Urology & Computer Aided Surgery

Pierre Mozer

Soutenance de thèse

Université Joseph Fourier

Ecole Doctorale « Ingénierie pour la santé, la Cognition et l'Environnement »

Spécialité : « Modèles et Instruments en Médecine et en Biologie »

TIMC/GMCAO - Urology Pitié-Salpétrière

JURY

Marie-Odile Berger (Rapporteur)
Alain Le Duc (Rapporteur)
Dan Stoianovici
François Richard
Jocelyne Troccaz (Directrice)
Yohan Payan (Co-directeur)

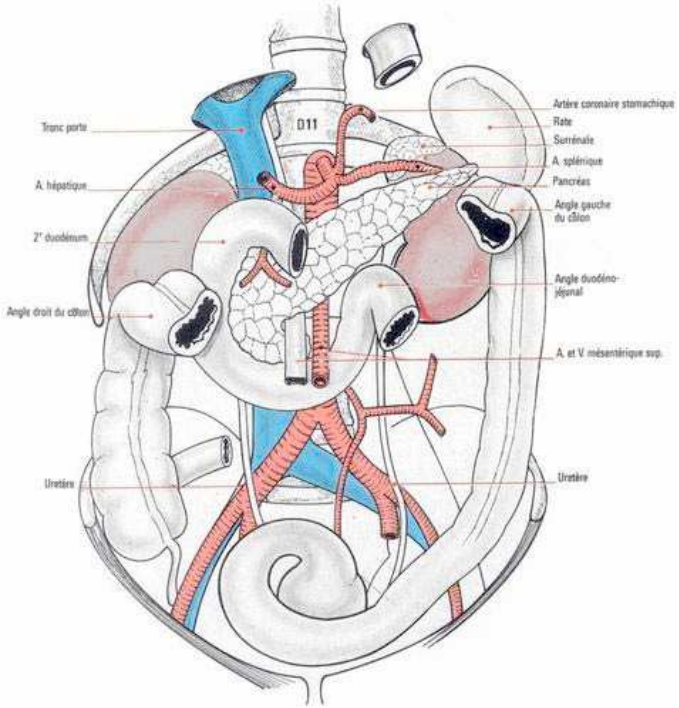
Presentation

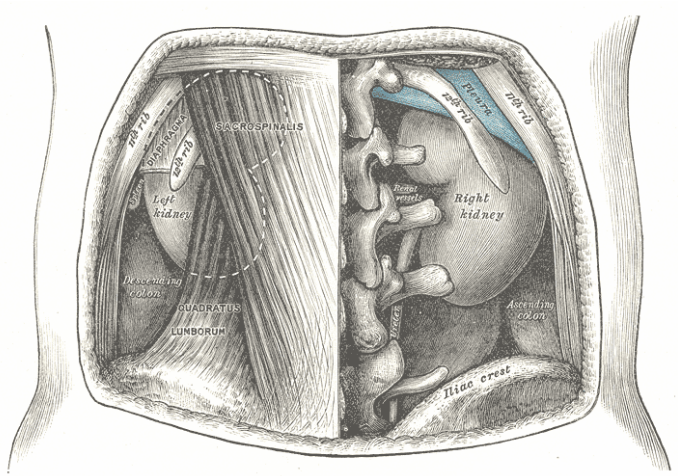
- Part I : Kidney
  - Percutaneous Renal Puncture
- Part II : Incontinence
  - S3 Nerve Root Neuromodulation
- Part III : Prostate
  - MRI-Histology Registration
  - Transrectal Biopsies

Part 1 : Percutaneous Renal Puncture

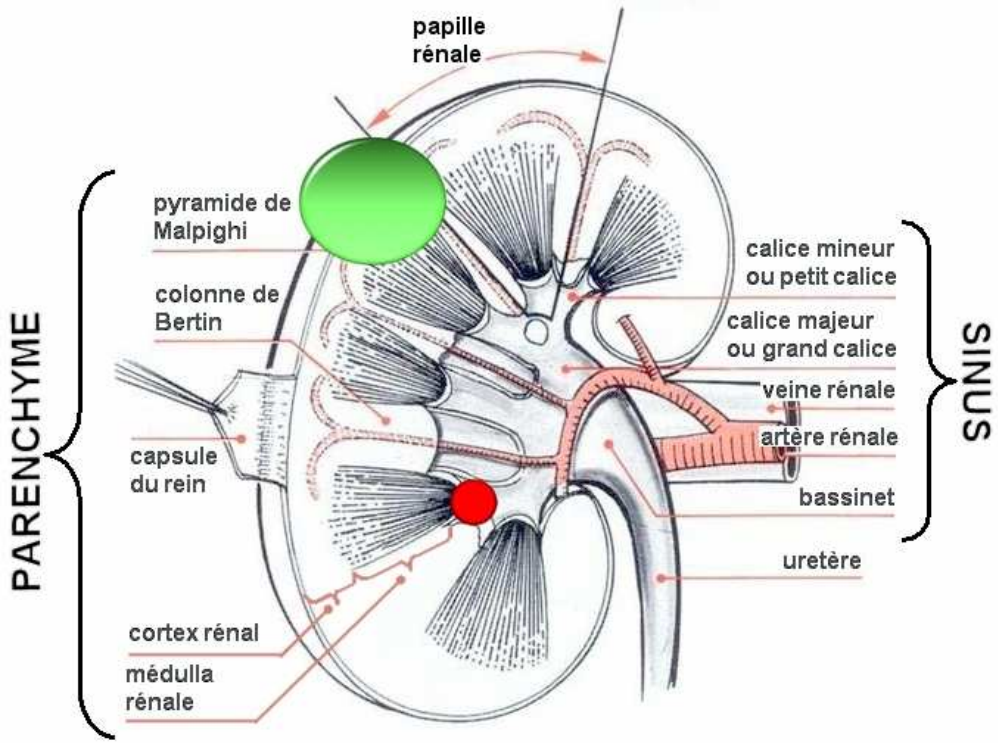
- Introduction
  - Anatomy
  - Clinical aims
  - PRP & CAS : state of the art
- Development of a navigation system : CT-scan and US registration
- Development of a system : Projection of the Ultrasound Puncture Tract onto Fluoroscopic Images

Anatomy


D11
Tronc porte
A. hépatique
2e duodénum
Angle droit du côlon
Uretère
Artère coronaire stomachique
Rate
Surrénale
A. splénique
Pancréas
Angle gauche du côlon
Angle duodéno-jéjunal
A. et V. mésentérique sup.
Uretère


SACROSPINALIS
Left kidney
Right kidney
Descending colon
QUADRATUS LUMBORUM
Ascending colon
Iliac crest

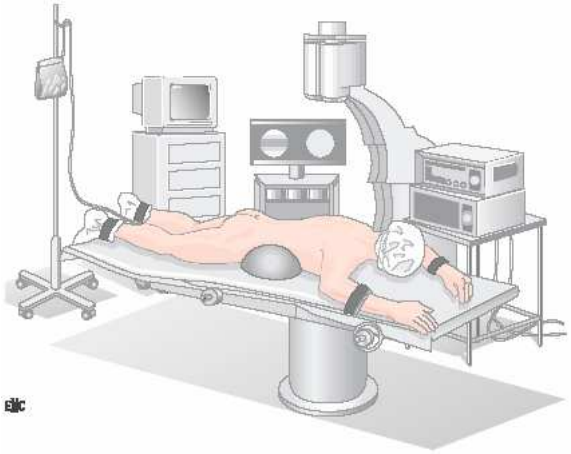
Clinical Aims

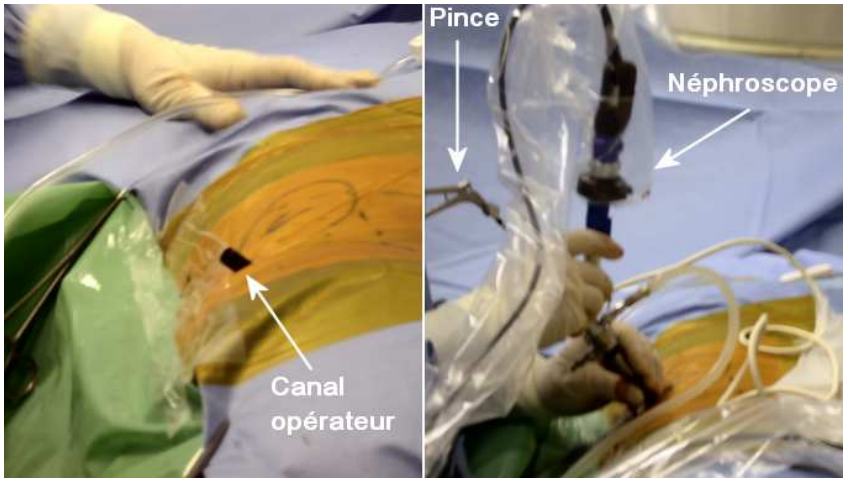


- Percutaneous :
  - Reach a target into parenchyma in case of cancer
  - Calix access in case of PCNL

PCNL

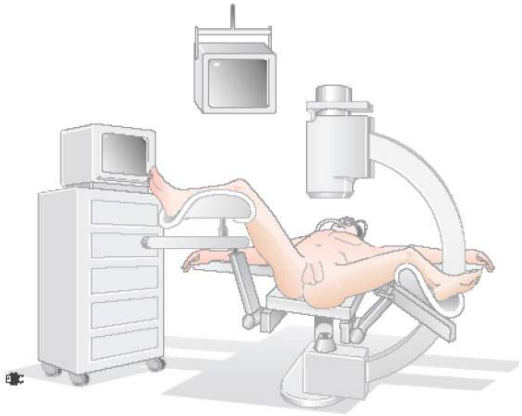
- 2500 cases each year in France





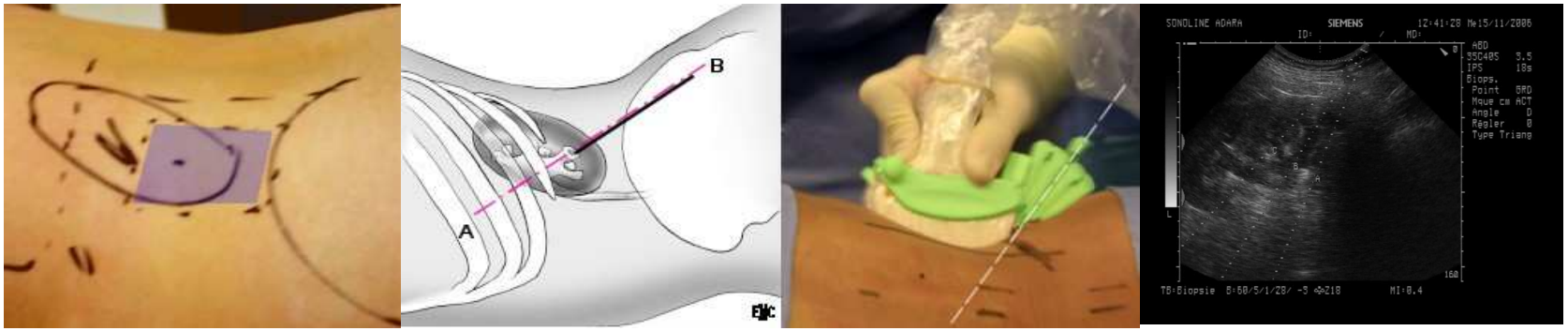
Percutaneous Acces for PCNL

- Intervention with 2 steps :
- First step :
  - Gynecological position
  - Ureteral stent
    - Dilatation of the calix
      - Contrast agent
      - Blue indigo-carmine



Percutaneous Access for PCNL

- Second step :
  - Prone position
  - Puncture with US and Fluoroscopy



Success and complications rates : function of experience

Target Characteristics

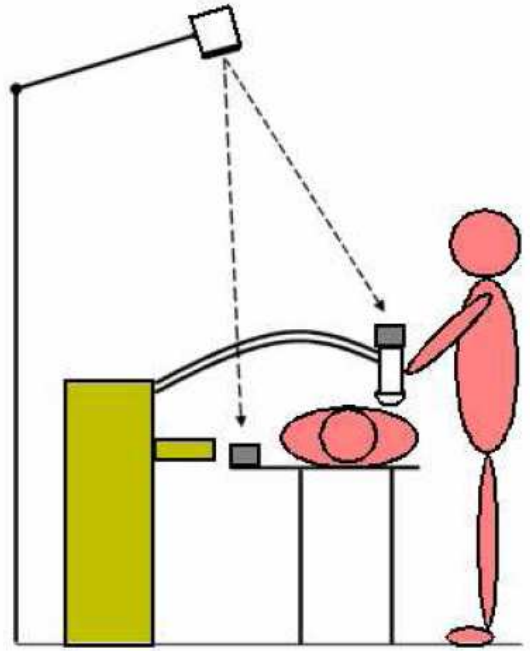
Distance	70 mm
Size	5-10 mm
Motion	30 mm
Speed	9 mm/s
Time	20-90 s

[Schwatz94]

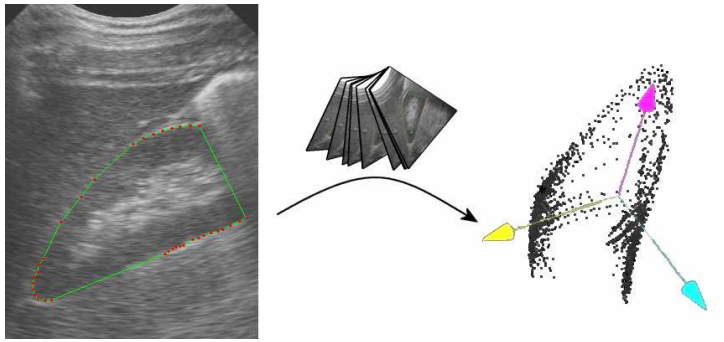
! No 3D data available for repositioning !

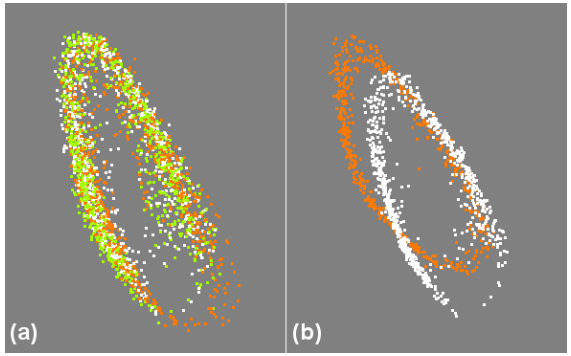
Study of Kidney movement amplitude and reproducibility

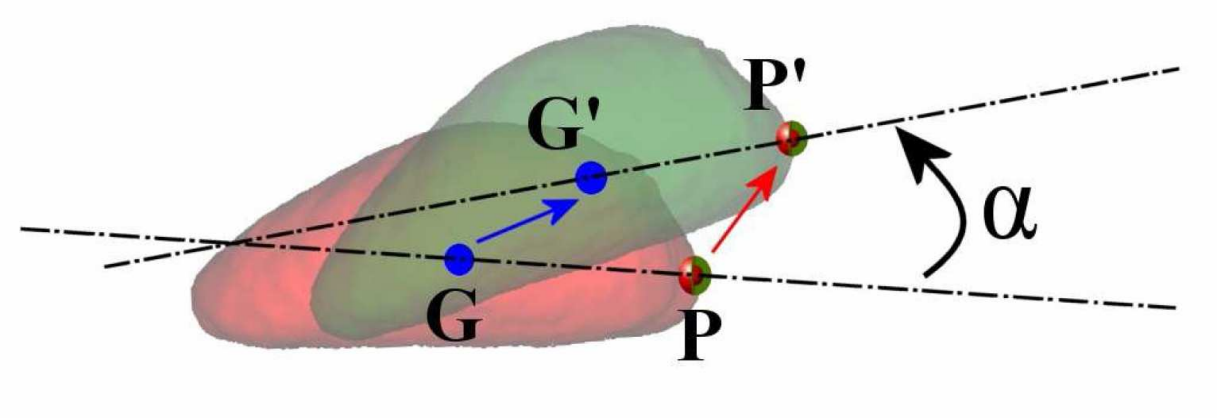
- 11 healthy volunteers
- US acquisitions
  - Calibrated and localized
  - Right kidney
  - Anterior access
  - Under spontaneous ventilation



Study of Kidney Movement Amplitude and Reproducibility







Study of Kidney movement amplitude and reproducibility

- Amplitude (mm and °):

	Mean	Std.dev	Min	Max
PP'	30.8	14.1	7.8	55.5
GG'	30.1	14.7	10.1	60.0
α	11.6	3.8	6.5	17.5

- Reproducibility of centroid position for each breathing cycle (mm):

	Mean	Std.dev	Min	Max
Δ G	5.9	3.9	1.3	15.9

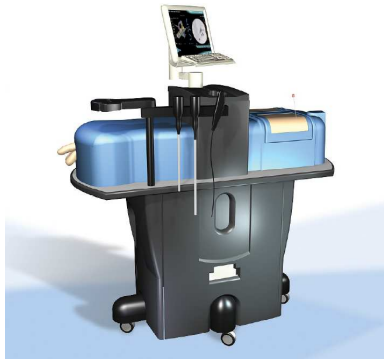
Study of Kidney movement amplitude and reproducibility

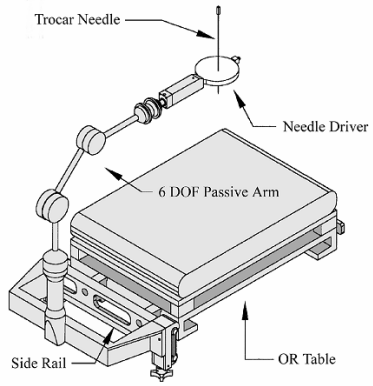
- The average values are coherent with the literature
- That gives hope to prove high repeatability under general anesthesia circumstances

Navigation Systems

- Pairing of homologous points (Skin markers or points picking)
- Accuracy : unknown

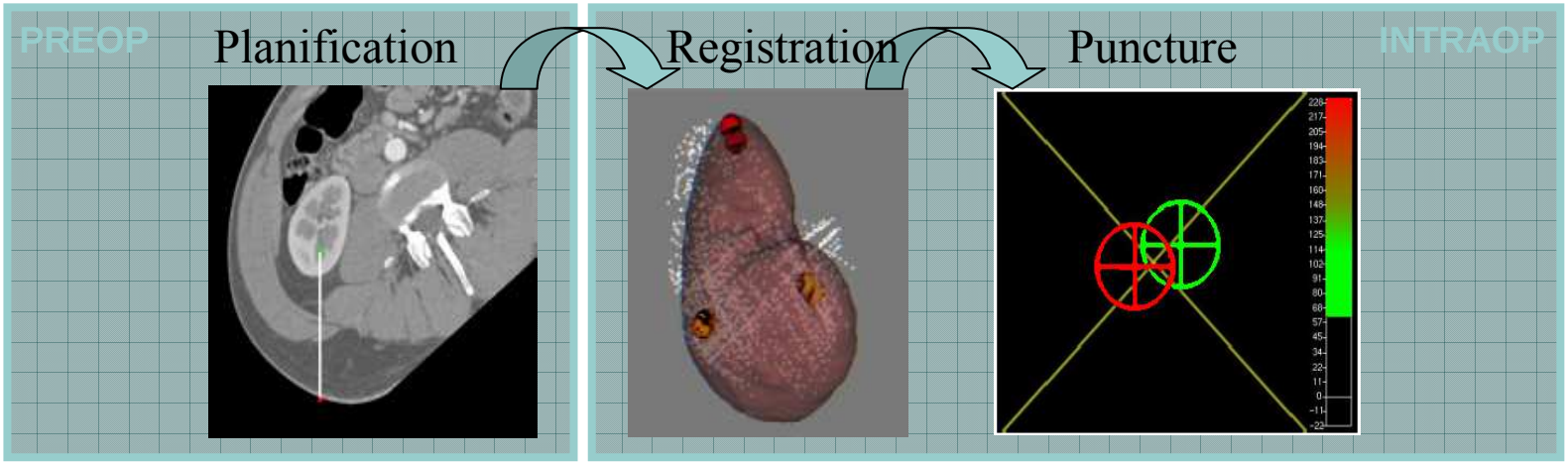
Simbionix™





[Stoianovici]

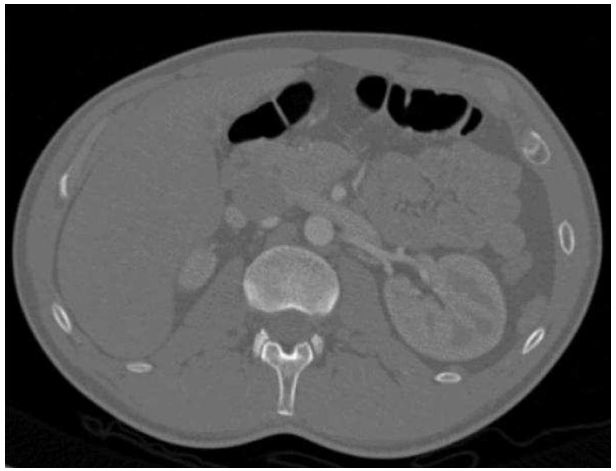
Navigation system by CT-scan and US registration



- Hypothesis on the kidney :
  - Reproducible positioning
  - Rigid

Preoperative CT-scan

Data from a healthy volunteer



First phase scan

(delay 15 sec)

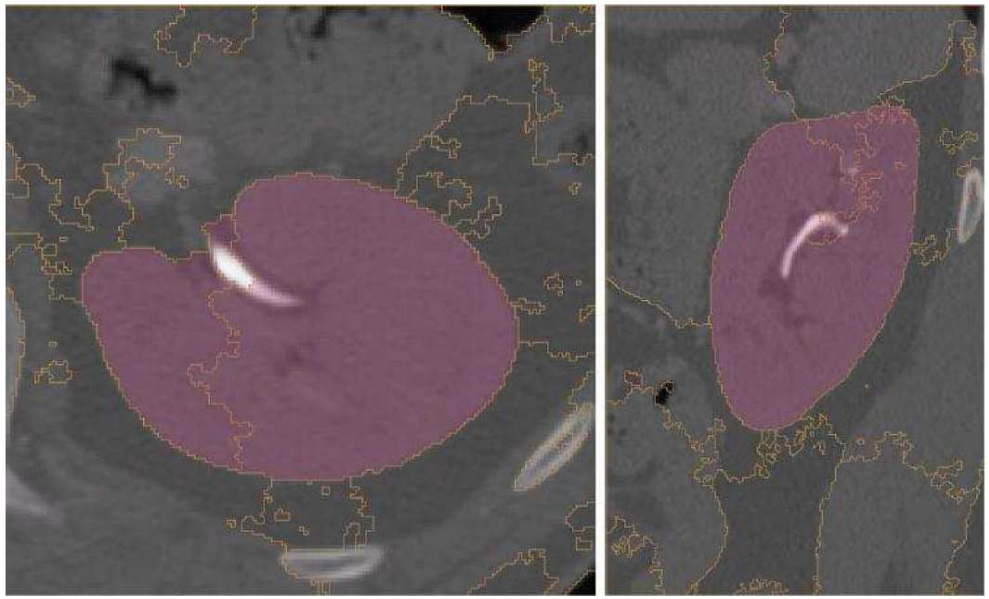
Second phase scan

(delay 180 sec)

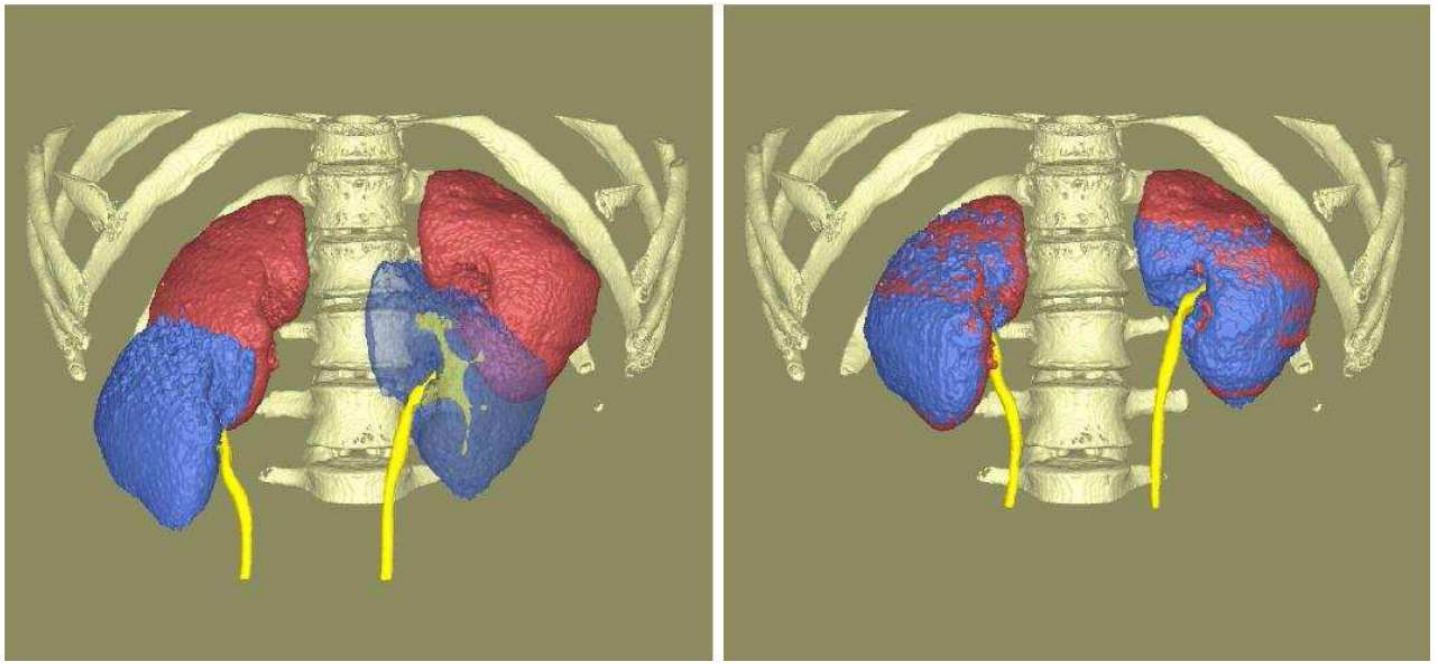
Voxel size =0.6x0.6x1.25 mm3

Preoperative CT-scan : Segmentation

- 3D watershed (Nabla™)

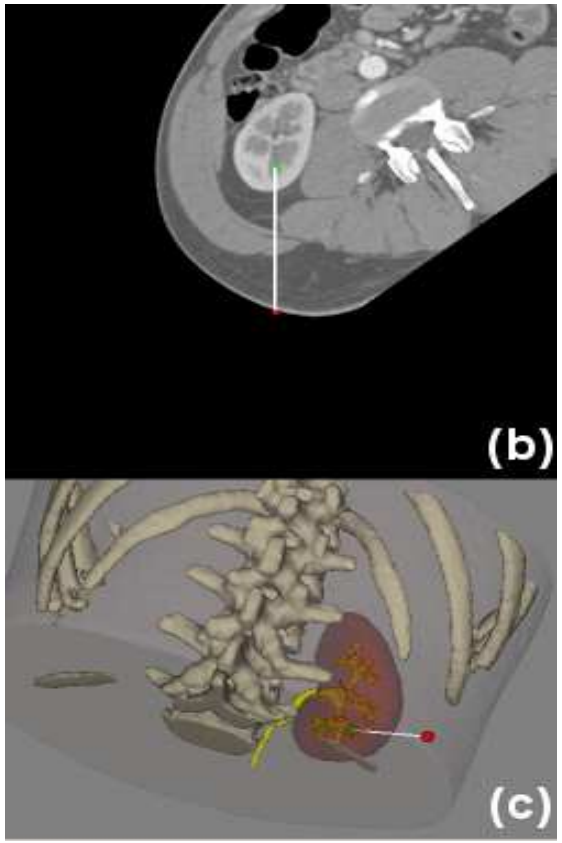


Preoperative CT-scan : First & Second Phase Registration

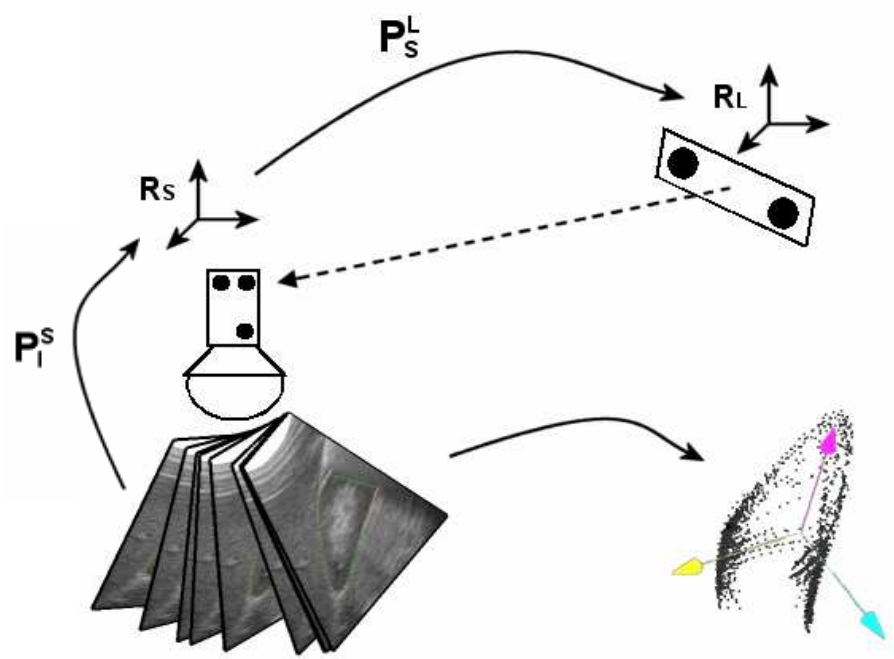


Champfer distance map - Analyze™

Preoperative CT-scan : Planning



Intraoperative :
US 2.5D Acquisition



Intraoperative : US & CT Registration

- Methods :
  - Geometric :
    - Pairing of homologous points
    - Clouds of points
  - Intensity-based
    - Similarity

US & CT Registration

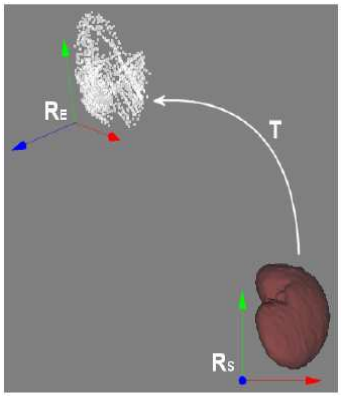
- « Initial Attitude », IA
  - Pairing of homologous points [Arun87]
- Rigid registration (6D) [Lavallée96]:

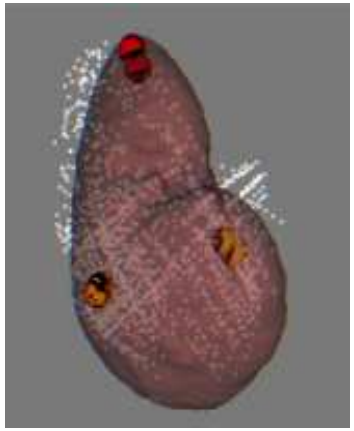
$$T(p) = Tx \circ Ty \circ Tz \circ Rx \circ Ry \circ Rz$$

  - Y=(y1,y2,…….,ym)
  - X=(x1,x2,…..xn)
  - m>>n
  - Minimization

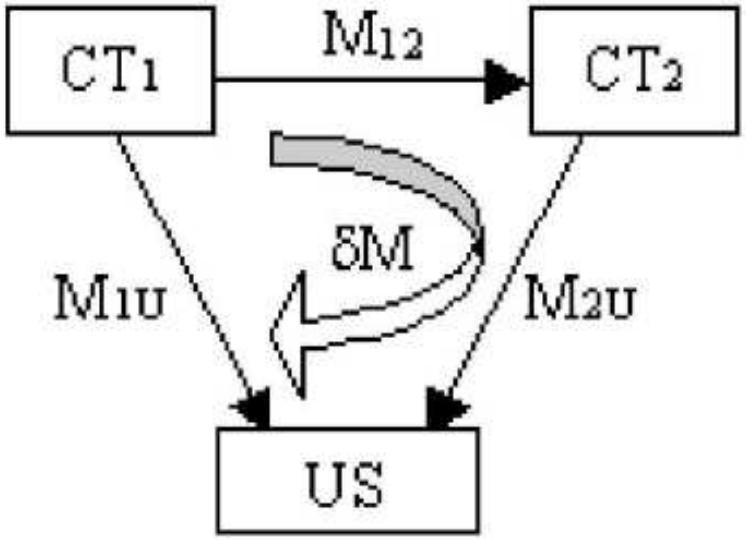
$$E = \frac{1}{\sigma} \sum_i d(Y, T(x_i))^2$$

  - by Levenberg-Marquardt
- Time : 3 s



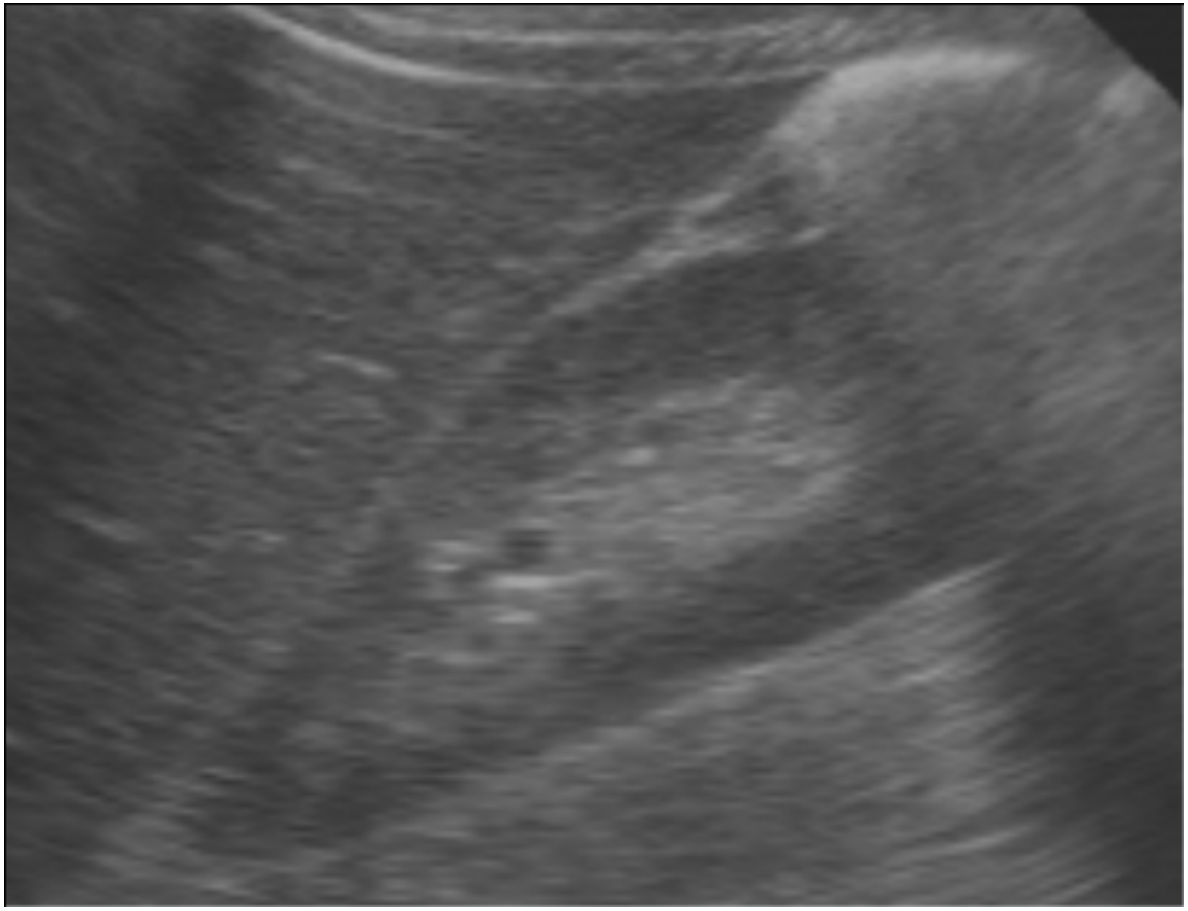


Registration : Evaluation Accuracy

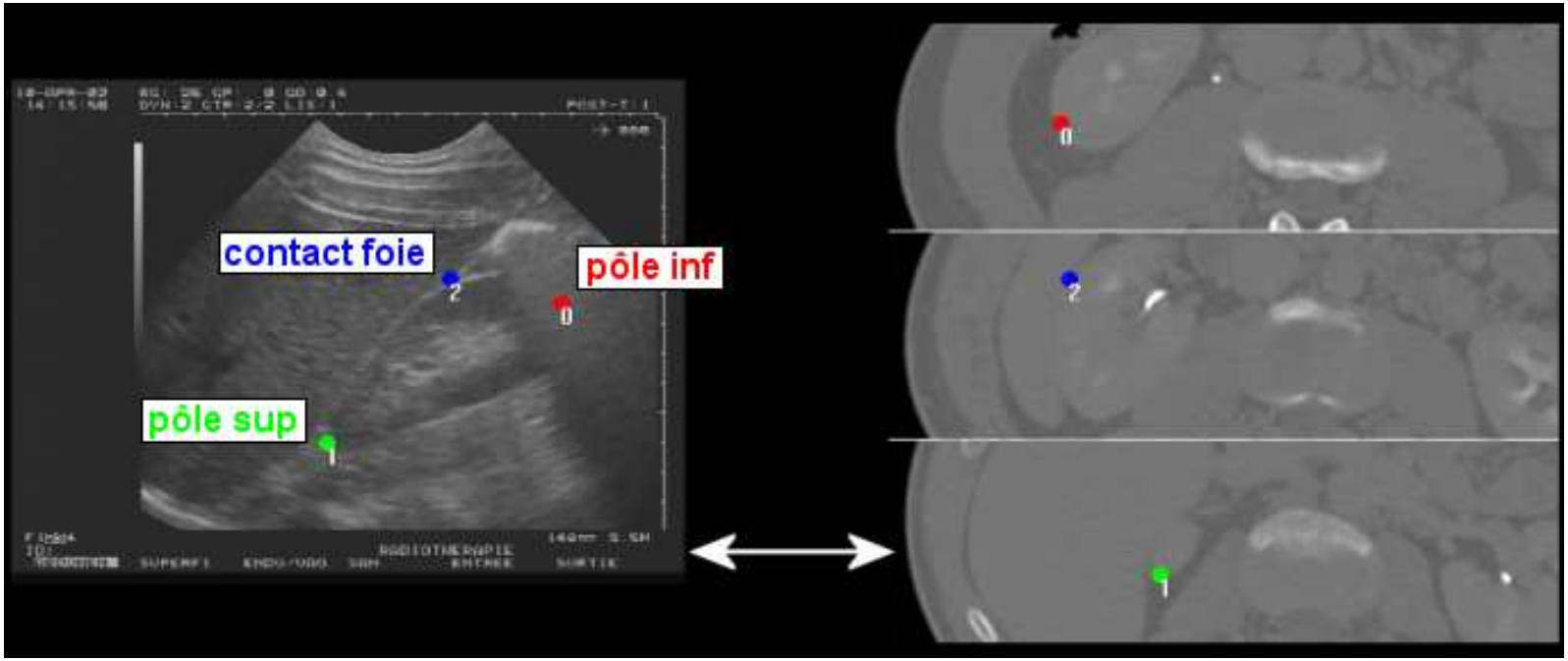


- Closed loop test :
  - $\delta M = M_{1U}^{-1} * M_{2U} * M_{12}$
- $\|\delta M * CT1 - CT1\| = 1.2 \pm 0.4mm$

US & CT Registration - Visualization



Registration : Evaluation of pairing of homologous points



Registration : Evaluation of pairing of homologous points

- One operator
- 22 registrations by paring of 3 points
- Compare to transformation obtain by registration of clouds of points (bronze standard – [Jannin])
- Results :
  - G =12.9 mm ± 6.9
  - Long Axis =17.5°± 9.9.
- Error is bigger than the target.

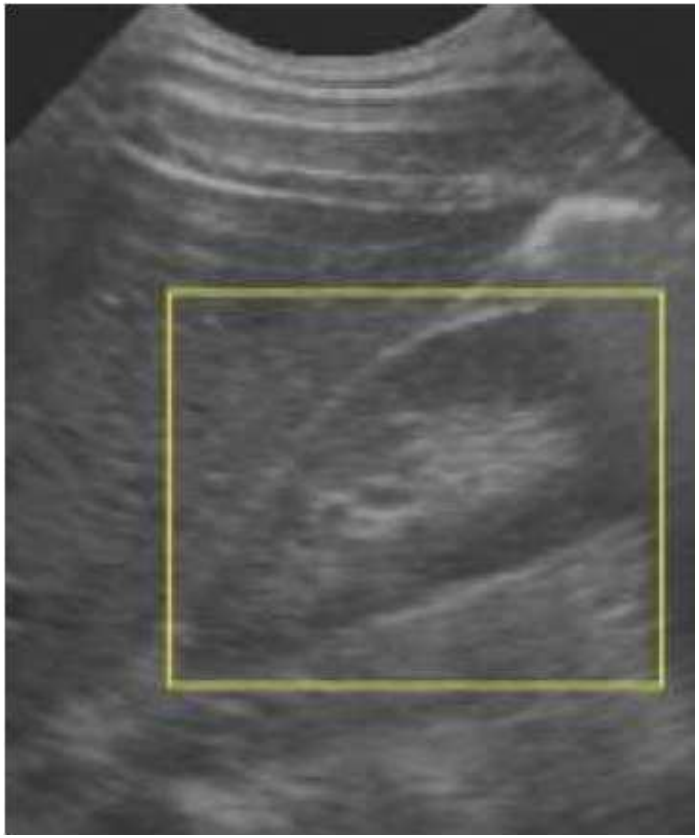
CT-US registration : Intensity-based Registration

- Iterative method to search for an optimal transform between two sets of data V1 (CT) and V2 (US)
- Similarity measure between the voxels of the two data sets

CT-US registration : Intensity-based Registration

- [Leroy07]
- Preprocessing :
  - CT : median and Sobel gradient filter
  - US :
    - Speekle (sticks filter)
    - Shadow removal
- Similarity measure : Correlation ratio
- Minimization : Powell-Brent

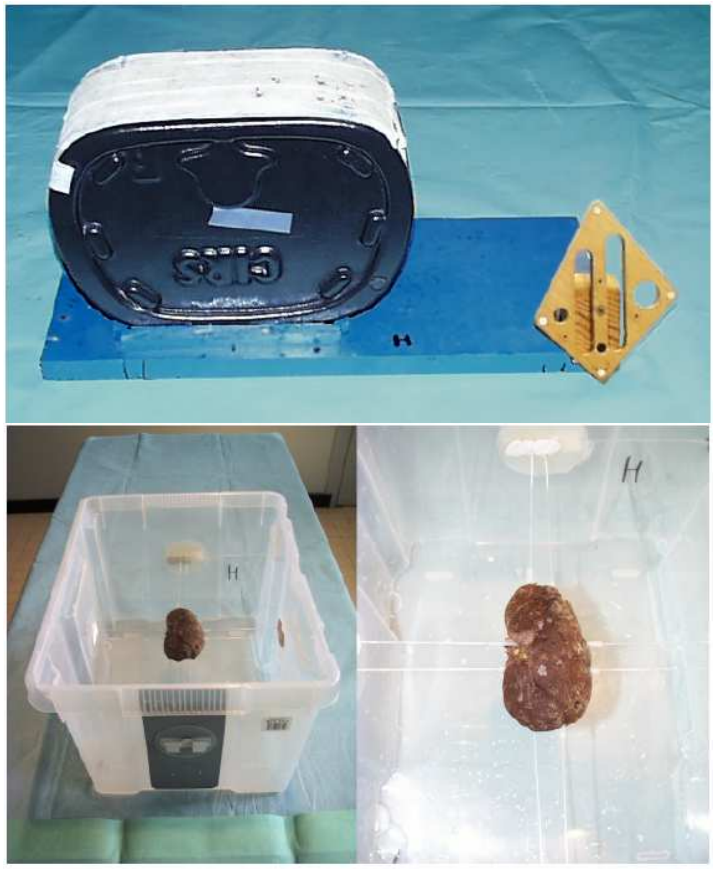
CT-US registration : Intensity-based Registration



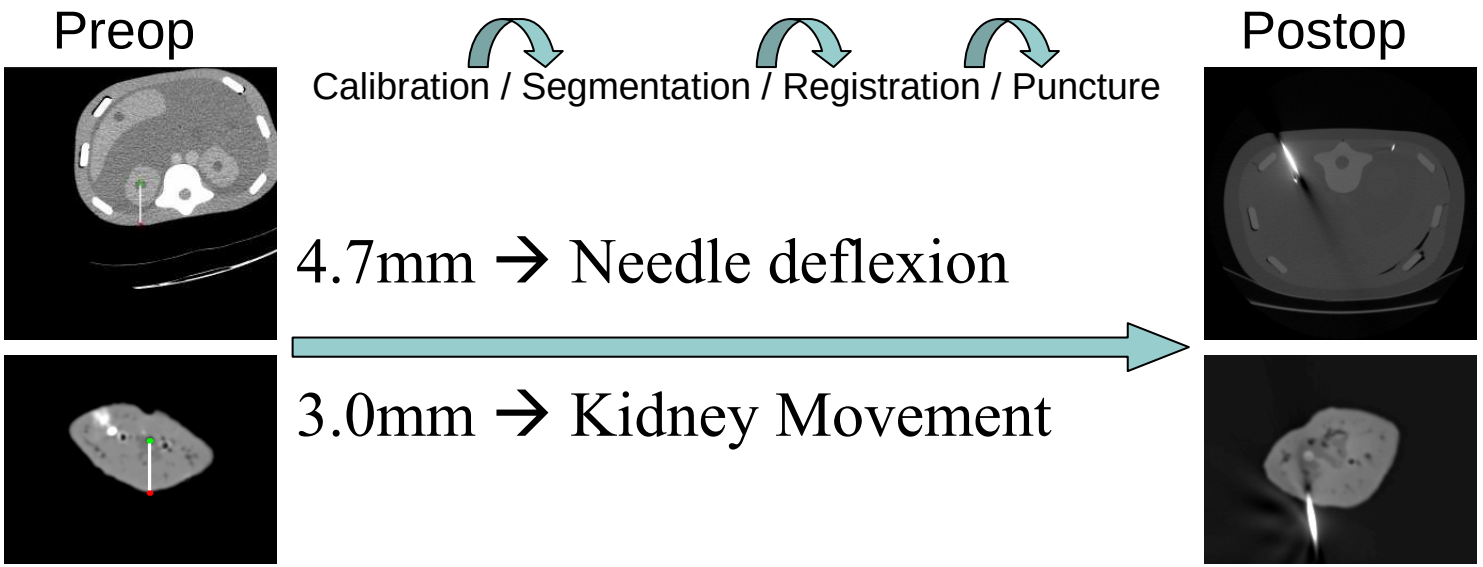
- Bounding box
- Accuracy :
  - Intensity-based vs clouds of points
  - 20 registrations
    - Time : 90 s
    - Centroïd G ~ 5mm

Phantom tests

- Registration :
  - Clouds of points



Phantom tests

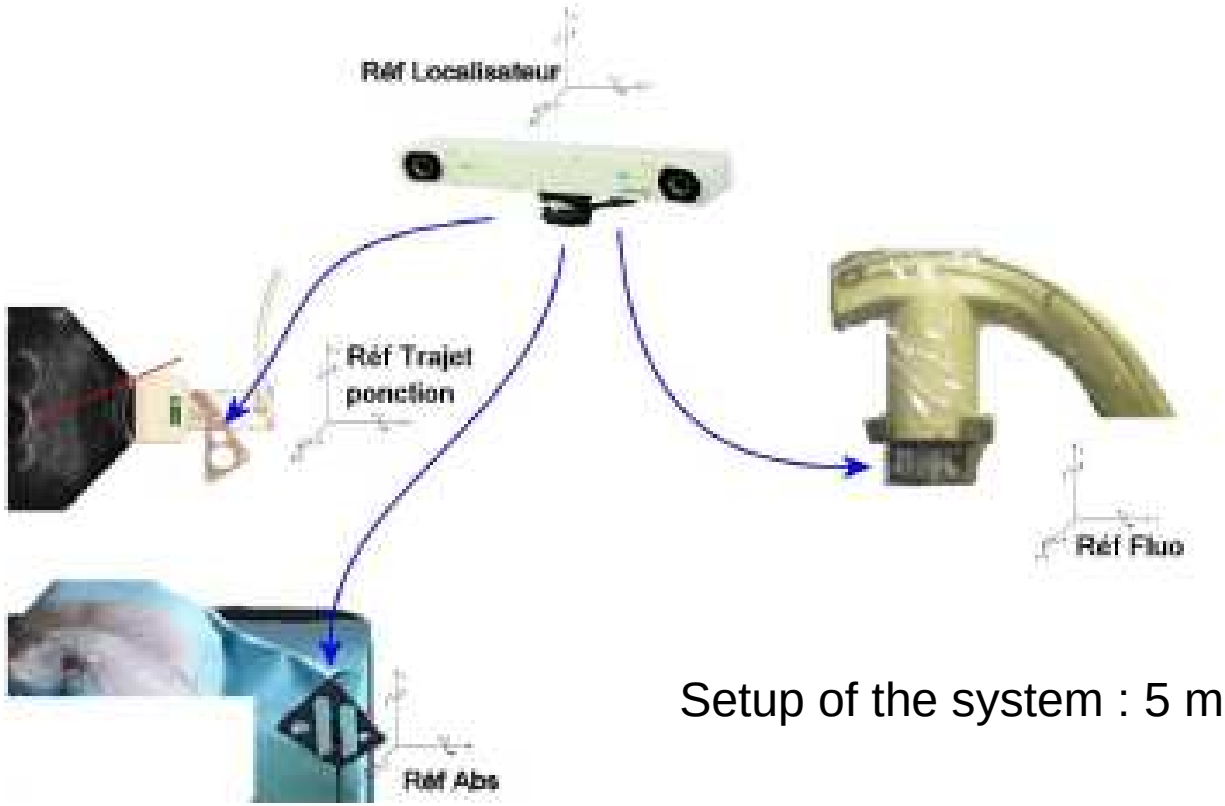


Registration : Conclusion

- Image processing :
  - Pairing of homologous points :
    - Error > target size
  - Clouds of points :
    - Important interaction between clinician and system -> Would need automatic segmentation for clinical practice
  - Intensity-based :
    - Robustness need to be evaluated
    - US 3D

Projection of the Ultrasound Puncture Tract onto Fluoroscopic Images

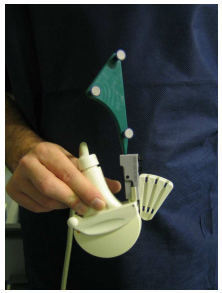
[Merloz]



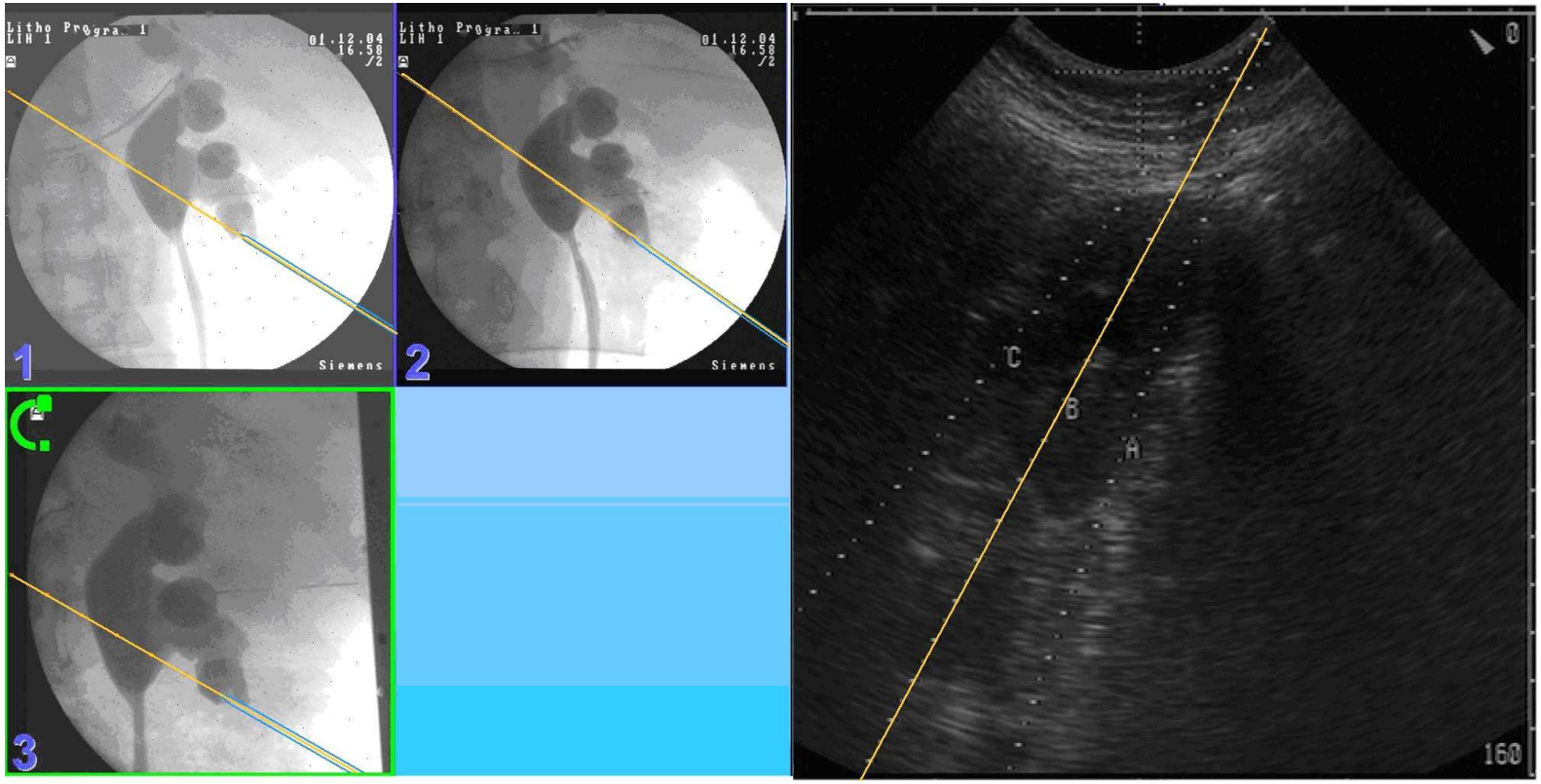
Setup of the system : 5 minutes

Projection of the Ultrasound Puncture Tract onto Fluoroscopic Images

- First step :
  - Fluoroscopic images in various orientations
  - *Fluoroscope is removed* from the operative field
- Second step :
  - Calibration of the puncture tract



Projection of the Ultrasound Puncture Tract onto Fluoroscopic Images

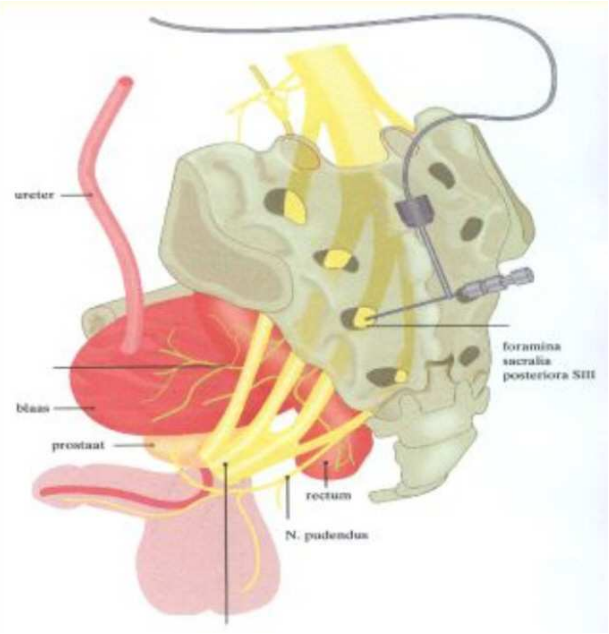


Clinical study

- 10 patients
  - Target surface = 158 mm2 (30 - 311)
  - Target reached on first attempt for 7 patients
  - 3 others : 3 puncture trials were necessary
    - Deformation of the needle
    - Mechanics improvement
- On going evaluation study
  - X-Ray exposure
  - # puncture

Part II :
S3 Nerve Root Neuromodulation

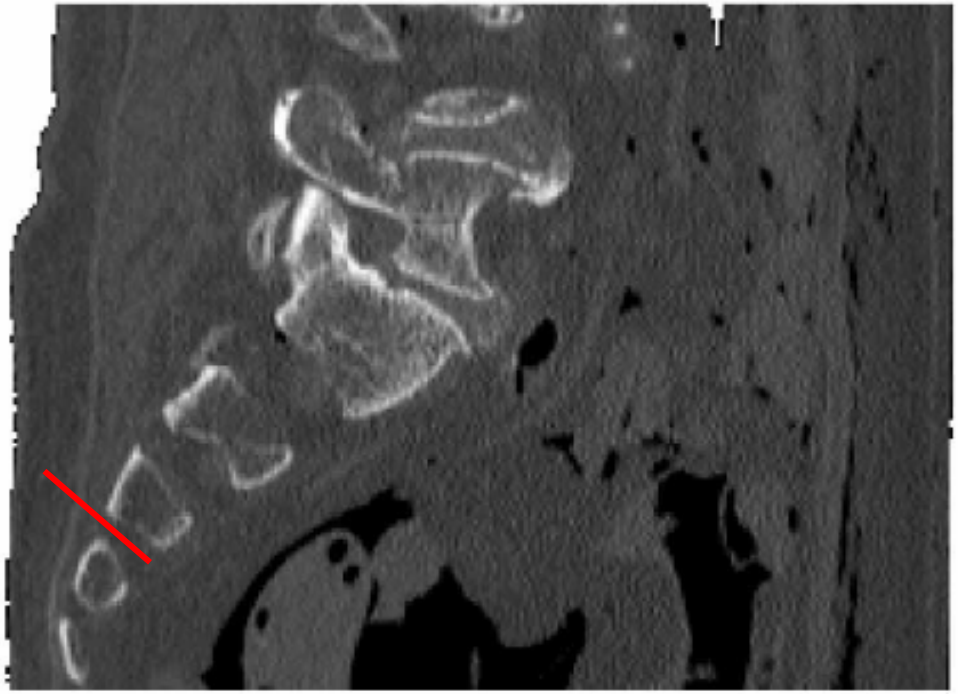
- Lower urinary tract symptoms
- Implantation :
  - Local anesthesia
  - Fluoroscopy



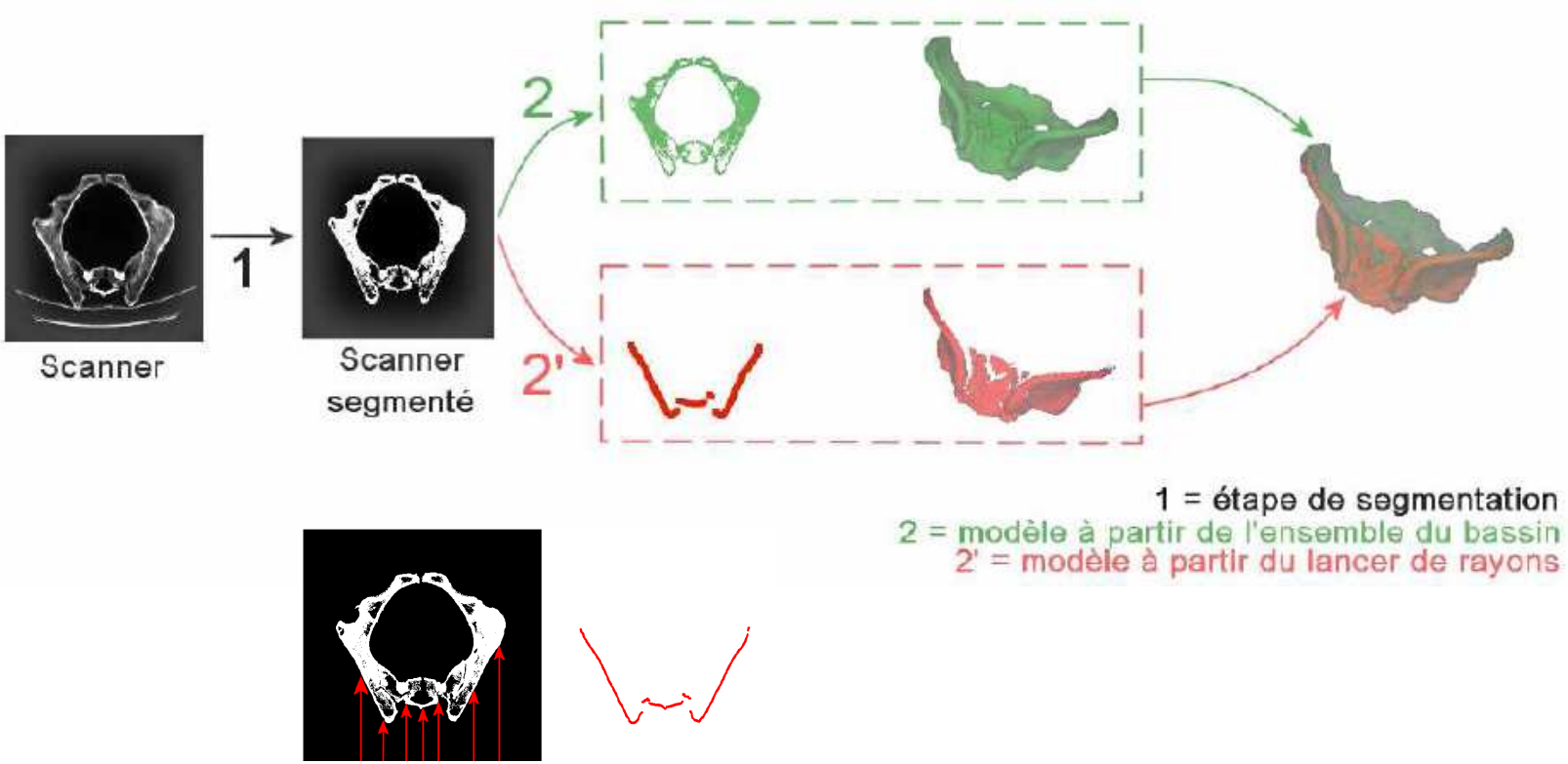
S3 Nerve Root Neuromodulation : Development Navigation System

- Aims :
  - Improve the precision of the implantation
  - Decrease X-ray exposure
  - Decrease local pain at site of puncture
- Principles [Tonetti01]:
  - Preoperative CT-Scan
  - Intraoperative CT-US registration (clouds of points)
- Hypothesis :
  - No movement
  - No deformation

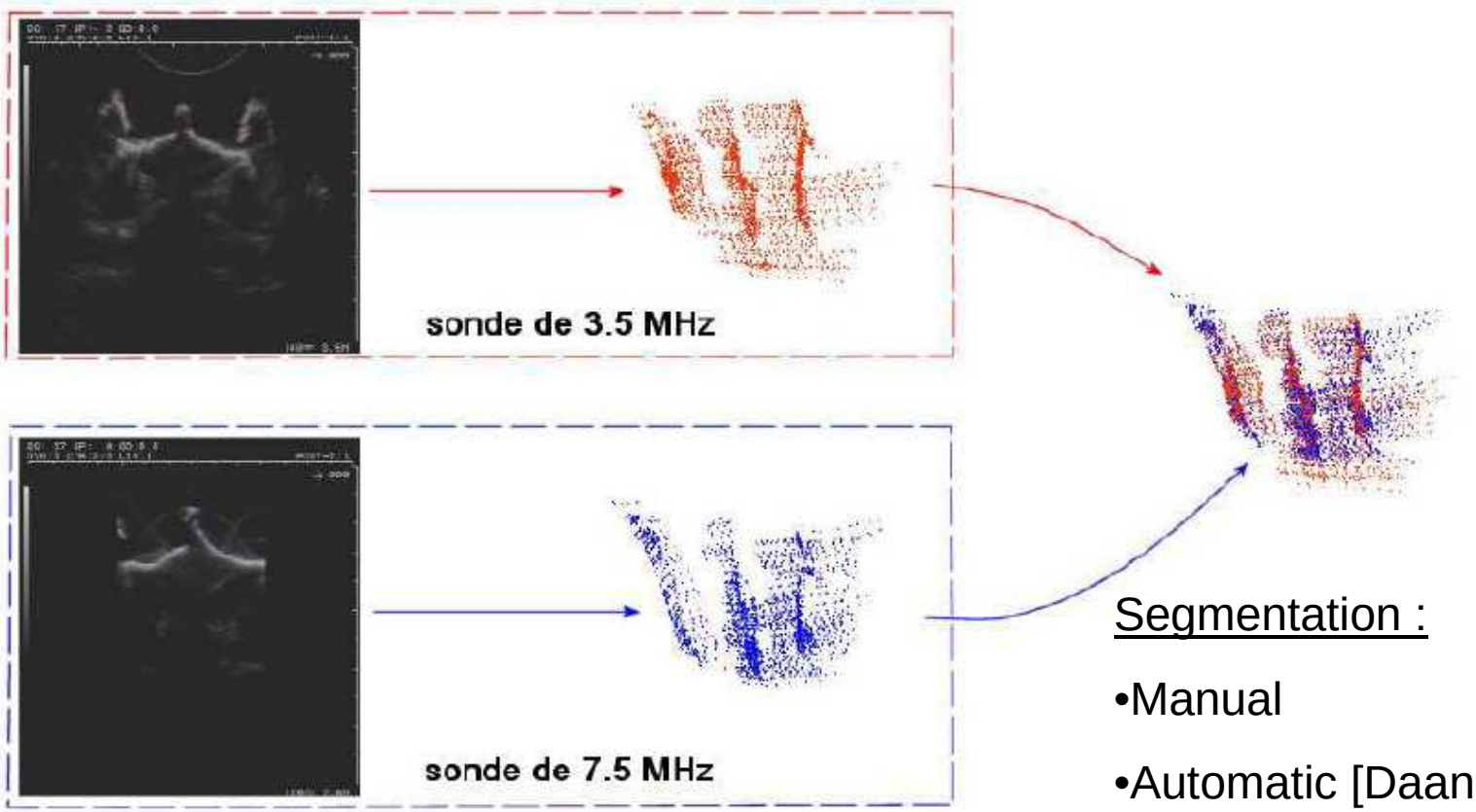
Preoperative CT-Scan



Preoperative CT-Scan : Segmentation



Intraoperative US : Acquisition & segmentation

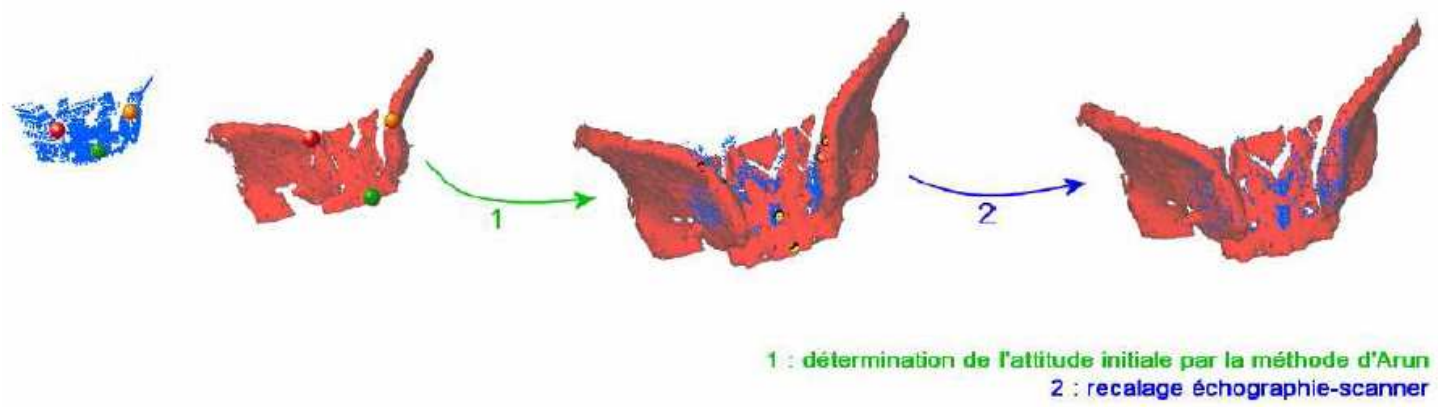


Segmentation :

- Manual
- Automatic [Daanen04]

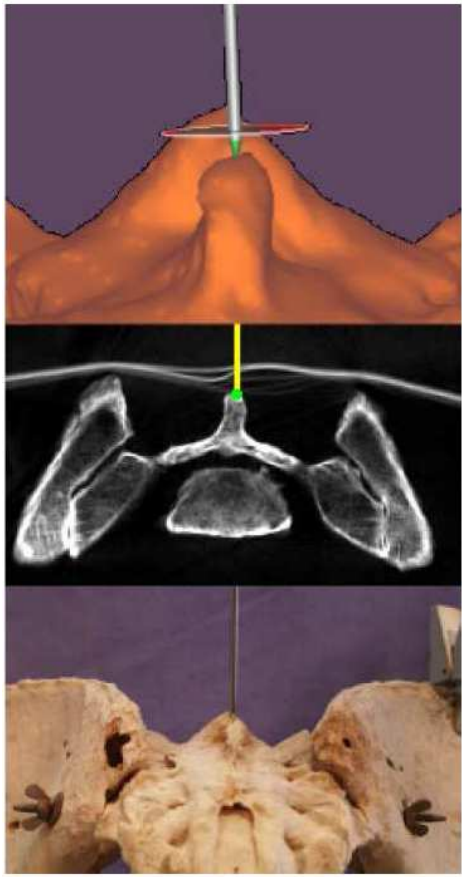
Registration

- Registration :
  - Method :
    - IA : Arun
    - [Lavallée96]
- US : No difference between 7.5MHz and 3.5MHz



Phantom

Phantom : Accuracy

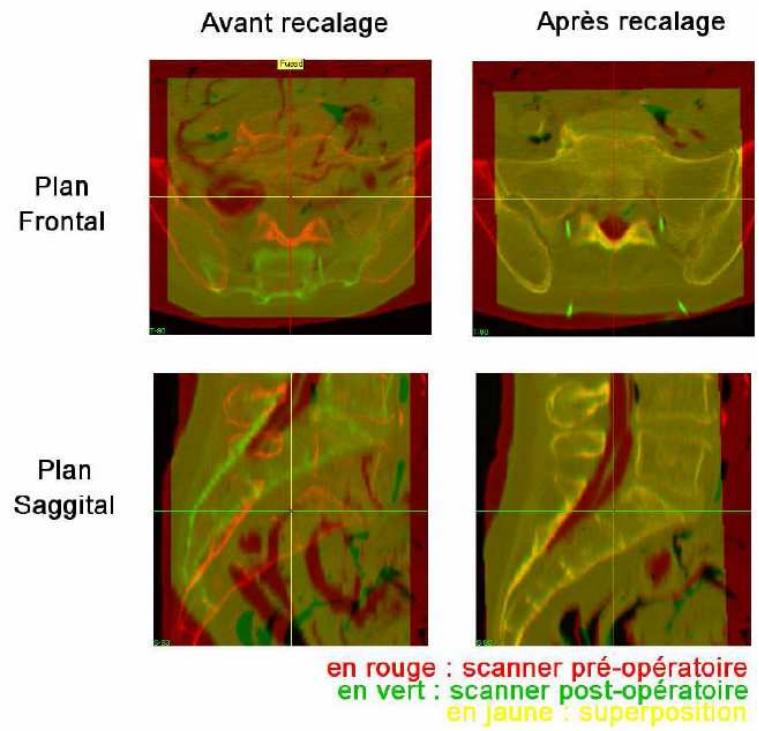


- Visual ~ 1 mm

Cadaver


Localisateur infra-rouge (Polaris)
Aiguille localisée dans l'espace par un corps rigide

Cadaver : accuracy

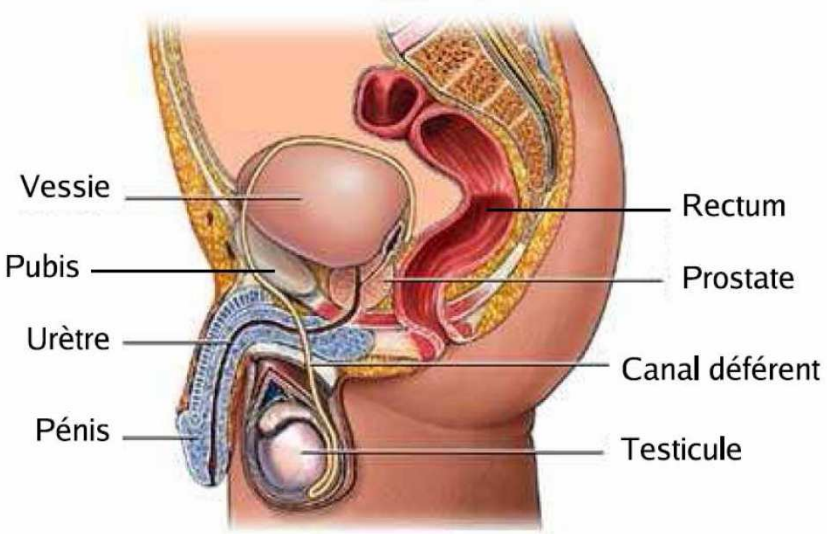


- 6 punctures :
  - S1,S2 and S3
  - Right and left
- Registration between preoperative and postoperative CT-Scan by MMI

d(pre-post) = 2.2mm [1.5-3.5]

Part III : Prostate

- First male cancer
- Diagnostic : Random transrectal biopsy
- Invisible with US
- MRI



- MRI_Histology registration
- Image-based prostate biopsy tracking for biopsy localization

MRI-Histology Registration

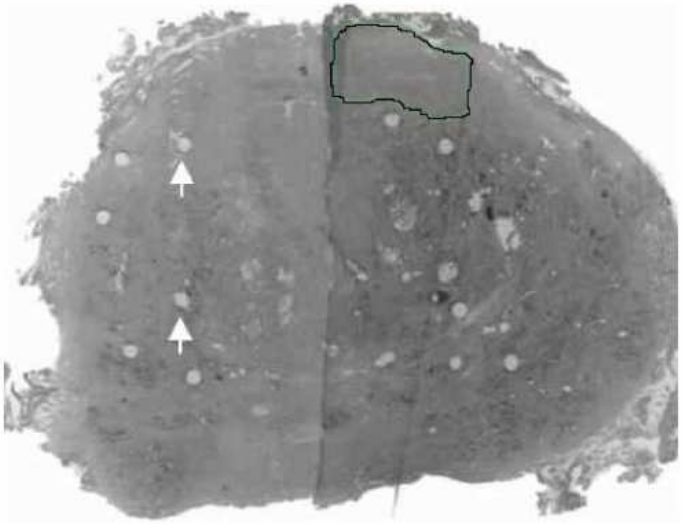
- Aims :
  - Statistical atlas of cancer for biopsy optimization [Shen04]
  - Improvement of MRI characterization
- Problems :
  - Deformation of the prostate ~ 30% [Egevad97] after histology process

MRI-Histology Registration

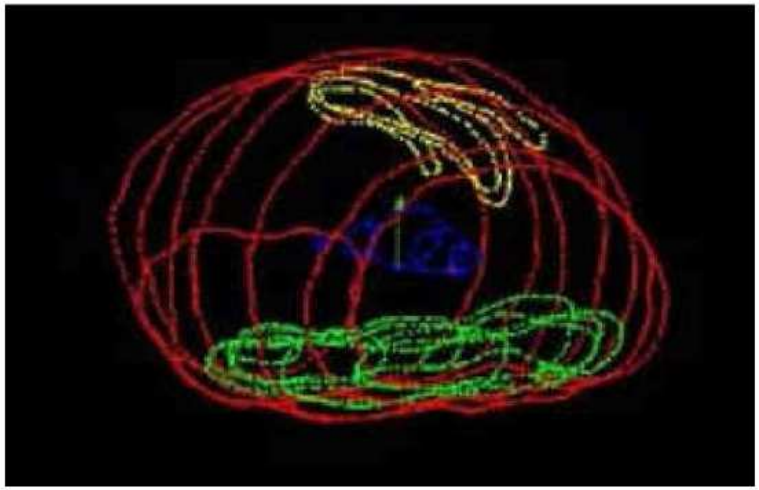
- Feasibility study
- Data :
  - 4 cadavers
  - 1 patient
- MRI acquisition
- Histology

MRI-Histology Registration

MRI-Histology Registration



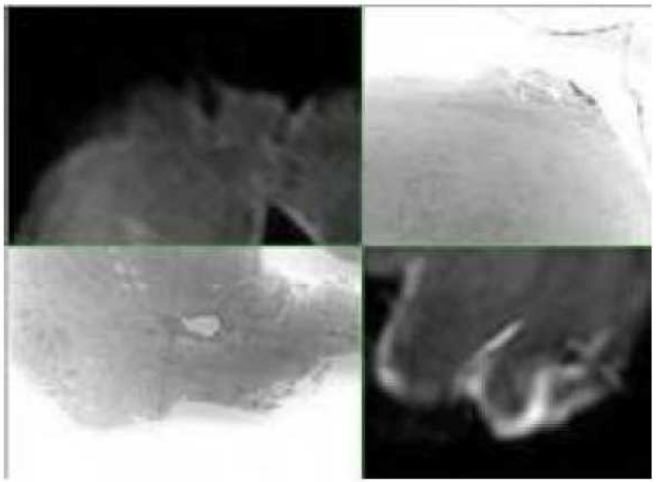
2D registration



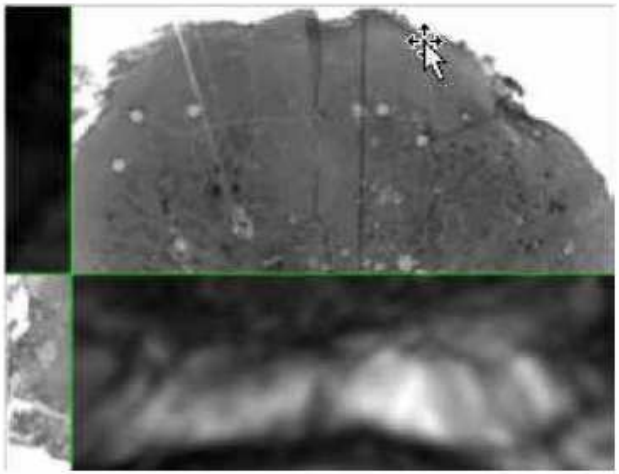
3D model

MRI-Histology Registration

Elastic registration [Lavallée96] based on the capsule



Cadaver

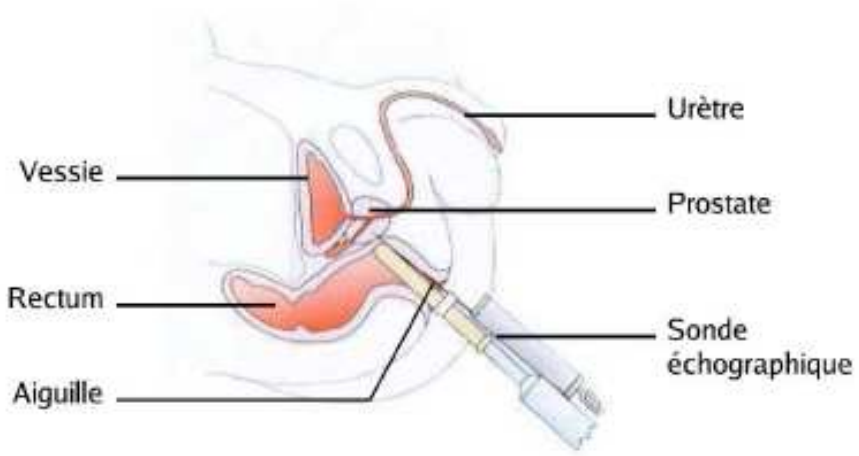


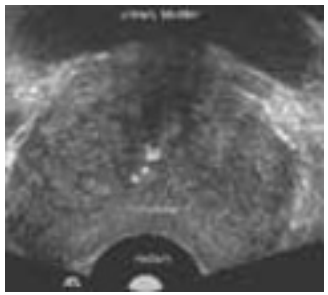
Patient

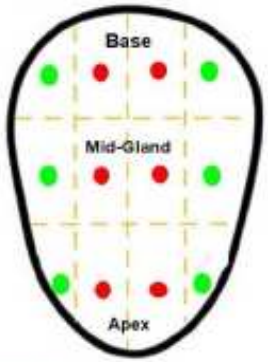
MRI-Histology Registration

- Time consuming from histology point of view
  - Need to work with plain slice (change of clinical practice)
- Need to take into account all the deformations

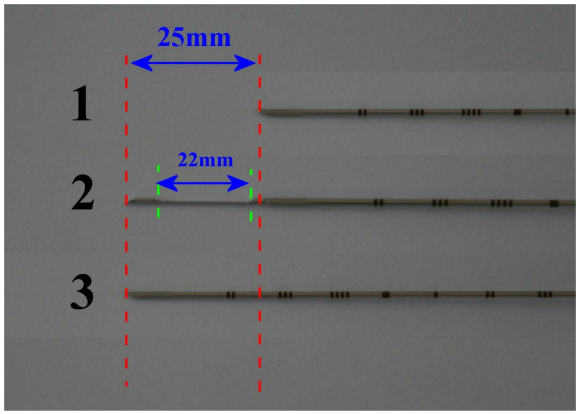
Prostate biopsy







Prostate biopsy

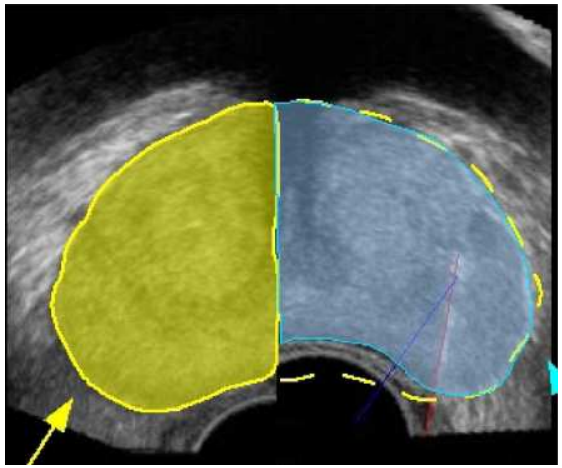


Prostate biopsy

- Rotations around the principal probe axis 180°
- Tilting of up to 40°

Prostate biopsy

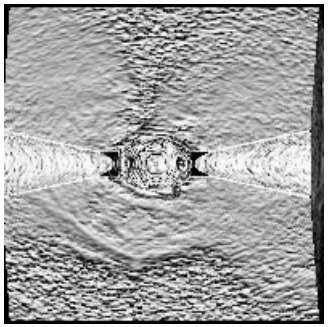
- Aim :
  - Every biopsy in a single reference volume
- Problems [Marchal06] :
  - Movement :
    - Patient
    - Prostate (1-2 cm)
  - Deformation :
    - Endorectal probe



Method

3D US

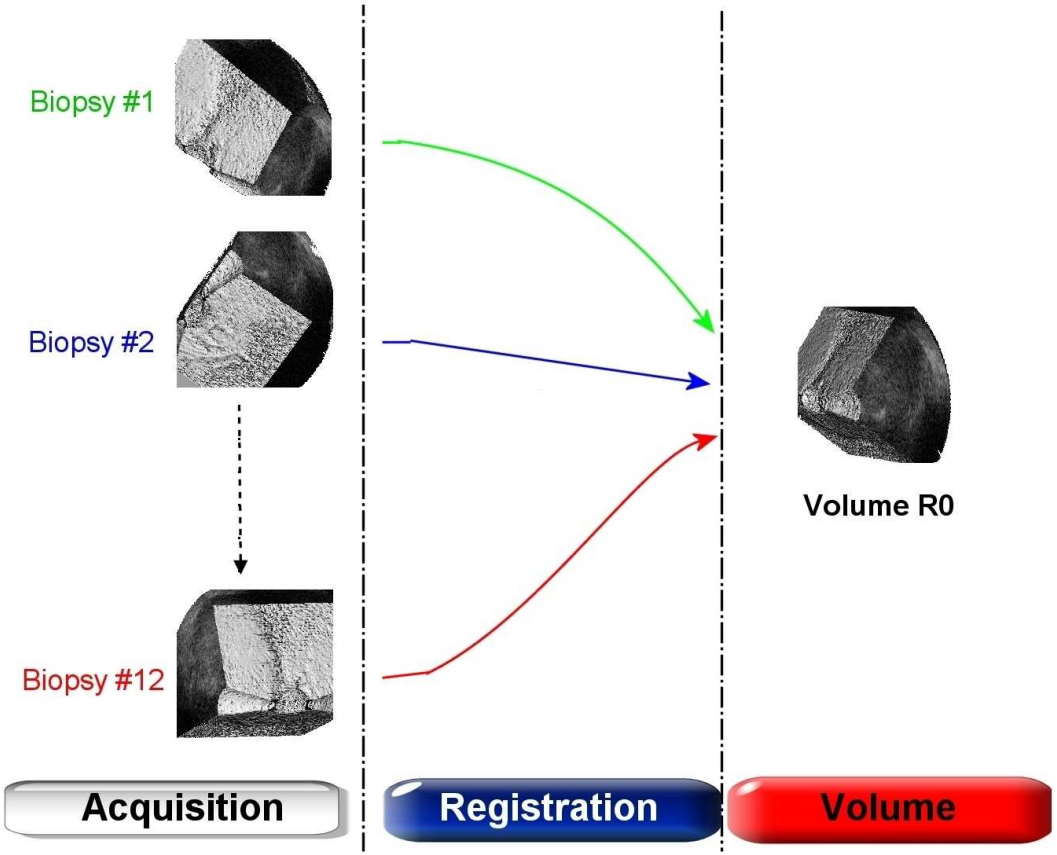
- 3 orthogonal plans
  - Real time
- 3D volume



•Time = 5s

•Voxel size = 0.37mm^3

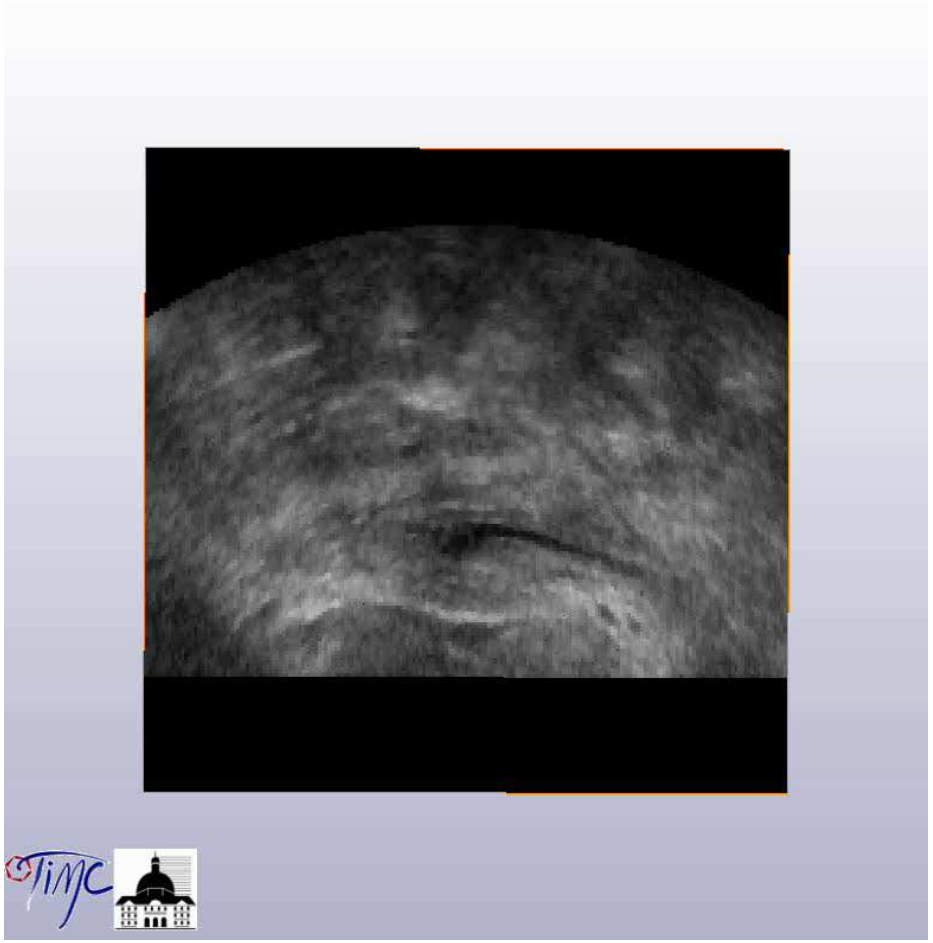
Prostate biopsy : Registration



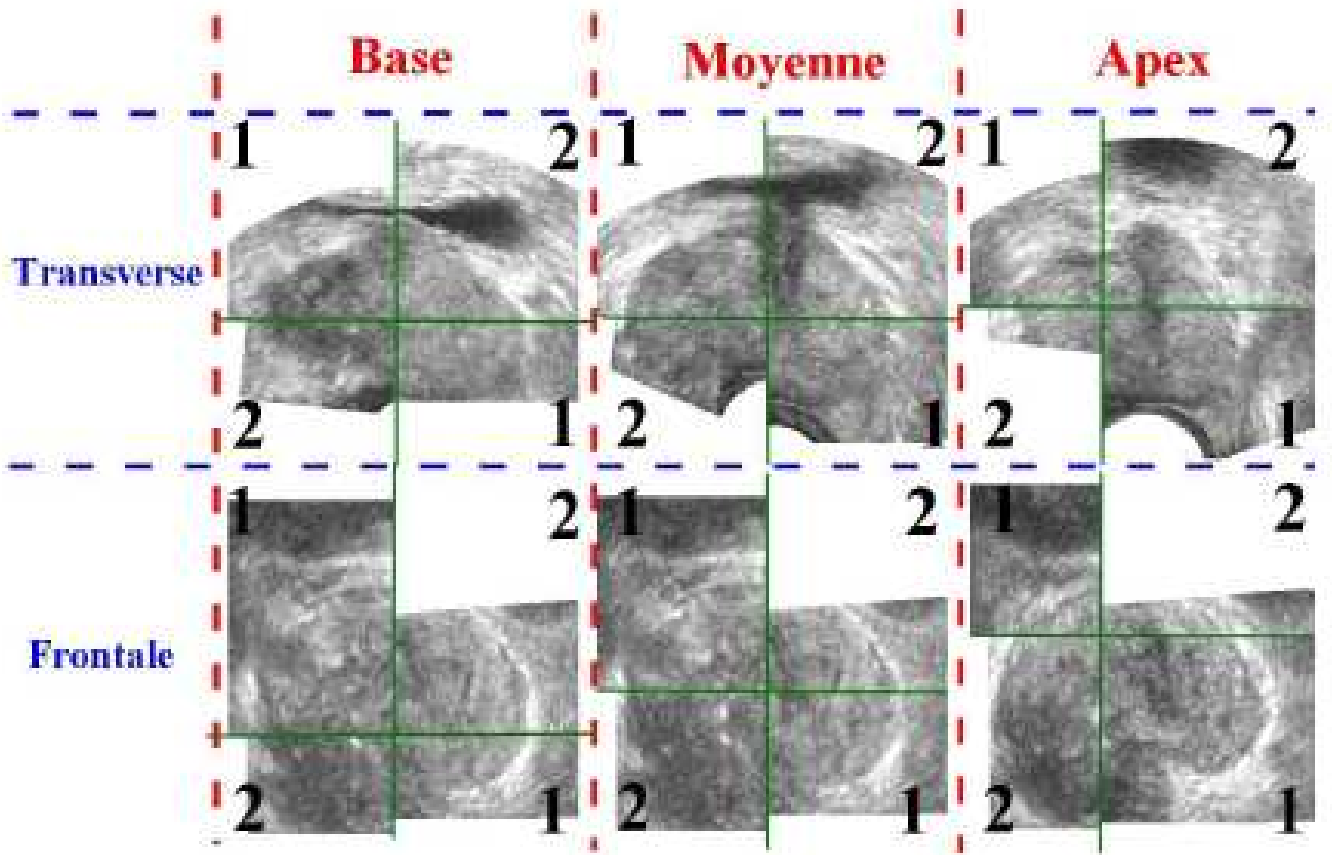
Method [Baumann07] :

Intensity-based Rigid registration
•Similarity Measure : Pearson correlation coefficient

Prostate biopsy : Registration



Prostate biopsy : Registration Visual evaluation of accuracy

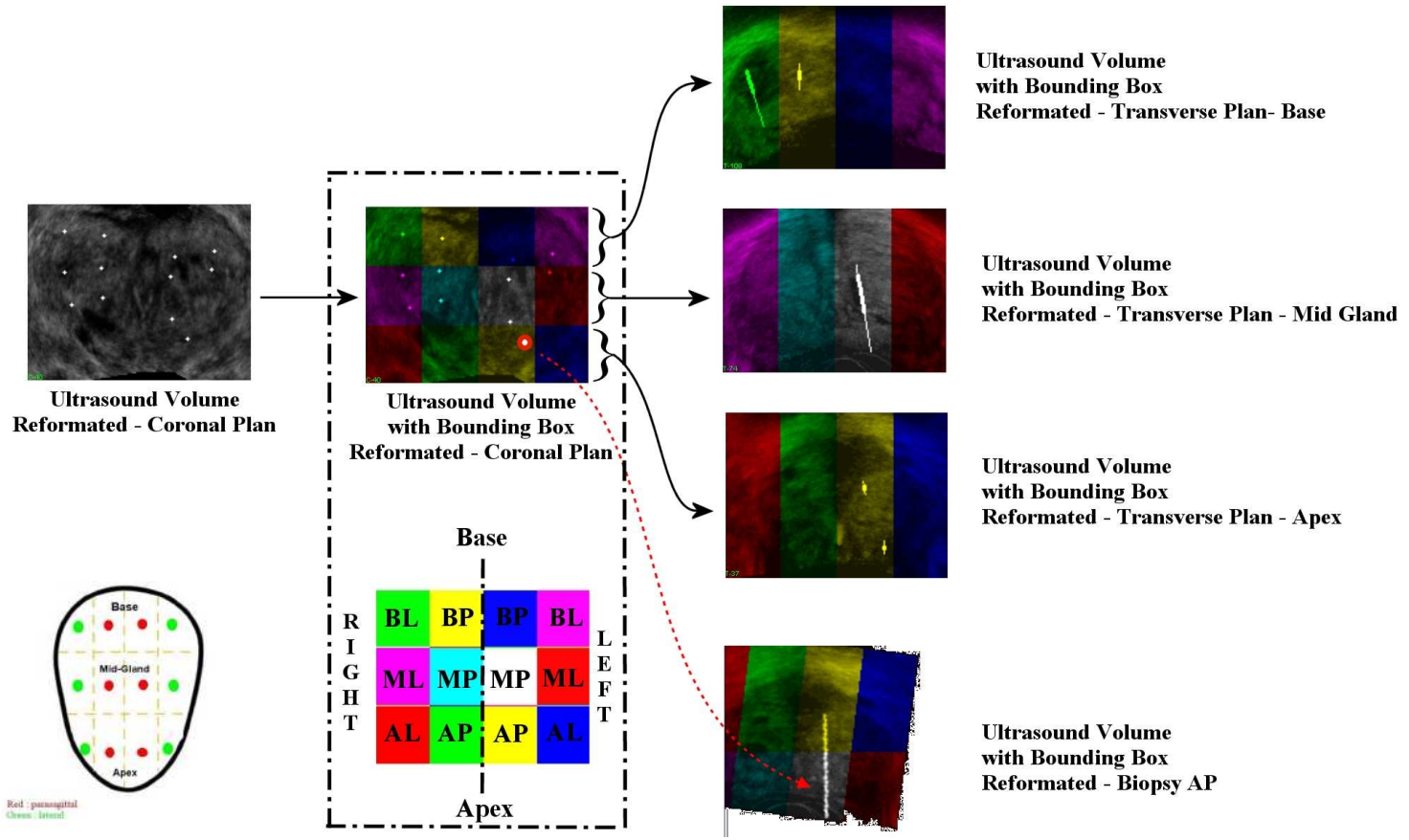


Prostate biopsy : Registration Computed evaluation of accuracy

15 patients

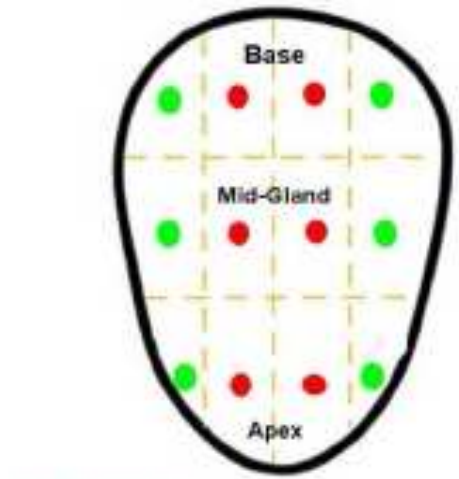
	3D-3D	3D-o2D
Registration success	96.7% (237)	87.7% (237)
Average computation time	6.5s (237)	2.3s (237)
Angular precision ϵ_A (reproducibility, r.m.s.)	1.75deg (229)	1.71deg (208)
Euclidean precision ϵ_E (reproducibility, r.m.s.)	0.62mm (229)	0.47mm (208)
Needle trajectory reconstruction (r.m.s.)	4.72deg (10)	4.74deg (9)
Needle trajectory reconstruction (max)	10.04deg (10)	10.5deg (9)
Calcification reconstruction (r.m.s.)	1.41mm (189)	1.37mm (181)
Calcification reconstruction (max)	3.84mm (189)	4.30mm (181)

Prostate biopsy :
Study of planning transfer - Results



Prostate biopsy : Planning transfer - Results

	Number of Biopsies performed towards the target	Number of biopsies inside the target	% of biopsies inside the target	Biopsy length inside the target (mm)	% of biopsy length inside the target
BL	29	16	55 %	13	61%
BP	28	17	61 %	14	62 %
ML	29	23	79 %	14	64 %
MP	29	29	100 %	16	71 %
AL	29	9	31 %	7	33 %
AP	28	14	50 %	13	61%
	172	108	63 %	14	62 %



Red : parasagittal
Green : lateral

Prostate biopsy : to do

- Take into account deformation
- Support real time
  - Development of a real time tracking device
    - Picking of a target in MRI image
    - Registration MRI-3D US
    - Tracking of the target

Conclusion

- From a clinical point of view :
  - 3 different topics
    - Kidney puncture
    - S3 nerve root neuromodulation
    - Prostate cancer
- From a scientific point of view :
  - One topic
    - Registration

Conclusion - Kidney

- Study of repositioning of the kidney :
  - Need to perform a study in position of treatment
  - 3D US
- Intensity-based registration :
  - Use of 3D US
  - Evaluation of robustness
- Fluoronavigation :
  - Clinical study on going
- Ergonomic :
  - Magnetic tracking
    - Kidney (ureteral stent)
    - US probe
    - Needle

Conclusion – S3 nerve root neuromodulation

- Development of a system to perform a clinical study
- Try to embedded it in the same navigation station than fluoronavigation

Conclusion - Prostate

- MRI-Histolgy registration :
  - Need to launch a project with anatomopathologist in the loop
- US registration :
  - On going clinical study about transfer planning
  - Need to:
    - Improve the speed for real time system
    - Take into account deformation
- Work on intensity-based registration between MRI & US

Conclusion

- Future in urology will probably be 0-1 by use of :
  - Image based therapy
  - Robotic
- Need to enlarge to other fields like biology.

Urology & Computer Aided Surgery

Pierre Mozer
TIMC/GMCAO – Pitié-Salpétrière
UJF

END