# Imagerie Médicale

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INRIA
Epidaure

## Plan

- Introduction aux images médicales :
- Introduction à la segmentation d'images
  - Méthodes de seuillage et classification
  - Modèles déformables :
- Modélisation
  - Simulation de chirurgie
  - Modélisation Cardiaque
  - Croissance de tumeurs



## Imagerie Médicale

Roentgen, 1895



## Development of Computed Tomography

History

- 1895 Röntgen — Discovery of X-rays
- 1917 Radon — Mathematical foundations
- 1963 Cormack — X-ray tomography idea
- 1972 Hounsfield — First CT scanning system
- 1989 Kalender — Introduction of helical CT
- 1998 — First multi-line CT system
- 2004 — Cone beam CT systems



## Caracteristiques des images médicales (1)

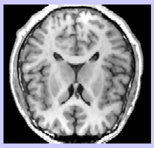
Les niveaux de gris sont liées aux <u>caractéristiques physiques des tissus</u> qui peut également être relié à un <u>phénomène physiologique</u>

Physique → Anatomie, Physiologie



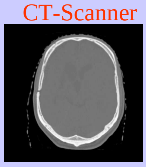
## Principales Modalités d'Imagerie

IRM



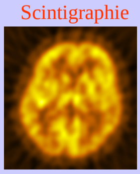
Densité et structure des Protons

CT-Scanner



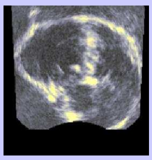
Densité d'absorption aux rayons X

Scintigraphie



Densité d'isotopes injectées

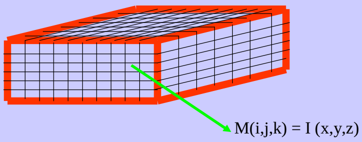
Ultrason



Variations d'impédance Acoustique

## Images Médicales 3-D

- Représentation discrète d'une partie du corps qui est décrite par une matrice à 3 dimensions (voxels)




- I(x,y,z) mesure certaines propriétés physiques ou chimiques du corps humain dans un élément de volume

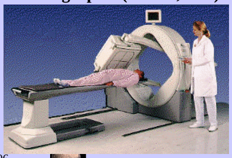


## Images Médicales 3-D

**scanner**

**IRM**

**Scintigraphie (TEMP,TEP)**



**Echographie**

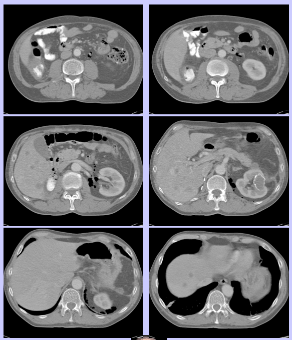


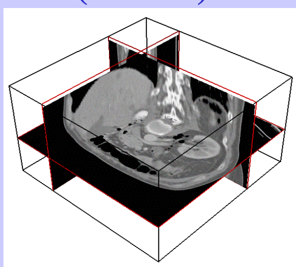
## Tomodensitomètre X (Scanner)

- Densité d'absorption des rayons X



## Tomodensitomètre X (Scanner)

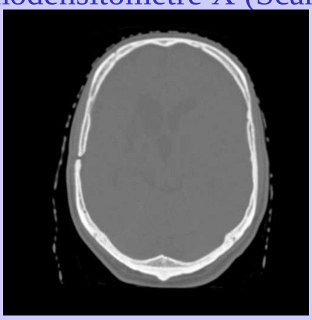




Taille: 512 x 512 x 128
Résolution: 0.5 x 0.5 x 1 mm



## Tomodensitomètre X (Scanner)



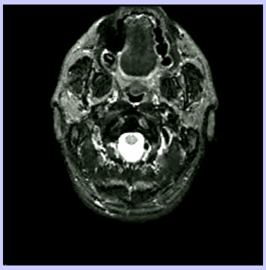
Axiale ou Transverse



## Imagerie par Résonance Magnétique

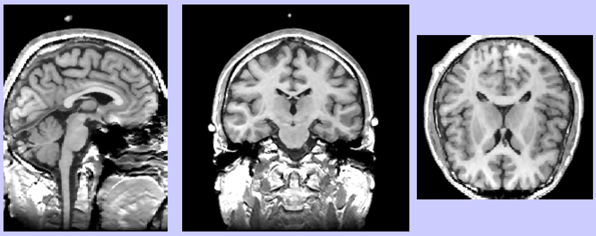
- Densité et structure des protons

## Flying through cross-sections





## Imagerie par Résonance Magnétique



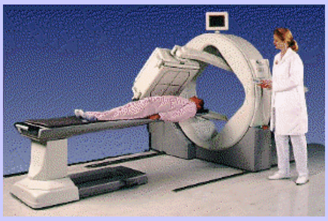
Coupe Sagittale — Coronale ou Frontale — Axiale ou Transverse

I(x,y,z) mesure une fonction de la densité et structure des protons

Résolution millimétrique. 16 millions de points



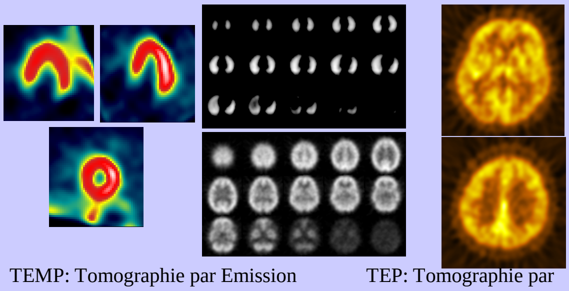
## Scintigraphies (Médecine Nucléaire)



- Densité traceurs radioactifs



## Scintigraphies (médecine nucléaire)



TEMP: Tomographie par Emission MonoPhotonique

TEP: Tomographie par Emission de Positons

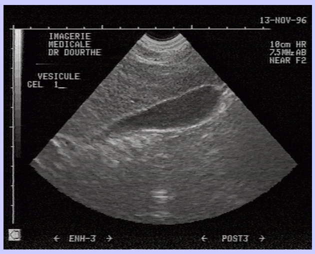


## Echographies

- Variation locale de l'impédance acoustique

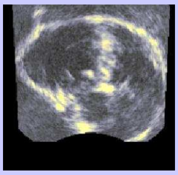


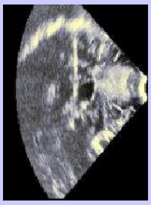
## Echographie




Vésicule

## Echographie





Axiale

Sagittale

Coronale

Tête



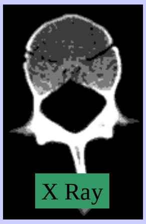
## Autres Modalités

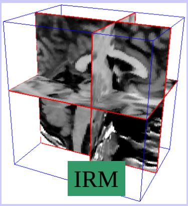
- IRM fonctionnelle (IRMf)
- IRM interventionnelle (IRMi)
- IRM Angiographiques (IRMa)
- IRM spectroscopique
- US Angiographiques, US Perfusion,
- Magnéto-EncéphaloGraphie (MEG)
- Electro-EncéphaloGraphie (EEG)
- Vidéo, Radiographies, etc.

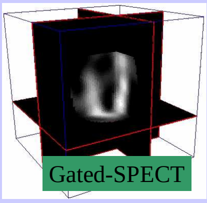


## Classification des modalités d'Imagerie (1)

- Dimensionalité




2D

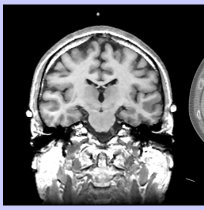
3D

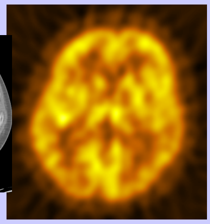
4D (3D+T)



## Classification des modalités d'Imagerie(2)

- Imagerie Anatomique ou fonctionnelle





IRM

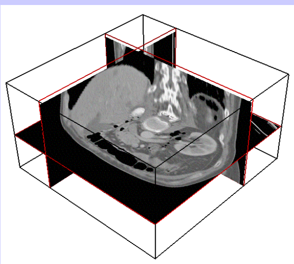
CT avec agent de contraste

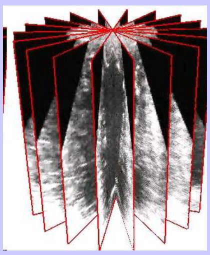
TEP scan



## Classification des modalités d'Imagerie(32)

- Géométrie d'acquisition





Cartesian

Cylindrical



## Imagerie Médicale

- Imagerie Médicale est utilisée à toutes les étapes de la pratique médicale:
  - Diagnostic
  - Planification de la thérapie
  - Contrôle de la thérapie

## Vision Globale

**DIAGNOSTIC** **THERAPIE**

Patient — Pré-opératoire → Patient

Patient ← Post-opératoire — Patient

**SIMULATION**

Patient Virtuel

Per-opératoire

Scanner
IRM
Echographie
MN

Echographie
Radios X
Vidéo
IRMi



## Imagerie Médicale(2)

- Les tendances en imagerie médicale :
  - Meilleure qualité d'images
  - ➡ Moins d'artefacts et meilleur contraste
  - Plus grande vitesse d 'acquisition
  - ➡ Imagerie 4D et moins d'artefacts dans les images 3D
  - Meilleure résolution des images
  - ➡ Images plus détaillées et plus volumineuses



## Imagerie Médicale(3)

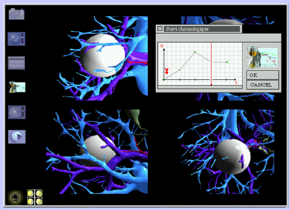
- Les images médicales ne sont pas utilisées de manières optimales :

- Visualisation 2D et partielle
- Peu ou pas d'évaluations quantitatives
- Expertise importante pour interpréter les images



## Imagerie Médicale(4)

- Requiert des outils informatiques :



Mais... Prend en compte les échecs possibles du logiciel

- Supervision par un expert médical



## Segmentation

*1. Introduction*

## Segmentation Task

- Large number of available algorithms
- Possible classifications :
  - Generic vs task-oriented
  - Bottom-up vs Top-down approaches
  - Boundary vs Region approaches
  - Explicit vs Implicit A priori knowledge
- Validation

## No Universal Segmentation Algorithm

- A segmentation algorithm has a limited range of application
- Example : deformable models

Bony Structures in CT
Hepatic Parenchyma in CT
Bony Structures in MR

High Contrast → Low Contrast

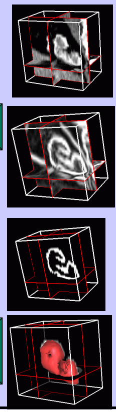
Lesions
Gray Matter
Liver

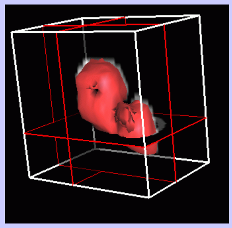
Non typical Shape → Typical Shape



## Bottom-up Approach

Medical Image
⇩
Feature Extraction
⇩
Feature Grouping
⇩
Region/Boundary Extraction

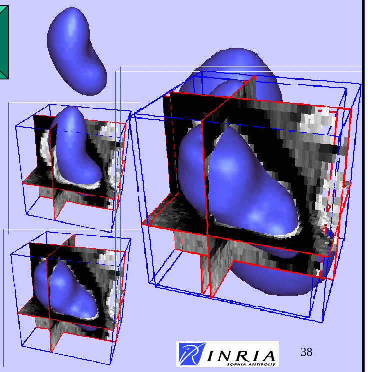






## Top-down approach

Model Construction : Shape and Appearance
⇩
Model Initialisation
⇩
Model Matching





## Region vs Boundary Methods

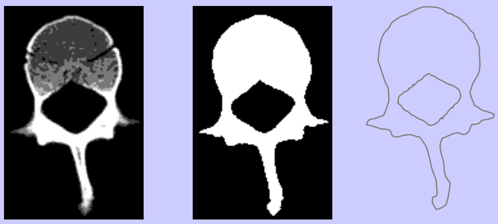


Image
Region-based segmentation
Boundary-based segmentation



## Computational vs Explicit A priori knowledge

- A priori knowledge about the structure to segment is the key to enhance robustness
- Computational knowledge : statistical analysis

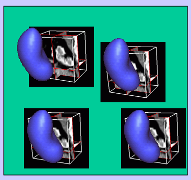


Image + structure Database → Training

Statistical classifier
Neural Networks
Principal Component Analysis
…..



## Explicit knowledge

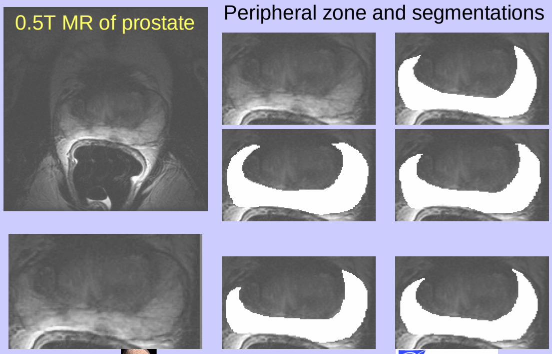
- Explicit knowledge : expert system
  - Define rules of delineation from expert
  - Translate predicate into high/low level image processing
  - Combine rules in a probabilistic framework

## Validation of Segmentation Algorithm

- Intrinsic Validation : comparison against
  - Observation of Physical Phantoms
    - Difficult and expensive to build
    - May not be representative of real data
  - Simulated images (MNI Brain Atlas,…)
    - Difficult to simulate artefacts
  - Segmentation of experts
    - Large inter and intra variability of segmentation across experts
    - May not be representation of population variability



How to judge segmentations of the peripheral zone?






## Validation of Segmentation Algorithm (2)

- Extrinsic Validation : comparison against other segmentation algorithms
  - Only possibility when no ground truth exists (Inter-patient registration of images) or when it not available
  - Estimate consistency, repeatability and size of convergence basin



## Two Segmentation Methods

Focus on 2 segmentation methods :

•**Bottom-up** : Thresholding /Classification

•**Top-down** :3D and 4D deformable models

| | Thresholding /Classification | Deformable Models | Markov Random Field |
|---|---|---|---|
| Shape Information | None | Important | local |
| Intensity Information | Essential | Important | Important |
| Boundary / Region | Region | Boundary | Region |



## Deux Méthodes de Segmentation

Description de 2 méthodes de segmentation :

•**Basée Voxel** : Thresholding /Classification

•**Basée Modèle** :Modèles déformables 3D et 4D

| | Thresholding /Classification | Deformable Models | Markov Random Field |
|---|---|---|---|
| Shape Information | None | Important | local |
| Intensity Information | Essential | Important | Important |
| Boundary / Region | Region | Boundary | Region |



## Segmentation

*2. Seuillage/ Classification*

## Seuillage et Classification

- Idée principale :

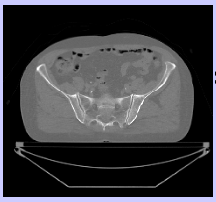
*une structure est uniquement caractérisée par ses niveaux de gris dans l'image*

→ Valide pour les structures fortement contrastées

- Algorithme de seuillage élémentaire :
  - Seuillage entre deux niveaux de gris (fenêtrage)
  - Opérations de morphologie mathématique
    - Erosion et Dilation
    - Fermeture et Ouverture
    - Extraction de composantes connexes



## Images Fortement Contrastées (1)



Seuillage interactif →

Exemple : Image scanner du bassin

Image Seuillée

## Images Fortement Contrastées (2)

Isosurface →

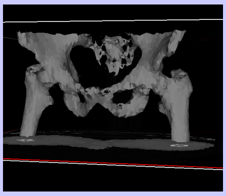


Image après opérations de morphologie mathématique

## Thresholding + mathematical morphology + connected components



## Limitation of thresholding

Thresholding :

- Choice of threshold can be computed from grey-level histogram
- Does not assume any spatial correlation of voxel intensity
- Does not take into account the effect of **partial volume effect** (PVE)

→ Use of classification methods

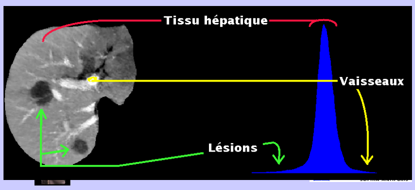


## Classification Method

- It is often not valid to consider that a voxel belongs to a single tissue type.
- It is therefore reasonable to estimate that each voxel $x$ has a probability $p_k(x)$ of belonging to a tissue class k $(1 \leq k \leq K)$

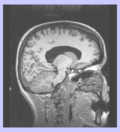
$$\sum_{k=1}^{K} p_k(x) = 1$$

CT scan image of the Liver with 3 tissue classes

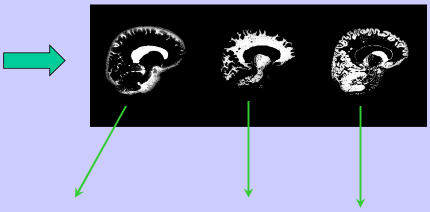


# Classification des tissus du cerveau

- Application pour l'IRM du cerveau



Courtesy of D. Vandermeulen



Fluide Céphalo-rachidien — Matière Blanche — Matière Grise



# Classification Method (2)

- Various classification methods :
  - Fuzzy c-means
    - General classification approach
    - Non parametric
  - EM Algorithm
    - Parametric approach (mixture of Gaussians)
    - Can take into account bias field
  - Curve fitting
    - Use a hierarchical approach
    - Non-linear optimization



# Isosurface et Isocontours (1)

- Etape de polygonalisation :

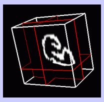
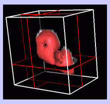


Image Voxel binaire ou avec niveaux de gris



Surface Discrète (triangulation)



# Isosurface et Isocontours (2)

- Plusieurs stratégies :
  - 1) Image Binaire ⇒ extraction du bord des voxels
  - 2) Extraction de contours puis connexion des contours par une surface
  - 2) Image Binaire ou niveaux de gris ⇒ extraction d'isosurfaces associées à un seuil c

En 2D, Extraction d 'isocontours I(x,y)=c

En 3D, Extraction d 'isosurfaces I(x,y,z)=c



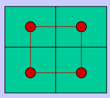
# Isosurface et Isocontours (3)

- Choix du seuil c :
  - peut-être une valeur flottante
  - pour la plupart des algorithmes, on utilise une valeur non-entière
- Propriétés des isosurfaces :
  - surfaces fermées ou avec une seul bord correspondant au bord de l'image
  - La normale à la surface est donnée par le vecteur gradient de l'image

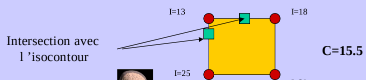


# Extraction d'Isocontour

- Calcul en 2D d'un isocontour
  - Utilisation de la dualité entre pixels et points

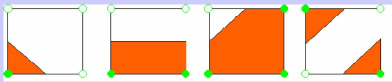


  - On calcul l'intersection de l'isocontour avec chaque pixel par une interpolation ( linéaire )



## Extraction d'Isocontour (2)

- Calcul de l'isocontour à l'intérieur de chaque pixel :



- Algorithme :

Calcul des intersections → Détermination des pixels intersectés → Calcul de l 'isocontour pour chaque pixel

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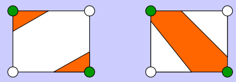
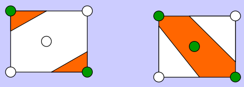
## Extraction d'Isocontour (3)

- Ambiguité : 2 choix sont possibles:



- On utilise l'un ou l'autre ou la moyenne des intensités au centre du pixel :



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## Segmentation

*2. Seuillage/ Classification*

## Segmentation d'images à l'aide de modèles déformables

- Un modèle déformable est un récipient pour stocker de l'information a priori sur la géométrie et l'apparence de structures anatomiques
- Deux niveaux de connaissance a priori:

| | Faible Connaissance a priori | Grande Connaissance a priori |
|---|---|---|
| Forme | Contrainte de continuité C1 ou C2<br>Initialisation avec formes génériques (sphère, …) | Contrainte de Forme<br>Initialisation avec forme moyenne |
| Apparence | Utilise information de gradient et/ou intensité | Utilise profils d'intensité ou appariement de blocs |

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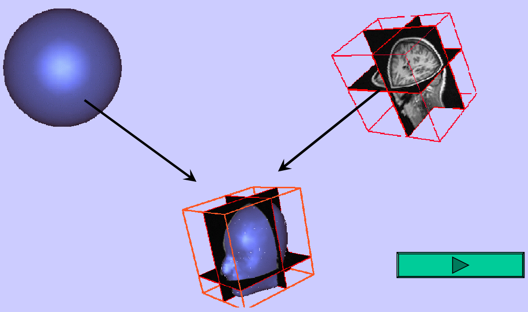
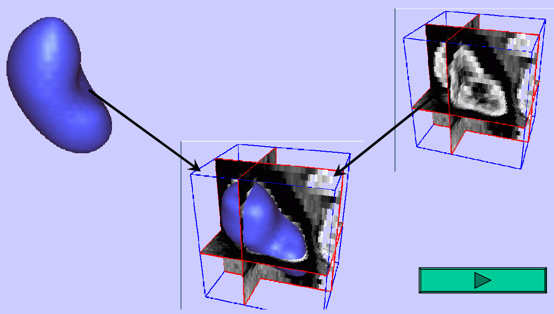
## Faible connaissance A Priori



•Valide pour des structures fortement contrastées

•Peut demander une intervention de l'utilisateur

## Forte connaissance A Priori

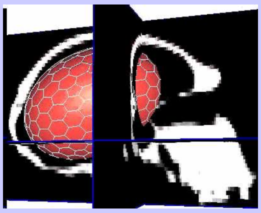


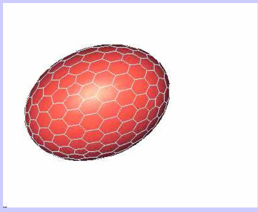
•Valide pour une structure donnée et une modalité donnée

•Plus robuste à l'exception des formes « anormales »

## Segmentation: endocranium

CT scan image, Bony structures





Time of convergence : 13,8 s

model: 1169 $cm^3$

mold: 1150 $cm^3$



## Visible Human

Joseph Paul Jernigan (died August 5th 1993)



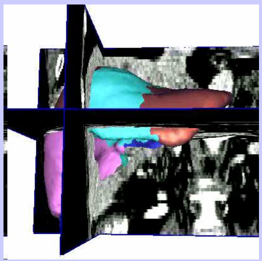

## Reconstruction du Foie

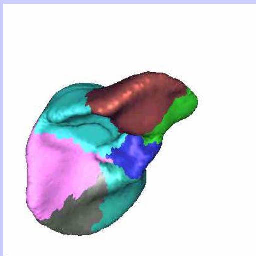
**Deformation à partir d 'un modèle de référence issu du *« Visible Human Project »***



## Segmentation: foie

Image scanner de l'IRCAD, extraction du foie



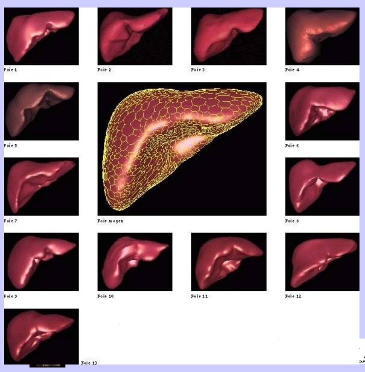


Temps de convergence: 2 mn 12 s

Extraction des segments de Couinaud

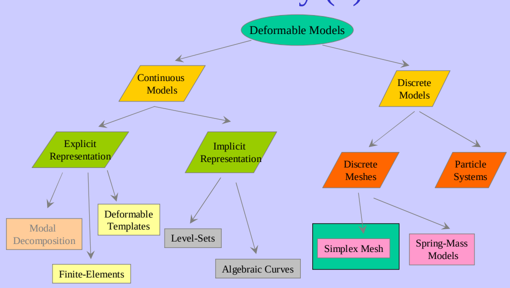


## Variabilité anatomique du Foie





## Deformable Model Geometry (3)

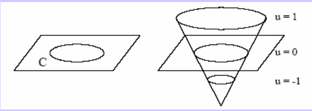


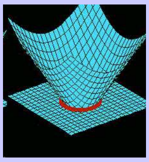

[Montagnat2001]

## Deformable models

- Level-sets
  - Curve/Surface $C$ (in $\Re^2/\Re^3$) that corresponds to an iso-level of a surface/hypersurface (in $\Re^3/\Re^4$)

$$C(t) = \{(x, y) \mid u(x, y, t) = 0\} \quad u_t + F\,|\nabla u| = 0$$



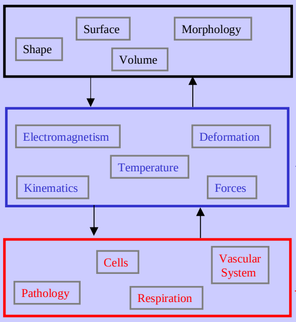
  - Implicit representation



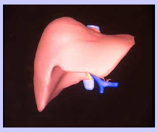
## Modélisation

*3. Computational Models of the Human Body*

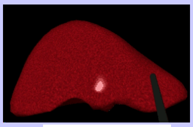
## Modeling Levels



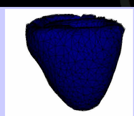

***Anatomy***



***Physics***

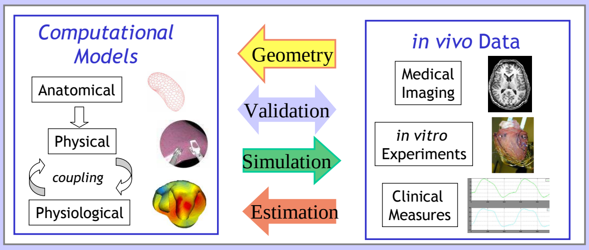


***Physiology***





## Modeling and Imaging



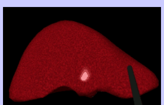

Mesh construction from medical images

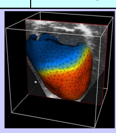


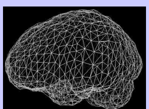
## Example of Computational Models of the Human Body

- 3 applications of human modeling

| Application Type | Organ | Real/Time Constraint | Image Interaction | Physiological Modeling |
|---|---|---|---|---|
| **Surgery Simulation** | Liver | Yes | Validation | No |
| **Diagnosis & Therapy Planning** | Heart | No | Image Segmentation | Yes |
| **Prediction of outcome** | Brain | No | Validation | No |







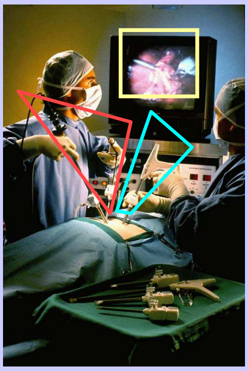


## Surgery Simulation


### Acknowledgments:

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

## Need for Training



- Hand-eye Synchronisation
- Camera being manipulated by an assistant
- Long instruments going through a fixed point in the abdomen



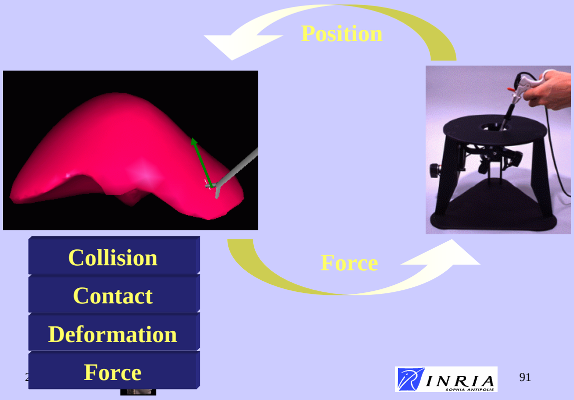
## EPIDAURE SIMULATION

*[Cotin, 1997] [Picinbono, 2001] [Forest 2003]*

- Hepatectomy Simulation by laparoscopy
- Includ




## Simulator Workflow





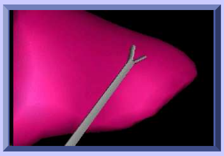

## Different Technical Issues

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



## Modeling basic surgical gesture


Gliding


Gripping


Cutting (pliers)


Cutting (US)



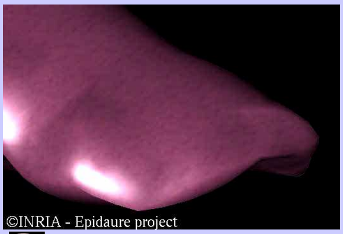
## A Family of Models (1/3)

| | |
|---|---|
| Pre-computed Linear Elastic Model | ☺ Very Fast<br>☹ No topology changes |

## A Family of Models (2/3)

Elastic Model
« Tensor-Mass »

- 🙂 Topology Changes
- ☹ Limited to small displacements



©INRIA - Epidaure project



## A Family of Models (3/3)

Non-Linear Elastic Model

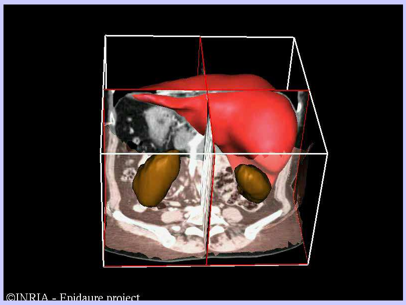
- 🙂 Large Displacements
- ☹ Small Deformations



## Complete Simulation




## Complete Simulation



©INRIA - Epidaure project



## Cardiac Modeling

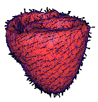
## CARDIOSENSE3D
http://www.inria.fr/CardioSense3D


### Acknowledgments:

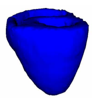
- Maxime Sermesant, Valérie Moreau, Nicholas Ayache
- INRIA projects member of the ICEMA collaborative action (Sosso, Macs, Caiman, University of Nantes),
- NIH (Elliott Mc Veigh), Guy's Hospital (D. Hill)
- Philips Research France


Electromechanical Model of the Heart

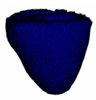
Anatomical Model



Electrical Model



Electro mechanical Coupling



Medical Simulator

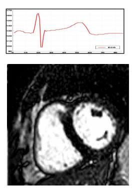
*pathology simulation*
*intervention planification*

Parameters

*cardiac function :*
- *ejection fraction*
- *wall thickness*
- *strain, stress*

Patient Data

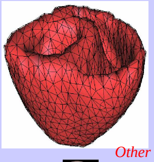
ElectroCardioGram

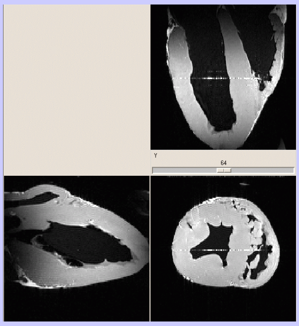


## Myocardium Geometry

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

Courtesy of Hsu, Duke University



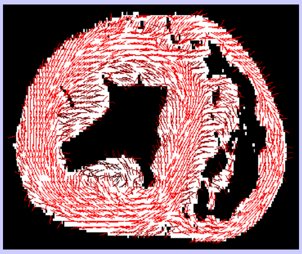


*Other Data available, Courtesy of P. Hunter, Auckland University*



## Fiber Directions (canine Data)

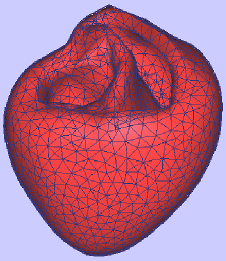
- From high resolution Diffusion Tensor MRI



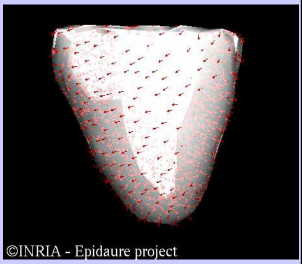
E.W. Hsu and C.S. Henriquez, *Myocardial fiber orientation mapping using reduced encoding diffusion tensor imaging*, Journal of Cardiovascular Magnetic Resonance, 2001.



## Geometrical Model of Human Heart



Finite Element Mesh




Fiber Directions

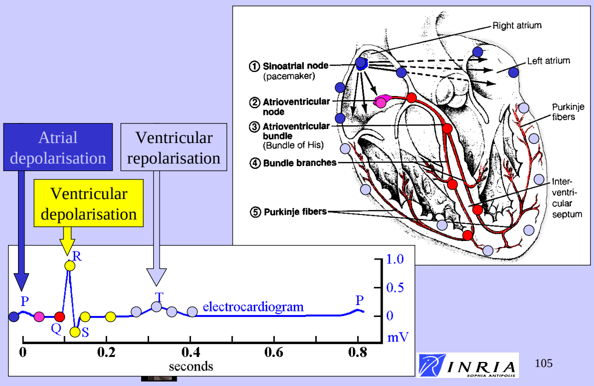


## Different Levels of Modeling

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



## Heart Electrical Activity






## Electrical Model

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

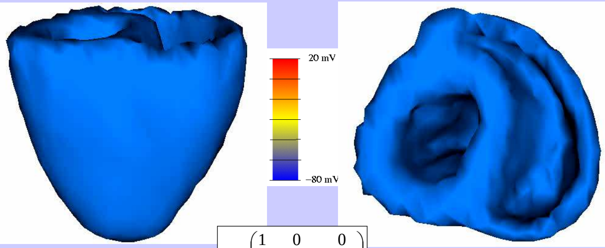
$$\begin{cases} \dfrac{\partial u}{\partial t} = div(D\nabla u) + f(u) - z \\ \dfrac{\partial z}{\partial t} = b(u - cz) \end{cases}$$

$u$ 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)

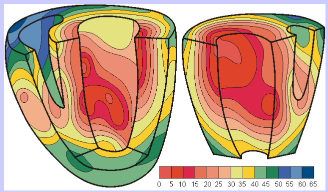



$$D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0.25 & 0 \\ 0 & 0 & 0.25 \end{pmatrix}$$

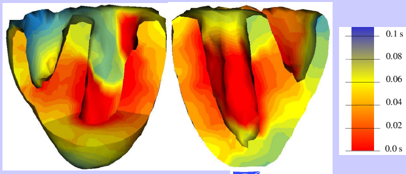


## Comparison of Isochrones

Durrer et al.




ICEMA at INRIA





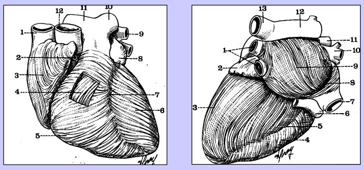

## Different Levels of Modeling

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



## Biomechanical Properties

The myocardium is composed of muscle fibre bundles:

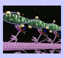
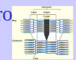
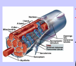
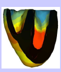


It is an active non-linear viscoelastic anisotropic incompressible material.



## Excitation-Contraction Coupling

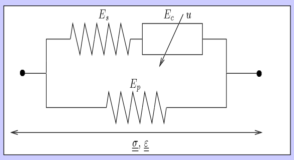
*From Bestel-Clément-Sorine, MICCAI'01*

| Scale: | | System: | Control: |
|---|---|---|---|
| Nano |  | molecular motors<br>*Langevin equations*<br>*(SDE) Ratchet or Power-stroke models* | Calcium ions<br>*still to be designed…* |
| Micro |  | sarcomeres<br>*Huxley-like models*<br>*(PDE)* | ionic currents<br>*Luo-Rudy-like models*<br>*(ODE)* |
| Meso |  | myocytes<br>BCS model<br>*(ODE)* | action potential<br>*FHN-like* models<br>*(ODE)* |
| Macro |  | myocardium<br>*dynamics equations*<br>*(PDE with BCS Constitutive Law)* | action potential<br>*FHN-like* models<br>*(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
$\sigma$ stress
$\varepsilon$ 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
$\varepsilon_c$ contractile strain
$\sigma_c$ 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.

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## $F_c$: Simplified electromechanical model for image segmentation

k piecewise constant → Piecewise linear viscoelastic anisotropic material

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

Only electrical command on contraction stress $\sigma_c$

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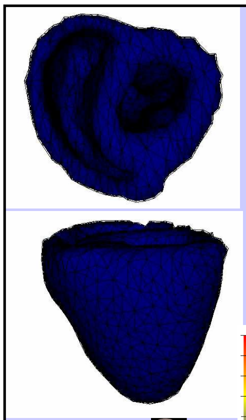
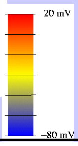


## Electro-Mechanical coupling

- 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

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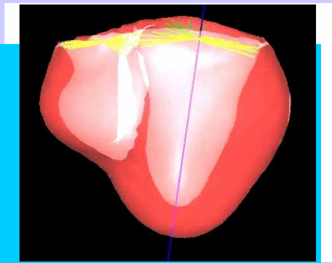
## Cardiac Cycle Simulation



- 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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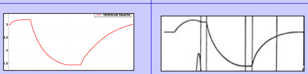
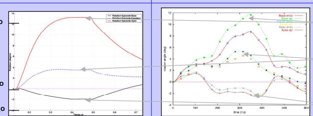
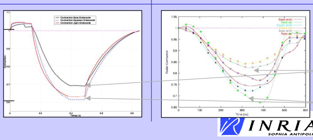
## Cardiac Cycle Parameters

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



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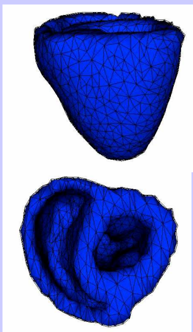
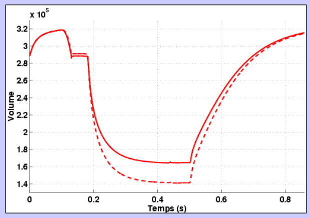
## Simulating an Infarct



*Infarcted zone simulation*




*volume*

ejection fraction:
56 % → 48 %

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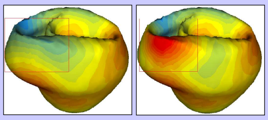
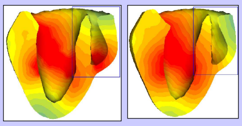
# Simulating Electrical Pathologies

- Ectopic Focus in RV
  - Wolff-Parkinson-White

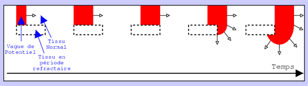


- Bundle of His defect in RV
  - Right Branch Block



pathological

- Fibrillation




*Wave-break*