Analyse d'Images Médicales et Modélisation: de l'acquisition à la quantification

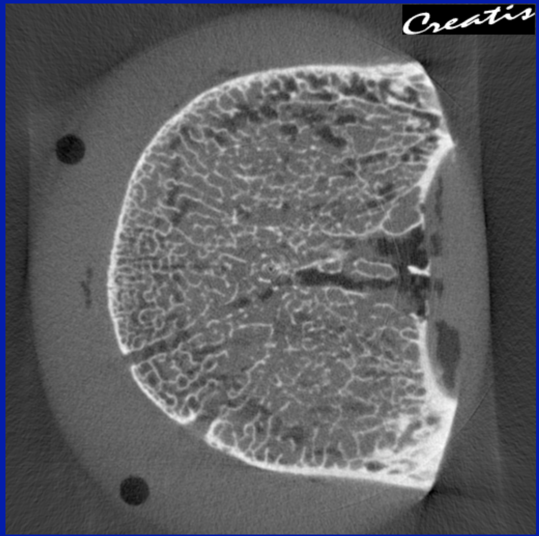
Patrick CLARYSSE

CREATIS-LRMN, CNRS UMR5220, Inserm U630, Lyon, France

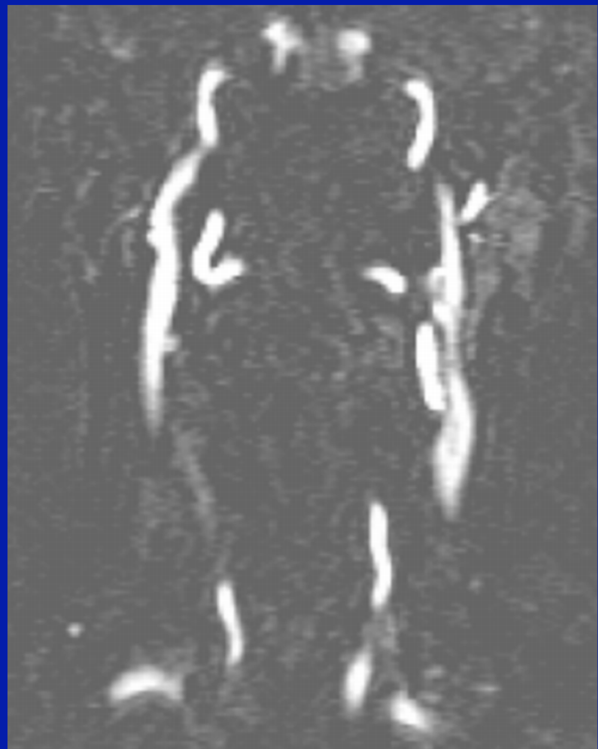
Patrick.clarysse@creatis.insa-lyon.fr

http://www.creatis.insa-lyon.fr/~clarysse

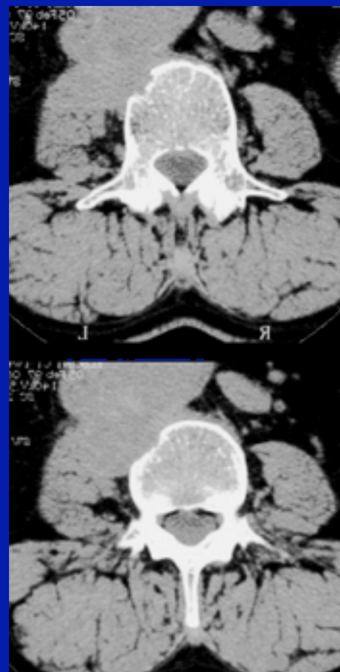

Patient
Data collection
clinician
Decision
action

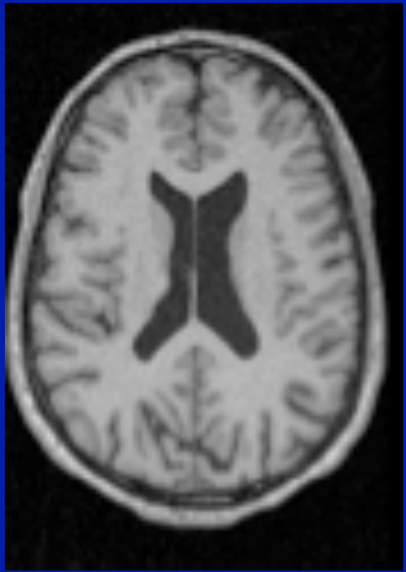


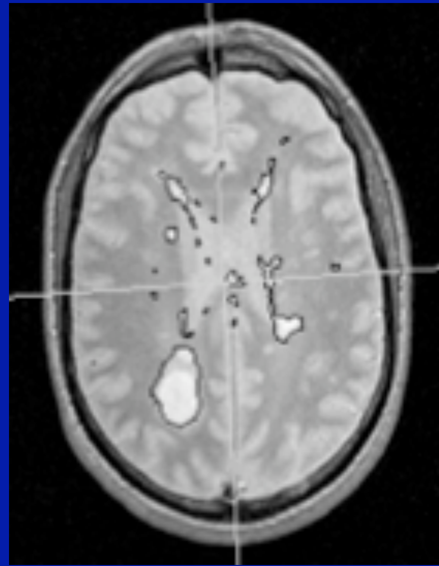
Bone image HRX



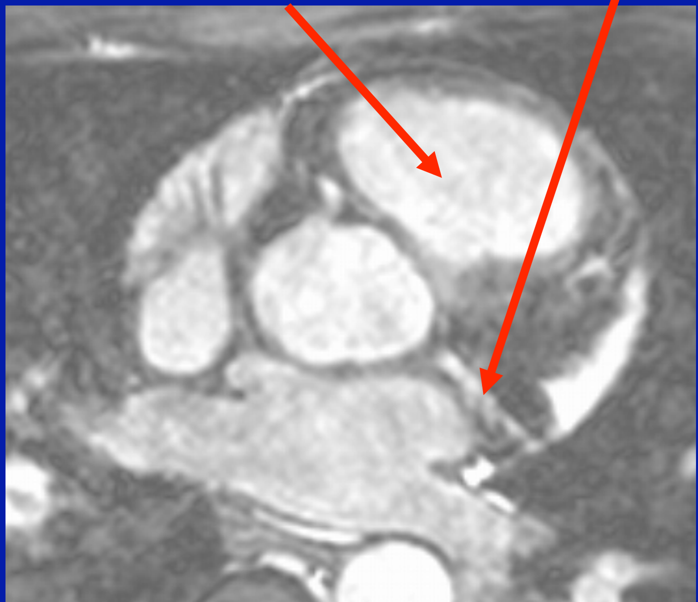
MRA Carotid







Cavity Vessel



MRA coronary

Stenosis detection

Creatis LRMN

Difficulties

- Images = Partial measurements
- Objectives: Recover the truth
  - shapes, functions…
  - normal and abnormal patterns

➡ Inverse problem:

- ➢ Not a unique solution
- ➢ Stability upon the data

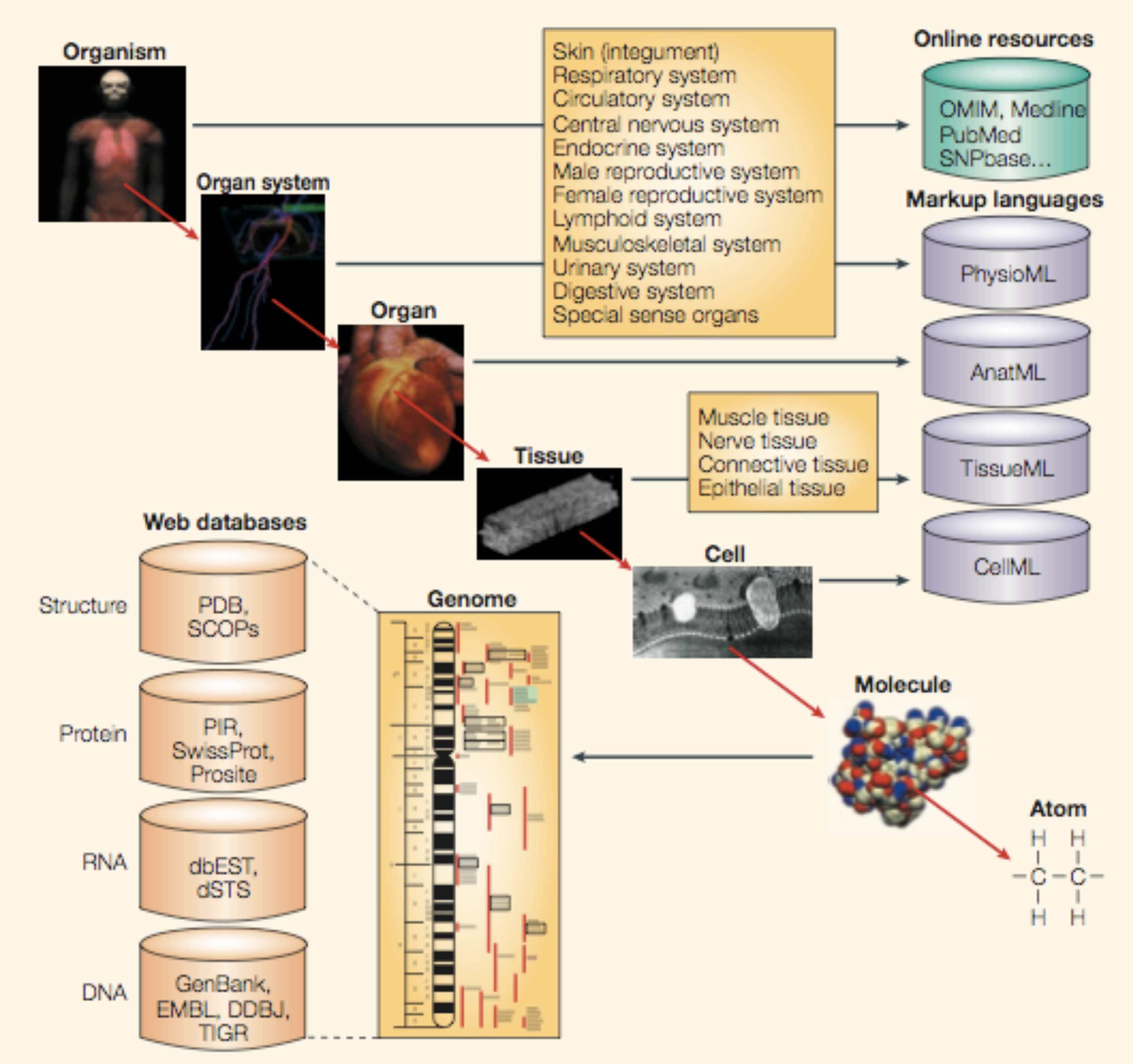
Creatis LRMN

From ill-posed to well-posed
The image segmentation example

- Regularization (smoothness constraint)
- Adding prior information:
  - Shape constraints: average shape, topology, shape statistics…
  - Static and dynamic properties
  - Other functional properties
  - Appearance model (image)

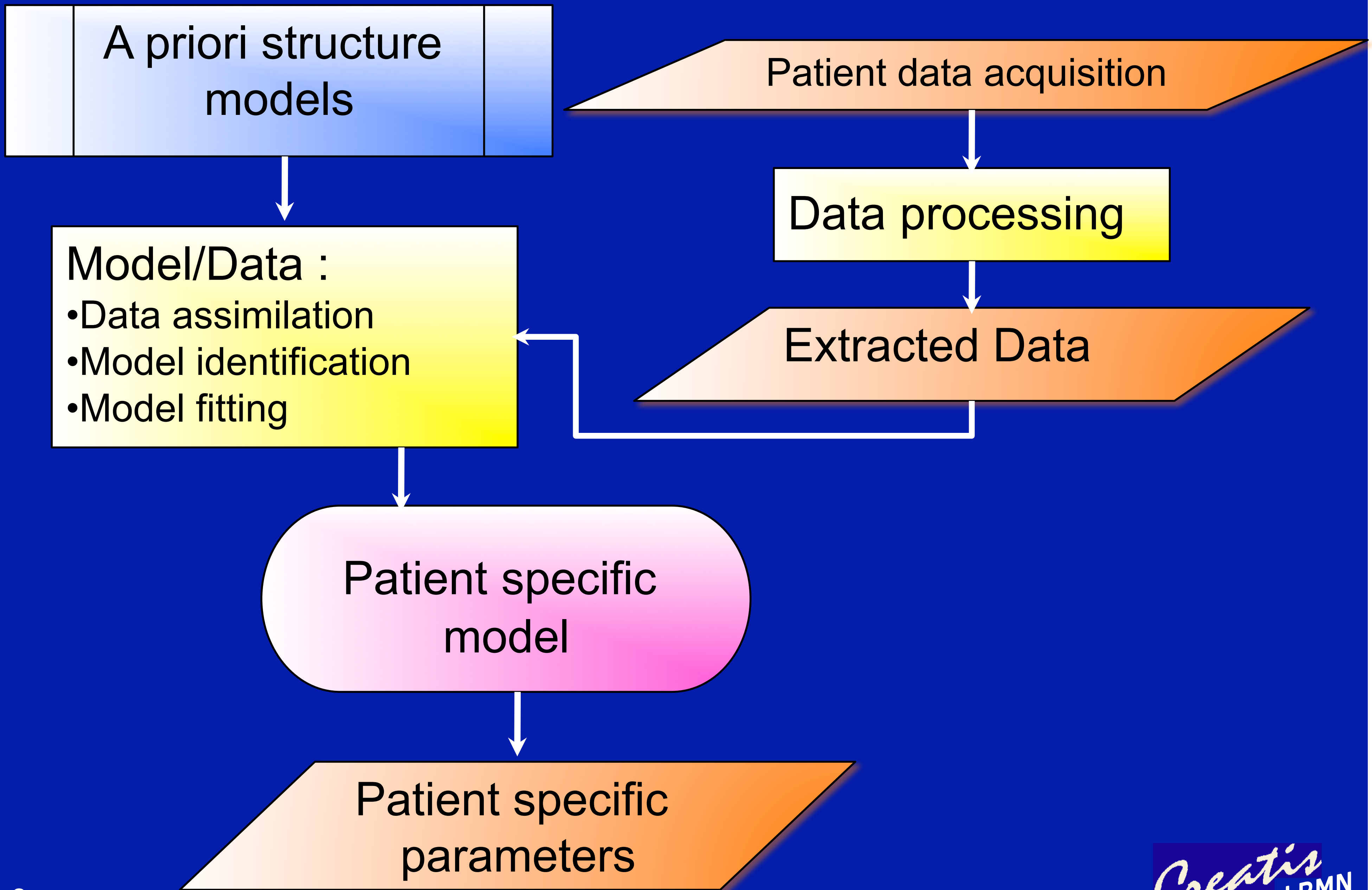
➢ ***a priori* structure models**

The Modeling perspective

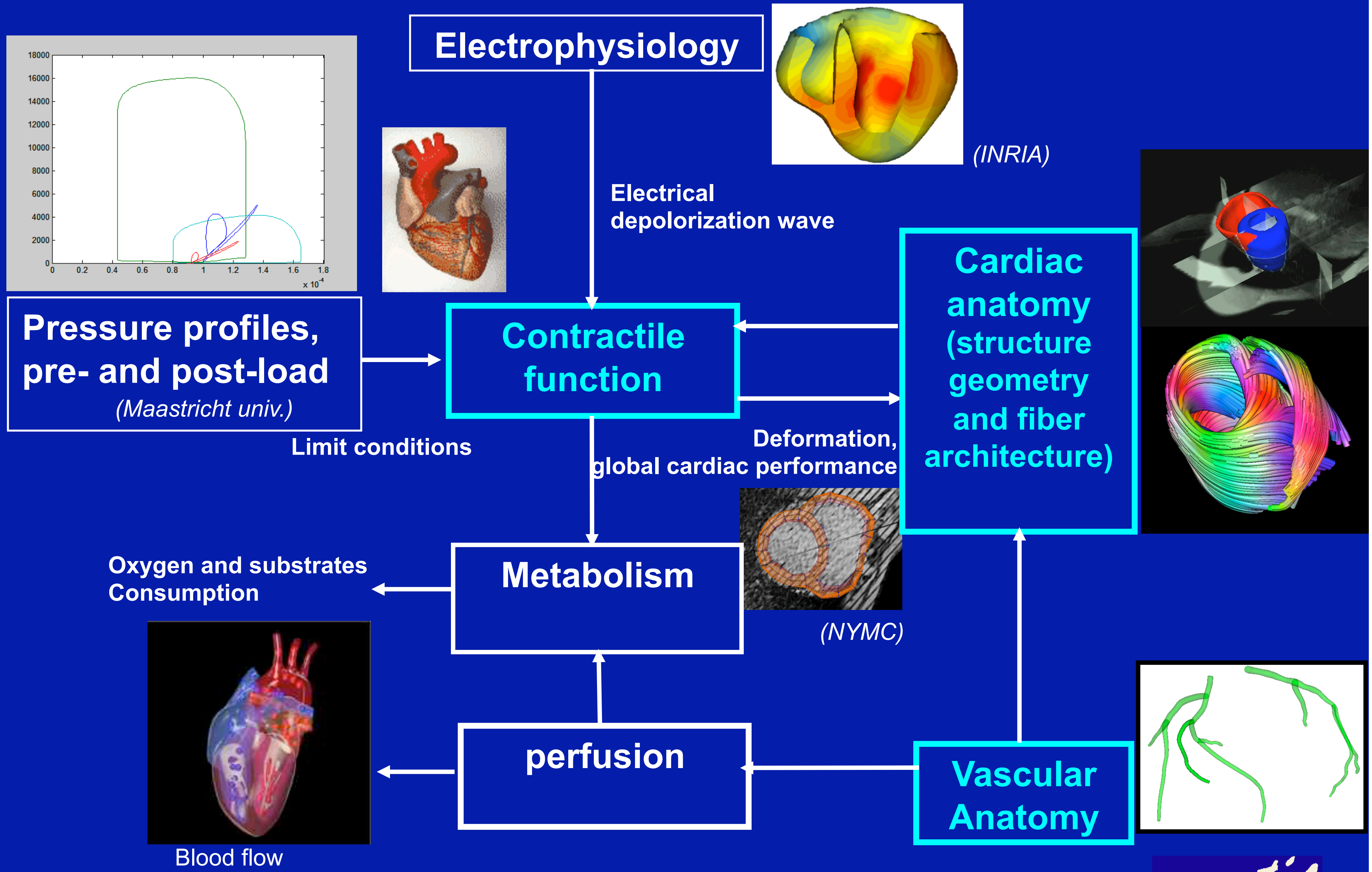


From Hunter & Borg Nature Rev, 2003 (Physiome & VPH projects)

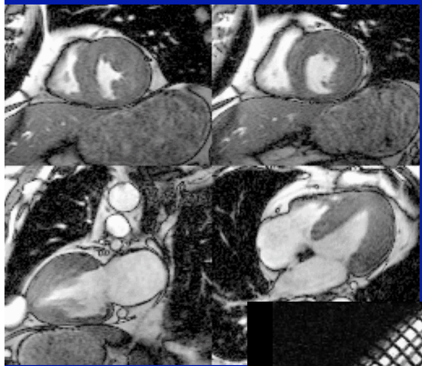
Patient specific Modeling



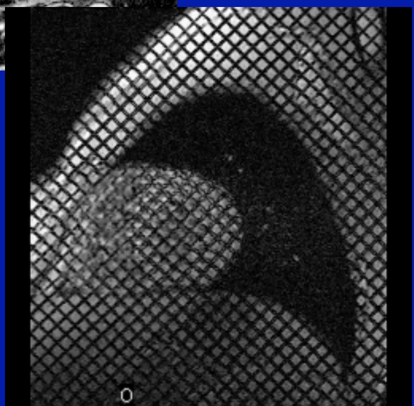
Patient specific cardiac modeling



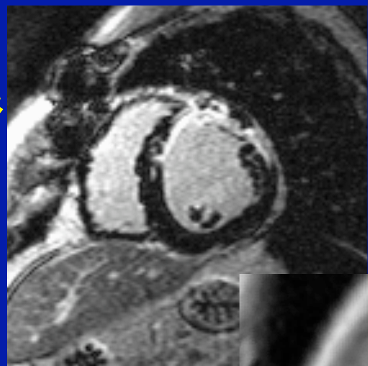
Available data



MRI:
Anatomy &
contractile
function

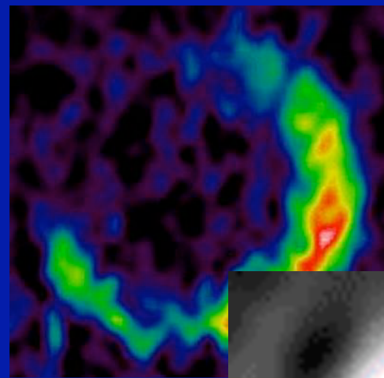


→ cm.s^{-1}, cm.s^{-2}

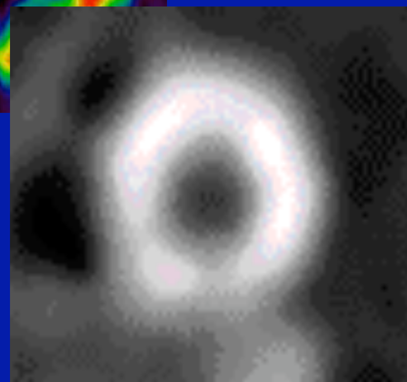


MRI:
perfusion

→ ml.g^{-1}.min^{-1}

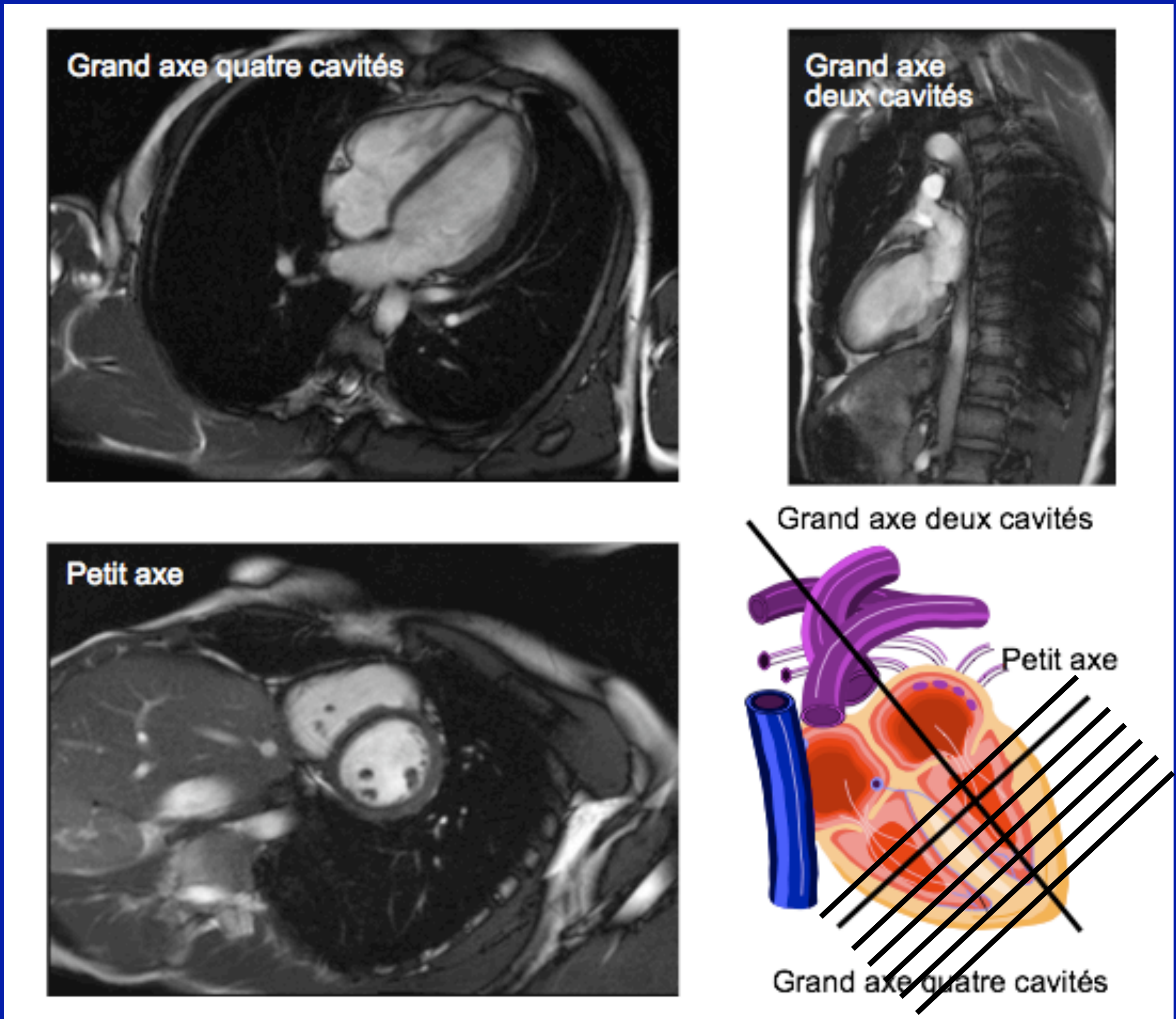


PET:
metabolism



→ mmol.g^{-1}.min^{-1}

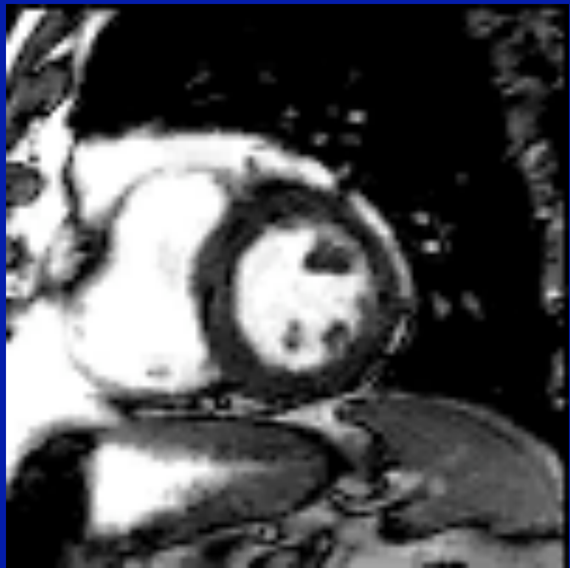
MR imaging

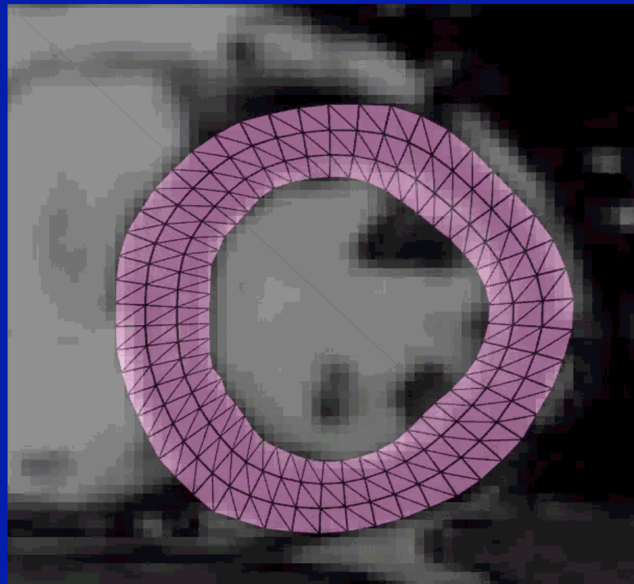


Standard multi-slice cine images

→ Human & small animal

Dynamic cardiac segmentation



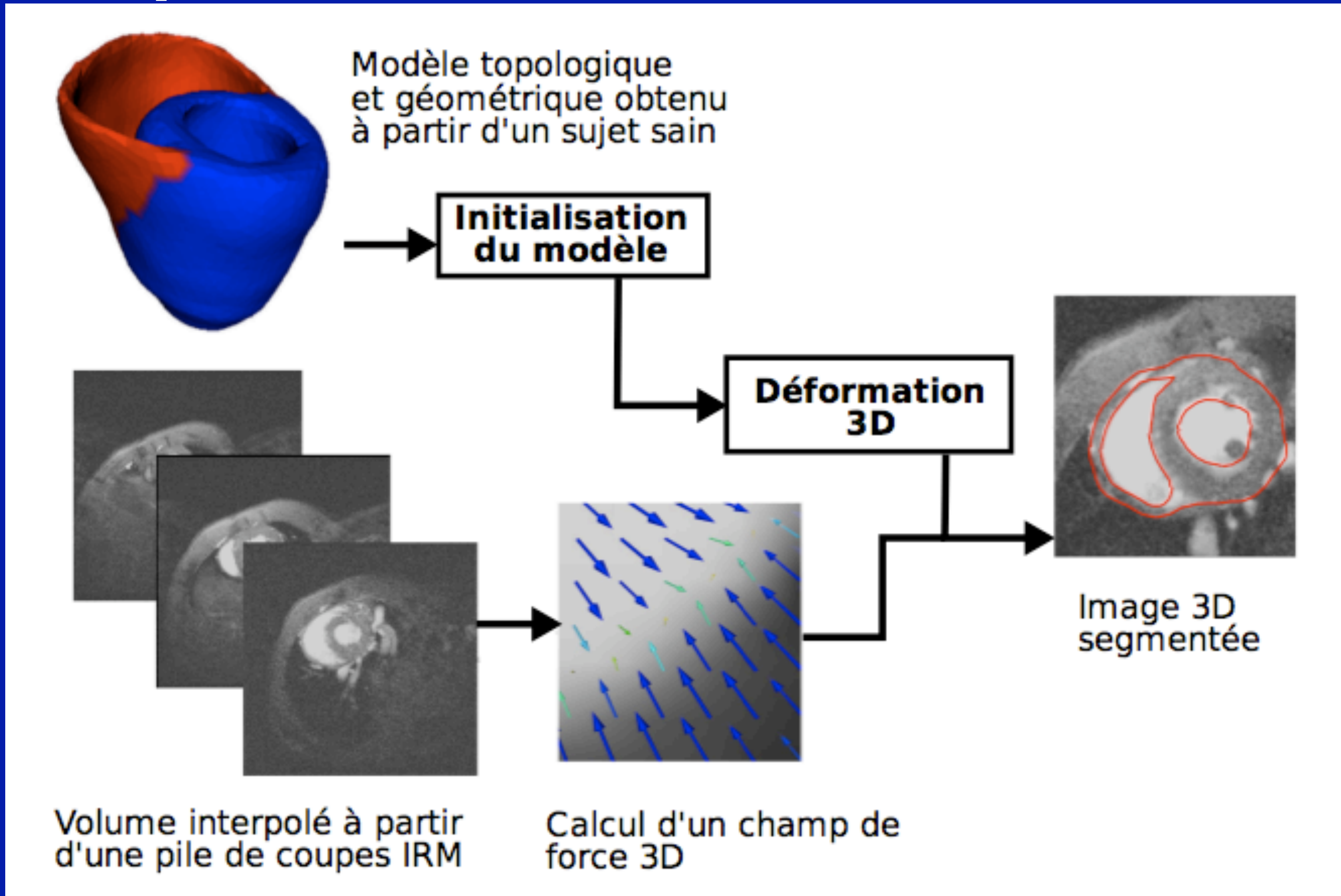


- **Objective:**
  - segmentation and tracking of the heart in temporal image sequences (MRI)
  - Characterizing the shape and dynamics of normal and pathological hearts

Creatis LRMN

The Deformable Elastic Template (DET)

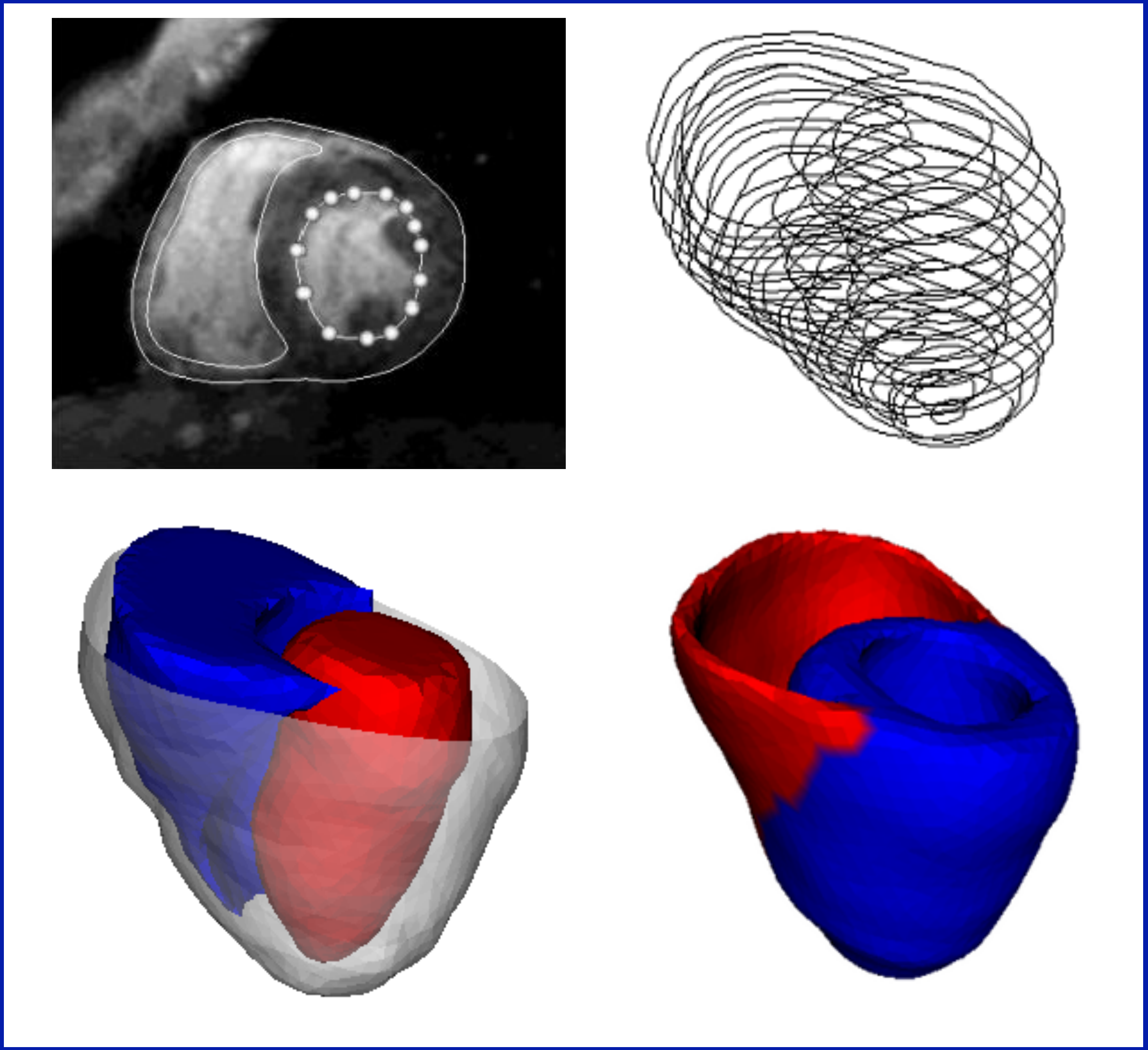
- **Principle**



→A bio-inspired model

Creatis LRMN

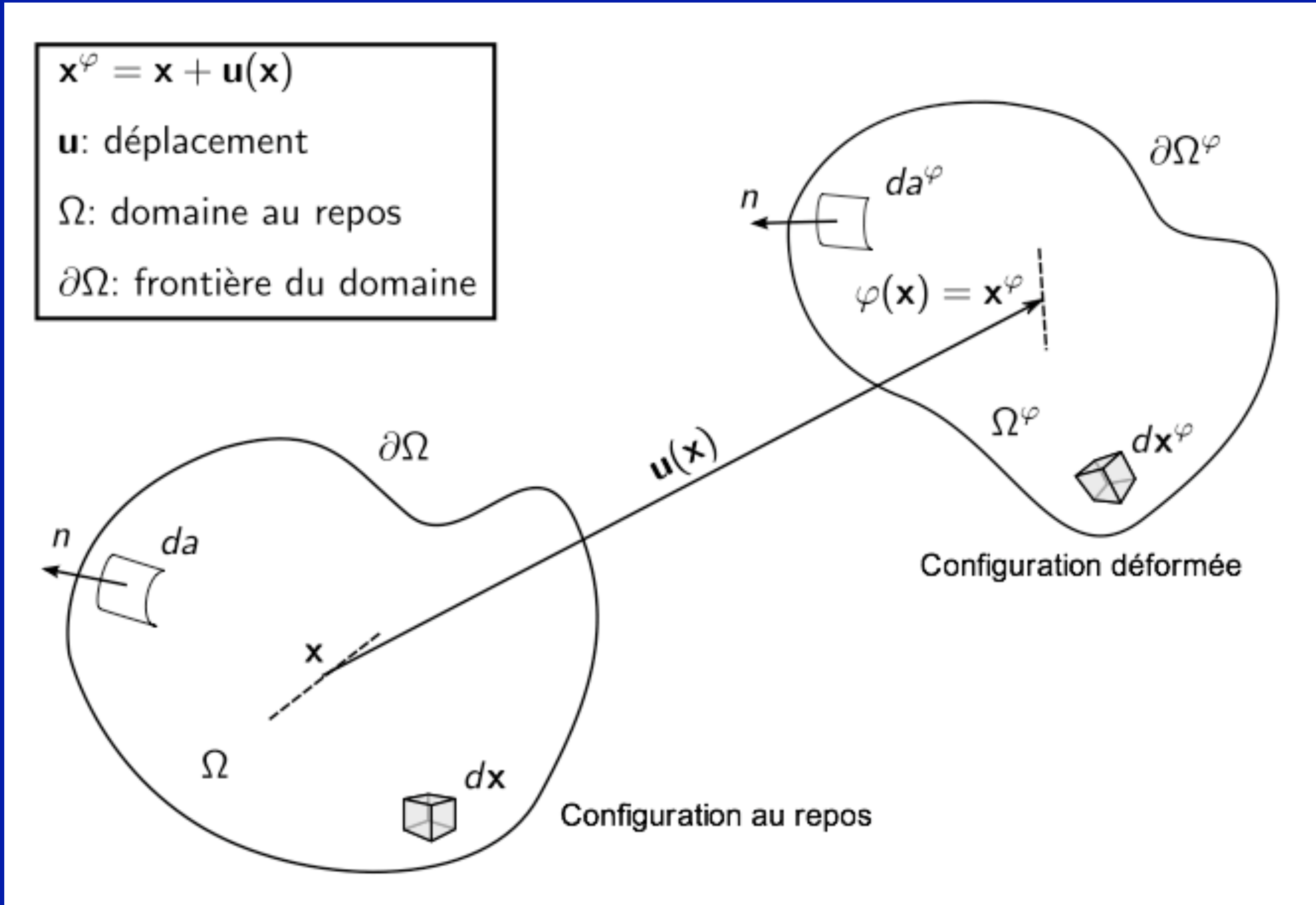
Reference *a priori* model



Mailleur GHS3D, Gamma Project, INRIA

DET Patient specific model adaptation

- Elastic deformation



- **Elastic solid under constraints :**
  - **Equilibrium equation**

$$\begin{cases} \operatorname{div} \boldsymbol{\sigma} = 0 & \text{in } \Omega_0 \\ \boldsymbol{\sigma}_{\boldsymbol{n}} = f & \text{on } \partial\Omega_0 \end{cases}$$

  - **Potential energy**

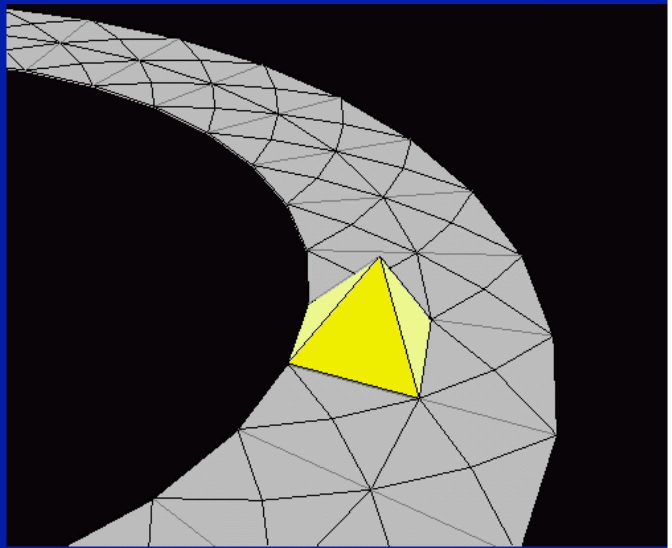
$$E(u) = \underbrace{\frac{1}{2}\int_{\Omega_0} \varsigma^T(u)\epsilon(u)\,dx}_{E_{elastic}} - \underbrace{\int_{\delta\Omega_0} f^T \cdot u\,ds}_{E_{image}}$$

  - **Elastic Energy**

$$E_{elastic} = \frac{1}{2}\int_{\Omega} \mu \nabla u^T \nabla u + (\lambda + \mu)\operatorname{div}(u)\operatorname{div}(u)\,d\Omega$$

With λ, μ the Lamé Coefficients

- Optimization: FEM
  - Partitioning the domain in elements
  - Linear basis functions



  - Solving the system
    - Algorithm M1: incremental load

$$\text{M1} \quad \begin{cases} \mathrm{u}^{k+1} - \Delta t \,\mathrm{div}\, \sigma(\mathrm{u}^{k+1}) = \mathrm{u}^k \quad \text{dans } \Omega_0 \\ \sigma_n(\mathrm{u}^{k+1}) = \underline{f(\mathrm{I} + \mathrm{u}^k)} \quad \text{sur } \partial\Omega_0 \end{cases}$$

$$\Rightarrow \quad \mathrm{KU} = \mathrm{F}$$

    - FEM solution: evolution equation

$$\frac{d\mathrm{U}}{dt} + \mathrm{KU}(t) = \mathrm{F}(\underline{\mathrm{U}(t)})$$

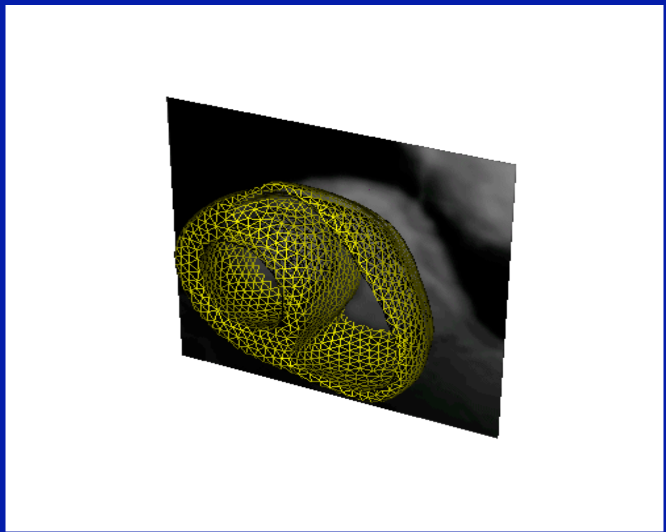
$$\mathbf{U} = (u_1, u_2, u_3, \ldots u_N)$$

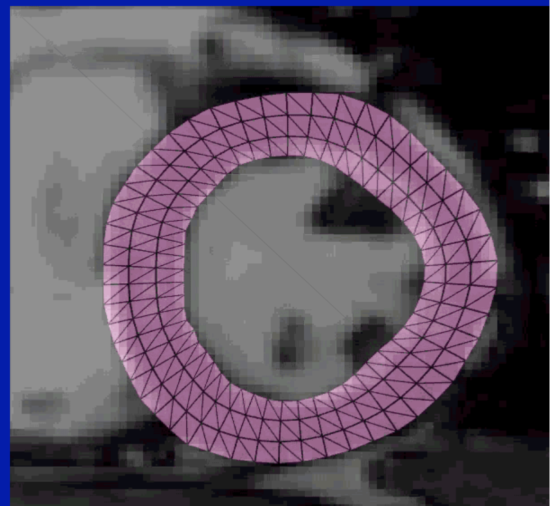
K: stiffness matrix

$$(\mathrm{I} + \Delta t\, \mathrm{K})\mathrm{U}^{k+1} = \mathrm{U}^k + \Delta t\, \mathrm{F}(\mathrm{U}^k)$$

DET story

- 2D linear static DET :
  [PhD thesis F. Vincent, 2001]
- 3D linear static DET, bi-ventricular model :
  [PhD thesis Q-C. Pham, 2002]
- Non-linear static DET,
  [PhD thesis Y. Rouchdy, 2005]
  (Collab. ICJ, J. Pousin)
- Dynamique DET,
  [PhD thesis J. Schaerer, 2008]
  (Collab. ESIEE, L. Najman, J. Cousty)





- **Non linear algorithm *[Rouchdy, 2005]***
  - **To avoid the linearization of the def tensor**

$$\begin{cases} div\sigma\left(u(\lambda)\right) = 0 & \text{in } \Omega \\ \sigma\left(u(\lambda)\right).n = \lambda f\left(u(\lambda)\right) & \text{on } \partial\Omega \end{cases}$$

Where λ [0,1] is an evolution variable

  - **With an explicit Euler scheme:**

$$\mathbf{A}^k\mathbf{U}_{k+1} = \mathbf{A}^k\mathbf{U}_k + \left(\lambda_{k+1} - \lambda_k\right)\mathbf{F}\left(\mathbf{U}_k\right)$$
$$\text{with } \mathbf{A}^k = \mathbf{K}^k - \lambda_k\mathbf{D}^k$$

Collab. Inst. C. Jordan, INSA Lyon
MATH-STIC CNRS project

- **Border constraint:** $f\left(\mathbf{I}+u\right)=0$
  - **Singular perturbation approach *[Schaerer, 2008]***

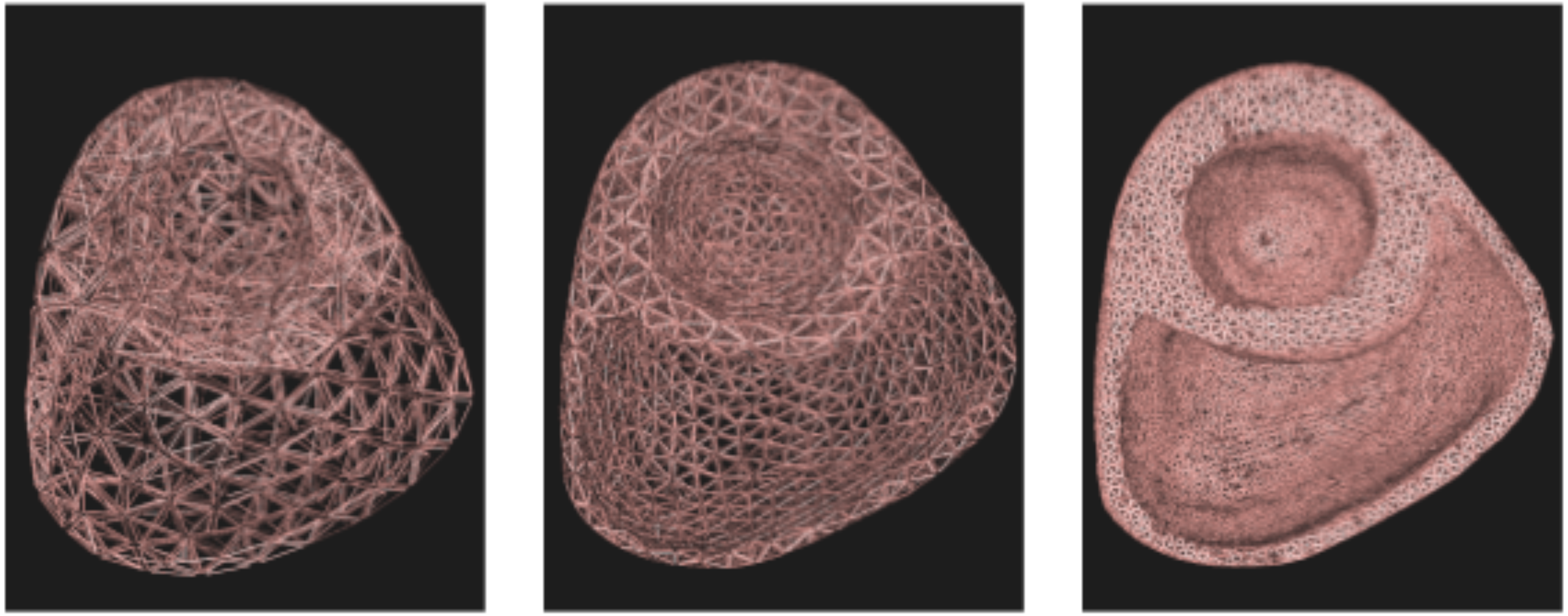
$$\left(\Delta t e^{-\beta k}\mathbf{K}+\mathbf{I}\right)\mathbf{U}^{k}=\Delta t F\left(\mathbf{U}^{k-1}\right)+\mathbf{U}^{k-1}$$

With Δt the time step and β a parameter controlling the decrease

  - ***If the force field derive from a potential and is* Lipschitz then the algo converges**

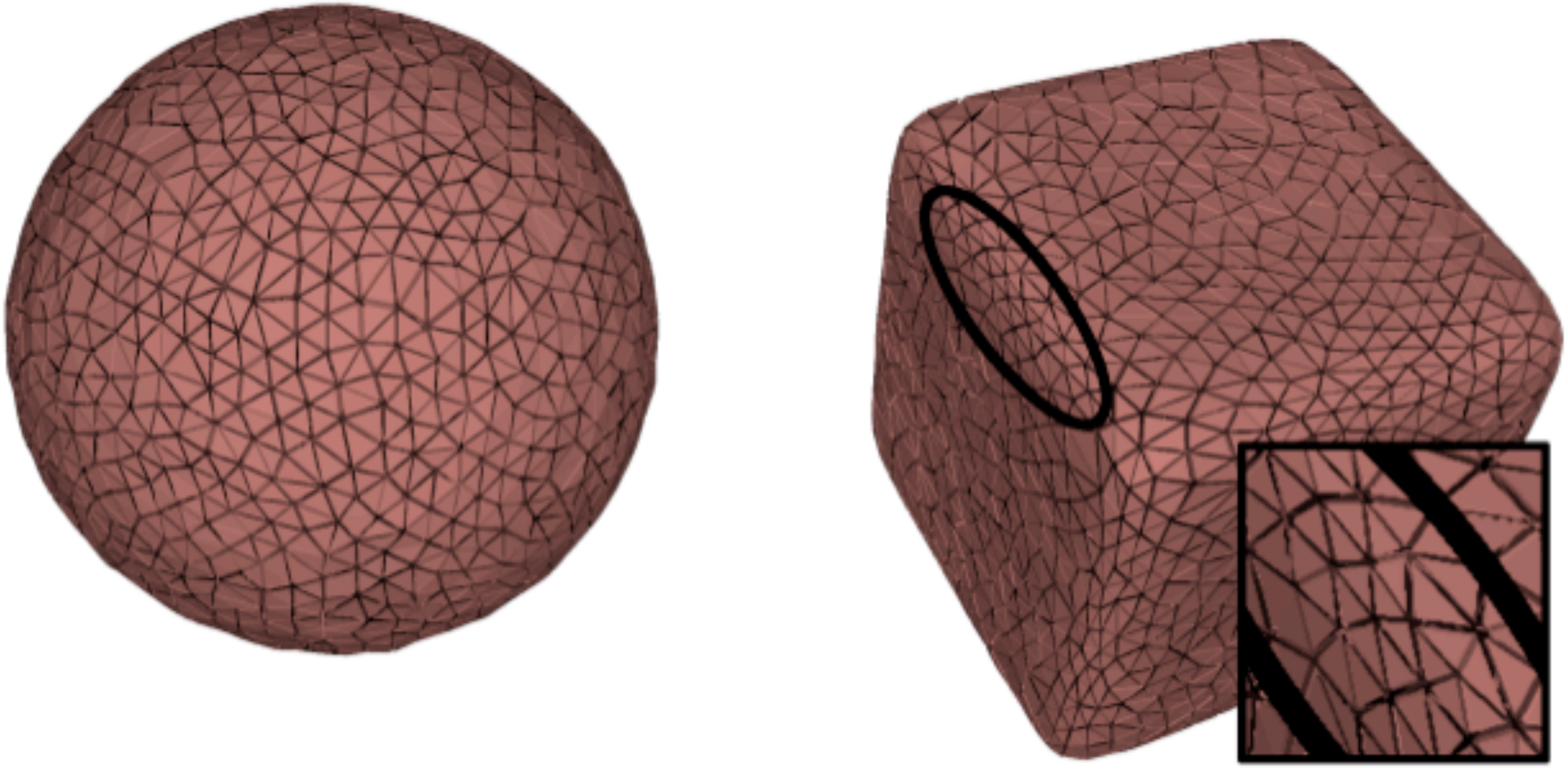
Collab. Inst. C. Jordan, INSA Lyon
MATH-STIC CNRS project

- **Multiresolution meshes**



149 points 362 points 3438 points

- **Impact of the non linear DET**



Maillage initial de boule
(≈ 6000 points)

Maillage déformé

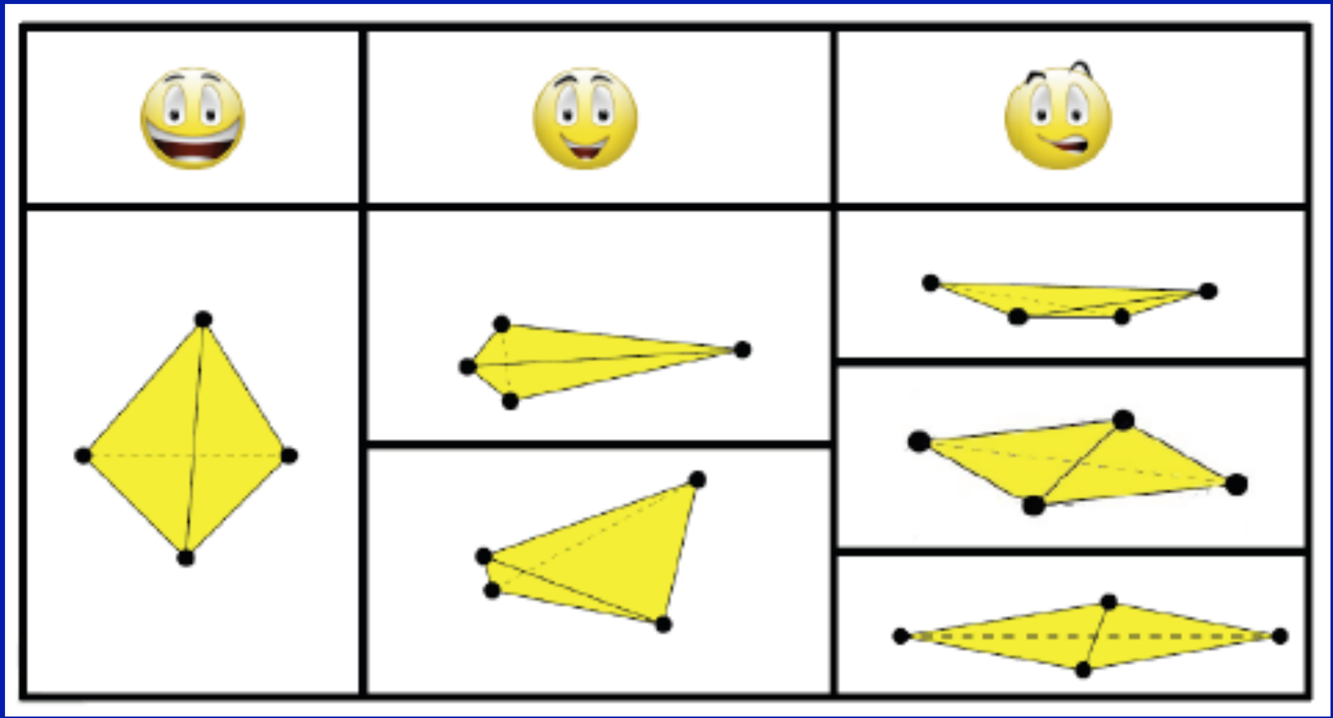
- **Critère de qualité**: rayon de la sphère inscrite au tétraèdre sur la longueur de sa plus grande arrête, compris entre 0 et 1

	Cube linéaire	Cube non-linéaire
Sans multirésolution		
Temps de calcul	54s	1m25s
Qualité moyenne	0.58	0.61
Qualité minimale	0.10	0.17
Multirésolution à 3 niveaux		
Temps de calcul	26s	46s
Qualité moyenne	0.58	0.61
Qualité minimale	0.13	0.17

⇒ L'algorithme non-linéaire permet une meilleure stabilité numérique

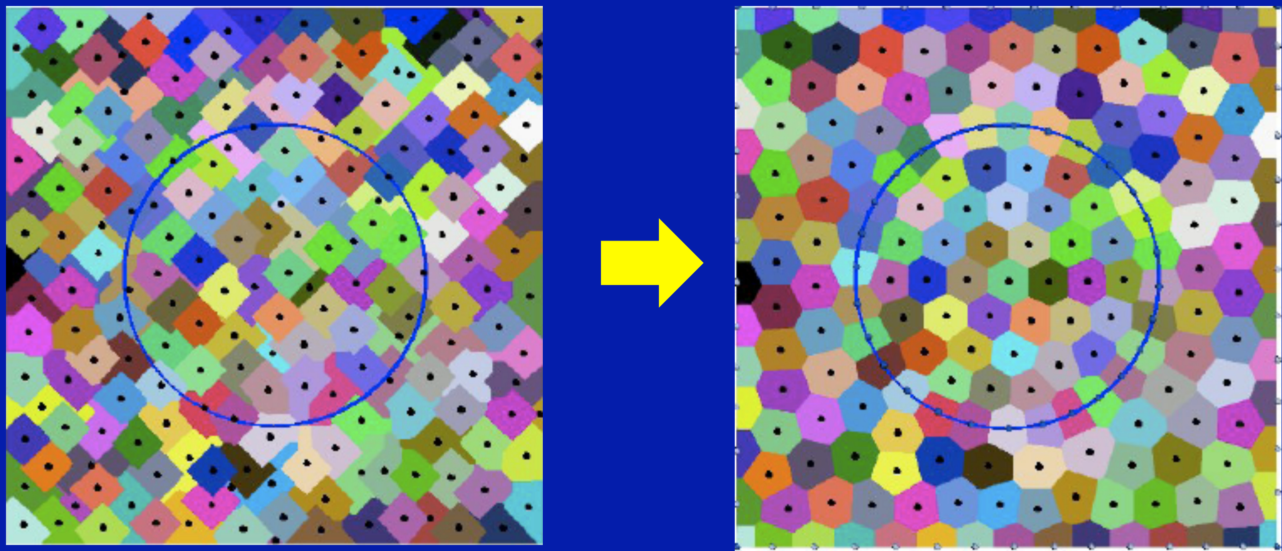
Mesh Quality for FE methods

- Discretization error
- Interpolation error
- Matrix conditionning



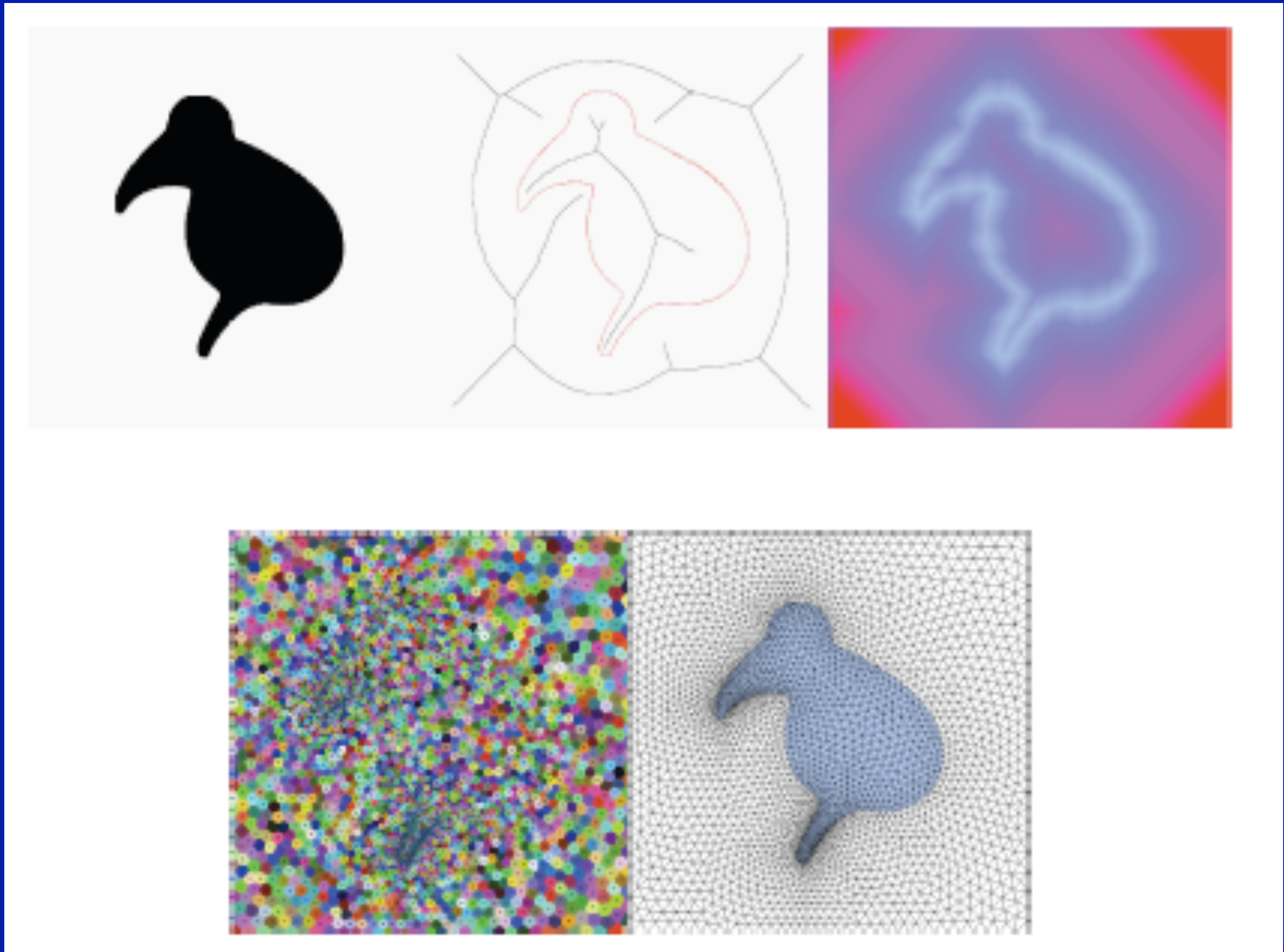
Reconstructing 3D meshes from voxels
J. Dardenne thesis

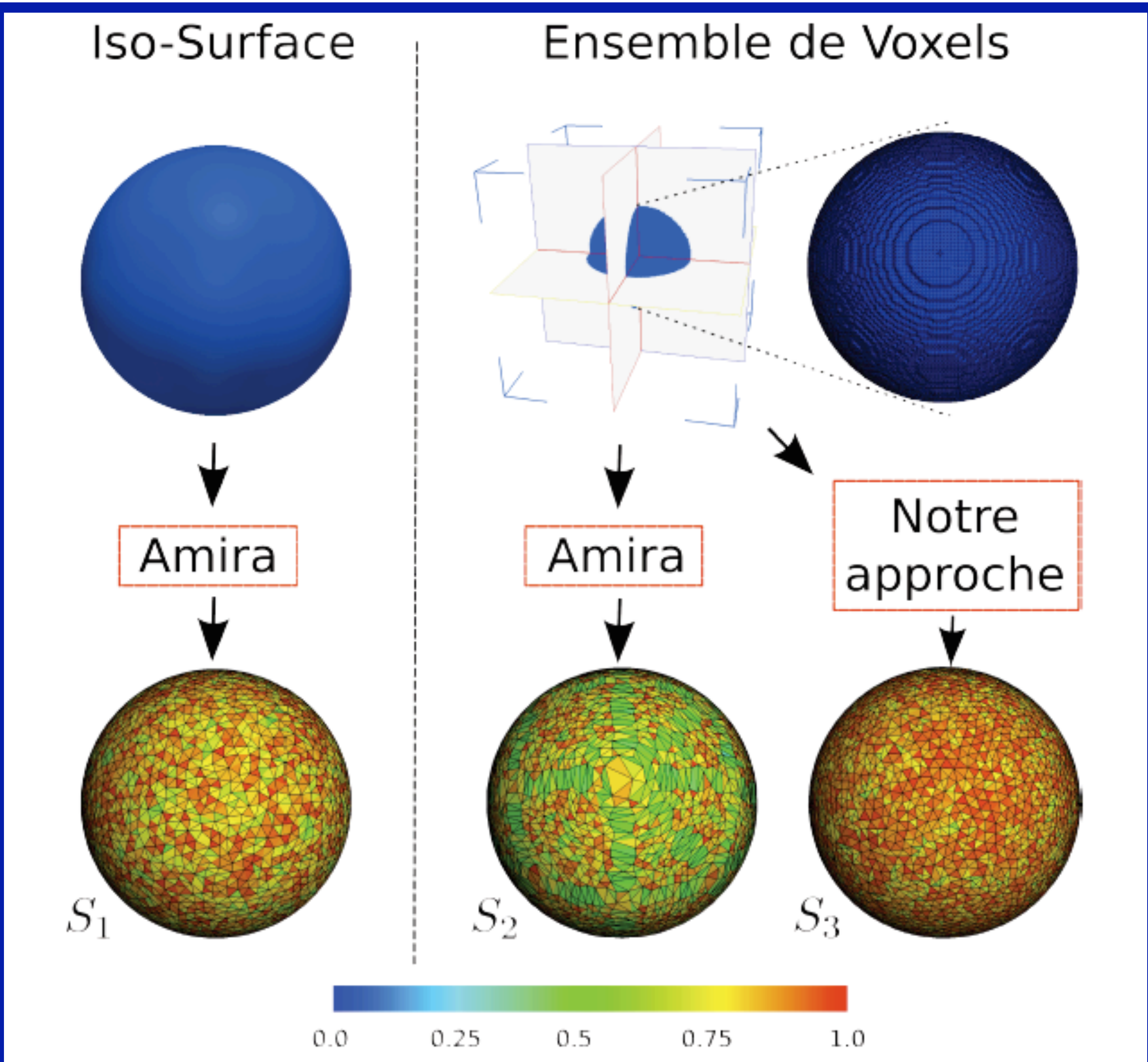
- **Domain partitioning with frontier preservation (energy minimization approach)**



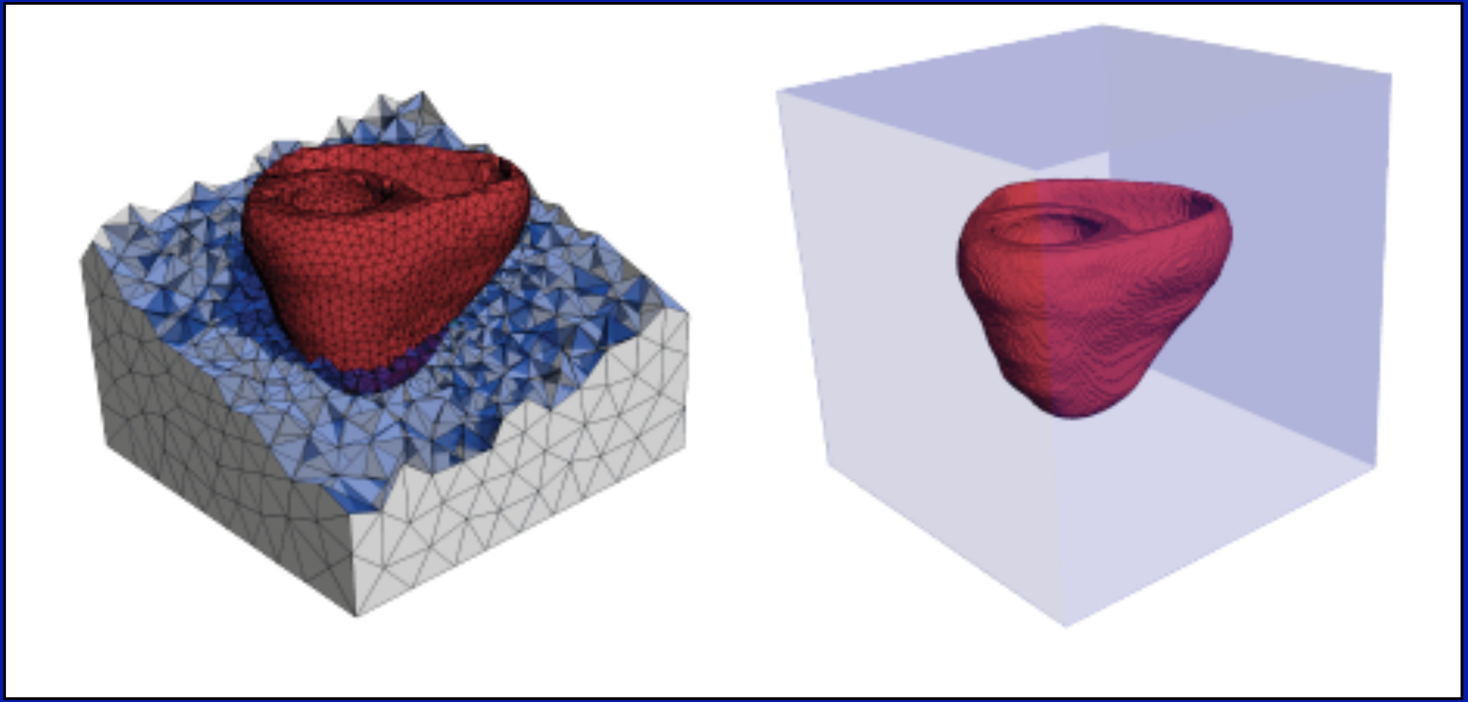
J. Dardenne, S. Valette et al.. **Variational tetraedral mesh generation from discrete volume data.** ***The Visual Computer, pp (in-press), 2009.***

- **Adaptive mesh density through a density map**





J. Dardenne, S. Valette et al., **Variational tetraedral mesh generation from discrete volume data.** ***The Visual Computer, pp (in-press), 2009.***



DET automatic initialization

- Looking for a 3D affine transform T which minimizes:

$$J(p) = \sum_{i=1}^{N_c} \mathbf{d}_n^2(\mathbf{T}(\mathbf{p}, \mathbf{x}_i)) + \sum_{i=1}^{N_{nod}} (I(T(p, x_i)) - I_{nod}(x_i))^2$$

Where $p = \left(t_x, t_y, t_z, r_x, r_y, r_z, s_x, s_y, s_z, sh_{xy}, sh_{xz}, sh_{yz}\right)$

And $\mathbf{T} = \mathbf{T}_r \circ \mathbf{S} \circ \mathbf{R}$

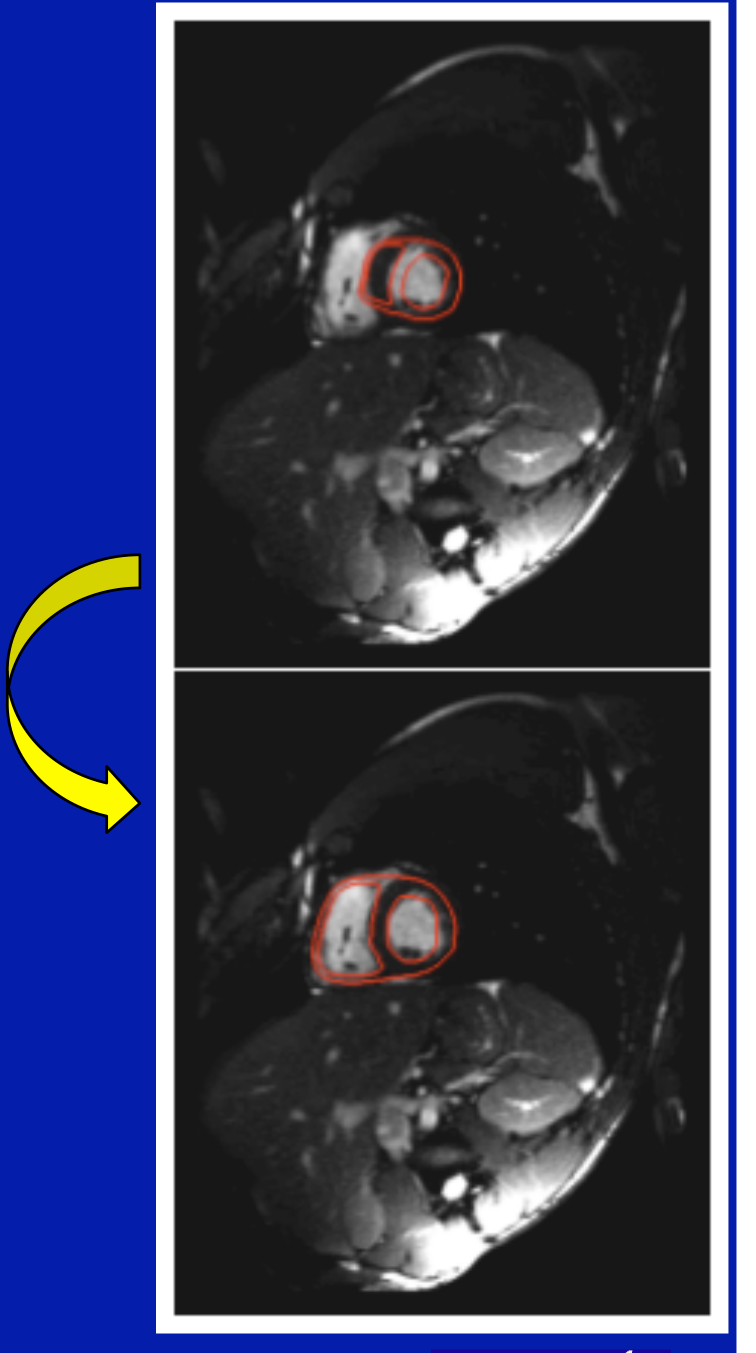
- Based on endocardial contours
- Multi-random-start simplex optimization method

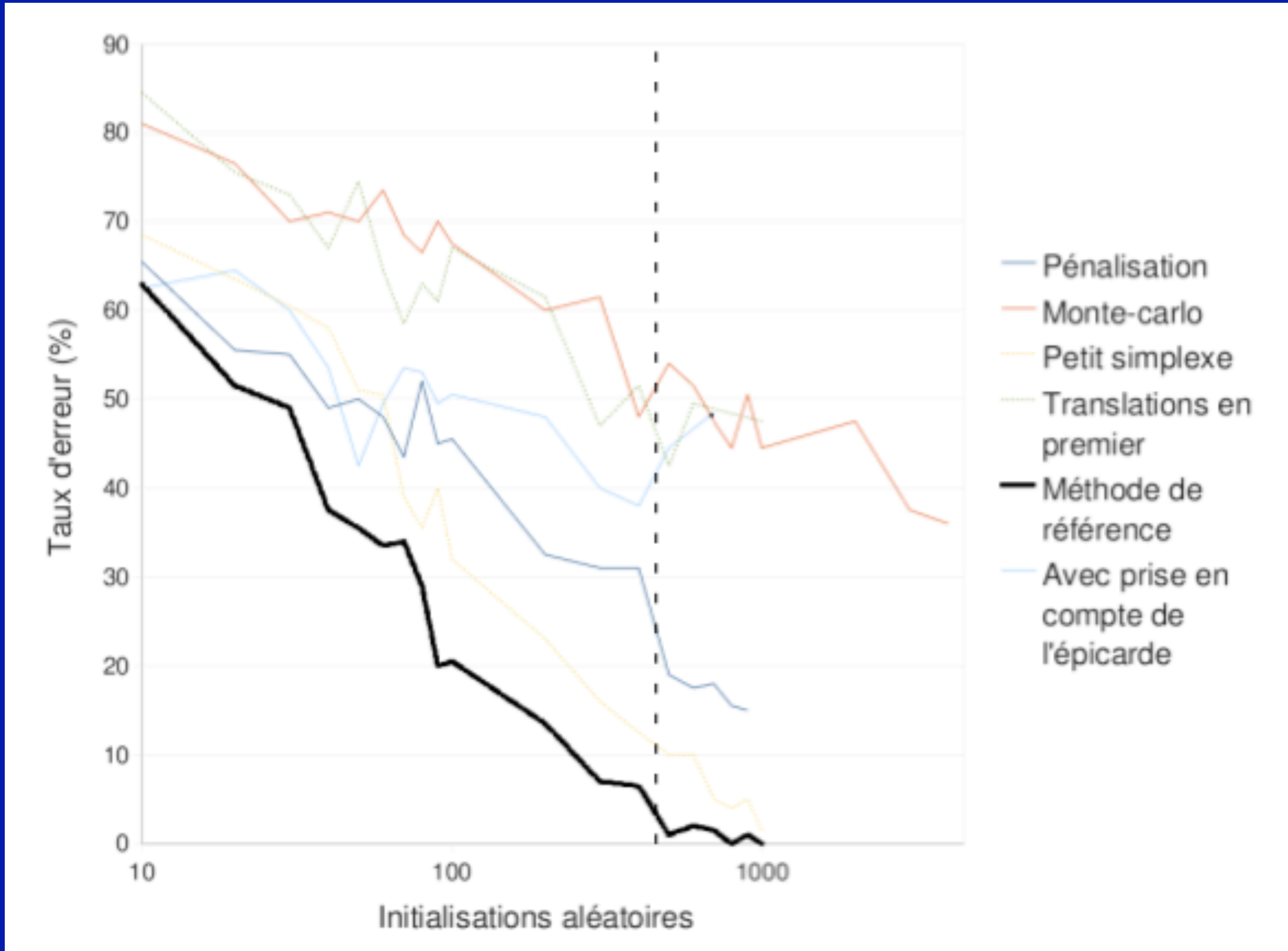
Creatis LRMN

- **Initialization evaluation**
  - **One ED 3D image**
  - **Comparison to a manual established reference**

$$\left\| p_{ideal} - p \right\|^2 < \Delta_p$$

  - **10-4000 random starts**
  - **200 registrations to estimate the error rate for each configuration**

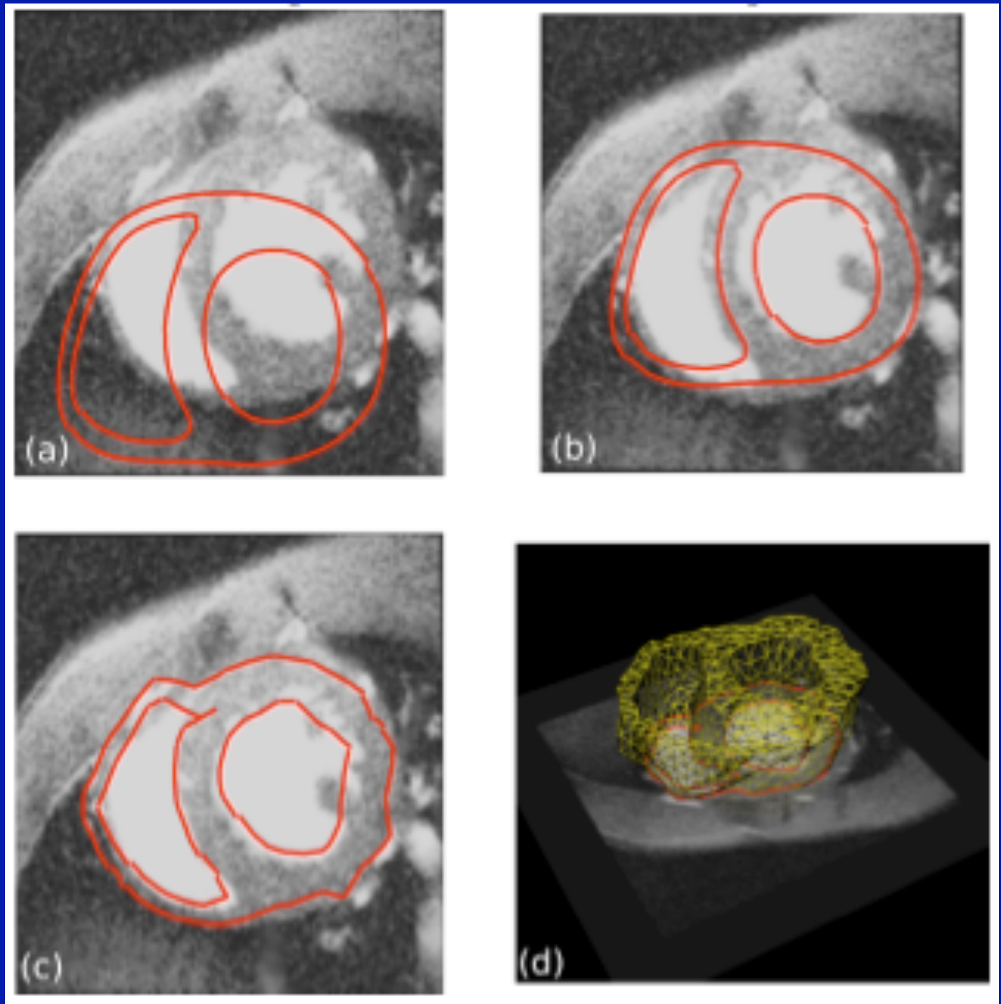


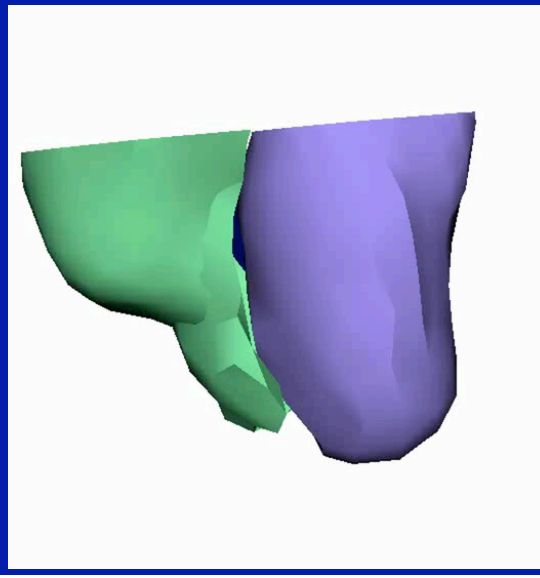


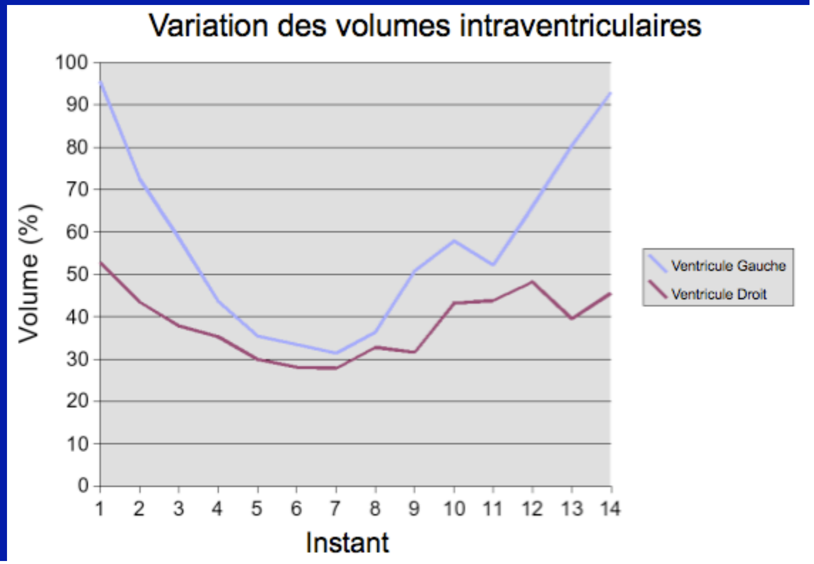
→ The proposed approach offers the best compromise

Some results

- Mouse Images 7T MRI(FLASH sequence FOV=25 mm2 , 256 ×256 pixels, slice thickness=1 mm), cardiac freq. = 450 bpm.







[Schaerer-05]

DET Spatio-temporal Model

- **Assumptions**
  - Continuous & periodic motion
- **Simplified fundamental equation of dynamics :**

$$\mathbf{D}\dot{\mathbf{U}}(t) + \mathbf{K}\mathbf{U}(t) = \mathbf{F}\left(\mathbf{U}(t), t\right)$$

- **Trajectory representation (Fourier)**

$$\mathbf{U}(t) = \sum_{n=0}^{N} \mathbf{A}_n cos(\frac{2\pi n}{N} t) + \mathbf{B}_n sin(\frac{2\pi n}{N} t)$$

Implementation of the non-linear problem

- **Pseudo instationnary scheme: a series of linear problems**

$$\begin{cases} \frac{d\mathbf{U}}{d\tau} & = \mathbf{F}(\mathbf{U}) - \mathbf{A}\mathbf{U} \\ \mathbf{U}(0) = 0. \end{cases}$$

$$(\frac{1}{\Delta\tau} + \mathbf{A})\mathbf{U}^{\tau} = \mathbf{F}(\mathbf{U}^{\tau-1}) + \frac{1}{\Delta\tau}\mathbf{U}^{\tau-1}$$

→ Existence, uniqueness and asymptotic behavior with respect to τ can be demonstrated

[Schaerer et al., in revision]

1D+time illustration

$$\alpha u'(t) + k u(t) = f(t)$$

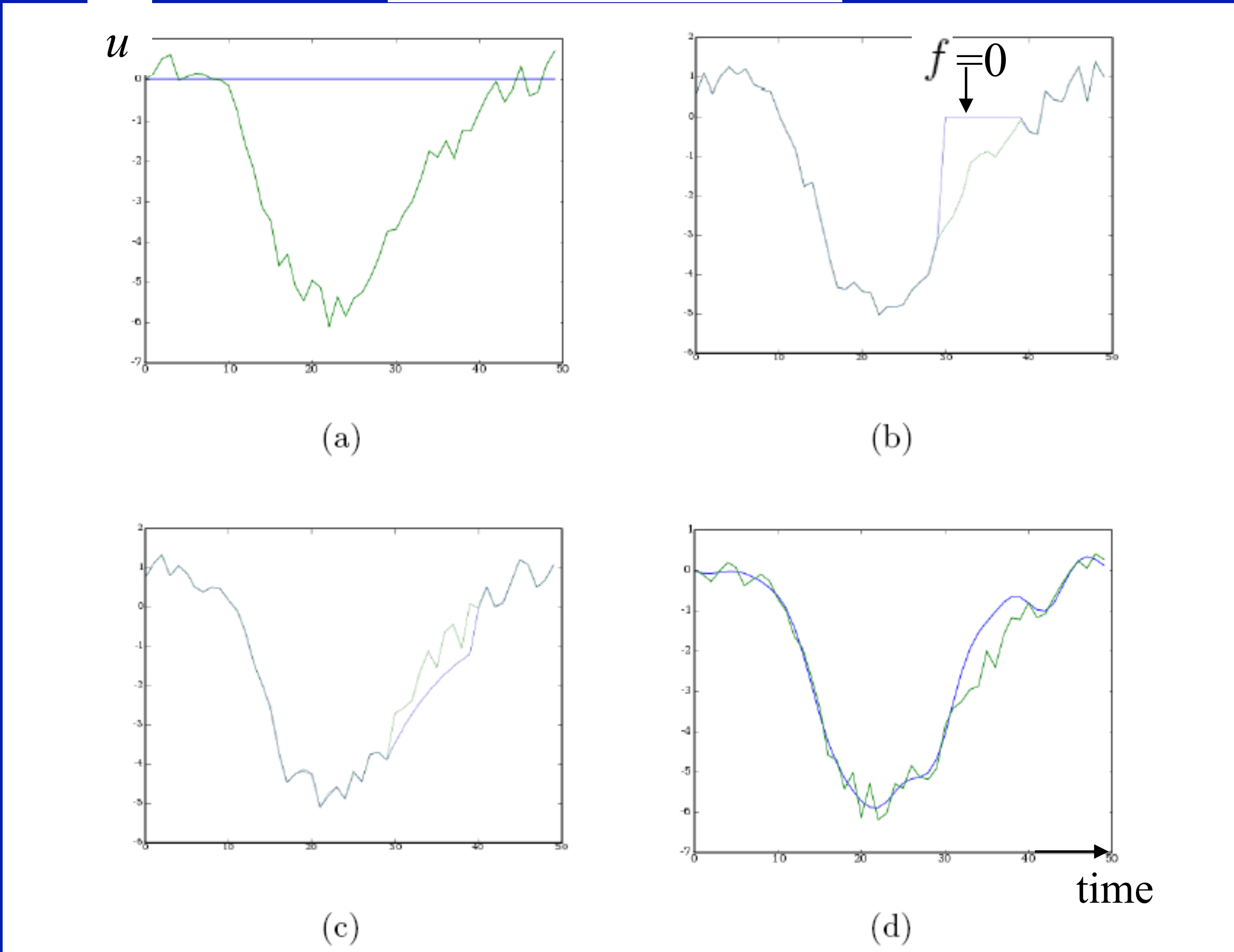
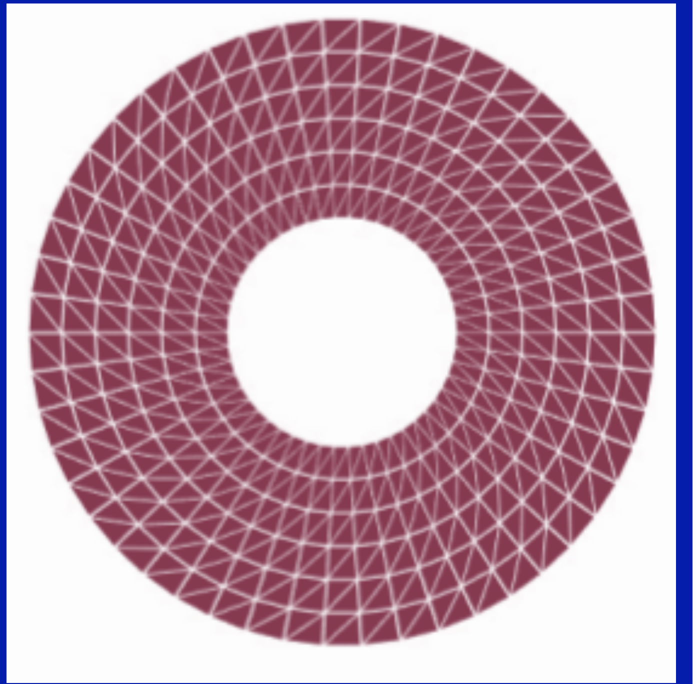
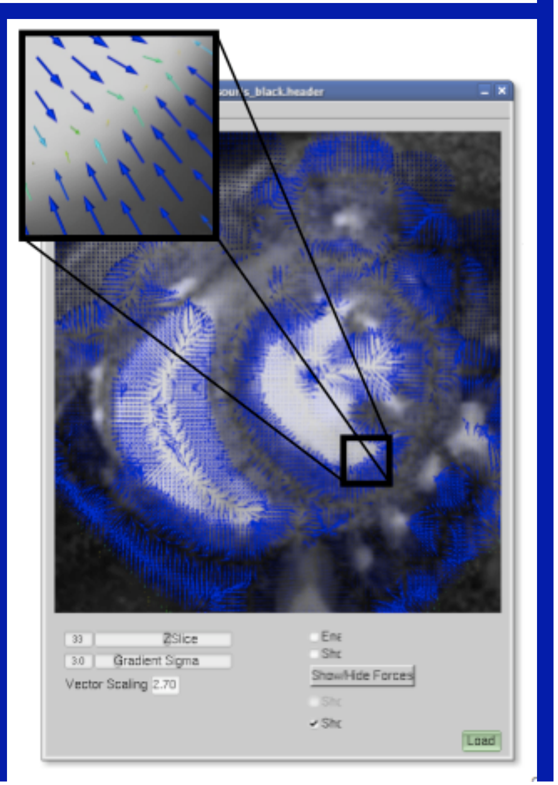


Fig. 1. Sample 1D results: (a) Target signal (green curve) and initialization ($\mathbf{U} = 0$), (b) Results without filtering or damping, (c) Results with damping but no filtering (d=0.2, k=1), (d) Results with damping and filtering (d=0.2,k=1 and 8 harmonics)

- **2D Implementation**
  - **Initial myocardial model: annulus**
  - **Constraint field from images**
    - **Gradient + GVF, but**
      - **Temporal jittering**
      - **Local lack of data**
    - **Morphological pre-segmentation as a constraint (PhD thesis J. Cousty, ESIEE) + GVF**

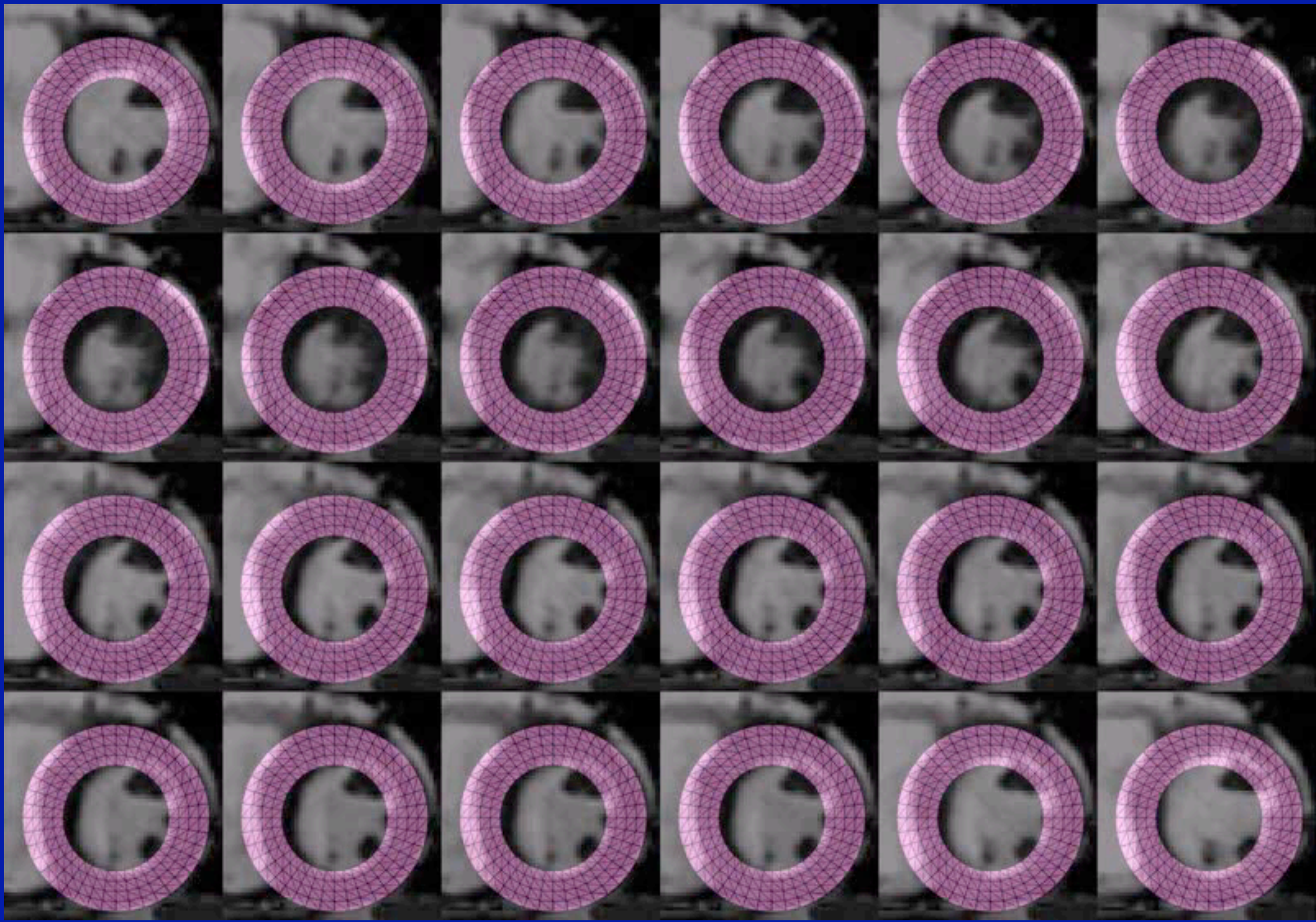


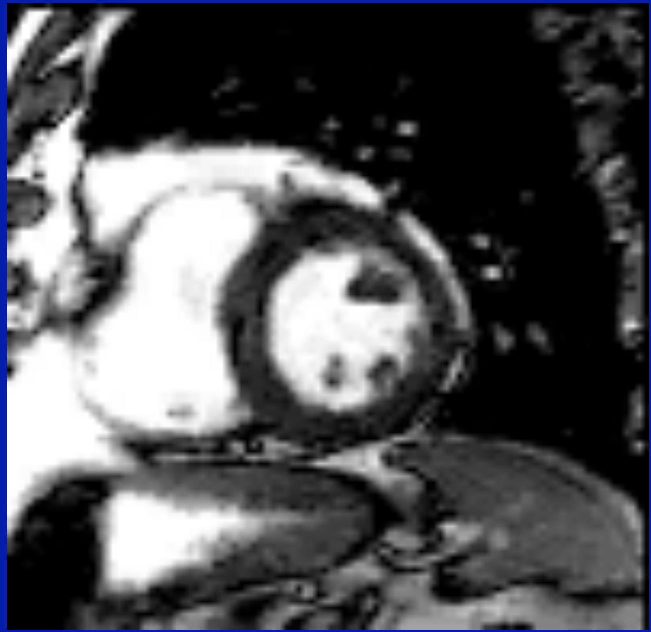


Dynamic DET segmentation Results

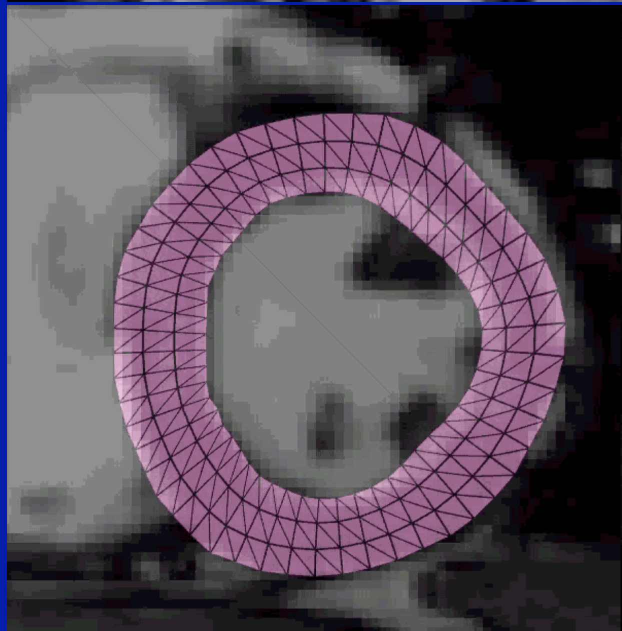
- MRI in vivo Sequences
  - Human cardiac MRI database at http://laurentnajman.org/heart
    - 18 cases
    - multi-phase, multi-slice cine-MRI
      - 5-10 slice levels 256x256
      - ~1mm in plane, 5-10mm slice thickness
      - 15-30 phases
  - IMPEIC project: 'Initiative Multicentrique pour une Plateforme d'Evaluation en Imagerie Cardiaque' (supported by GDR STIC-Santé)

Time →

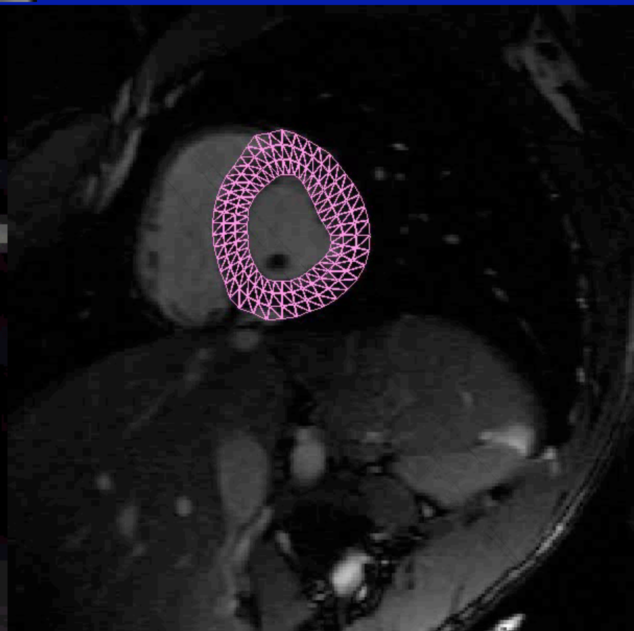




in vivo MRI Sequence from the database

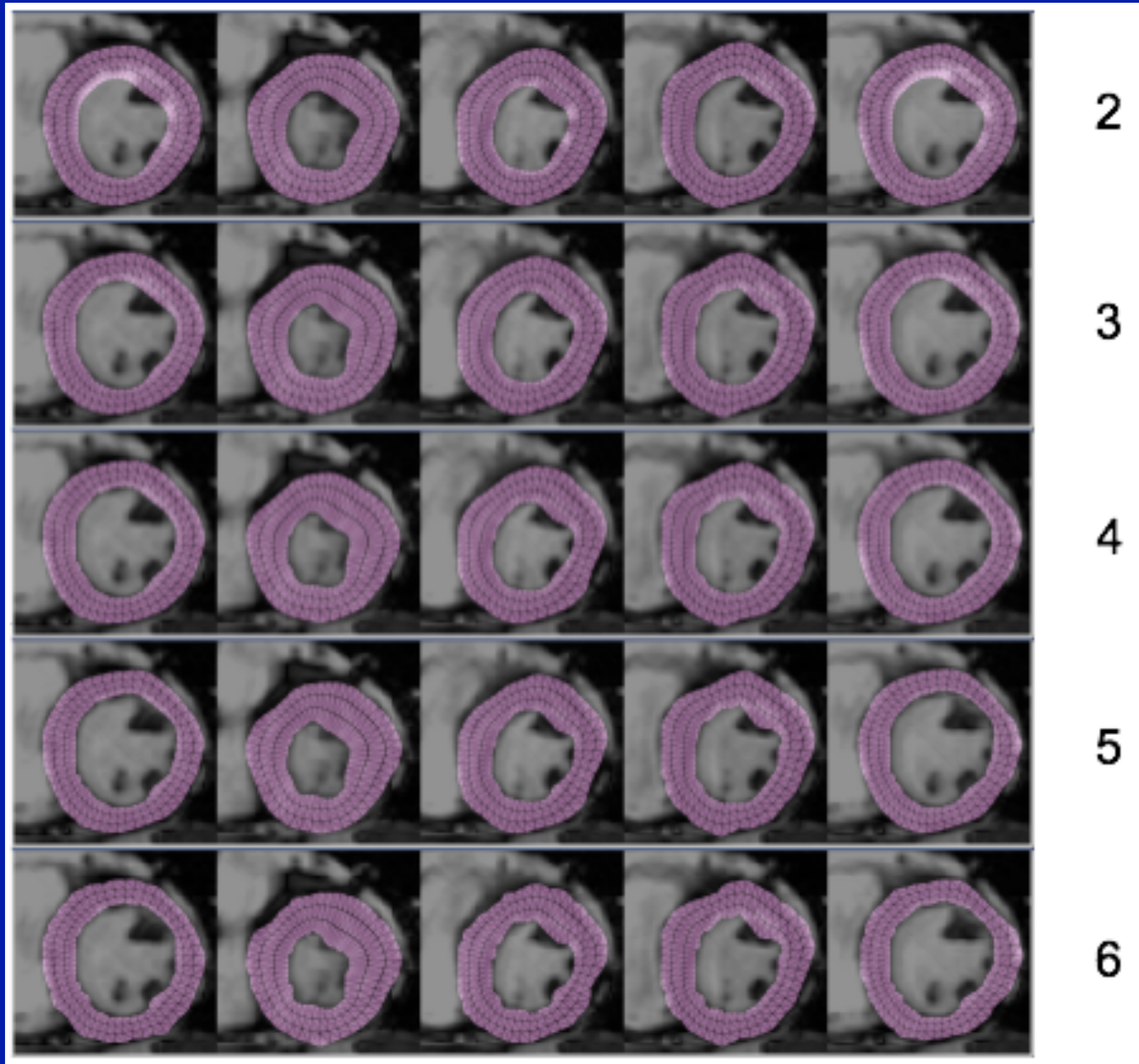


Segmentation with pre-segmentation



GVF based Segmentation

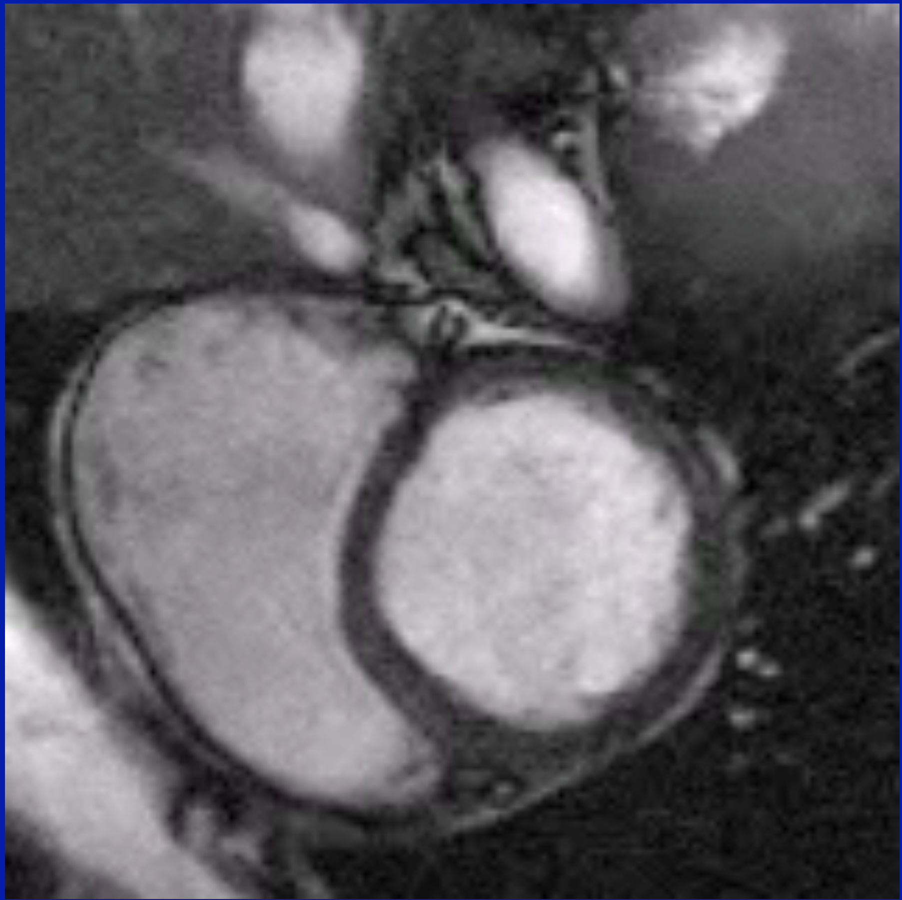
- **Harmonic order impact**



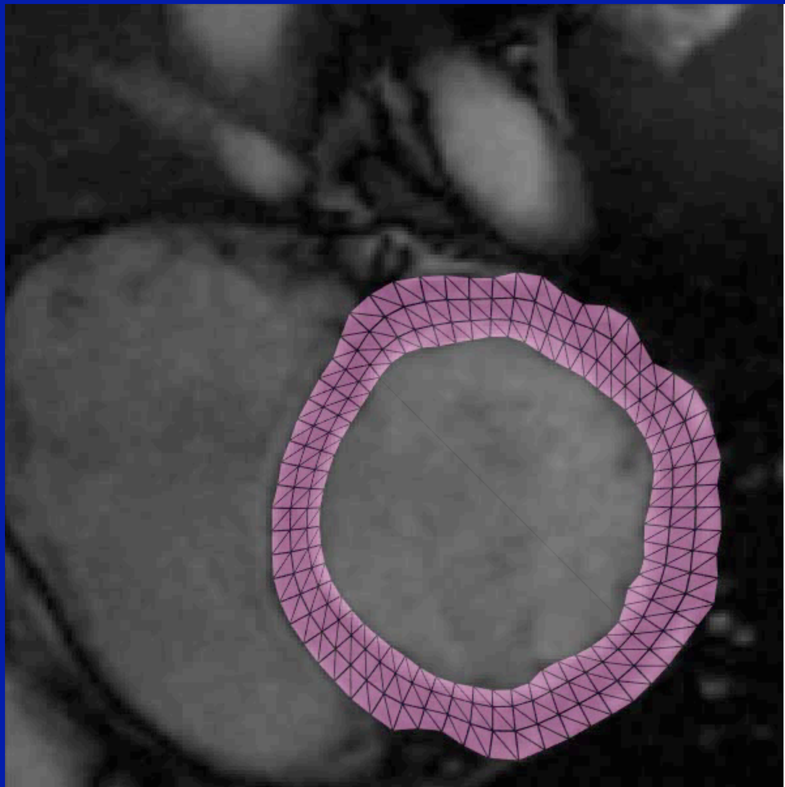
Dynamic DET motion tracking Results

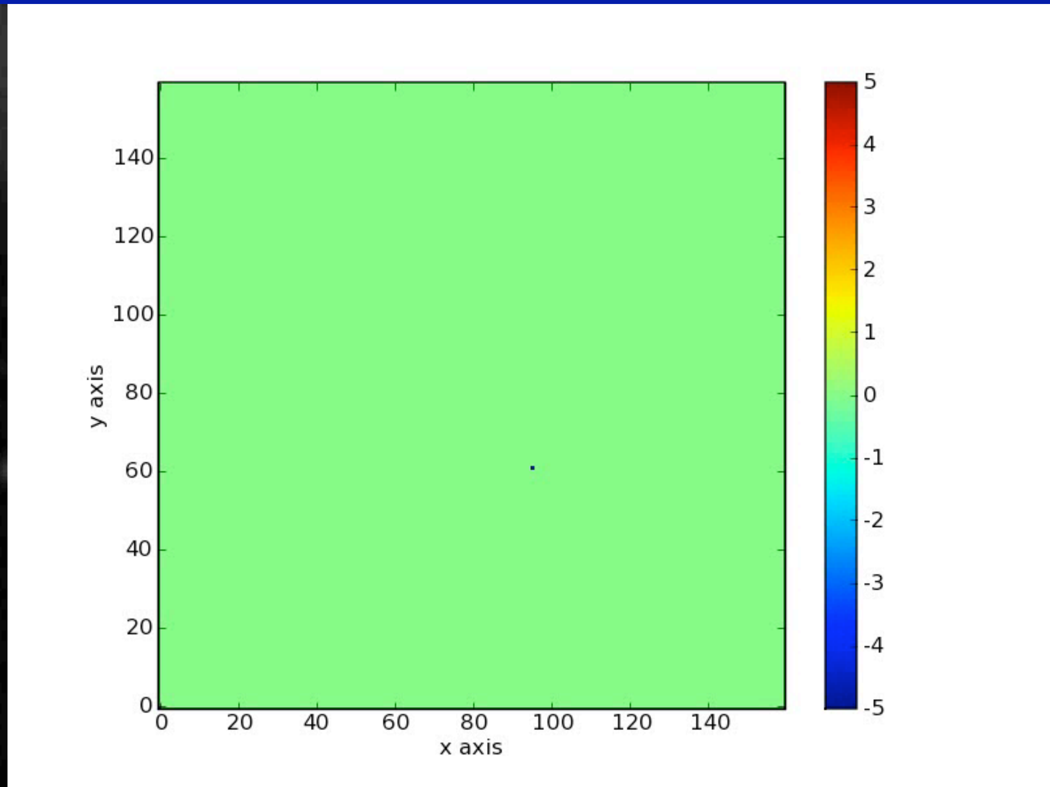
- **Synthetic 2D MRI Sequences**
  - **Spatio-temporal reference heart model** *[Clarysse, MEDIA 2000]*
  - **Simulated MRI Sequence** *[Delhay, submitted]*
  - **Parameters**
    - Model: normal/patho
    - Image: variable noise level

Creatis LRMN



Simulated Sequence ‘normal subject’,
~ basal level





Radial displacement
error (mm)

Conclusions on DET model

- Generic concept
  - Adaptable to various geometries :Tested on 3D US imaging
  - Dynamic DET: motion tracking in Cine MRI ➔ tagged MRI
- Still...
  - Parameter tuning
  - Template initialization
- Remarks
  - Computing a convenient force field (modality dependent)
  - Simplifying image information
    → low level processing
    → multi-resolution approaches

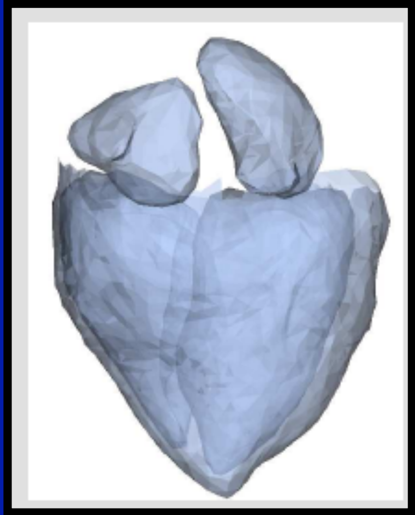
Creatis LRMN

A Priori Statistical dynamical model

Learning based static model (4 chambers)

- 15 healthy subjects [*Lötjönen et al.*, 2004]
- Short Axis + Long Axis slices (End- Diastole)

Set of n geometrical models
whose points are spatially coherent



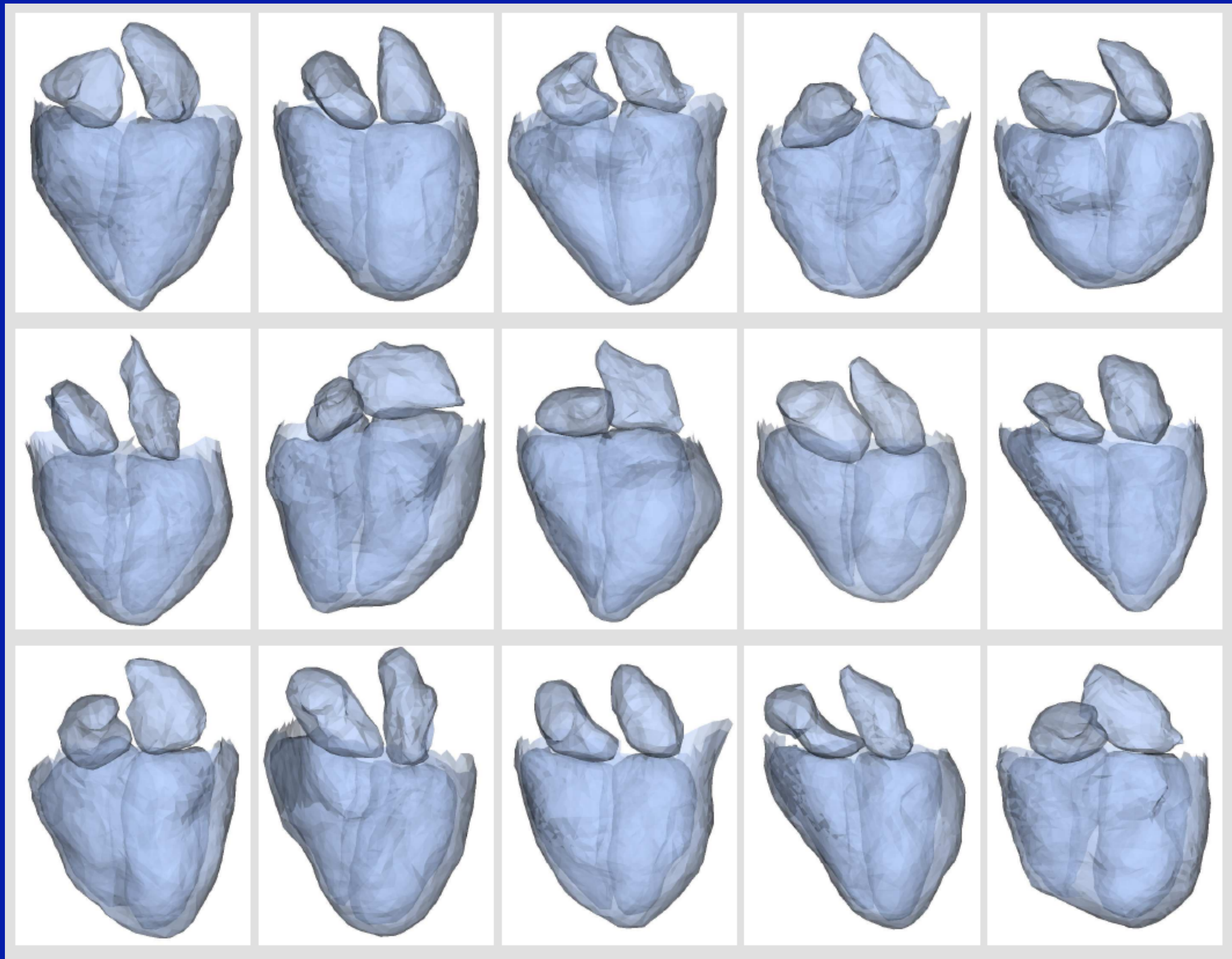
$$\bar{\mathcal{S}} = \frac{1}{n}\sum_{p=1}^{n}\mathcal{S}(p) = \frac{1}{n}\sum_{p=1}^{n}\left(\boldsymbol{x}^{i,p}\right)_{1\leq i\leq m}$$

Semi-landmarks number = 2086

Collab. J. Lötjönen, HUT & VTT, Finland

- **Inter-individual variability**

Subject 1



Subject 15

Learning based dynamic model

[Delhay *et al.* Cinc 05]

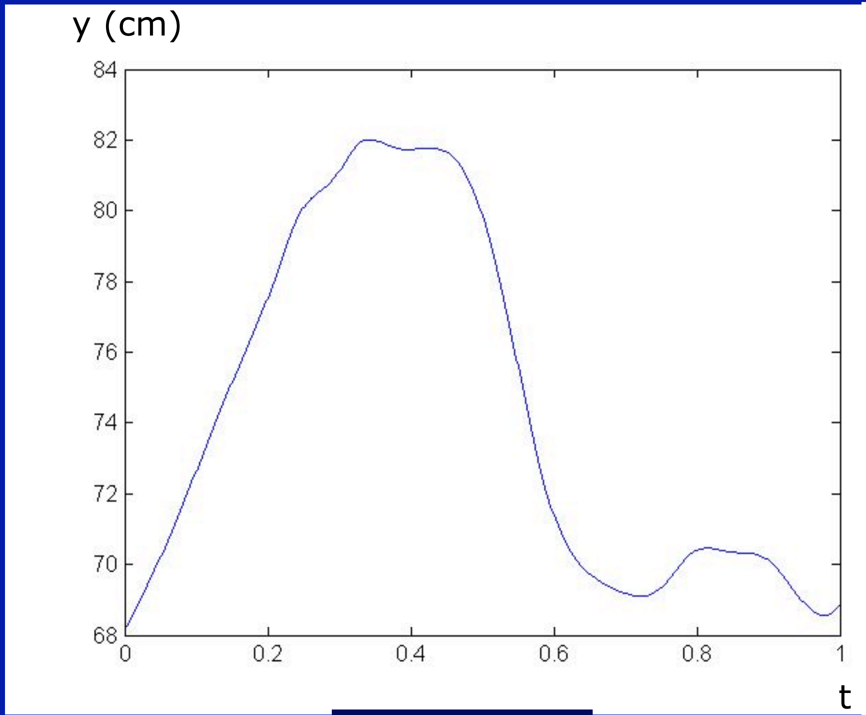
➡ Atlas transport through the sequence

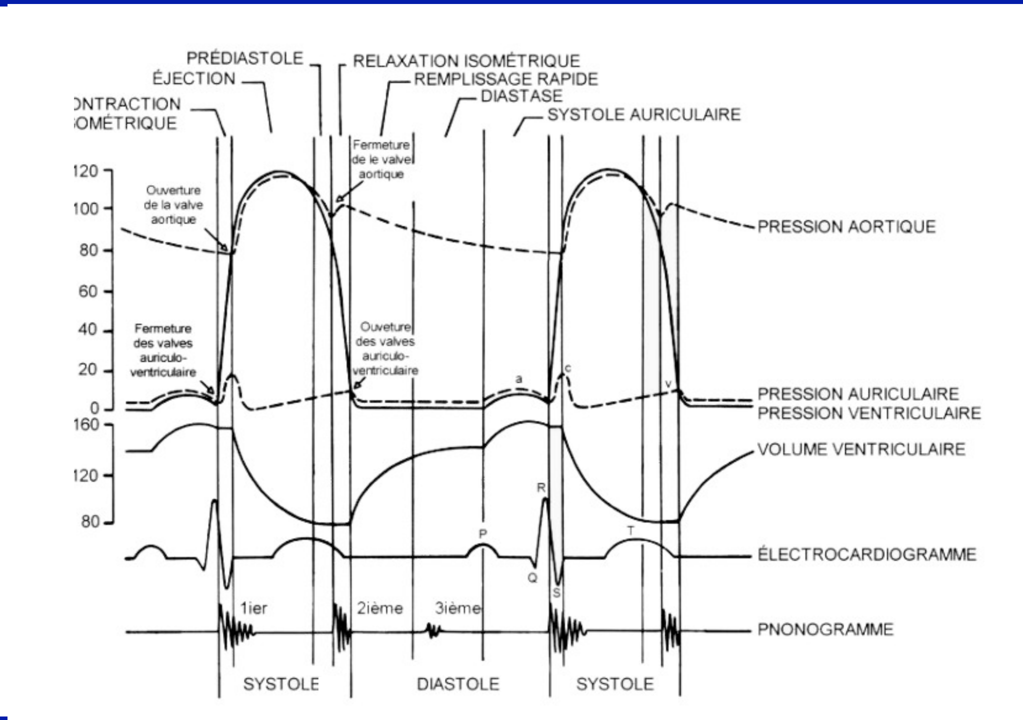
For each subjects:
sequential non–rigid
registrations
[*Lötjönen and Mäkelä*, 2001]

+

Manual corrections

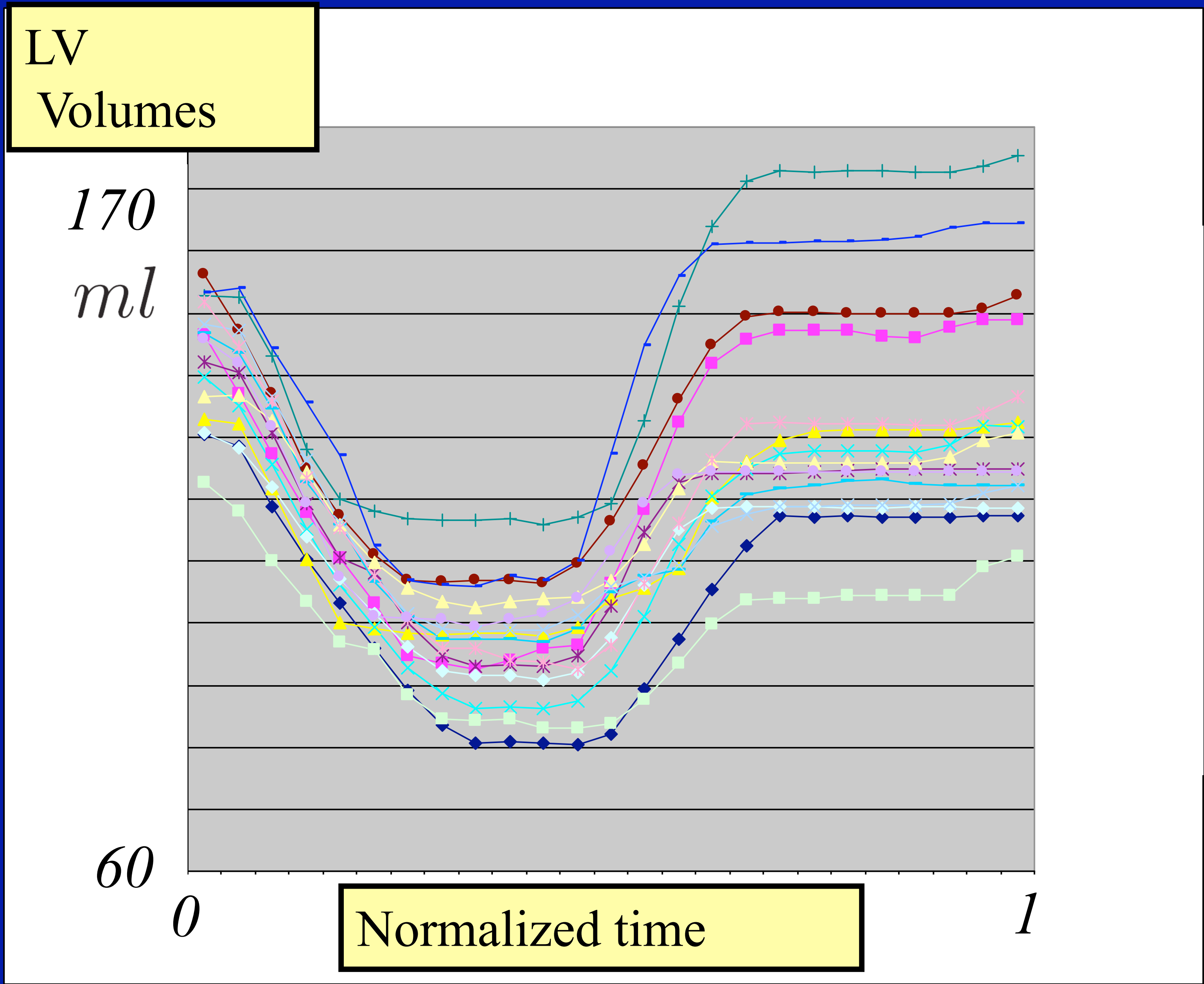
Trajectory normalisation for 15 healthy volunters, ~2100 pseudo-landmarks over the whole heart



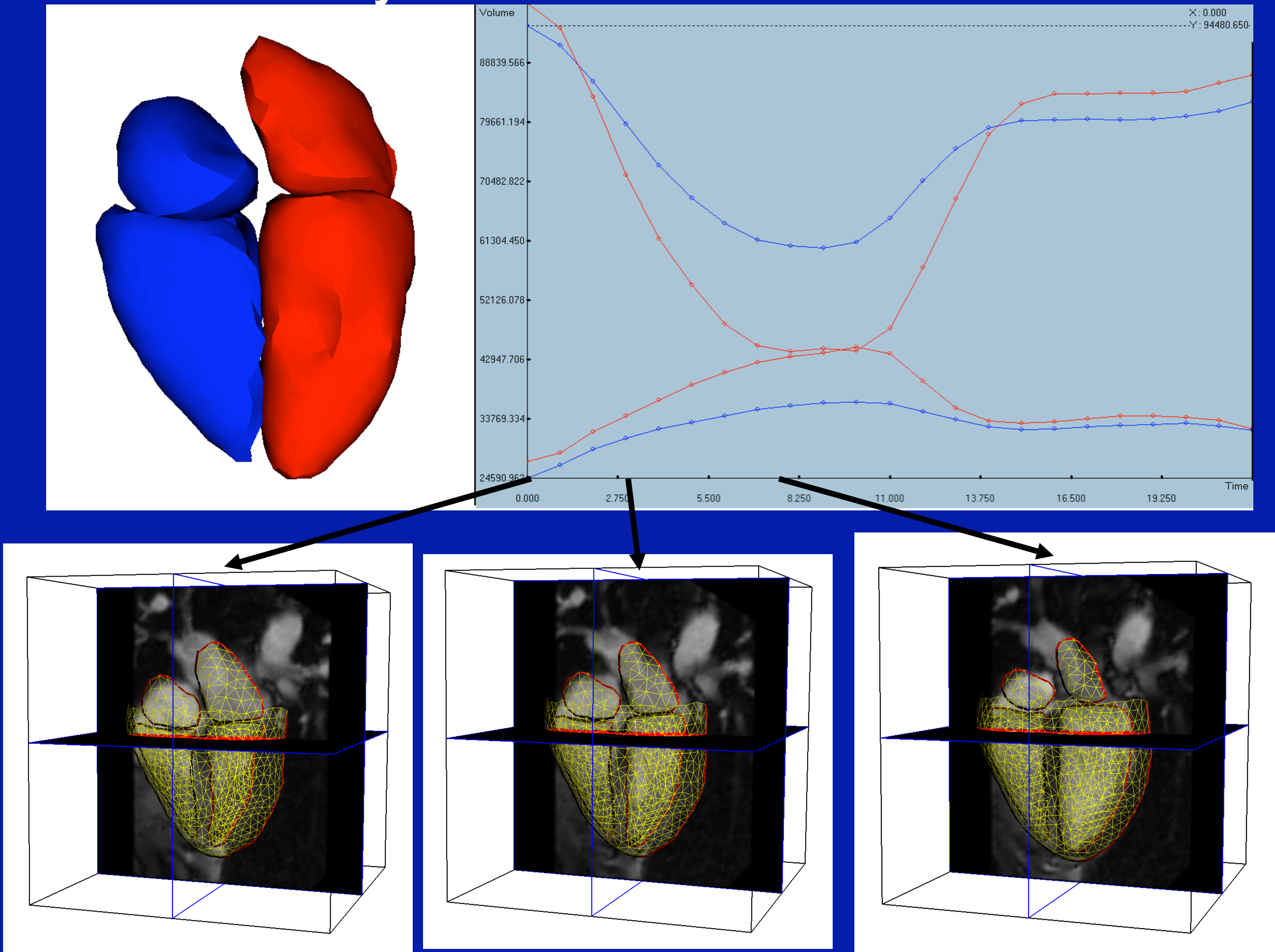


0 1

D S D


LV
Volumes
170
ml
60
0
Normalized time
1

Mean dynamical model



Landmark variability modeling

Parzen Windowing

- Only one parameter
- Continuous probability density function (*PDF*)

$$p(\boldsymbol{x}^i(t)) = \frac{1}{nh}\sum_{p=1}^{n} K\left(\frac{\|\boldsymbol{x}^i(t) - \boldsymbol{x}^{i,p}(t)\|^2}{h}\right)$$

n : number of subjects in the data set

$\boldsymbol{x}^{i,p}(t)$: Coordinates of the landmark i at time t

K : Gaussian kernel

h : Kernel size

A priori driven segmentation

A priori regularizing term C

$$\mathcal{J}(I_c, I_s, \boldsymbol{\varphi}) = \mathcal{A}(I_c, I_s, \boldsymbol{\varphi}) + \alpha\mathcal{R}(\boldsymbol{\varphi}) + \gamma\mathcal{C}(\boldsymbol{\varphi})$$

$$\mathcal{C}(\boldsymbol{\varphi}, h) = \frac{1}{2}\sum_{i=1}^{m}(1 - p(\boldsymbol{x}^i(t_j), h))^2$$

Jacobian of the transformation

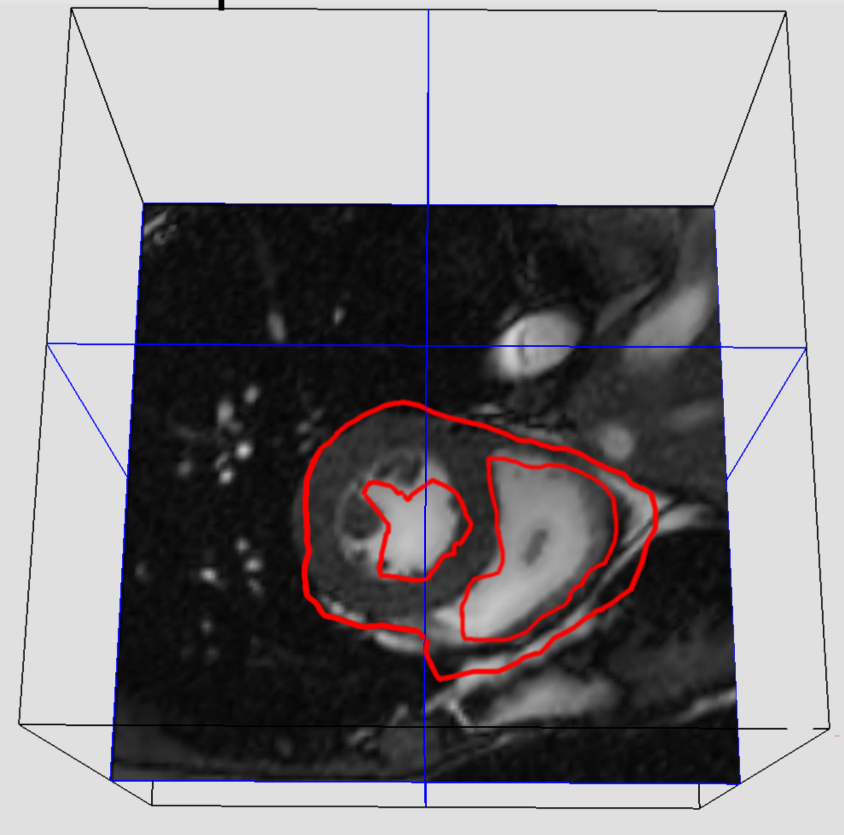
$$\frac{\partial \mathcal{C}_i(\boldsymbol{\xi}, h)}{\partial \boldsymbol{\xi}} = \Big(1 - p(\boldsymbol{\varphi}_{t_0;t_j}(\boldsymbol{x}^i(t_0), \boldsymbol{\xi}), h)\Big) \cdot$$

$$\ldots \quad \times J \times \frac{\partial p(\boldsymbol{\varphi}_{t_0;t_j}(\boldsymbol{x}^i(t_0), \boldsymbol{\xi}), h)}{\partial \boldsymbol{x}}$$

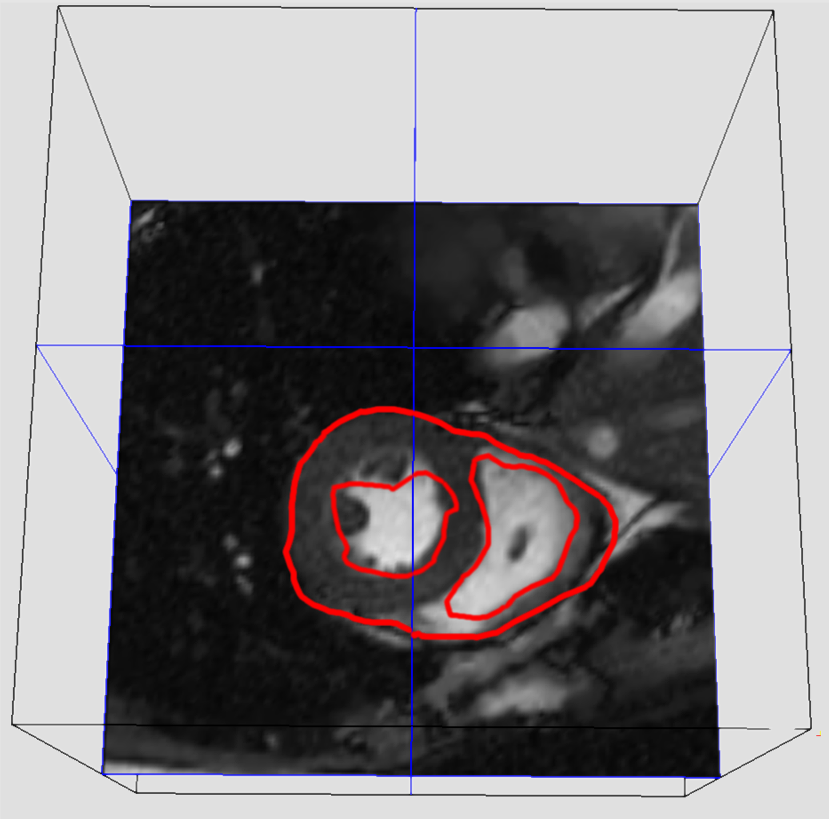
Derivative of the Parzen function

Preliminary results : on 3D real cardiac data (Structures tracking)

Sequential estimations



Sequential estimations + model



instant: 5/25

$\alpha = 0.1 \quad \gamma = 0.4$

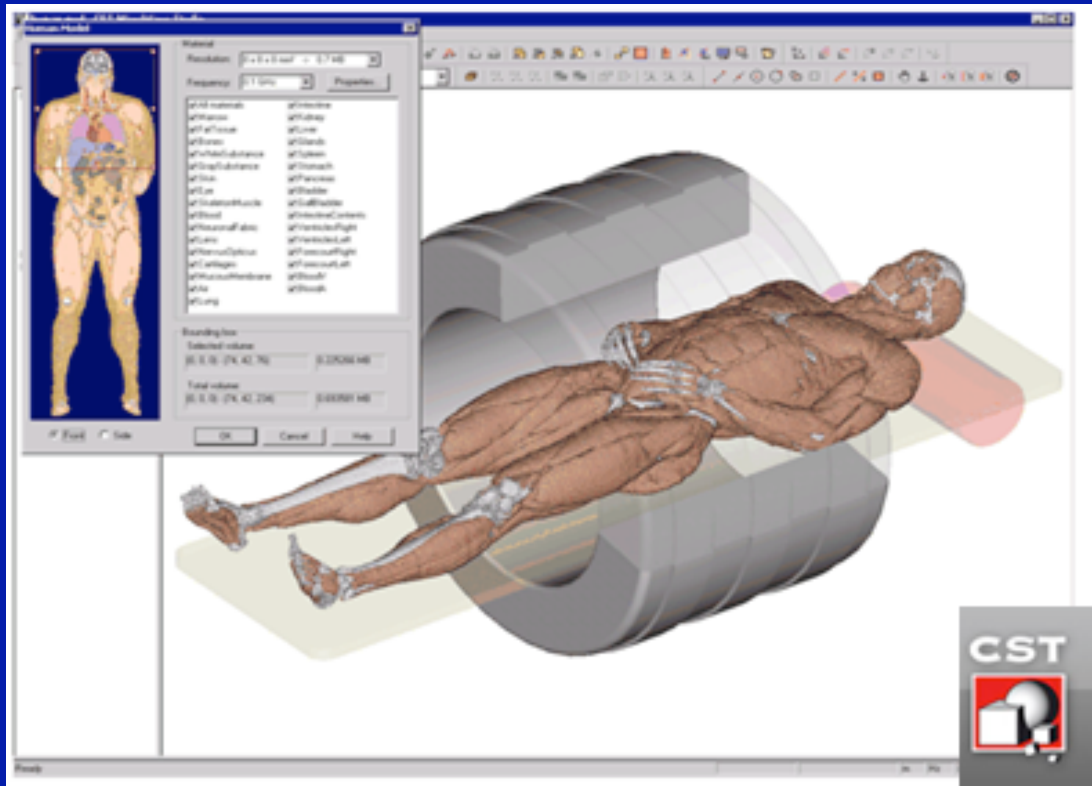
$h = 5.0mm$

Conclusions on Learning based models

- Generic concept
  - Adaptable to various anatomical structures
  - Adaptable to deformable structures
- But
  - Construction of the a priori model is laborious
  - Difficulties to construct large sample sets
    ➔ limitation in shape variations (normal & abnormal)
- Artificial enlargement *[Koikalainen, IEEETMI-2008]*
  - *Partitioning the structure into separate parts*
  - *Non-rigid local perturbations*
- Artificial smoothness
  - Covariance matrix to induce smoothness to def. modes
  - PCA + FEM

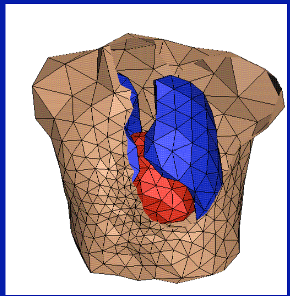
Method's evaluation : a whole numeric approach

➔ 3D virtual model and imaging



http://www.cst.com/

• Components



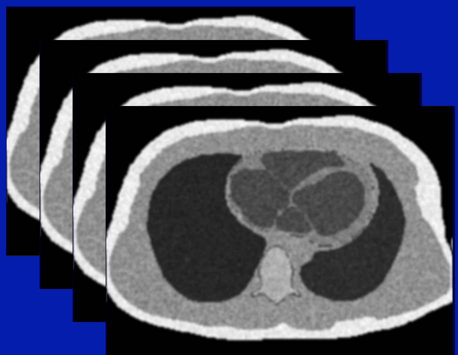
Models

↓

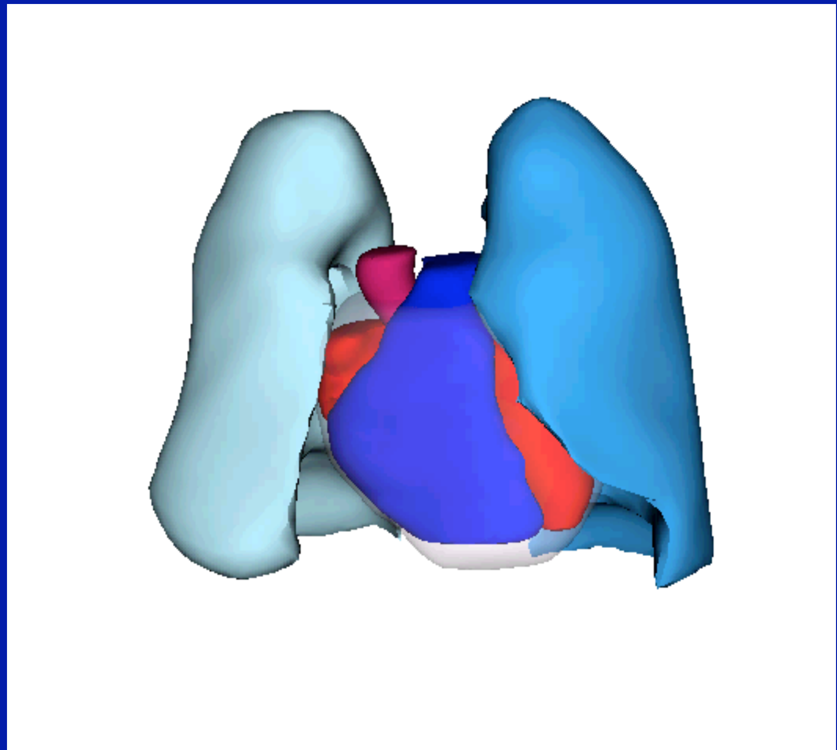
Medical imaging modality simulators

↓

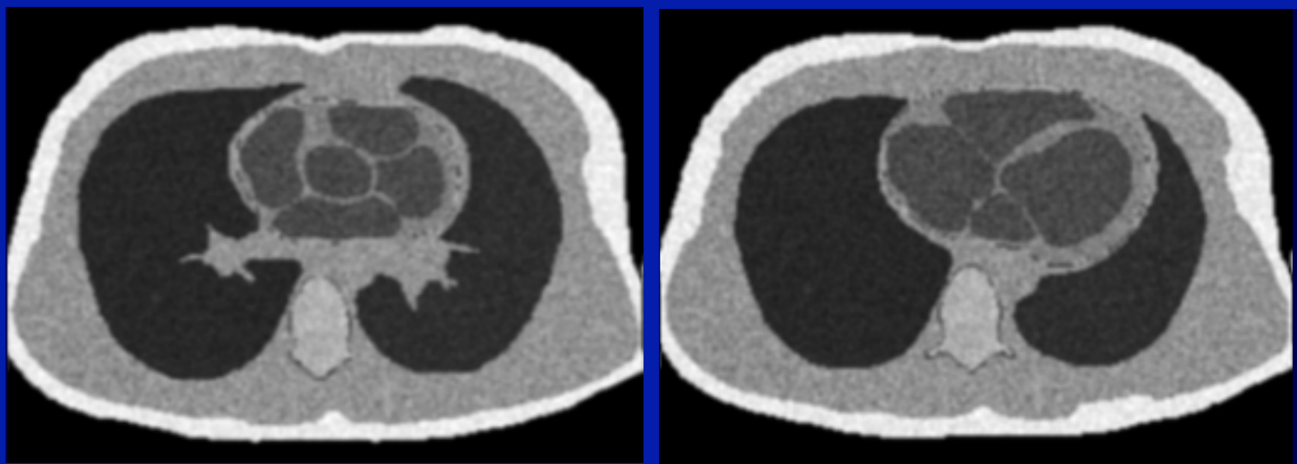
Simulated images



Breathing thorax & beating heart model



[Haddad, PhD thesis 2007], [Haddad et al, IEEE EMBS, 2007]

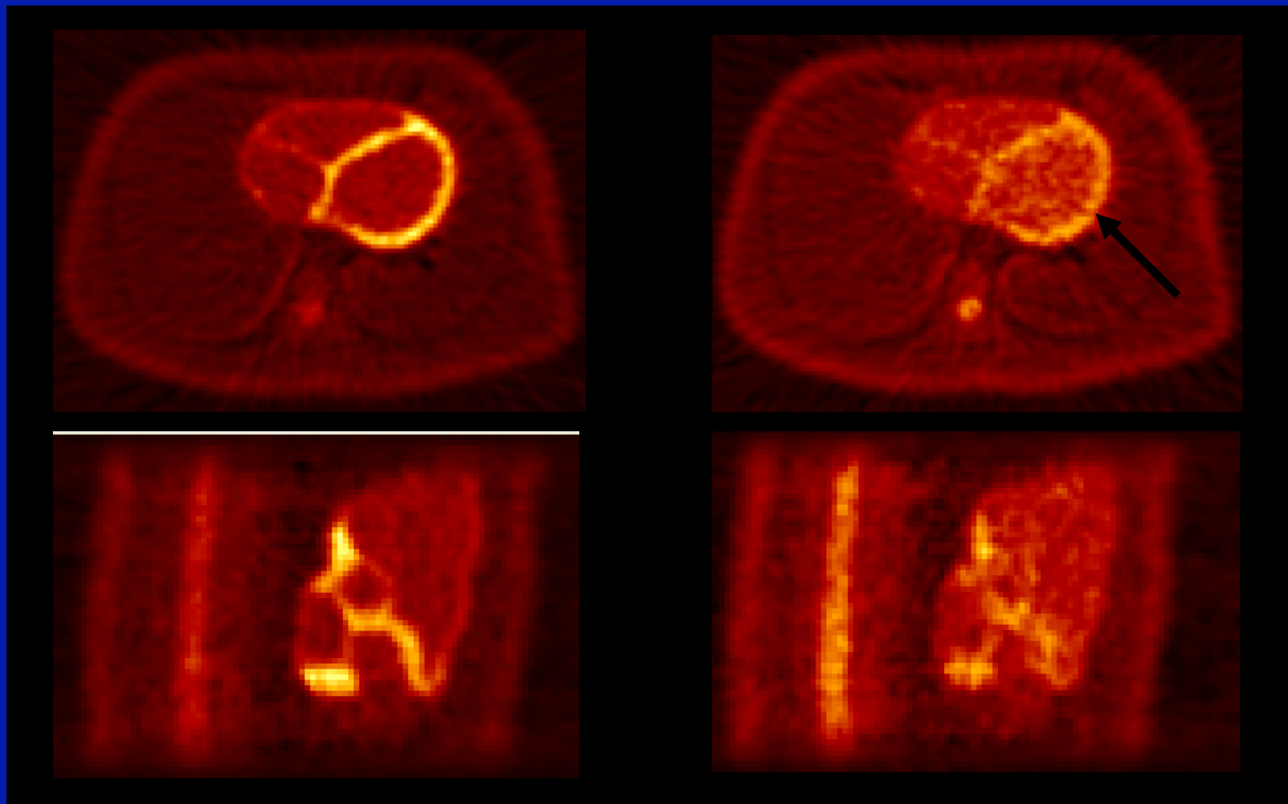


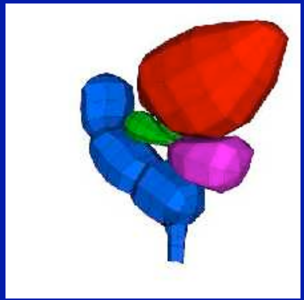
Simulated images, MRI Simulator SIMRI, CREATIS-LRMN *[Benoit-Cattin et al, JMR,05]*

PET simulation with SORTEO (Cermep, Lyon):

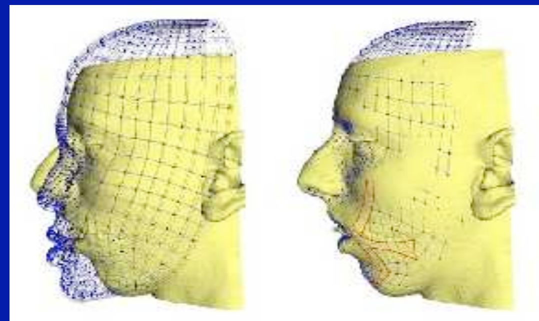
Simulated **emission** PET images for healthy and ischemic models (hypocaptation of glucosis)

	Healthy model	Ischemic model (F-18 collecting in the myocardium with 40% of its initial value)
Axial slice		
Sagittal slice		





→ **Simed project**
(P. Clarysse – E. Promayon)



Simulation en Imagerie Médicale pour le Diagnostic et la Thérapie

@

→ Virtual Physiological Human European NOE

Collaborations / Support

Creatis LRMN

Dynamic Imaging Team

Past PhD students:

- M. Han
- F. Vincent
- Q. C. Pham
- T. Mäkelä
- N. Pauna
- R. Haddad
- Bertrand Delhay

PhD students:

- M. Berkane
- J. Vandemeulebroucke
- L. Grezes-Besset
- T. Schilling

Post-docs:

- J. Schaerer

HUT, Finland

Prof. T. Katila
J. Nenonen

Collaborations

- T. Arts, CARIM, Maastricht
- N. Costes, CERMEP, Lyon
- J-M Morvan, IGD, Lyon
- J. Pousin, Inst. C. Jordan, Lyon
- C. Ginestet, CLB, Lyon
- D. Clot, LASS, Lyon

Technical Research Centre of Finland (VTT)

J. Lötjönen

VTT INFORMATION TECHNOLOGY

Supports

Région Rhône-Alpes: Cluster ISLE, ADemo, Santé & HPC, Cancéropole
CNRS: PICS 1932, AS ICOMIM
GDR STIC-Santé: Projet IMPEIC
Ministère de la Recherche: ACI AGIR
ANR: GWENDIA
Europe: EGEE, VPH

- **Thank you!**