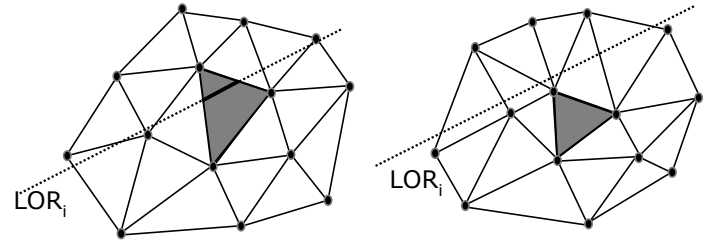


# Reconstruction of 4D-PET images

## multiphysics model

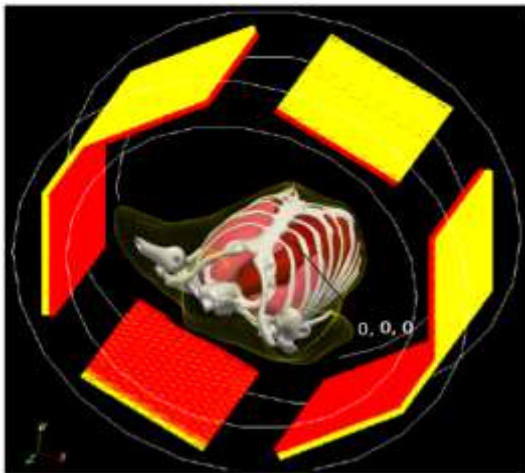
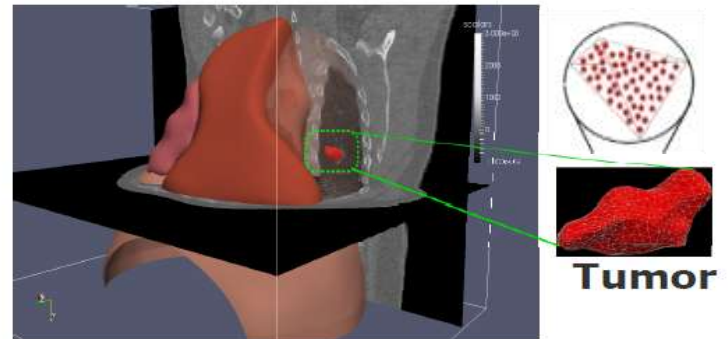


- Tissues implicit tracking
- Taking into account volume variations

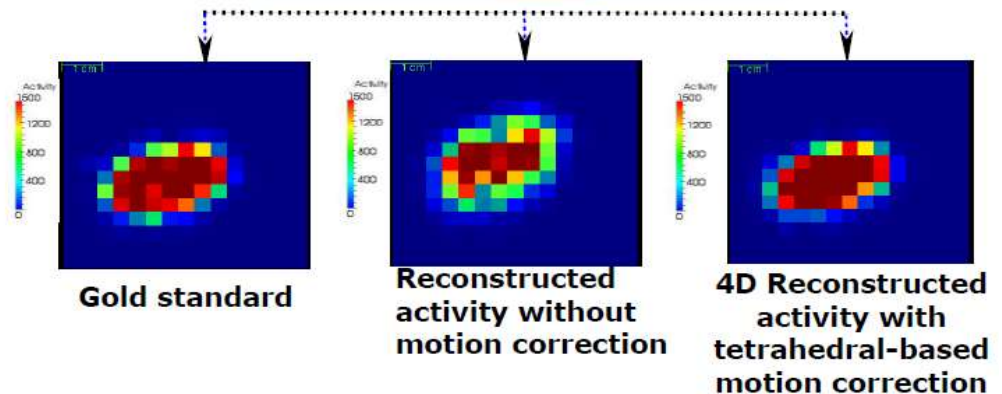


Dose accumulated over  
Deforming tetrahedra

Radioactivity  
reconstructed  
on tetrahedral elements



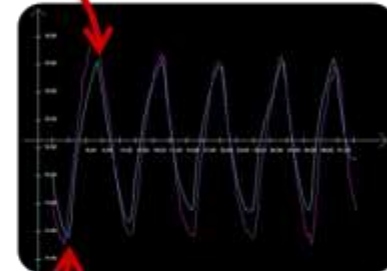
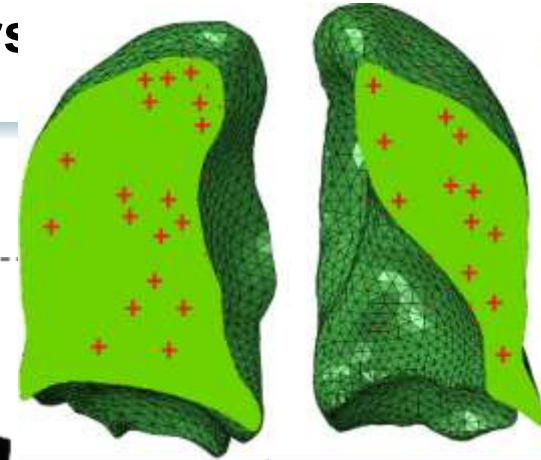
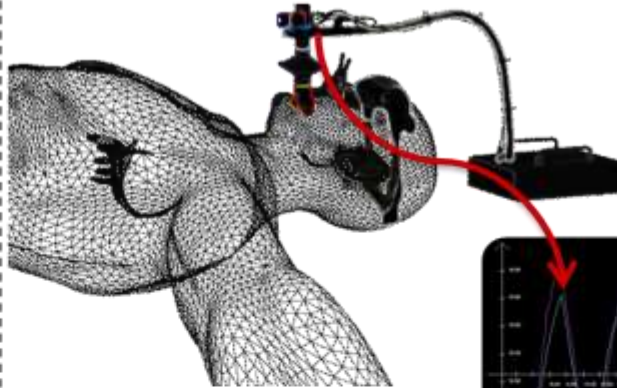
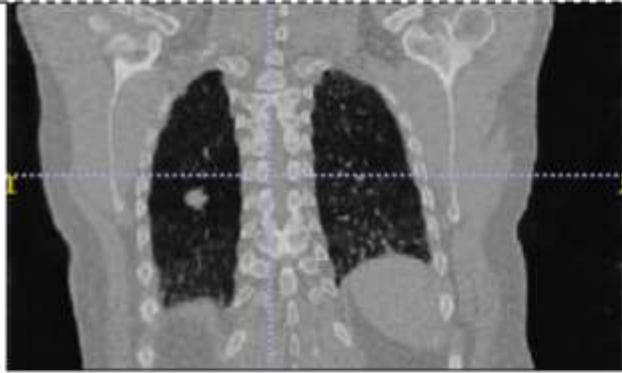
PET Scanner



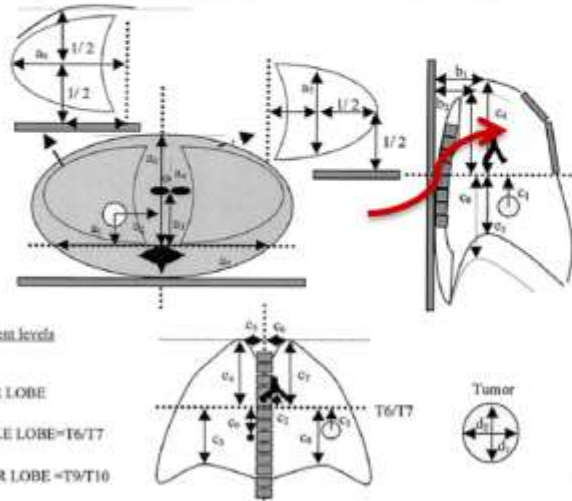
# Current works

## 1. Clinical validation of the model by external sensors

- Spirometer
- Image processing



ation



Interne Protocol

Clinical validation

# Current works

1. Clinical validation of the model by external sensors
  - Spirometer
  - Thorax movement tracking (RPM markers )

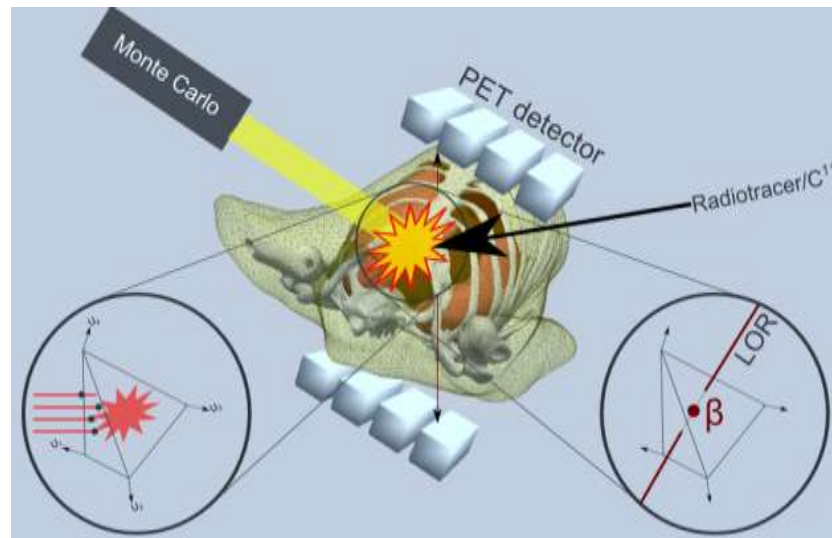


**Realistic anthropomorphic phantom  
Lung Cancer LuCas (PSI)**

# Conclusion

## ■ Extension of the current works towards :

- Tracking different internal organs from external surrogates in real time, based on patient specific data
- A potential Pre-Therapeutic tool for adaptive dose based on 4D patient specific,
- Contributing to the development of on-line control systems for Radio hadrontherapy (4D PET, Gamma prompt)



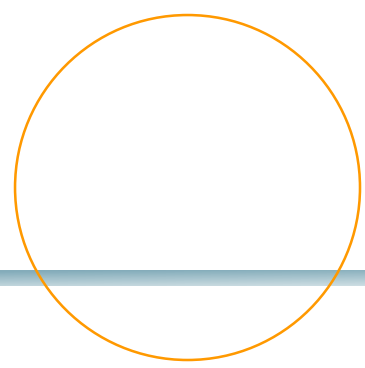
**Dose accumulated over  
deforming tetrahedra**

**Radioactivity  
reconstructed  
on tetrahedral elements**

# Akknowledgment:

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- Thanks to the following fellows for their strong contribution to this project:
  - Liris: B. Shariat, J. Azencot, M. Giroux and Y. Touileb
  - IPNL: M. Beuve, E. Testa and D. Dauvergne



**Thank you for your attention**