Models in medical image analysis and simulation

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Epidaure Project

INRIA Sophia-Antipolis

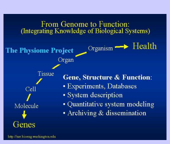
Virtual Human

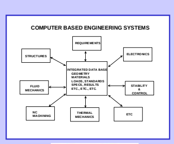
Development of computational models of the human body driven by :

- Better Understanding of biology and physiology at different scales
- New *in vivo image modalities* of the human body
- Fast Growth of computer technology and computer science

Global modeling of the human body

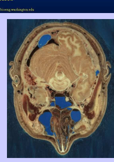
Physiome Project
International consortium





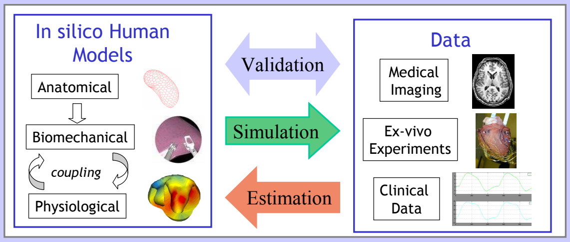
Digital Human
International consortium

Visible Human
NLM, USA



ESI Group
Virtual Dummies for crash tests

Combining Images and Models

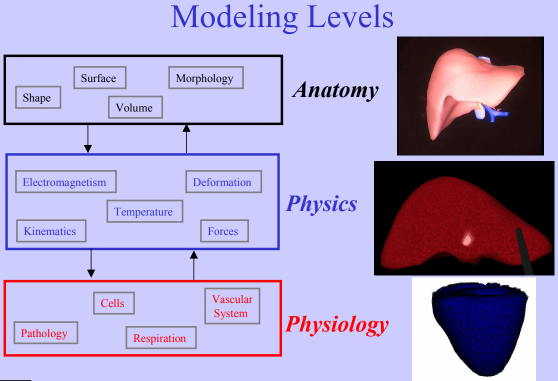


Improvement of Models based on observations from Medical Images

Combining Images and Models

- **<u>1st Goal</u>**: Validation Quantitative Models
  - Reach a better understanding of human physiology and pathology by comparing measured and computed physical values
- **<u>2nd Goal:</u>** Assessment of physical parameters (diagnosis)
  - Guess physical parameters (pressure, speed, stress) by assuming that the physical behavior and boundary conditions are known
- **<u>3rd Goal</u>** : Prediction of physical behavior (therapy)
  - Predict anatomy based on the modeling of a physical phenomenon occurring during therapy (brain shift, cranofacial surgery)

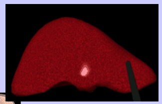
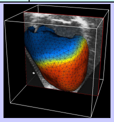
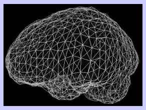
Modeling Levels



Overview of the talk

- 3 applications of human modeling

Application Type	Organ	Real/Time Constraint	Image Interaction	Physiological Modeling
Surgery Simulation	Liver	Yes	Reconstruction	No
Diagnosis	Heart	No	Image Segmentation	Yes
Prediction of outcome	Brain	No	Validation	No

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Surgery Simulation

Acknowledgments:

- Clément Forest, Guillaume Picinbono, Stéphane Cotin, Jean-Christophe Lombardo, Nicholas Ayache
- INRIA projects member of the AISIM collaborative action (Imagis,Sharp,Macs)
- IRCAD

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Motivations of surgery simulation

- Increasing complexity of therapy and especially surgery
  → Increasing need for training surgeons and residents
- Medical malpractice has become socially and economically unacceptable
  → Increasing need for objective evaluation of surgeons
- Natural extension of surgery planning

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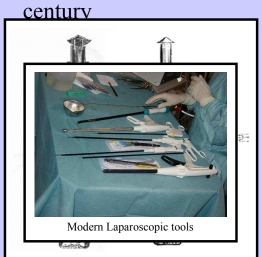
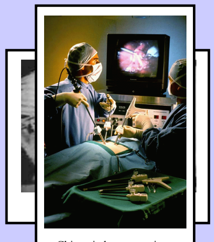
Simulation of laparoscopic surgery

- Laparoscopy originates from middle of XIXth century



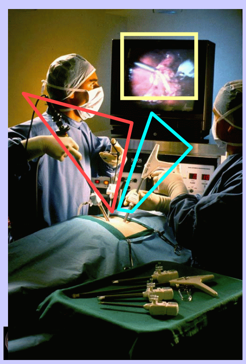
Modern Laparoscopic tools

Endoscope of Desormeaux, 1853



Chirurgie laparoscopique
(source, US Surgical Corporation)

Need for Training



Hand-eye Synchronisation

Camera being manipulated by an assistant

Long instruments going through a fixed point in the abdomen

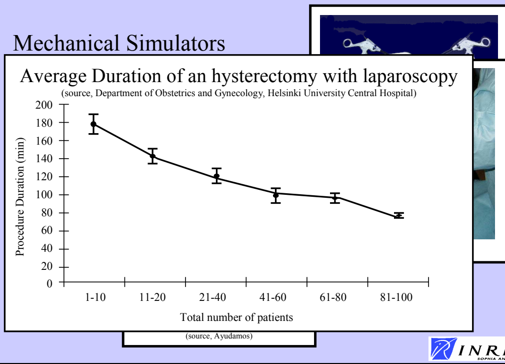
Medical Robotics
Minimally Invasive Therapy

Zeus *(Computer Motion)*
Courtesy of L. Soler (IRCAD)

Da Vinci *(Intuitive Surgery)*
Courtesy of E. Coste-Manière (Chir)

Current Training Techniques

- Mechanical Simulators



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Training versus Rehearsal

- Training: Modelling a ***standard*** patient for teaching classical or rare situations
- Rehearsal: Modelling a ***specific*** patient to plan and rehearse a delicate intervention, and evaluate consequences beforehand

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Surgery Training

Level of Simulation	Required Technology	Example
Skill Level	Real Instrument Setup	Instrument Motion
Task Level	Visual Feedack	Suturing, Clipping, Cutting
Procedure Level	Force Feedback	Detach Gallbladder, Resect Liver
Intervention Level	Physiology Monitoring	Cholecystectomy, Hepactectomy

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Description of a Simulator

Medical Expert

⇅

Man-Machine Interface

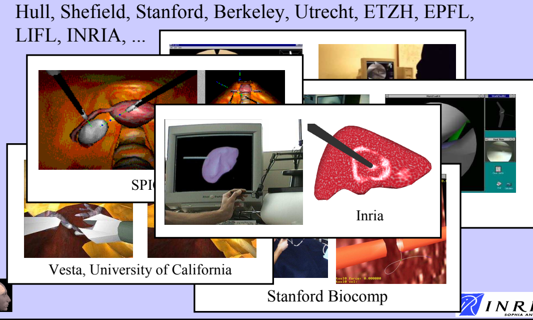
⇅

Modeling Engine

Source Surgical-Science

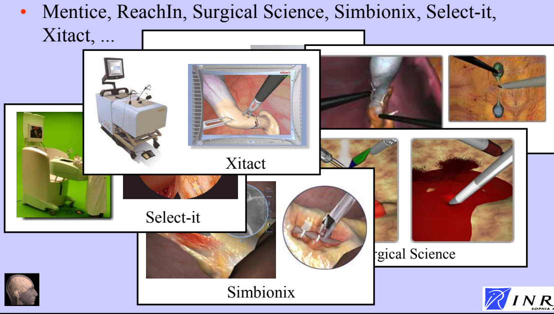
Simulators built at Universities

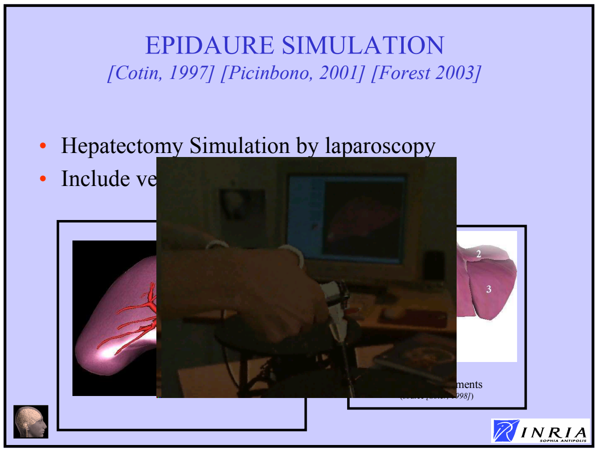
- Hull, Shefield, Stanford, Berkeley, Utrecht, ETZH, EPFL, LIFL, INRIA, ...

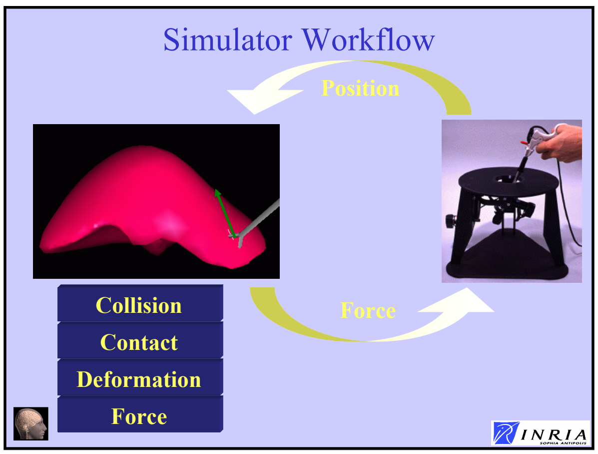


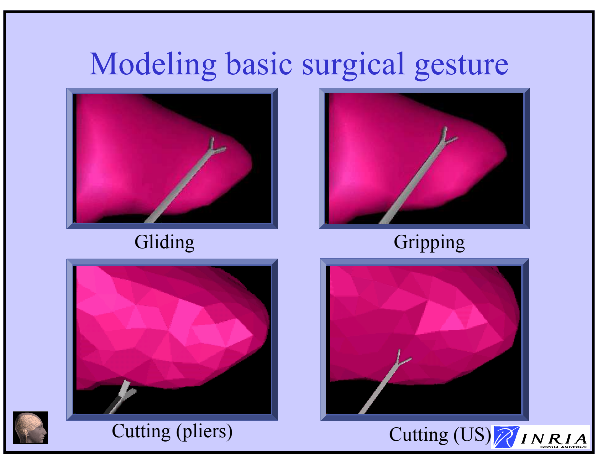
Simulators built by companies

- Mentice, ReachIn, Surgical Science, Simbionix, Select-it, Xitact, ...




EPIDAURE SIMULATION
[Cotin, 1997] [Picinbono, 2001] [Forest 2003]
• Hepatectomy Simulation by laparoscopy
• Include ve
ments
INRIA


Simulator Workflow
Position
Force
Collision
Contact
Deformation
Force
INRIA


Modeling basic surgical gesture
Gliding
Gripping
Cutting (pliers)
Cutting (US)
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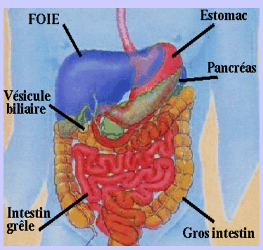
Different Technical Issues

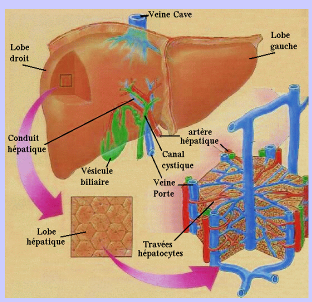
- Mesh Reconstruction from Images
- Soft Tissue Modeling
- Tissue Cutting
- Collision Detection
- Contact Modeling
- Surface Rendering
- Haptic Feedback

With real-time constraints

Hepatic Surgery

Hepatic Surgery Planning and Simulation

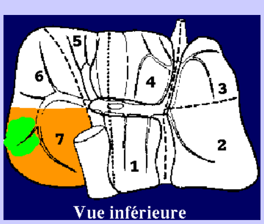




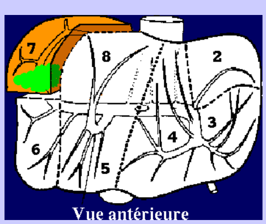
Surgical Context

Main Surgical Landmark :

Liver Anatomical Segmentation



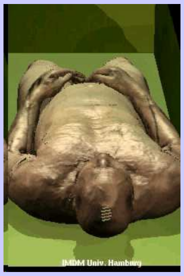
Vue inférieure

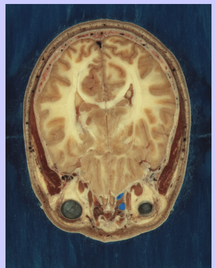


Vue antérieure

Visible Human

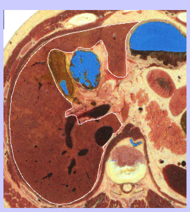
Joseph Paul Jernigan (died August 5th 1993)





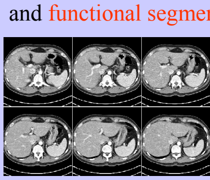
Liver Reconstruction

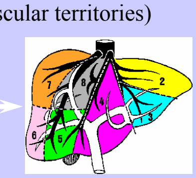
Deformation from a reference model reconstructed from the « *Visible Human Project* »



Specific Geometric Model

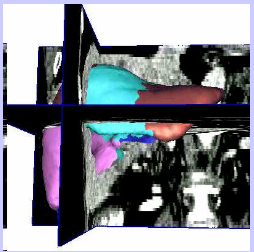
- Should correspond to the actual CT images of a given patient, and should provide external surface and functional segments (vascular territories)



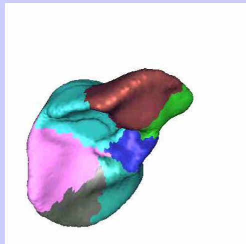


Liver Segmentation

CT scan image of the abdomen

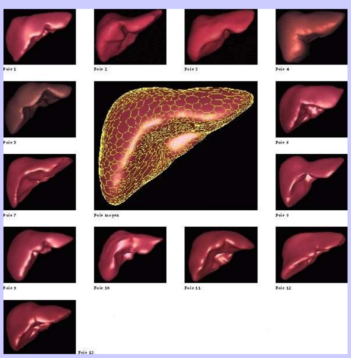


Time of convergence : 2 mn 12 s



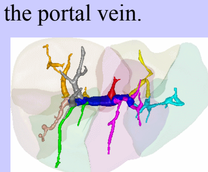
Extraction of Couinaud segments

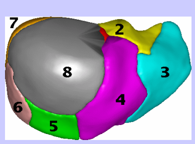
Liver Segmentation



Functional Segments

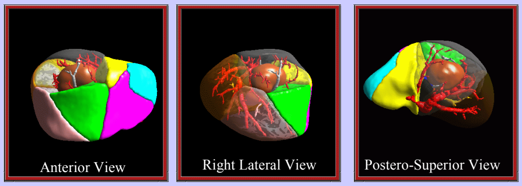
- Extraction of first branches of the portal vein
- Couinaud Segmentation defined by computing the influence zones (Voronoi) of the first branches of the portal vein.



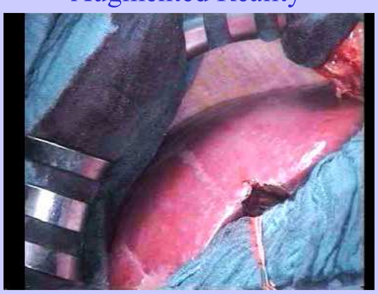


Planning with a geometric model

- Surgeon may plan his intervention by evaluating the relative position of lesions and Couinaud Segments.



Control of Planning with Augmented Reality



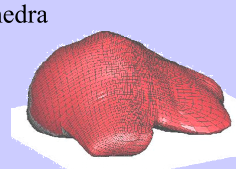
IRCAD

3D/2D non-rigid registration

Volumetric Mesh Building

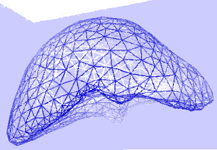
- Liver meshed with hexahedra

3 months work
(courtesy of ESI)



- Liver meshed with tetrahedra

Automatically generated (10s with GHS3D Software)



Different Technical Issues

- Mesh Reconstruction from Images
- Soft Tissue Modeling
- Tissue Cutting
- Collision Detection
- Contact Modeling
- Surface Rendering
- Haptic Feedback

With real-time constraints

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Specific Constraints

- Real-time constraints :
  - 25 Hz for visual feedback
  - 500 Hz for haptic feedback
- Boundary conditions posed in terms of specified displacements (essential BC)
  - Global Stiffness Matrix continuously updated
- Mesh Topology changes when simulating cutting

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Soft Tissue Characterization

- The mechanical behavior of most soft tissues is very complex.
- A soft tissue is usually composed of different constituents :
  - Fluids : water and blood
  - Fibrous materials : muscle fibers, neuron fibers
  - Membranes : Glisson capsule
  - Parenchyma : hepatic or cerebral parenchyma

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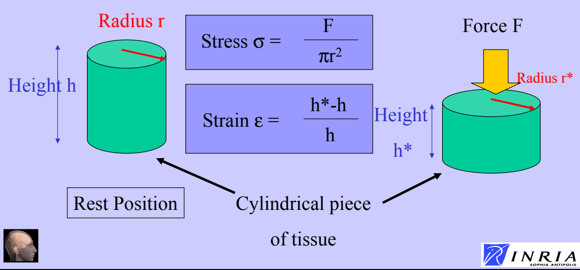
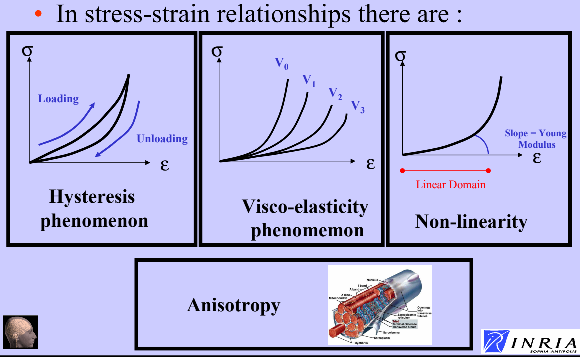
Soft Tissue Characterization

- To simplify the characterization, one may use a stress-strain analysis



Soft Tissue Characterization

- In stress-strain relationships there are :



Soft Tissue Characterization

- Different methods to assess soft tissue parameters:
  - Rheology In-vitro
  - Rheology In-vivo
  - Elastometry based on imaging
  - Solving inverse problems

Methods to access Soft Tissue Parameters

- In vitro Rheology :
  - can be performed in a laboratory. Technique is mature
  - Not realistic for soft tissue (perfusion, …)
- In vivo Rheology :
  - can provide stress/strain relationships at several locations
  - Influence of boundary conditions not well understood

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Methods to access Soft Tissue Parameters

- Elastometry:
  - mesure property inside any organ non invasively
  - validation ? Only for linear elastic materials
- Solving Inverse Problems:
  - well-suited for surgery simulation (computational approach)
  - require the geometry before and after deformation

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Soft Tissue Modeling

- Proposed Models have 3 characteristics:
  - Using Volumetric Models

    Simulation of parenchymatous structures
  - Using Continuum Mechanics

    Simulation of linear and non-linear elastic materials
  - Using Finite Element Modeling

    Based on P_1 Linear Tetrahedron Element

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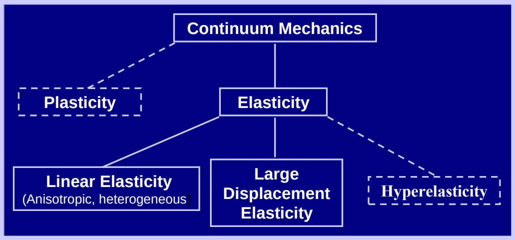
Continuum Mechanics



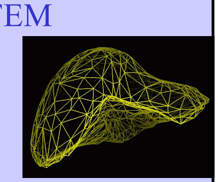
Global Stiffness Matrix

- Minimization of energy yields a linear system of equations

$$F = [K]\, u$$

- with
  - [K] Rigidity Matrix (3n.3n)
  - u Displacement vectors (3n)
  - F External forces (3n) + boundary conditions

Complexity of FEM



- Low resolution liver model:
  - N = 1969 (9517 Tetrahedra)
- CPU Time for solving $F = [K]\, U$ is 5s

→ Need to find other algorithms for deforming soft tissue

Rule of thumb : Sacrifice dynamic realism for speed

A Family of Models

Pre-computed Elastic Model / Tensor-Mass Model / Non-Linear Elastic Model

Very Fast / Topology Changes / Large displacements

Small Deformations / No Topology Changes / Limited to small displacements

Soft Tissue Models

	Pre-computed Elastic Model	Tensor-Mass and Relaxation-based Model	Non-Linear Tensor-Mass Model
Computational Efficiency	+ + +	+	-
Cutting Simulation	-	++	++
Large Displacements	-	-	+

Tensor-Mass Model

- Relies on a dynamic linear elastic model with an explicit time discretisation
- Newtonian law of motion:

$$M\ddot{U} + C\dot{U} + KU = F$$

M is the mass matrix
C is the damping matrix

Tensor-Mass Model (2)

- Choice of matrices :
  - <u>Mass</u>
    - To optimise the time step during cutting, one can use :

$$M = m_0 [Id_3]$$

  - <u>Damping</u>
    - Depending on the scheme, one can use :

$\mathbf{C} = \gamma_1 m_0 [\mathbf{Id}_3]$ Or $\mathbf{C} = \gamma_1 m_0 [\mathbf{Id}_3] + \gamma_2 \mathbf{K}$

Tensor Mass Model (3)

- Explicit scheme:
  - Euler method

$$M\ddot{U} + C\dot{U} + KU = F$$

$\frac{^{t-\Delta t}U - 2\,^{t}U + ^{t+\Delta t}U}{(\Delta t)^2}$ $\frac{^{t}U - ^{t-\Delta t}U}{\Delta t}$

  - Euler method with centered FD

$$M\ddot{U} + C\dot{U} + KU = F$$

$\mathbf{C} = \gamma_1 m_0 [\mathbf{Id}_3] + \gamma_2 \mathbf{K}$

$\frac{^{t-\Delta t}U - 2\,^{t}U + ^{t+\Delta t}U}{(\Delta t)^2}$ $\frac{^{t}U - ^{t-\Delta t}U}{2\Delta t}$

  - Runge-Kutta method of order 4

$\mathbf{C} = \gamma_1 m_0 [\mathbf{Id}_3]$

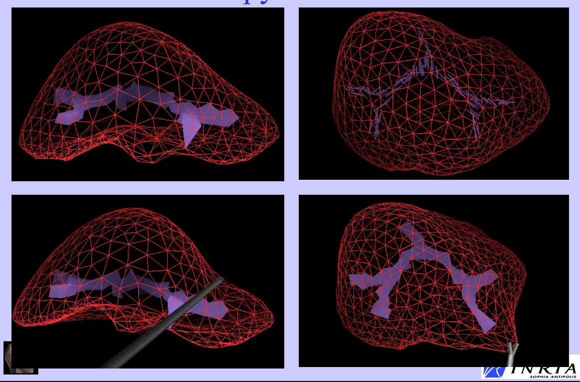
Tensor-Mass Model (4)

- Comparison between the 3 approaches

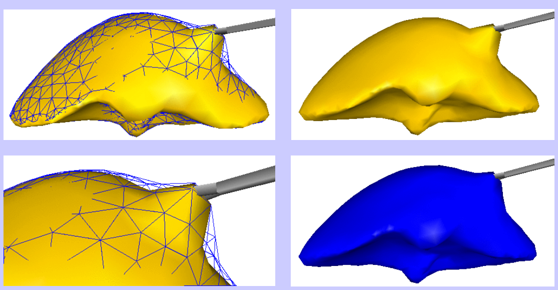
	Euler Method	Euler with centered FD	Runge Kutta
Computation time	small	small	high
Damping	Rayleigh	mass	mass
Time Step	small	medium	high

- Computation of time step
  - Courant criterion or matrix analysis

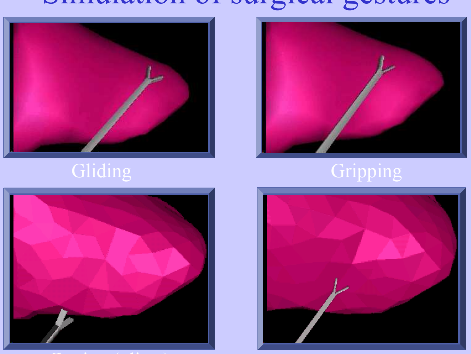
Anisotropy from vessels



Anisotropy from the Glisson capsule

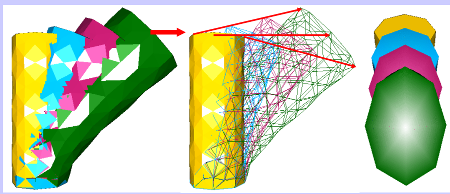


Simulation of surgical gestures

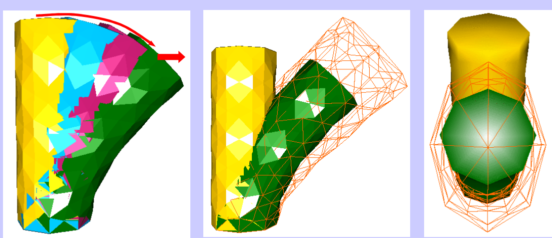


Shortcomings of linear elasticity

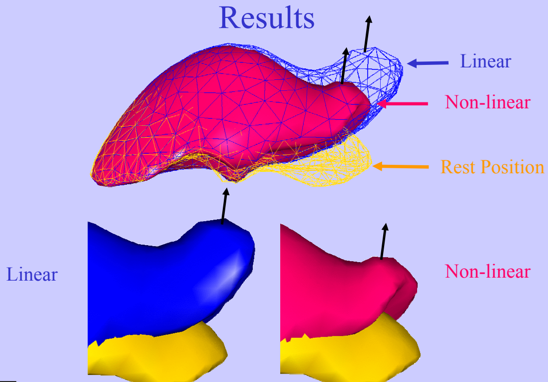
- Non valid for « large displacements»



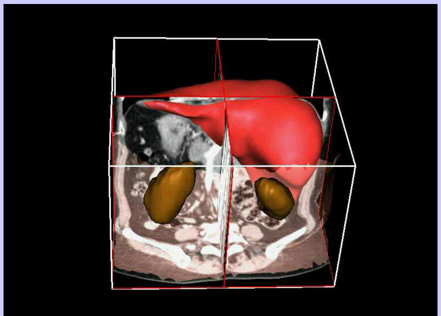
Large Displacement Elasticity



Results



Complete Simulation



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Incompressibility Constraints

- Biological Tissues are Incompressible
  - Hooke law: incompressible $\Leftrightarrow \lambda \to \infty$
  - Leads to instabilities
- Avoid flat tetrahedra at contact zones
- Add a penalty force linked to volume variation of each tetrahedron
  - Force proportional to volume variation
  - Oriented along the normal of the opposite triangle

$$\mathbf{F}_p^{incomp} = \alpha\, f\left(\frac{V - V_0}{V_0}\right) \mathbf{N}_p^{def}$$

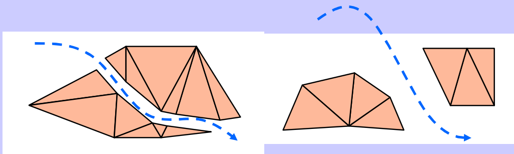
Different Technical Issues

- Mesh Reconstruction from Images
- Soft Tissue Modeling
- Tissue Cutting
- Collision Detection
- Contact Modeling
- Surface Rendering
- Haptic Feedback

With real-time constraints

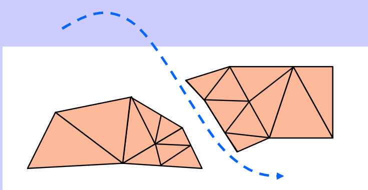
Different algorithms for cutting tetrahedral meshes

- Split of tetrahedra
  [Bielser, 2000] [Mohr, 2000] [Nienhuys, 2001]
  - + Accurate, realistic
  - - Decrease of Mesh Quality
- Removing Tetrahedra
  [Forest, 2002]
  - + Keeps a good mesh quality
  - - Gross cut

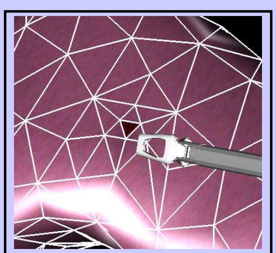


Proposed Technique

- Remove Tetrahedra
- Refine Mesh before removing material

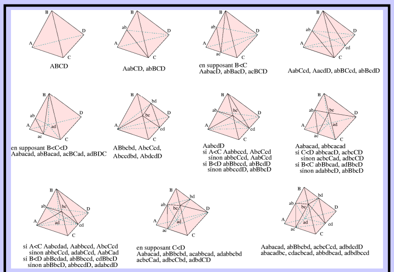


Dynamic Refinement



Example of refine-before-cutting

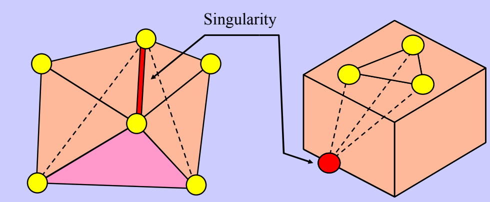
Refinement by Edge Split



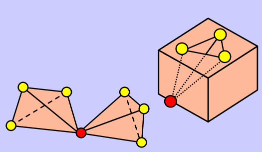
Decomposition of tetrahedra by edge split

Topological Singularities

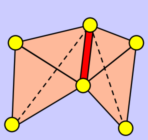
- Removing a tetrahedron may create a singularity (zero thickness at edge and vertices)



Definitions



- Several connected components of the neighborhood of a vertex



- Edge has more than 2 adjacent triangles on the surface

Why Topological Singularities are a problem ?

- Need for a single unambiguous normal vector at each vertex :
  - Surface Rendering
  - Haptic Rendering
- Need for a simple neighborhood around each vertex
  - Neighborhood computation
  - Optimised data structure

Different Technical Issues

- Mesh Reconstruction from Images
- Soft Tissue Modeling
- Tissue Cutting
- Collision Detection
- Contact Modeling
- Surface Rendering
- Haptic Feedback

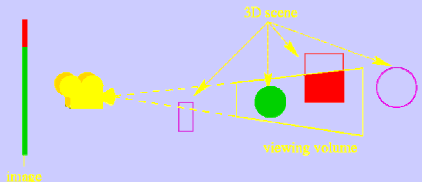
With real-time constraints

Previous Work

- A lot of research on Collision Detection
- Hierarchy of oriented bounding boxes:
  Gottshalk & al. - *Obb-tree: A hierarchical structure for rapid interference detection* - SIGGRAPH'96
- public domain package *RAPID*
- Very efficient,
  but needs pre-computation

The Rendering Process

- Camera = viewing volume + projection



- Two steps: geometry & rasterization

Collision Detection and Rendering analogy

a tool collides the organ

⇔

a part of the organ is inside the tool

⇔

if we define a camera with a viewing volume
that matches the tool geometry,
the organ will be in the picture.

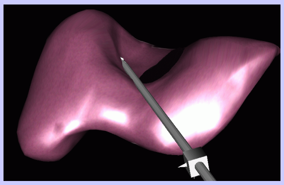
Different Technical Issues

- Mesh Reconstruction from Images
- Soft Tissue Modeling
- Tissue Cutting
- Collision Detection
- Contact Modeling
- Surface Rendering
- Haptic Feedback

With real-time constraints

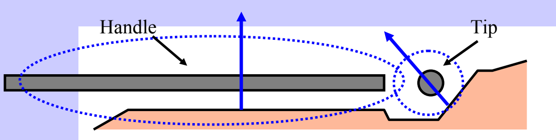
Tool-Soft Tissue Interaction

- Prevent penetration of tool inside the soft tissue
  - Detect intersections
  - Push explicitly mesh vertices outside the tool



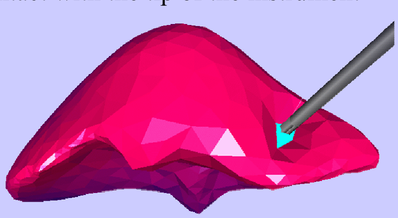
First Approach *[Picinbono, 2001]*

- 2 different tools : tip and handle
- Compute average normal in the neighborhood of the contact
- Projection of vertices in this plane



Collision Processing

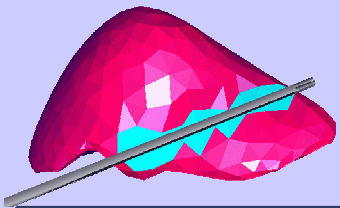
- Contact with the tip of the instrument



Projection on the plane defined by the tip of the instrument and the average normal of intersected triangles

Collision Processing

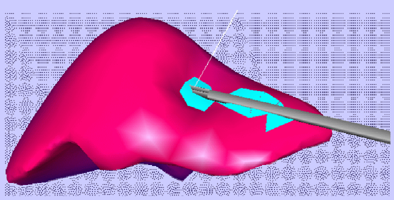
- Contact with the handle of the tool



Projection on the plane defined by the tool direction and the averaged normal direction

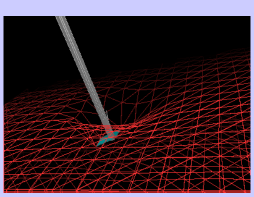
Collision Processing

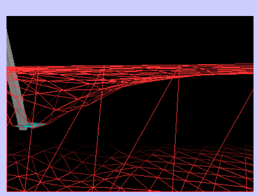
- Perform 2 detections simultaneously



Possible interactions

- Slip on the surface



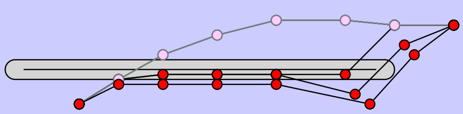


Limitations of this approach

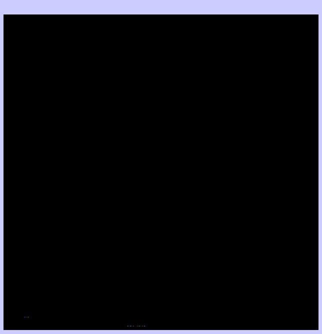
- Same normal vector for all triangles in the same neighborhood
- Leads to instabilities when handling a complex geometry

New approach

- Three steps
  - Prevent vertices to collide with the tool axis
  - Move vertices near the tip of the tool
  - Move vertices outside the volume of the tool



Example



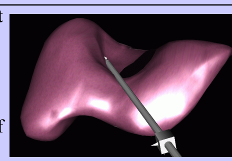
Different Technical Issues

- Mesh Reconstruction from Images
- Soft Tissue Modeling
- Tissue Cutting
- Collision Detection
- Contact Modeling
- Surface Rendering
- Haptic Feedback

With real-time constraints

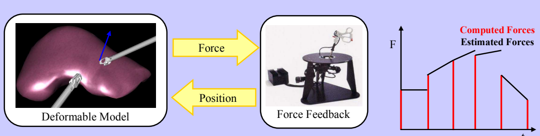
Haptic Feedback

- Principle
  - Give a realistic sense of contact with the soft tissue
- Motivation
  - Increase realism
  - Naturally limit the amplitude of hand motion
- Pitfalls
  - Frequency update of haptics > 500 Hz
  - Frequency update of deformable models ≈ 30 Hz



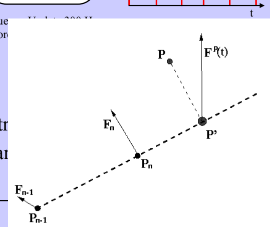
Mouvement non contraint par le retour d'effort

First approach *[Picinbono, 2001]*



Frequency Update 20 Hz
Force Computation

Freque
For

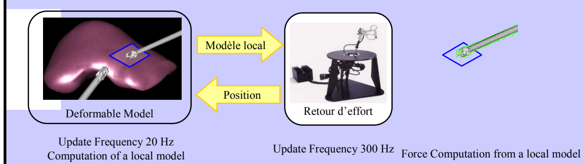


- Unstable if complex geometr
- Difficult extrapolation for lar

$$F^{p}(t) = F_n + \frac{\|P' - P_n\|}{\|P_n - P_{n-1}\|}(F_n -$$

Local Model

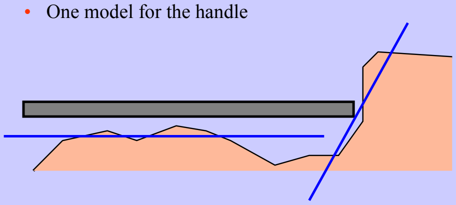
[Mendoza, 2001] [Balaniuk, 1999] [Mark, 1996]



- Smooth Transition from one local model to the next

Computing the local model

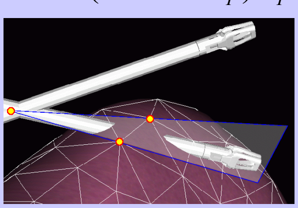
- Described as a set of planes
- One model for the tip
- One model for the handle



Force Computation

- Proportional to the penetration of the tool tip in the planes described by the local model

$$F = k.(EndP - O_P).\vec{n}_P$$



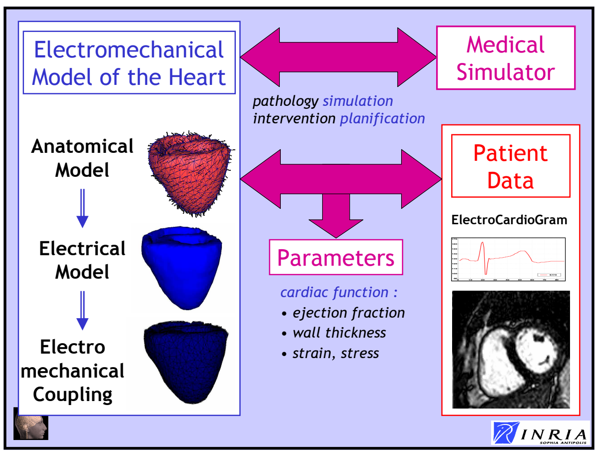
Limitations

- Sometimes difficult to compute local model
  - Stability issues
- Geometric Computation of forces
  - Realism

Cardiac Modeling

Acknowledgments:

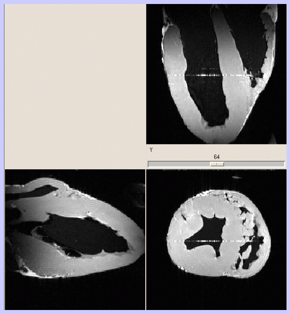
- Maxime Sermesant, Valérie Moreau, Nicholas Ayache
- INRIA projects member of the ICEMA collaborative action (Sosso, Macs, Caiman, University of Nantes),
- NIH (Elliott Mc Veigh), Guy's Hospital (D. Hill)
- Philips Research France

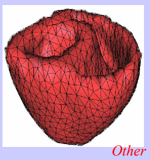


Myocardium Geometry

- Obtained from High Resolution Post-Mortem MRI of canine heart

Courtesy of Hsu, Duke University

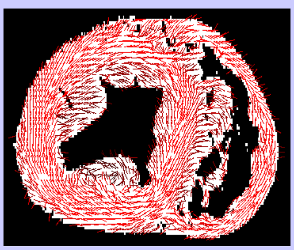




Other Data available, Courtesy of P. Hunter, Auckland University

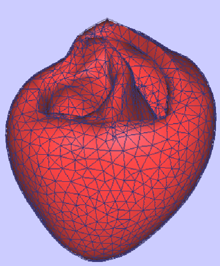
Fiber Directions (canine Data)

- From high resolution Diffusion Tensor MRI

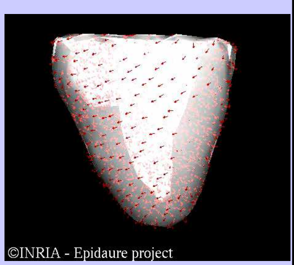


E.W. Hsu and C.S. Henriquez, *Myocardial fiber orientation mapping using reduced encoding diffusion tensor imaging*, Journal of Cardiovascular Magnetic Resonance, 2001.

Geometrical Model of Human Heart



Finite Element Mesh

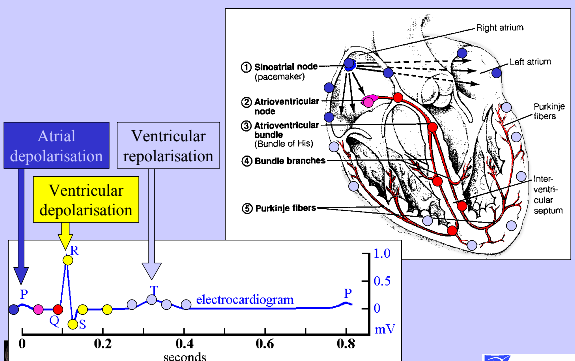


Fiber Directions

Different Levels of Modeling

- Geometrical Modeling
- Electrical Propagation
- Mechanical Coupling
- Parameter Identification

Heart Electrical Activity



Electrical Model

- Action potential u computation: 2 variables FitzHugh-Nagumo *Reaction-Diffusion* system

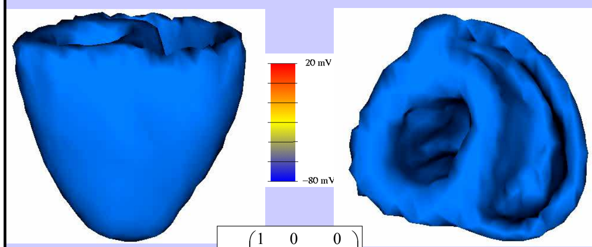
$$\begin{cases} \dfrac{\partial u}{\partial t} = div(D\nabla u) + f(u) - z \\ \dfrac{\partial z}{\partial t} = b(u - cz) \end{cases}$$

u action potential
D diffusion tensor
f ionic current
z repolarization variable
b repolarisation rate
c repolarisation decay

Or R. Aliev and A. Panfilov : A Simple Two-variable Model of Cardiac Excitation, *Chaos, Solitons & Fractals*, Vol 7, No 3, pp. 293-301,1996

Electrical Simulation

Anisotropic model (fiber geometry + Purkinje network)

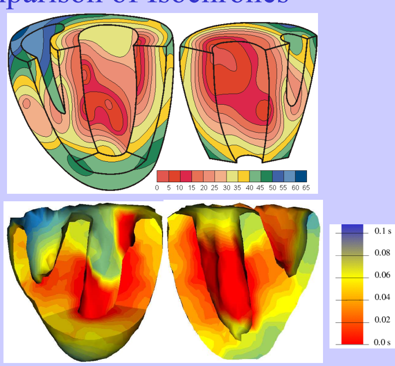


$$D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0.25 & 0 \\ 0 & 0 & 0.25 \end{pmatrix}$$

Comparison of Isochrones

Durrer et al.

ICEMA at INRIA

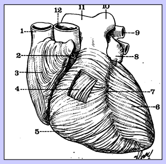


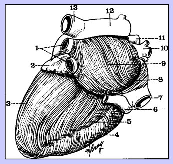
Different Levels of Modeling

- Geometrical Modeling
- Electrical Propagation
- Mechanical Coupling
- Parameter Identification

Biomechanical Properties

The myocardium is composed of muscle fibre bundles:

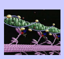
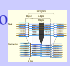
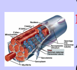




It is an active non-linear viscoelastic anisotropic incompressible material.

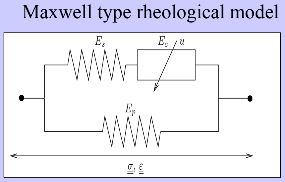
Excitation-Contraction Coupling

From Bestel-Clément-Sorine, MICCAI'01

Scale:		System:	Control:
Nano		molecular motors *Langevin equations* *(SDE) Ratchet or Power-stroke models*	Calcium ions *still to be designed…*
Micro		sarcomeres *Huxley-like models* *(PDE)*	ionic currents *Luo-Rudy-like models* *(ODE)*
Meso		myocytes *BCS* model *(ODE)*	action potential *FHN-like* models *(ODE)*
Macro		myocardium *dynamics equations* *(PDE with BCS Constitutive Law)*	action potential *FHN-like* models *(PDE)*

Electro-Mechanical Coupling

- Derived from nano to macroscopic scale
- Bestel-Clément-Sorine constitutive law in Hill-Maxwell type rheological model



E_S series element
E_p parallel element
E_c contractile element
u action potential
σ stress
ε strain

- E_S and E_p: elastic material laws,
- E_c contractile electrically-activated element.

J. Bestel, F. Clément, and M. Sorine. A Biomechanical Model of Muscle Contraction. In *Medical Image Computing and Computer-Assisted Intervention* (MICCAI'01), 2001.

Bestel-Clément-Sorine Myofiber Model

Electromechanical coupling system derived from *nanoscopic* to *mesoscopic* scale

$$\begin{cases} \dfrac{dk_c}{dt} = -\left(|u| + \left|\dfrac{d\varepsilon_c}{dt}\right|\right) k_c + k_0 |u|_+ \\ \dfrac{d\sigma_c}{dt} = -\left(|u| + \left|\dfrac{d\varepsilon_c}{dt}\right|\right) \sigma_c + k_c \dfrac{d\varepsilon_c}{dt} + \sigma_0 |u|_+ \end{cases}$$

k_c contractile stiffness
u electrical action potential
ε_c contractile strain
σ_c contractile stress

J. Bestel, F. Clément, and M. Sorine. A Biomechanical Model of Muscle Contraction. In *Medical Image Computing and Computer-Assisted Intervention (MICCAI'01)*, 2001.

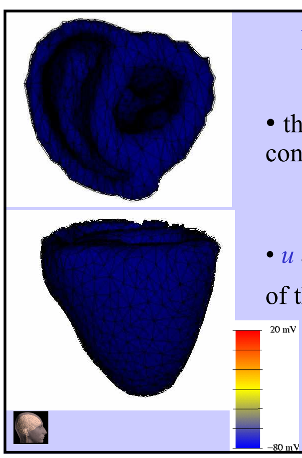
F_c: Simplified electromechanical model for image segmentation

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



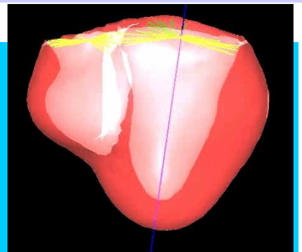
Electro-Mechanical coupling

- the "Action potential" u controls contractile element:
  - $u > 0$: Contraction
  - $u \leq 0$: Relaxation
- u also modifies stiffness k of the material.

- Ayache-Chapelle-Clément-Coudière-Delingette-Sermesant-Sorine-FIMH'01
- Sermesant-Coudière-Delingette- et al., MICCAI'02

Cardiac Cycle Simulation

- 4 phases :
  - filling
  - isovolumetric contraction
  - ejection
  - isovolumetric relaxation



- 2 Boundary Conditions :
  - Pressure constraint on the endocardium
  - Isovolumetric constraint on the endocardium

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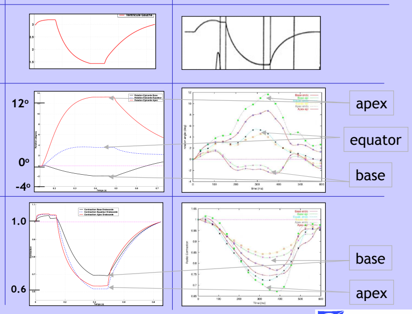
Cardiac Cycle Parameters

	Simulated	Measured par Philips (tagged MRI)
global *volume*		
local *twist*		
radial contraction		



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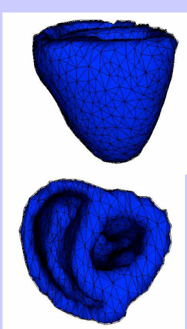
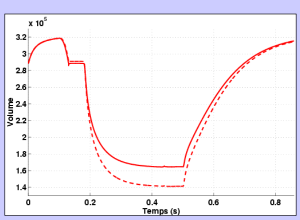
Simulating an Infarct



Infarcted zone simulation



volume

ejection fraction:
56 % → 48 %

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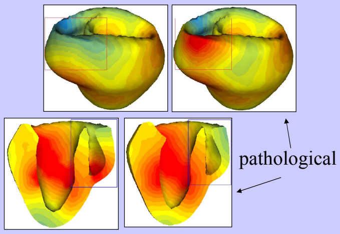
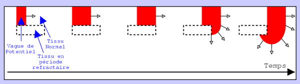
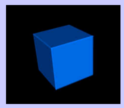
Simulating Electrical Pathologies

- Ectopic Focus in RV
  - Wolff-Parkinson-White
- Bundle of His defect in RV
  - Right Branch Block
- Fibrillation





Wave-break



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Brain Soft Tissue Modeling

Acknowledgments:
- Olivier Clatz, Nicholas Ayache
- Hopital La Pitié Salpétrière (D. Dormont)
- Centre Antoine Lacassagne (P.-Y. Bondiau)
- Brigham and Women’s Hospital (S. Warfield)

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