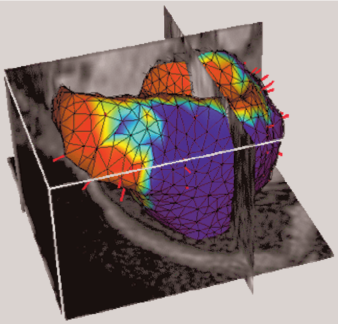
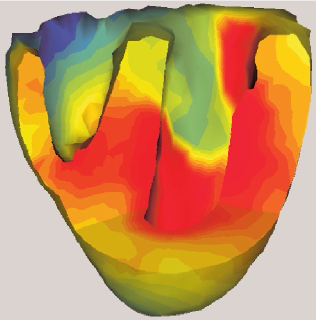


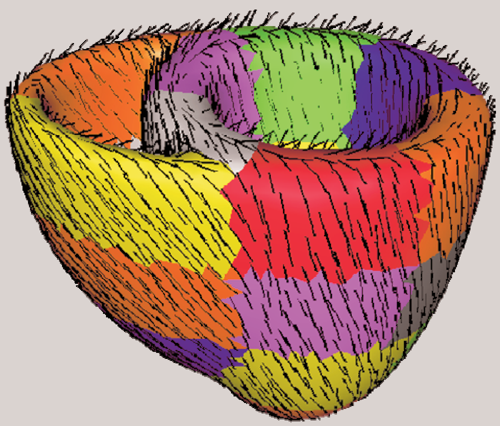


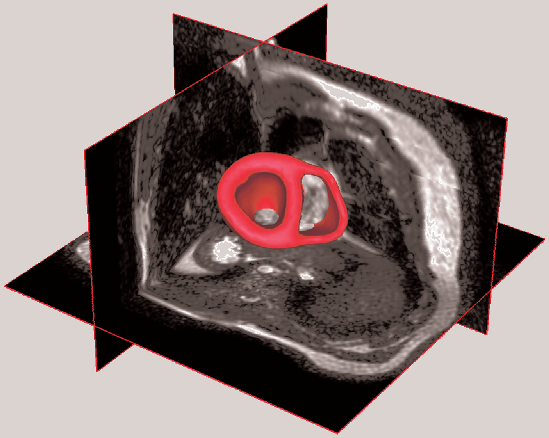
CARDIOSENSE3D

Hervé Delingette

INRIA Sophia-Antipolis
FRANCE

Herve.Delingette@inria.fr





European Meeting- November 2005

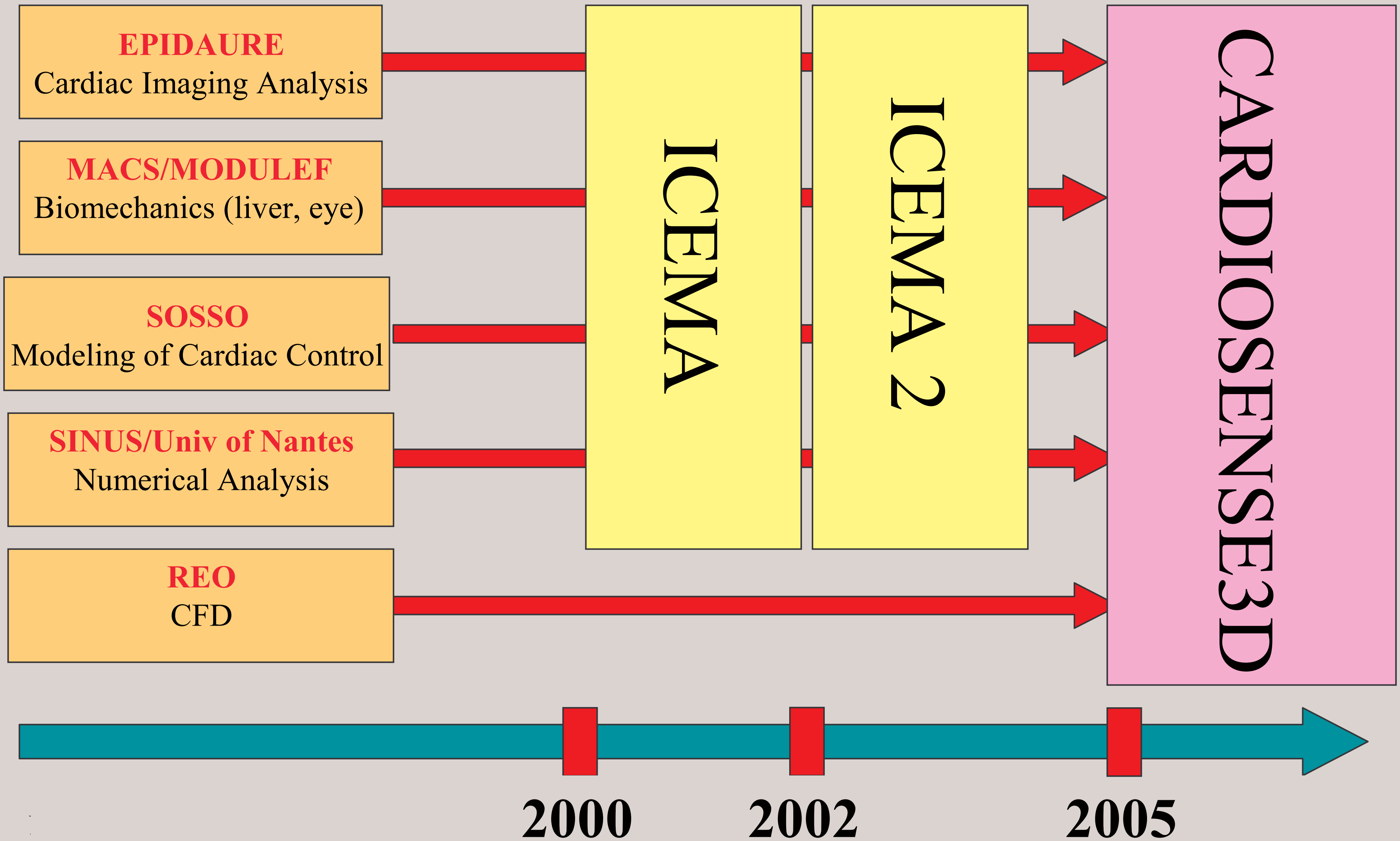
Overview

- Introduction
- Overview of past achievements
- Work in progress
- Perspectives

What is CardioSense3D ?

- An INRIA large initiative action **on cardiac modeling** :
  - Started in **May 2005**
  - It is a **4-year action** (evaluation at mid-term)
  - Transversal action that gathers **4 INRIA Teams** :
    - **EPIDAURE/ASCLEPIOS** (Medical Image Analysis and Simulation) : **N. Ayache**
    - **MACS** (Structural Mechanics) : **D. Chapelle**
    - **REO** (Fluid Dynamics) : **J-F. Gerbeau**
    - **SOSSO2** (Control and Modeling) : **M. Sorine**
  - Coordinated by **H. Delingette & M. Fernandez**

History of CardioSense3D



CS3D : a collaborative framework

- **Physiology & Control**
  - **Sosso**, INRIA
- **Numerical Analysis**
  - **Macs**, INRIA
  - **Reo**, INRIA
  - Caiman, INRIA
  - Gamma, INRIA
  - Pzlen Univ. (Czech Rep.)
- **Industrial**
  - Philips Research France
  - ELA Medical
- **Image Analysis/Simulation**
  - **Epidaure**, INRIA
  - University College (London)
  - Creatis, CNRS
- **Clinical Sites**
  - Guy's Hospital (London)
  - NIH (Washington)
  - HEGP, U 294 (Paris)
  - Montpellier Hospital (Montpellier)

Overview

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Overview of ICEMA achievement 2000-2004

http://www-rocq.inria.fr/sosso/icema2/icema2.html

- Introduction
- Geometrical Modeling
- Electrical Propagation
- Mechanical Coupling
- Clinical Applications

Overall Approach

- Build cardiac simulator coupling electrophysiology and mechanical contraction

- Keep the model complexity comparable to that of macroscopic observations (medical images,…) in order to identify parameters on patient-specific data.

- Develop applications to improve clinical practice

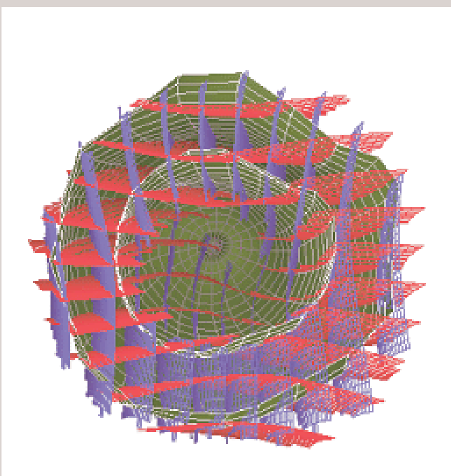
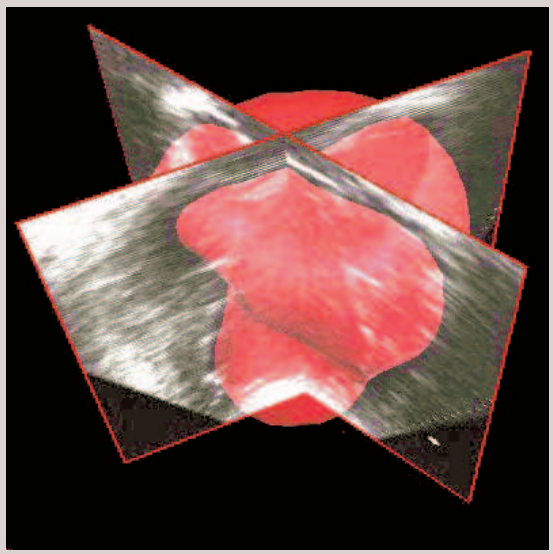
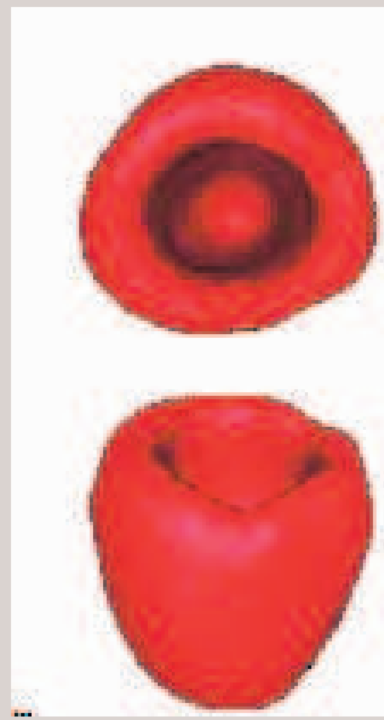
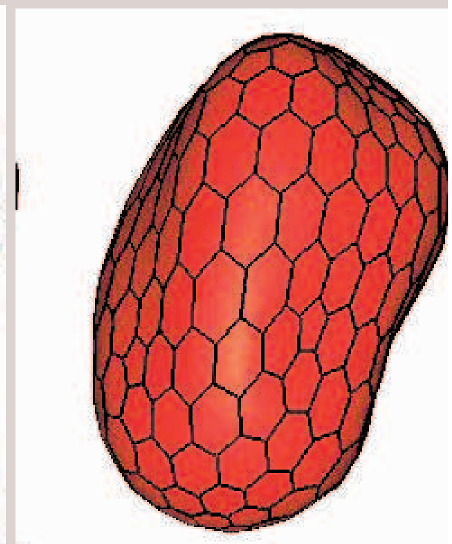
Overview of ICEMA achievement 2000-2004

http://www-rocq.inria.fr/sosso/icema2/icema2.html

- Introduction
- Geometrical Modeling
- Electrical Propagation
- Mechanical Coupling
- Clinical Applications

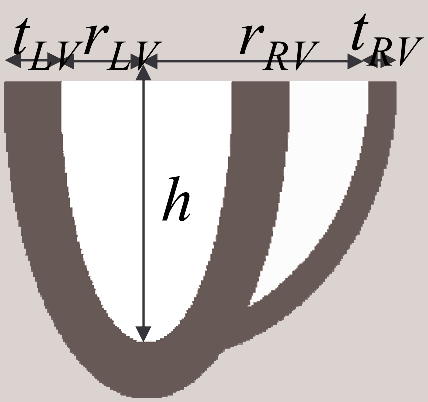
Large set of tools

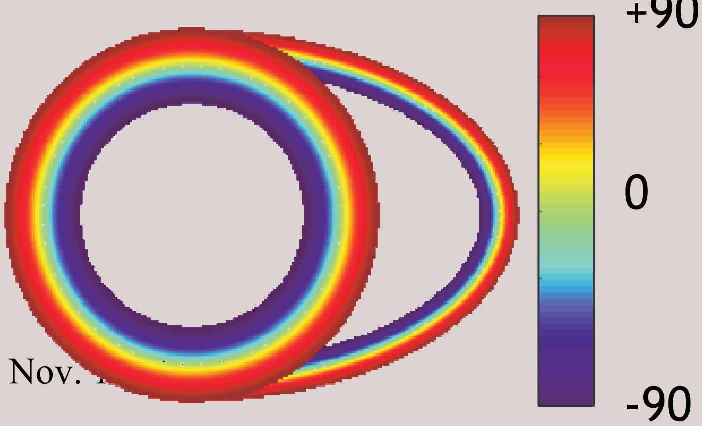
- Medical Image Segmentation

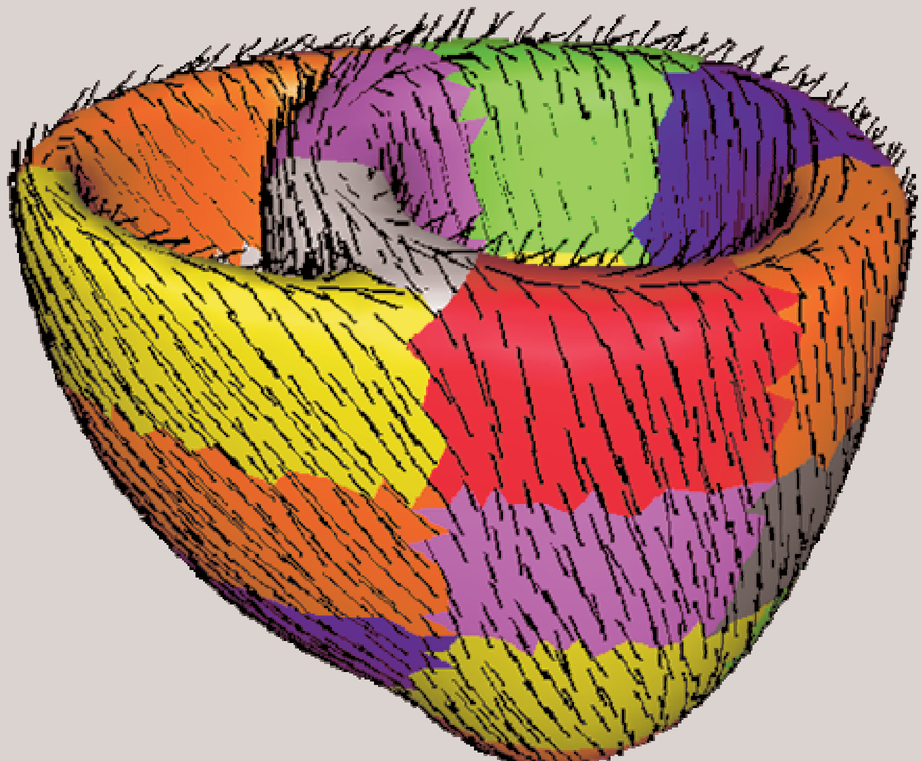
Tagged MRI	3D Echocardiography	Gated Spect	Blood-Pool MR
			

Large set of tools

- Medical Image Segmentation
- Generic and parameterizable bi-ventricular model

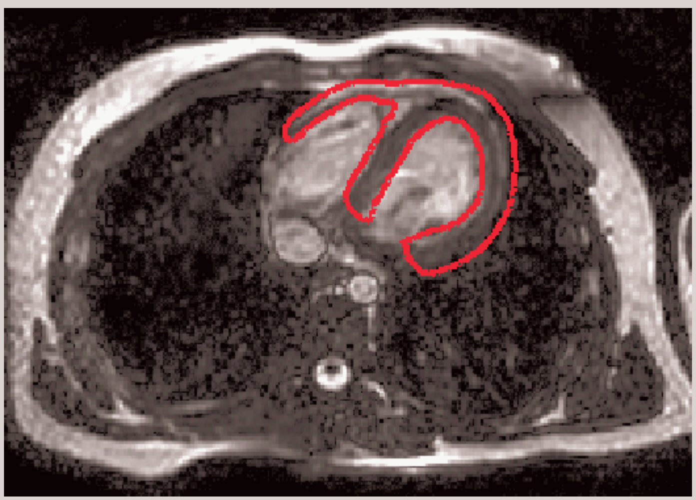


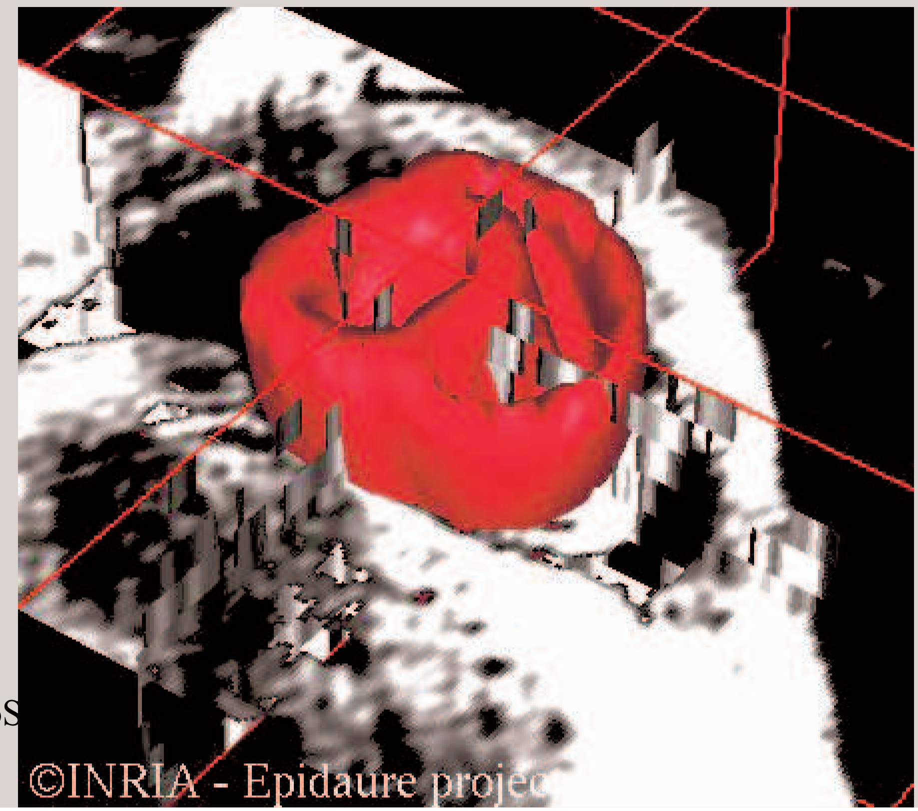




Large set of tools

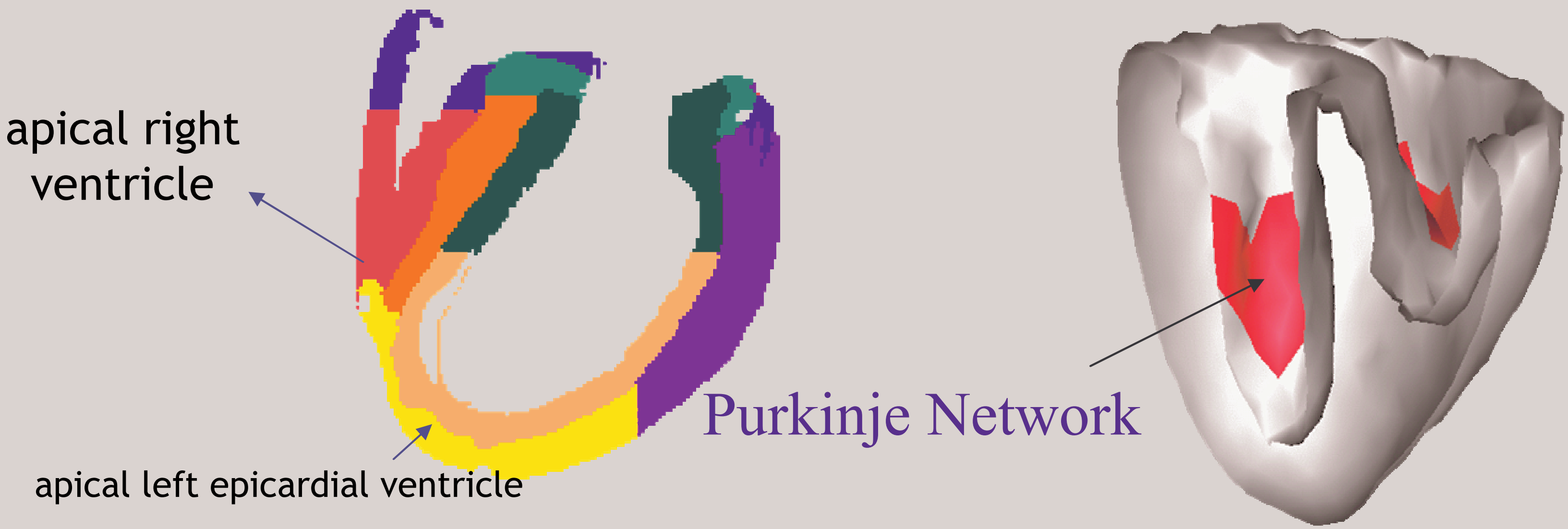
- Medical Image Segmentation
- Generic and parameterizable bi-ventricular model
- Registration of generic model towards patient-specific data





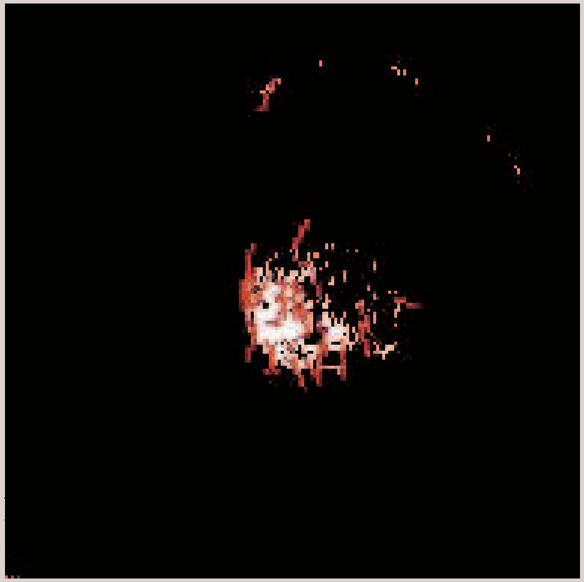
Large set of tools

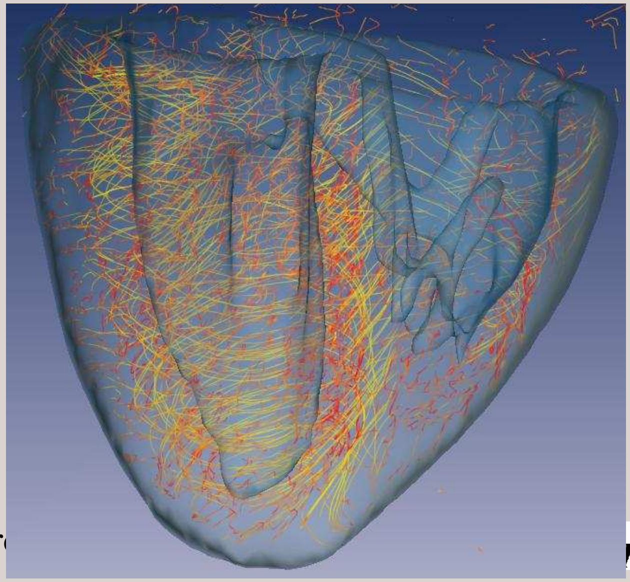
- Medical Image Segmentation
- Generic and parameterizable bi-ventricular model
- Registration of generic model towards patient-specific data
- Registration of a patient-specific model towards an atlas



Large set of tools

- Medical Image Segmentation
- Generic and parameterizable bi-ventricular model
- Registration of generic model towards patient-specific data
- Registration of a patient-specific model towards an atlas
- Analysis of Diffusion Tensor MR Images





Overview of ICEMA achievement 2000-2004

http://www-rocq.inria.fr/sosso/icema2/icema2.html

- Introduction
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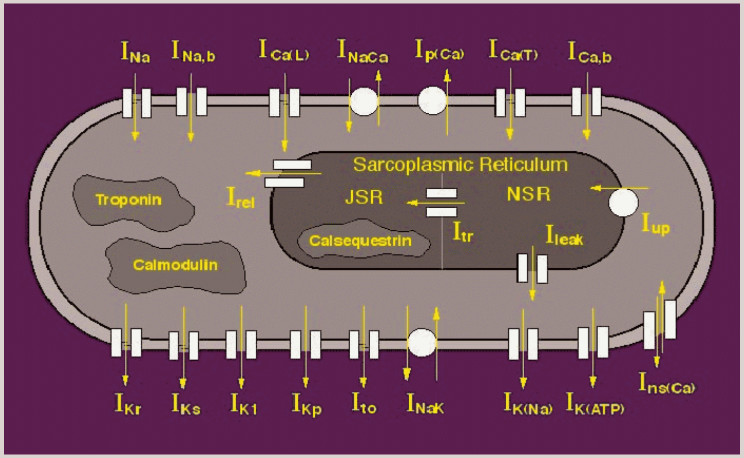
Electrophysiology Model



Two approaches:

1. Ionic models
   - Hodgkin-Huxley
2. <u>Phenomenological models</u>
   - FitzHugh-Nagumo

2. Aliev-Panfilov *Reaction-Diffusion* equations

$$\begin{cases} \partial_t u = \mathrm{div}\,(D\,\nabla u) + ku(1-u)(u-a) - uz \\ \partial_t z = -\varepsilon(ku(u-a-1)+z)) \end{cases}$$

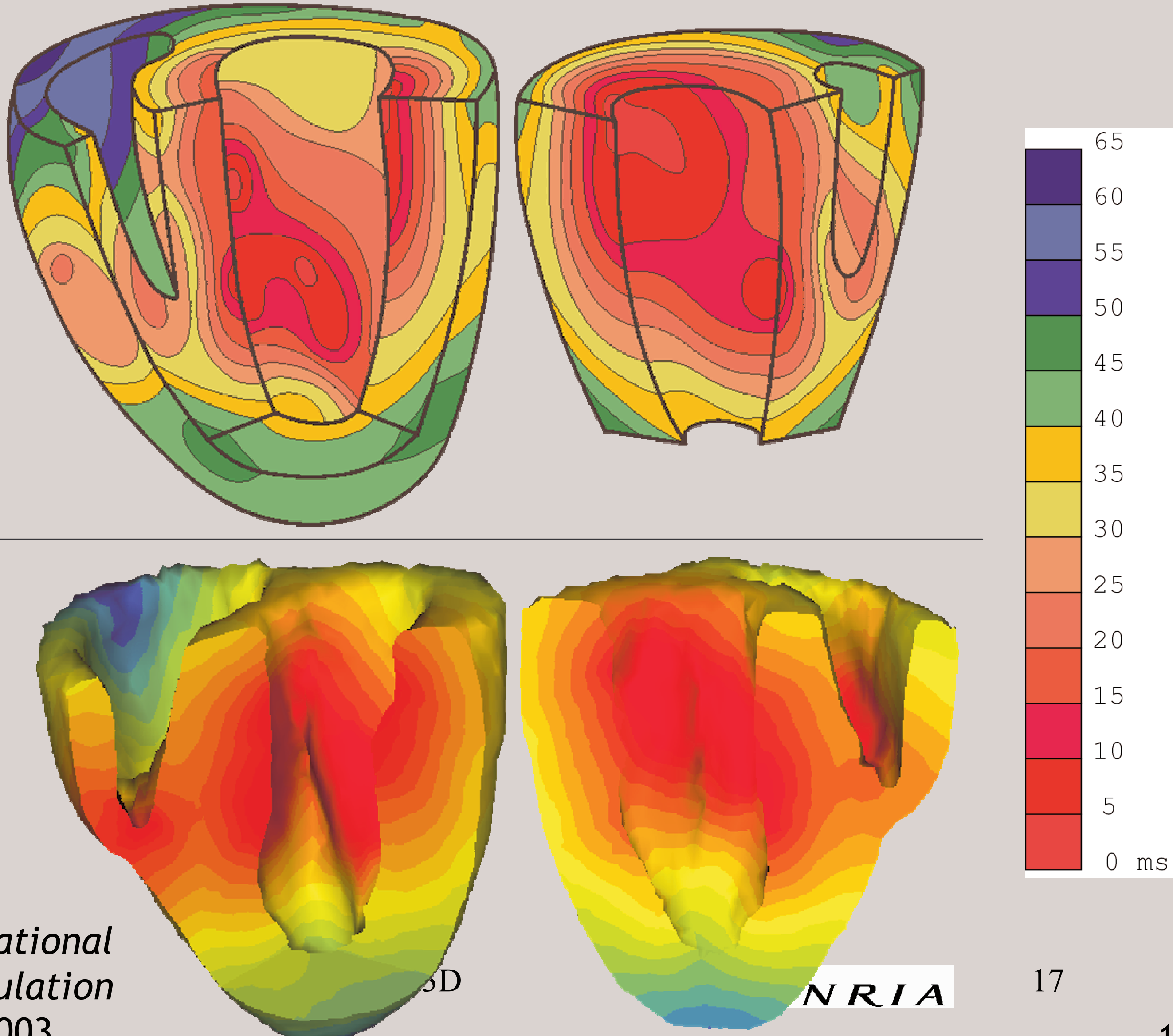
u action potential
D diffusion tensor including fibre orientations
z repolarisation variable

Propagation Validation

work done while in Epidaure, INRIA

Measures
From Durrer *et al*.

Simulation



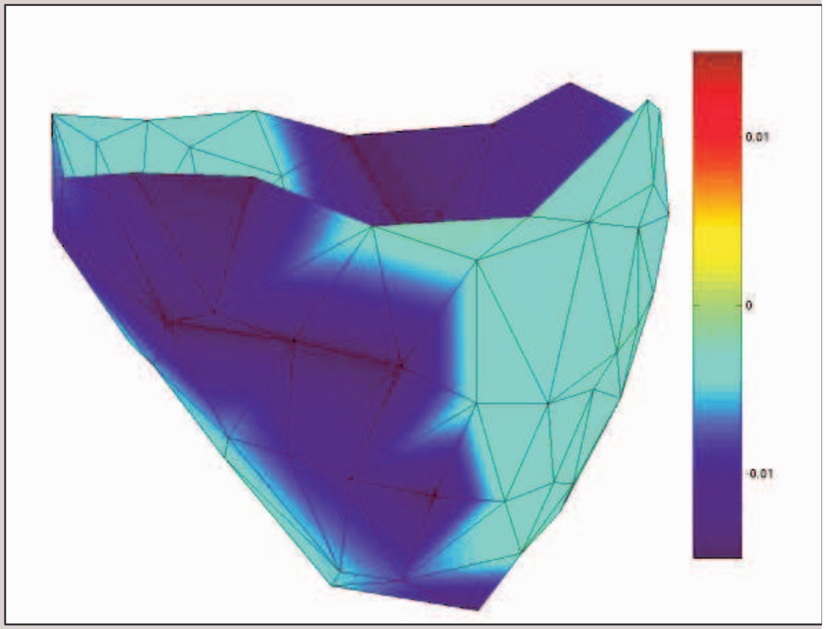
M. Sermesant *et al*., *International Symposium on Surgery Simulation and Soft Tissue Modeling*, 2003.

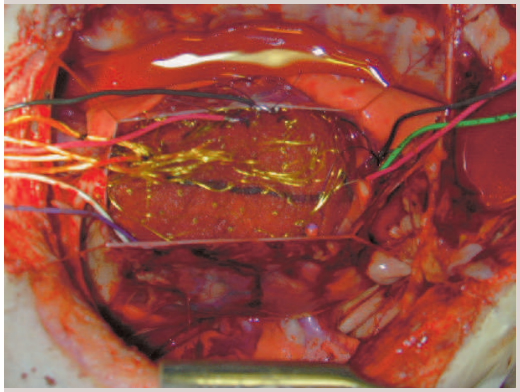
In Vivo Measures (Canine Heart)

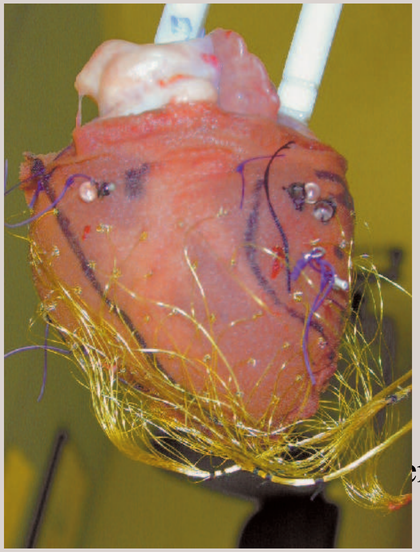
National Institute of Health, Laboratory of Cardiac Energetics

- Artificial electrical pacing
- Electrical: epicardial electrodes socket
  (128 positions* 500 t)
- Motion: MR Images
  (102 positions * 32 t)

Elliot McVeigh, Owen Faris







Identification of Parameters

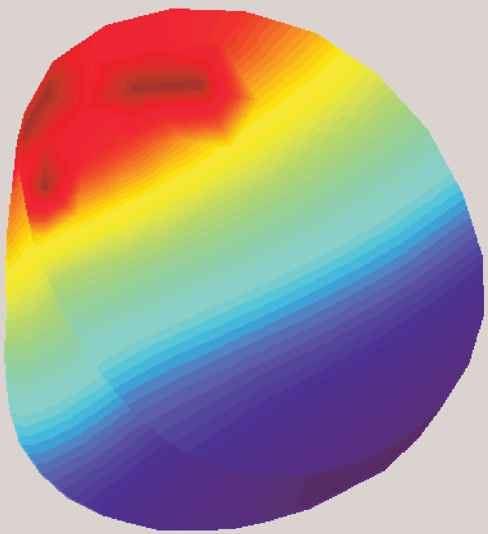
- Criterion : difference between depolarization times of simulations and measures
- Strategy
  - Adjust parameters globally first (ε,k,a,d)
  - Adjust locally the **apparent conductivity parameter** with a gradient descent, approximating derivatives with finite differences

V. Moreau, H. Delingette and N. Ayache :
Inria Research Report 5269, July 2004

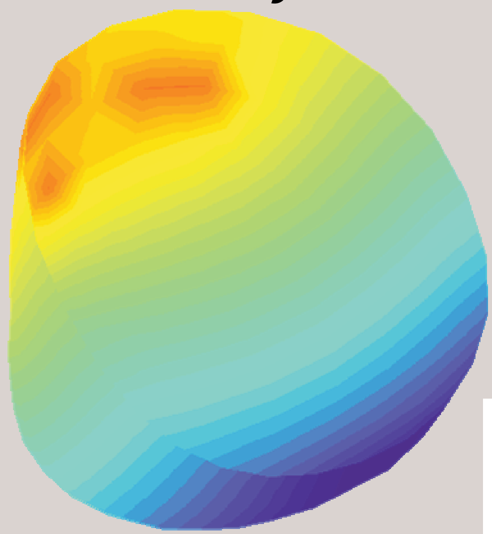
Local Parameter Adjustment

work with Valerie Moreau, Epidaure, INRIA

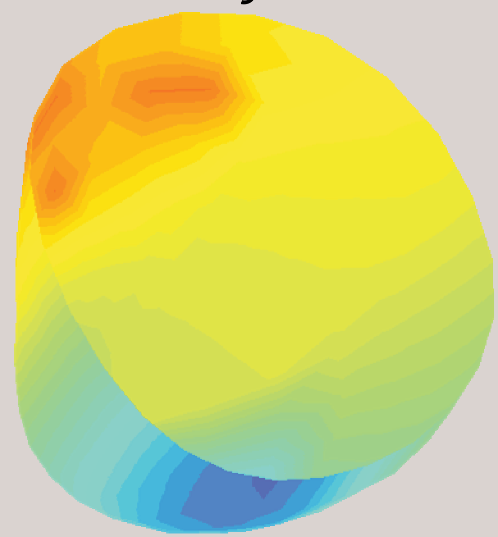
Reference Parameters

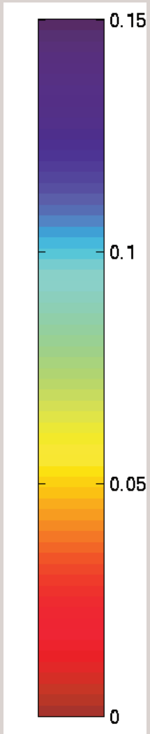


Global Adjustment

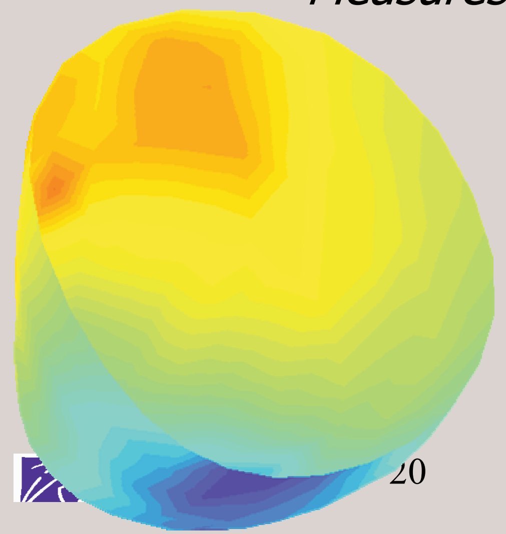


Local Adjustment





Measures

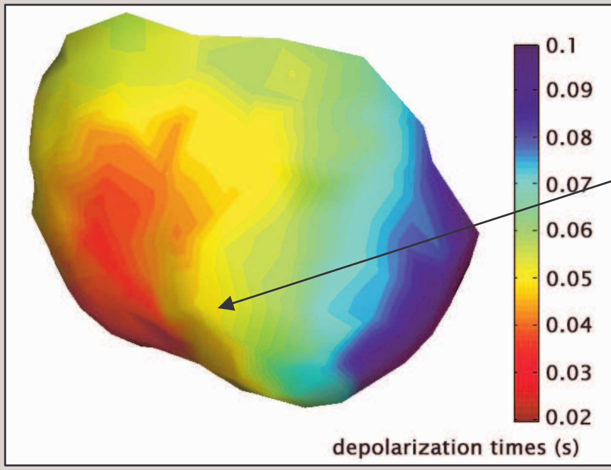


Isochrones with a local adjustment of the conductivity on the endocardial surface

Images courtesy of V. Moreau

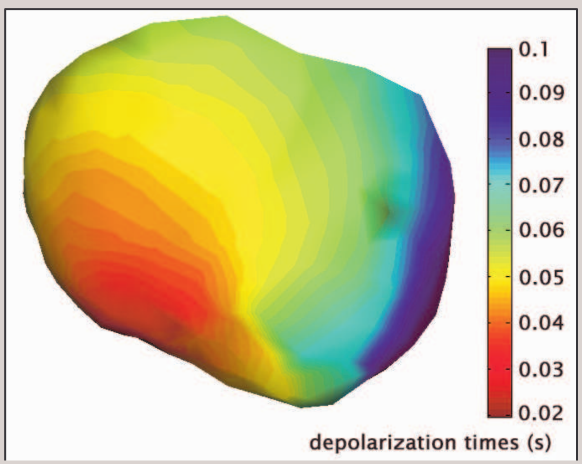
V. Moreau-Villéger, H. Delingette, M. Sermesant, O. Faris, E. McVeigh and N. Ayache. *Global and Local Parameter Estimation of a Model of the Electrical Activity of the Heart*. INRIA Research Report.

Apparent Conductivity



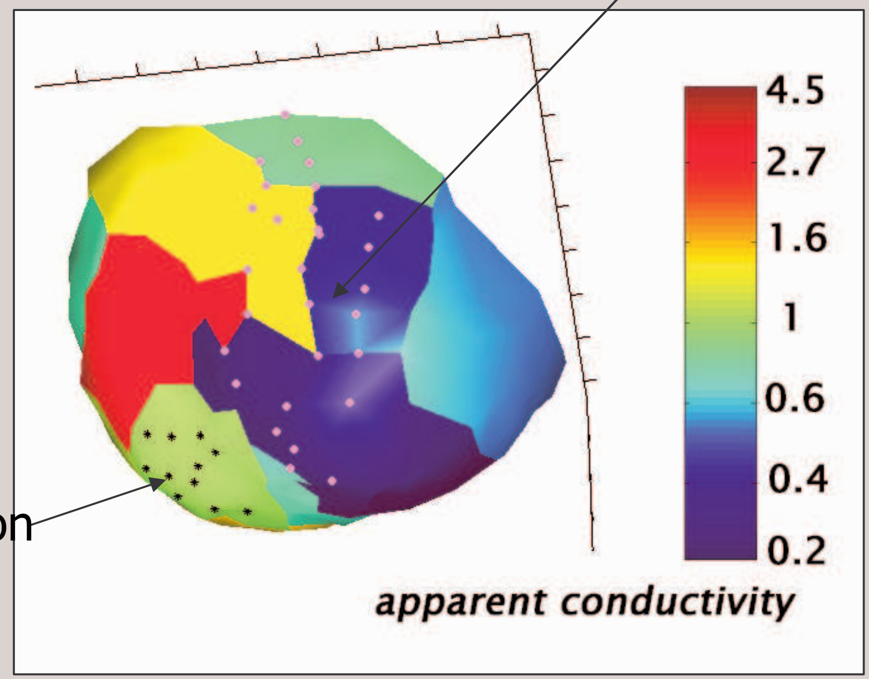
infarct

Measured depolarisation times



Simulated depolarisation times

infarct



stimulation

V. Moreau, H. Delingette, M. Sermesant, E. Mc Veigh, N. Ayache. *Estimating Local Apparent Conductivity with a 2-D Electrophysiological Model of the Heart*, FIMH 2005. IEEE Trans. Biomedical Engineering.

Overview of ICEMA achievement 2000-2004

http://www-rocq.inria.fr/sosso/icema2/icema2.html

- Introduction
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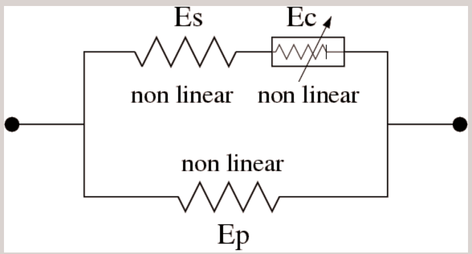
Electromechanical Coupling

Active nonlinear viscoelastic anisotropic and incompressible material

Bestel-Clément-Sorine constitutive law (ICEMA)



E_s series element
E_p parallel element
E_c contractile element

$$\rho \ddot{P} - \mathrm{div}(K_p\, \mathcal{E}_p + C_p\, \dot{\mathcal{E}}_p + \sigma_c + C_c\, \dot{\mathcal{E}}_c + K_c \xi_0) = 0$$

$$\partial_t K_c = K_0 |u|_+ - (|\dot{\mathcal{E}}_c| + |u|) K_c$$

$$\partial_t \sigma_c = \sigma_0 |u|_+ - (|\dot{\mathcal{E}}_c| + |u|) \sigma_c + K_c \dot{\mathcal{E}}_c$$

$$\sigma_c + C_c\, \dot{\mathcal{E}}_c + K_c \xi_0 = K_s(\mathcal{E}_p - \mathcal{E}_c)$$

Reduce parameters and computation time
➡ Design a model adapted to biomedical image analysis and pathology simulation

Simplified Model

k piecewise constant

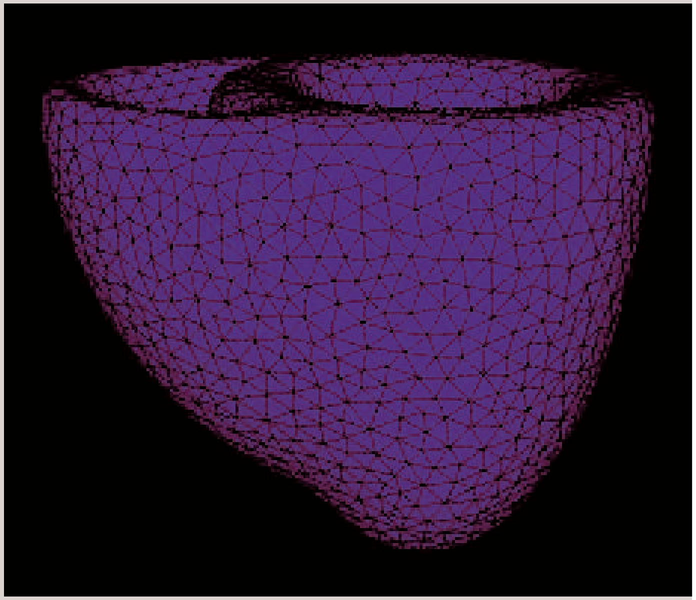
$$\frac{d\sigma_c}{dt} = -|u|\sigma_c + \sigma_0 |u|_+$$

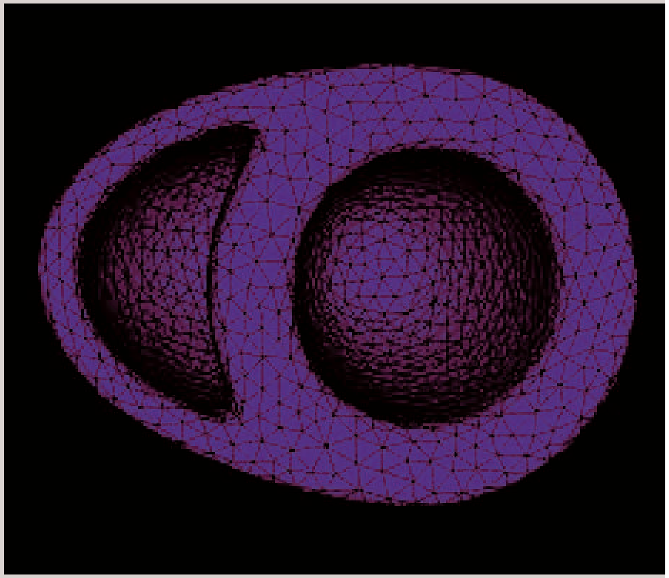
Piecewise linear viscoelastic anisotropic material

Only electrical command on contraction stress σ_c

Contraction Validation

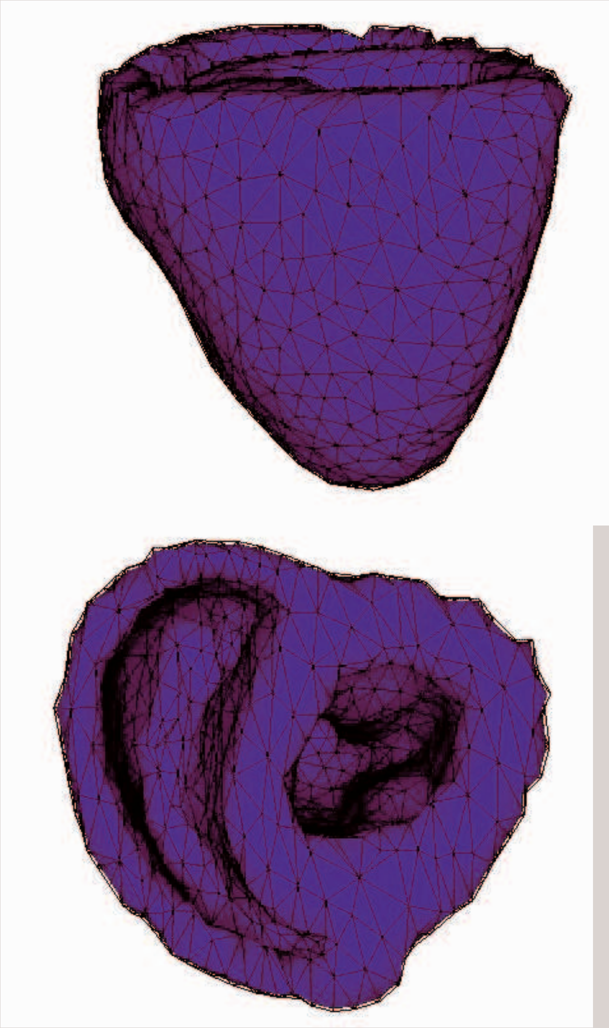
- 4 Cardiac Phases:
  - Filling
  - Isovolumetric contraction
  - Ejection
  - Isovolumetric relaxation
- 4 Different Boundary Conditions:
  - Pressure constraints on the endocardium
  - Isovolumetric constraints on the ventricles



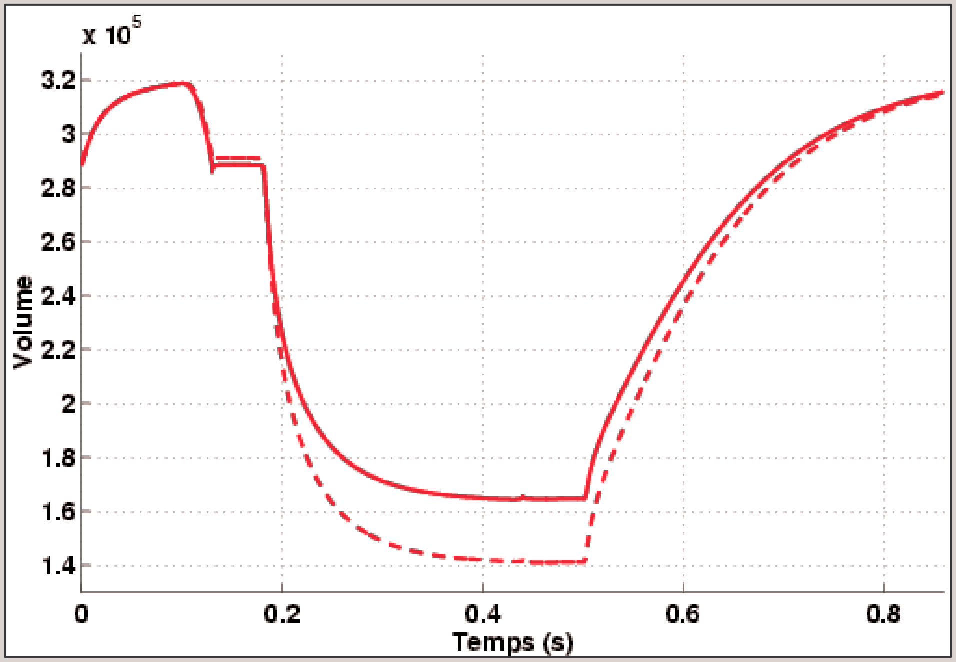


Color: action potential value

Simulating an Infarct (Toy example)



Infarcted zone simulation



volume

ejection fraction:
56 % → 48 %

Sermesant-Coudière-Delingette- et al., MICCAI'02

Overview of ICEMA 2000-2004

http://www-rocq.inria.fr/sosso/icema2/icema2.html

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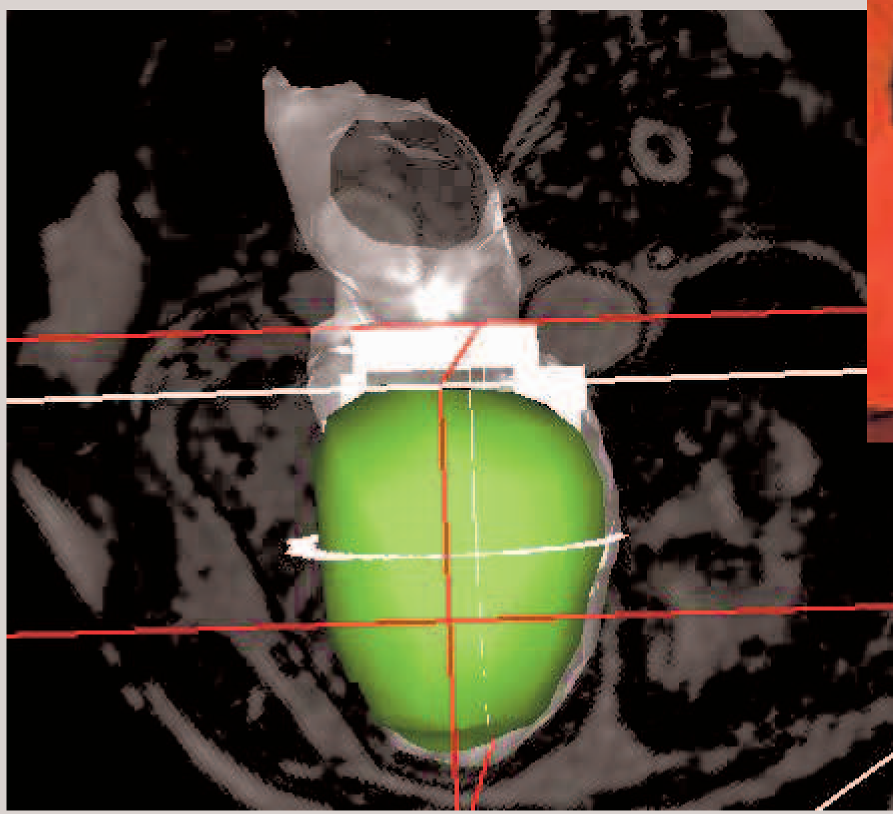
In Vivo Human Measurements

King's College, division of Imaging Sciences
The Guy's, King's and St Thomas' School of Medicine

- Electrical : Inserted basket of electrodes
- Motion : Tagged MRI + coupled Angiography

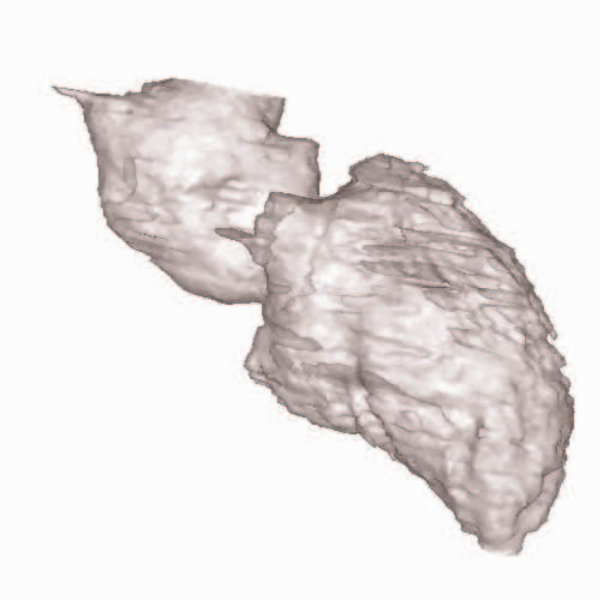


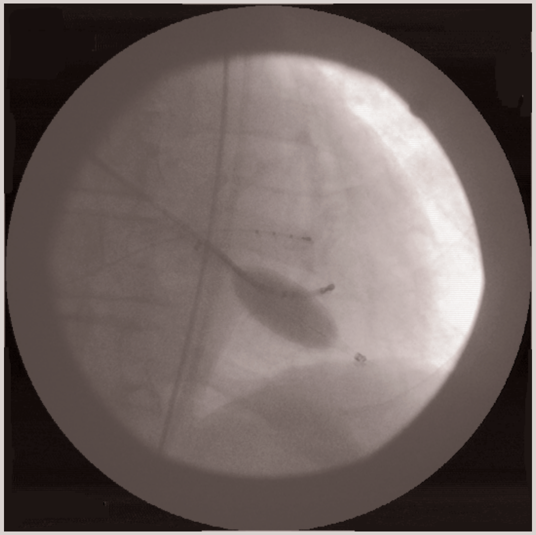
Sermesant-Hill et al.
Miccai'04

XMR Patient Imaging

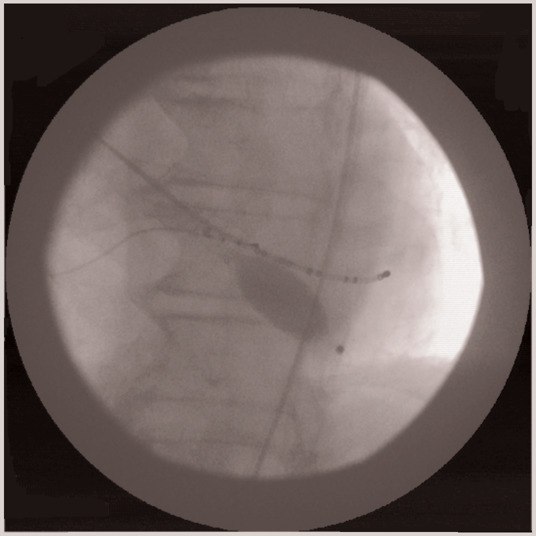
Clinical Case 2: Patient Details

- Male, aged 68 years
- Very poor LV function following MI
- EPS + Biventricular pacing
- SSFP three-dimensional multiphase sequence
- CSPAMM spiral tagged imaging sequence
- Non-contact mapping system:
  EnSite balloon catheter (*Endocardial Solutions*)

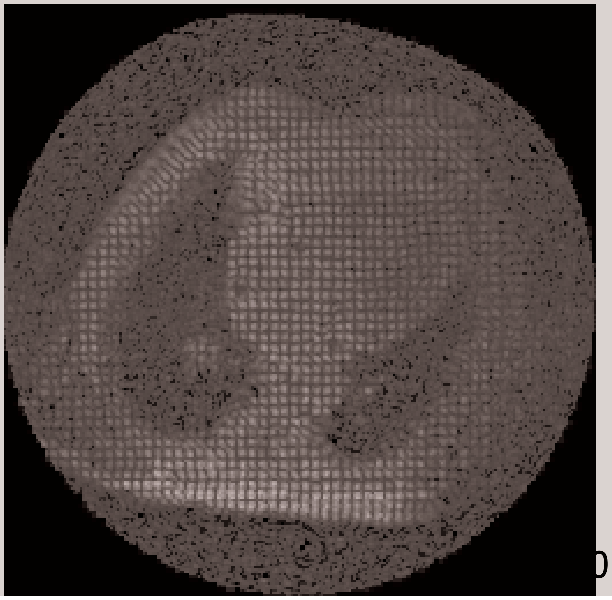




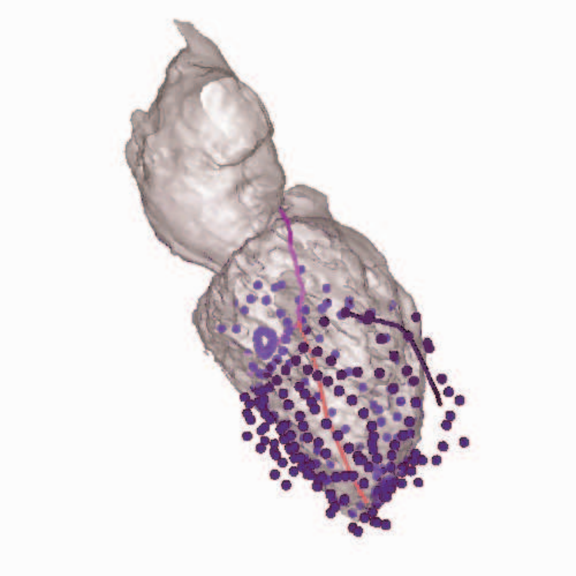
View 1

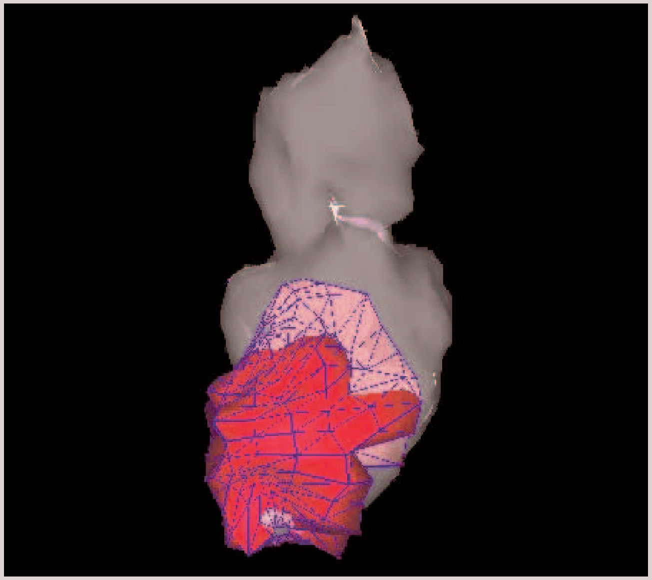


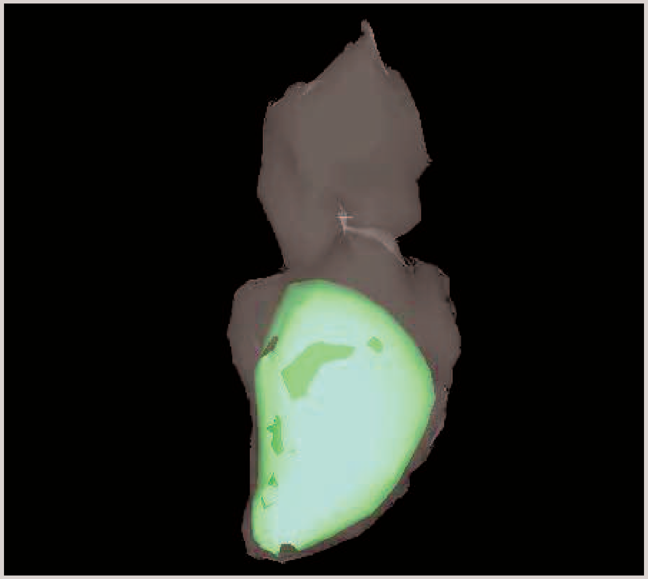
View 2



Clinical Case 2: Reconstruction and Visualisation







Ensite system generates estimation of end-diastolic endocardium:

BLUE: points from EnSite generated LV surface

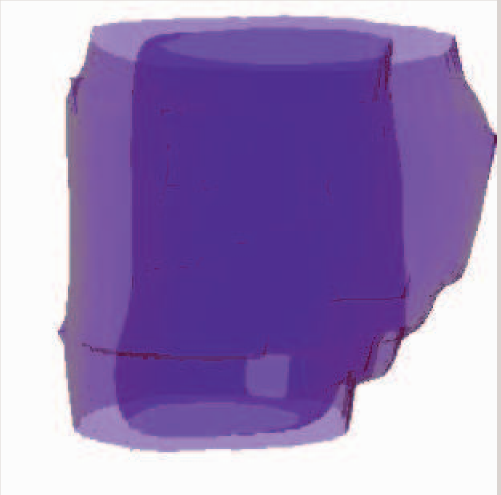
RED: Balloon catheter

PURPLE: Roving catheter

BLACK: Quadrapole catheter in RV

- EnSite surface point cloud meshed
- **Non-rigid surface-to-image registration** used to realign the EnSite mesh

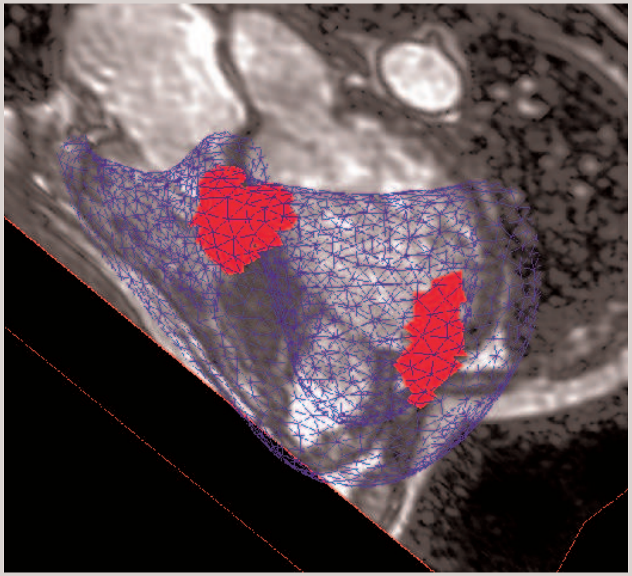
- **EnSite measures** displayed on surface from MR anatomy



- Motion extracted from tagged MRI:
  - **Very Poor LV Function**

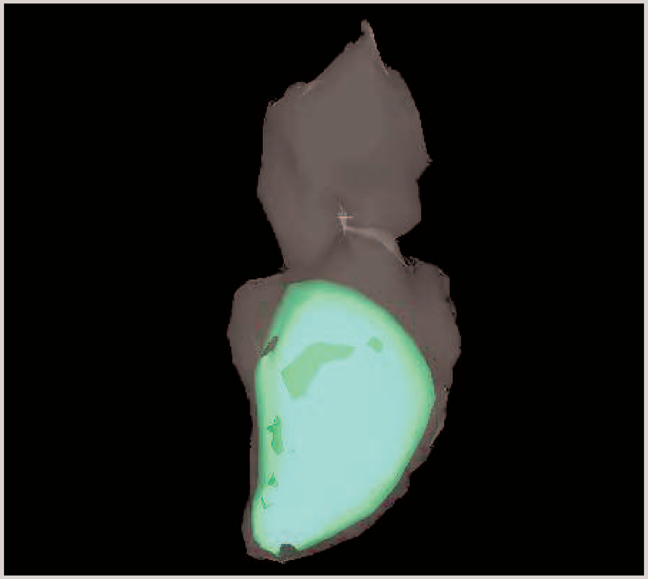
Simulation of a LBBB

- Case 2: Left Bundle Branch Block



Adjustment of the model
to the patient anatomy

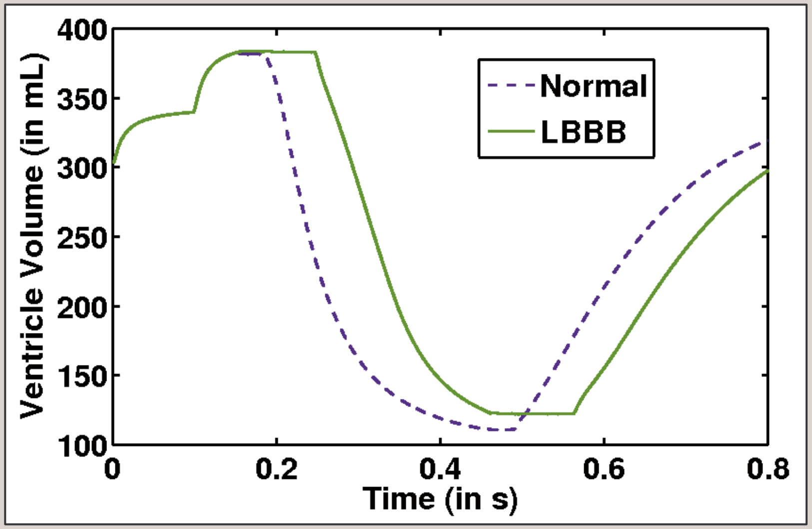
Integration of **infarcted zones with late enhancement MR**



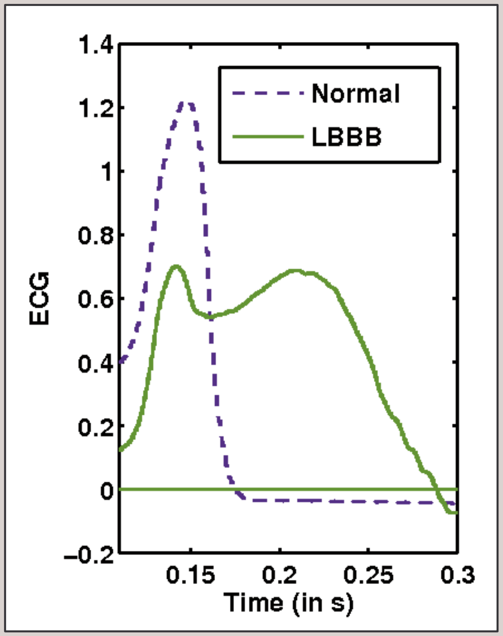
Simulation of the
endocardial electrical
activity

Simulation of a LBBB

- Introduce **scars**: less conductive, less contractile, stiffer,…



Simulated Left Ventricle Volume
with Branch Block and Scar



Simulated ECG with
Branch Block:
QRS complex

N

M. Sermesant, K. Rhode, G. Sanchez-Ortiz, O. Camara, R. Andriantsimiavona, S. Hegde, D. Rueckert, P. Lambiase, C. Bucknall, E. Rosenthal, H. Delingette, D. Hill, N. Ayache, R. Razavi. Simulation of cardiac pathologies using an electromechanical biventricular model and XMR interventional imaging, *Medical Image Analysis*, 2005. To appear.

Overview

- Introduction
- Overview of past achievements
- Work in progress
  - Estimation of mechanical parameters
  - Fast Marching Method in EP
- Perspectives

Estimation of Mechanical Parameters

- Model:

$$\begin{cases} \rho\ddot{P} - \mathrm{div}(K_p\,\mathcal{E}_p + C_p\,\dot{\mathcal{E}}_p + \sigma_c + C_c\,\dot{\mathcal{E}}_c + K_c\xi_0) = 0 \\ \partial_t K_c = K_0|u|_+ - (|\dot{\mathcal{E}}_c| + |u|)K_c \\ \partial_t\sigma_c = \sigma_0|u|_+ - (|\dot{\mathcal{E}}_c| + |u|)\sigma_c + K_c\dot{\mathcal{E}}_c \\ \sigma_c + C_c\,\dot{\mathcal{E}}_c + K_c\xi_0 = K_s(\mathcal{E}_p - \mathcal{E}_c) \end{cases}$$

Time discretisation

model at time t

$$\Phi^{(t)}(\alpha, y_t, y_{t-1}) = 0\ ,\ t = 0, \ldots, T$$

state variables at instants t and t-1

- Minimize objective function:

parameters *state variables*

$$F(\alpha) \equiv \frac{1}{2}\sum_{i\in I}(\varphi_i(\alpha, y_i) - \bar{\varphi}_i)^2$$

observations from simulations measurements

Data Assimilation

work with MACS INRIA project

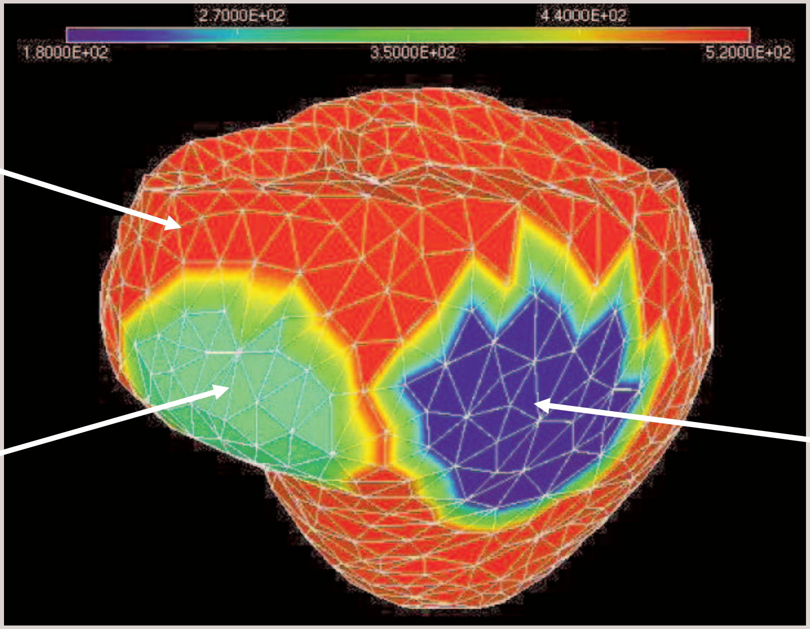
1. Change local contractility in 2 zones
2. Simulate heart cycle

   filling, isovolumetric contraction, ejection, isovolumetric relaxation
3. Under-sample displacements and add noise

   (30 random nodes / 2000 nodes)

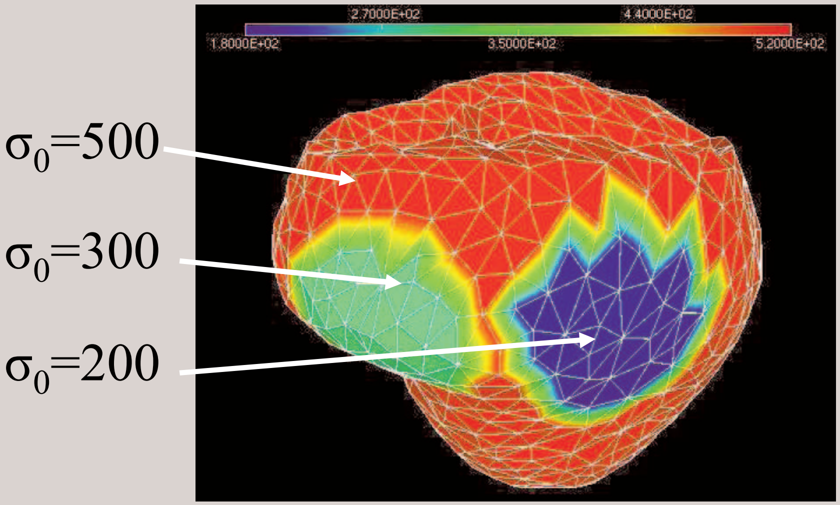
σ_0=500

σ_0=300

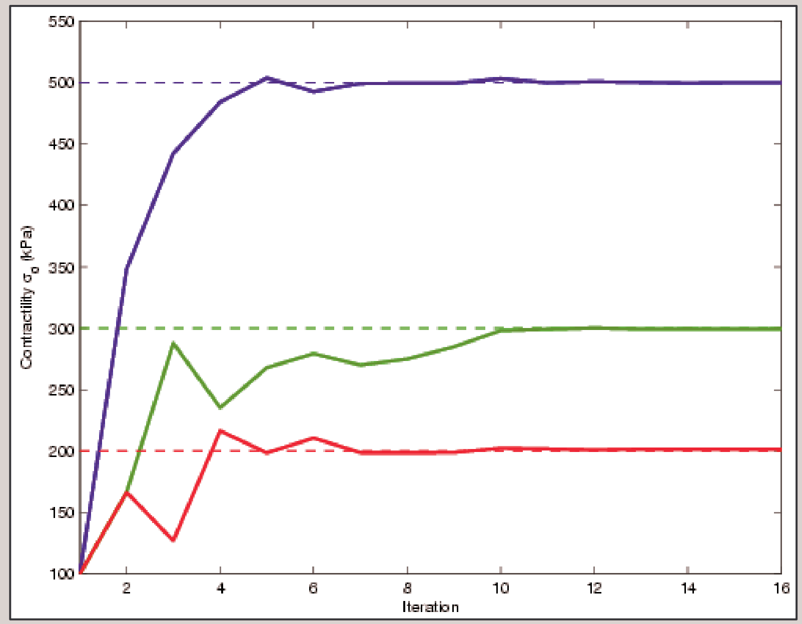


σ_0=200

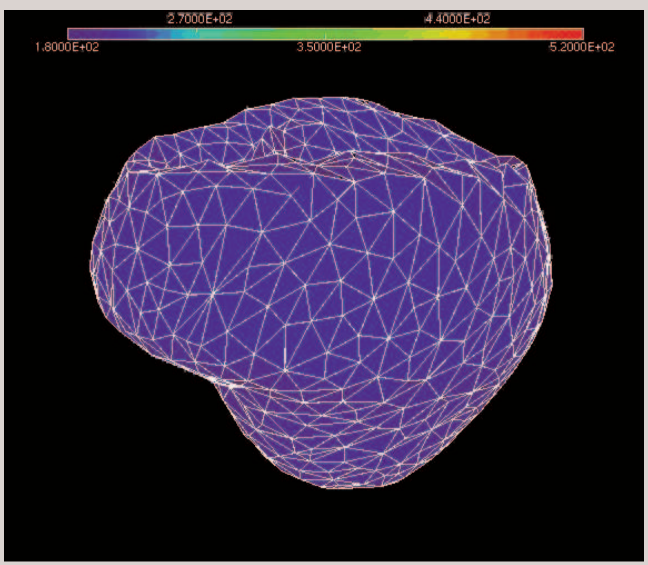
Data Assimilation



- Convergence of σ_0
- Starting from σ_0 =100



1 iteration ~ 1 h



Estimated σ_0 through iterations

M. Sermesant, P. Moireau, O. Camara, J. Sainte-Marie, R. Andriantsimiavona, R. Cimrman, D. Hill, D. Chapelle, R. Razavi. Cardiac function estimation from MRI using a heart model and data assimilation: advances and difficulties. In *Functional Imaging and Modelling of the Heart*, 2005.

Interventional Model

preliminary work

- Different clinical applications → different models
- Interventions: "real-time" implementation

$$c \left\| \nabla T \right\| - k \left\| \nabla T \right\| div \left(\frac{\nabla T}{\left\| \nabla T \right\|} \right) = 1$$

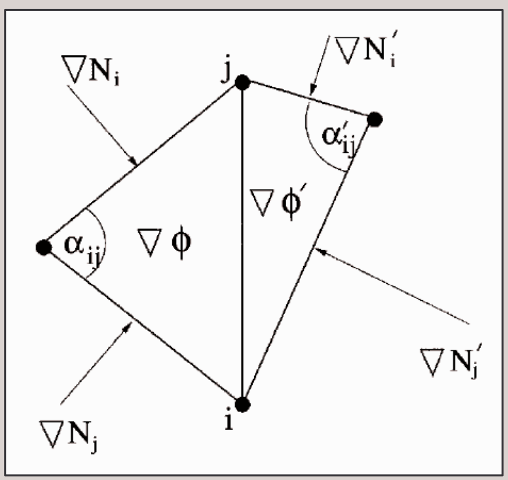
(Keener, Colli-Franzone)

- Eikonal-curvature
  - Fast-marching implementation
  - Interpolation, filtering
  - Local conductivity estimation

Fast-Marching Method

preliminary work

- Efficient method to solve $c\,\|\nabla T\| = 1$
- Extended to unstructured grids (triangulations)
- Proposed iterative method:
  - FMM
  - Compute curvature term:



$$\kappa(T) \approx \|\nabla T\|_i \frac{\sum_{n\in\mathcal{N}_i} W_j^i(T_j - T_i) + W_k^i(T_k - T_i)}{\sum_{n\in\mathcal{N}_i} meas(n)}$$

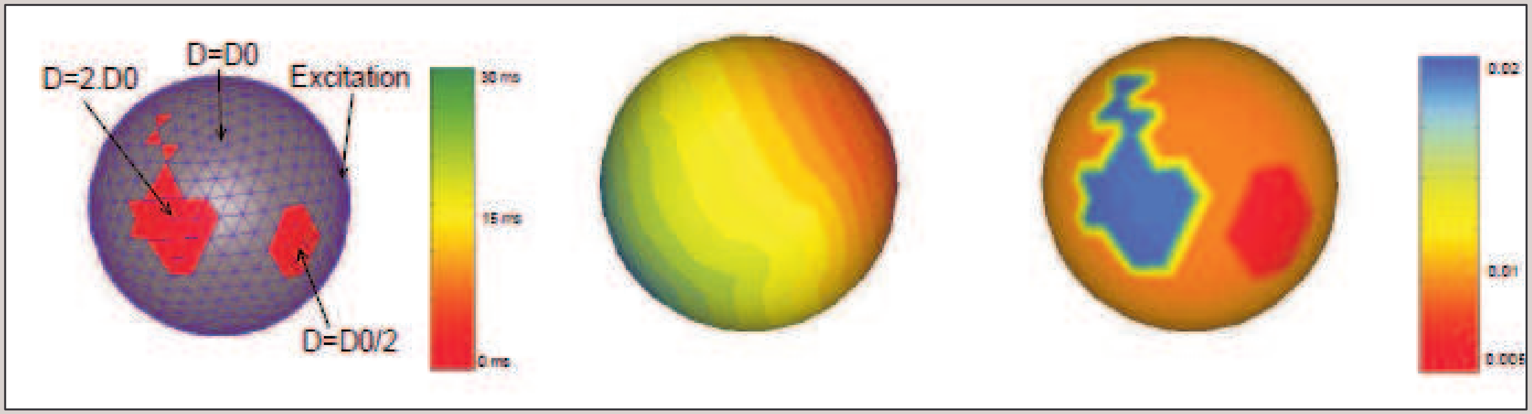
$$W_j^i = cotan(\alpha_k)/(2\|\nabla T\|_n)$$

(Barth, Sethian, 1998)

Local Conductivity Estimation

- Iterative method
  - Convergence of Eikonal-curvature
  - Adjustment of local conductivity *D* by comparing simulated and measured *T*

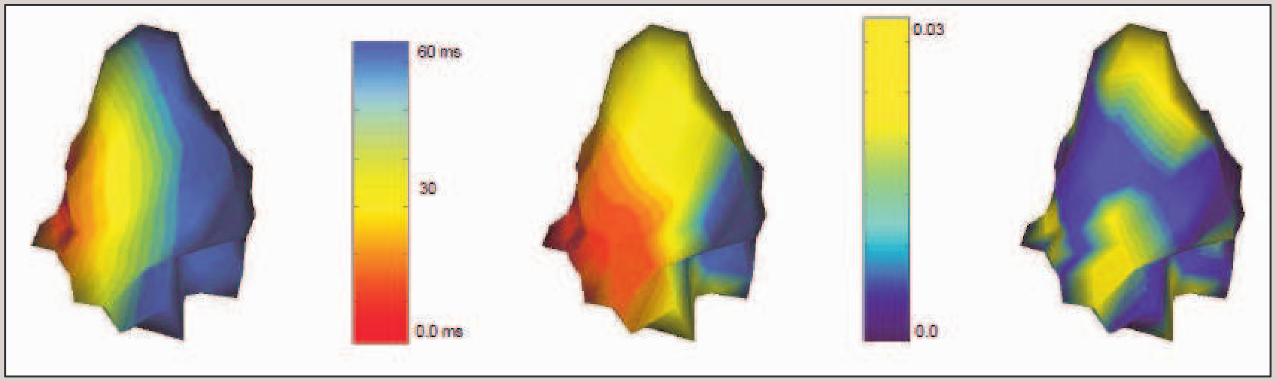
$$c\sqrt{kD}\|\nabla T\| - D\kappa(T) = 1$$



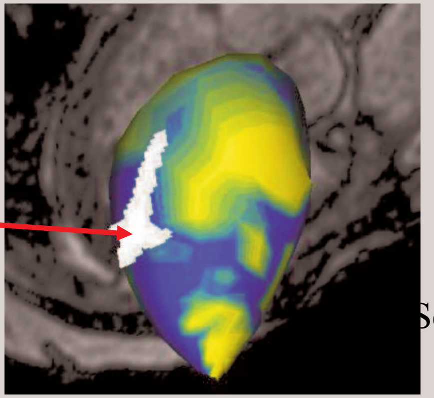
Adjustment to Clinical Data

preliminary work

- XMR interventional data
  - Endocardial surface geometry
  - Depolarisation times



initial isochrones *final* *conductivity*



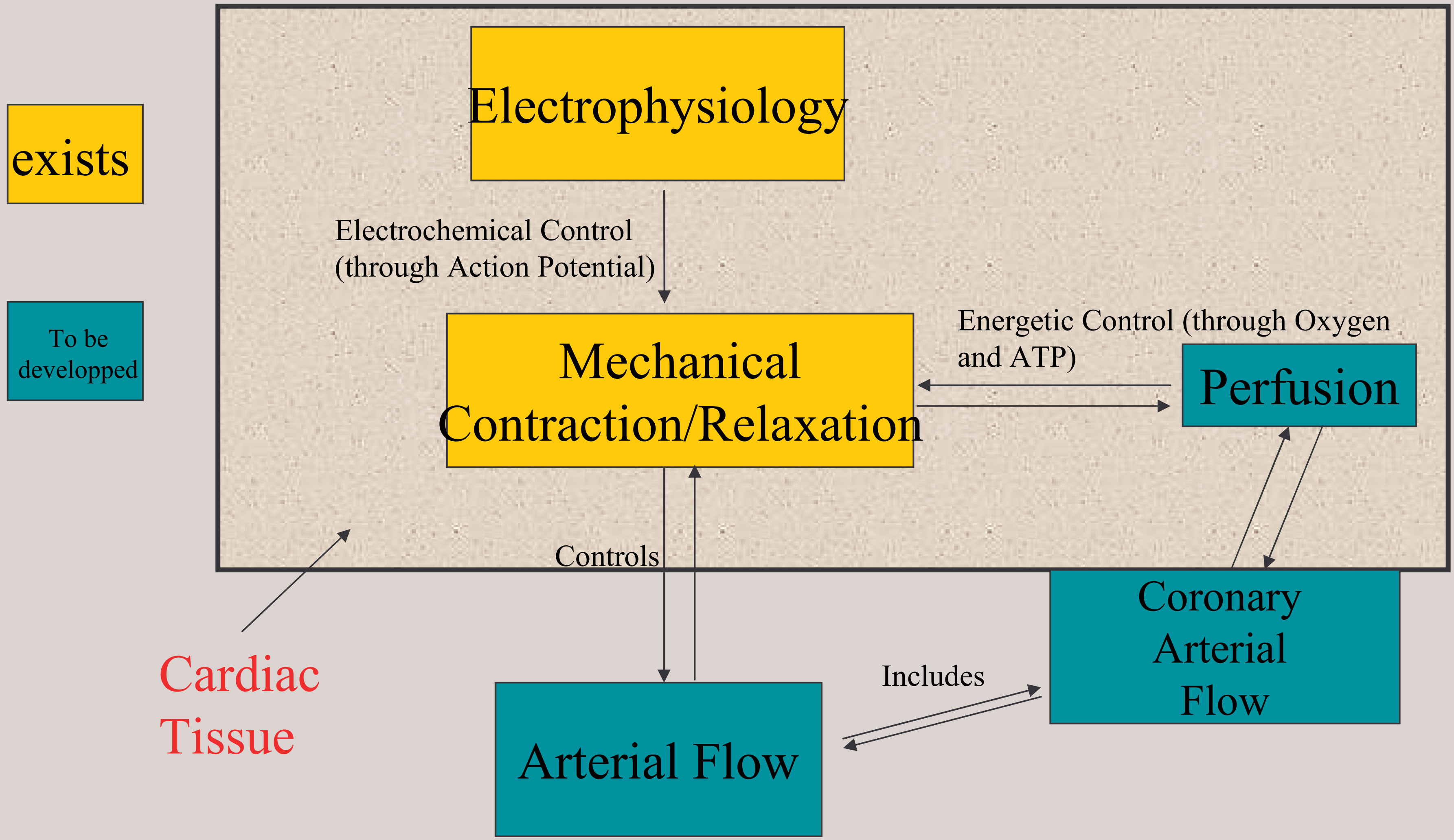
lesion

XMR electrophysiology data in patient MR image

Overview

- Introduction
- Overview of past achievements
- Work in progress
- Perspectives

I) Improving Cardiac Modeling (2/3)



II) Parameter estimation techniques (3/4)

	States to be estimated	Parameters to be estimated	Observations from which is based the estimation
Electrical Level	extra-cellular and action potential	electrical conductivity, fiber direction	ECG, 3D Mapping from endocardial catheters, ECG Imaging
Mechanical Level	displacement, stress, strain rate	contractility, compliance	Tagged or Cine MR Images, 3D echocardiographics images
Perfusion level	coronary pressure, coronary flow, oxygen pressure	porosity and permeability	CT angiography, MR angiography, cardiac CT, SPECT

Clinical Applications

- Potential List of applications :
  - Diagnosis of infarcted/ischemic tissue
  - Radiofrequency Ablation Planning
  - Multi-site stimulation Planning
  - Surgery Planning of akinetic plaques
  - Diagnosis of myocardial contractility

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www.inria.fr/CardioSense3D

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