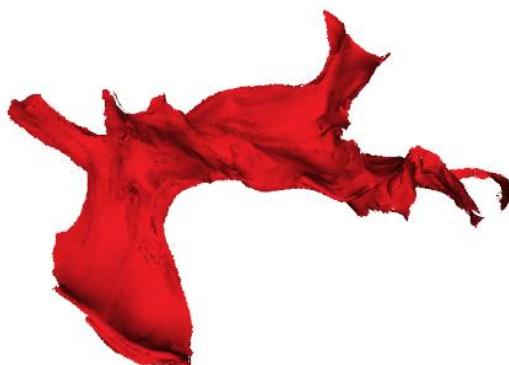


Thèse de Doctorat

July, 24th 2013

Acquisition, visualization and 3D reconstruction of anatomical data

Applied to human brain white matter



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Presentation summary

Introduction

- Basics on White Matter Fibers
- Investigation Means

State of the art

- Tractography Validation
- 3D Acquisitions of Anatomical Data
- 3D Medical Visualizations

Methodology

- 3D Acquisition
- 3D Registration
- Visualization & Interactions
- 3D Reconstruction
- Surfaces/MRI registration
- Comparisons

Results & Validations

Conclusion & Future Works

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Basics : Human Brain White Matter

④ Brain White Matter

- Composed of axons
- Organized in bundles
- Connection between cortical and sub-cortical areas

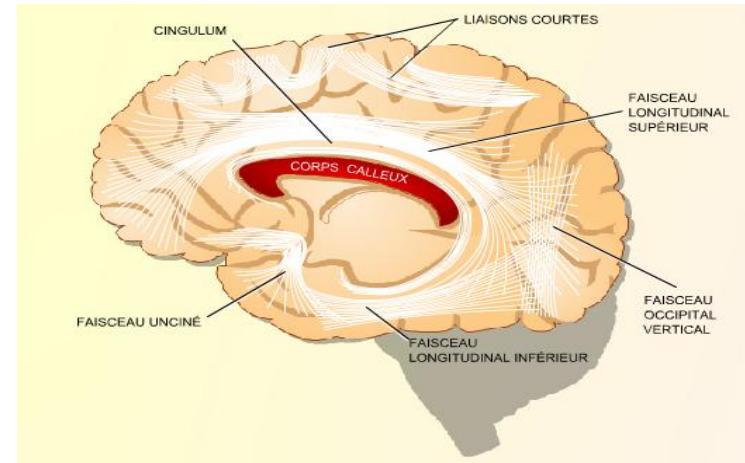


Fig1. Scheme of main fibers white matter bundles.

④ Implications in pathologies

- Neuro-degeneratives (Alzheimer, demencia),
- Inflammatory (sclérose en plaques, ...),
- Tumoral (gliomas),
- of development (autism, dyslexia,...)

Investigation Means

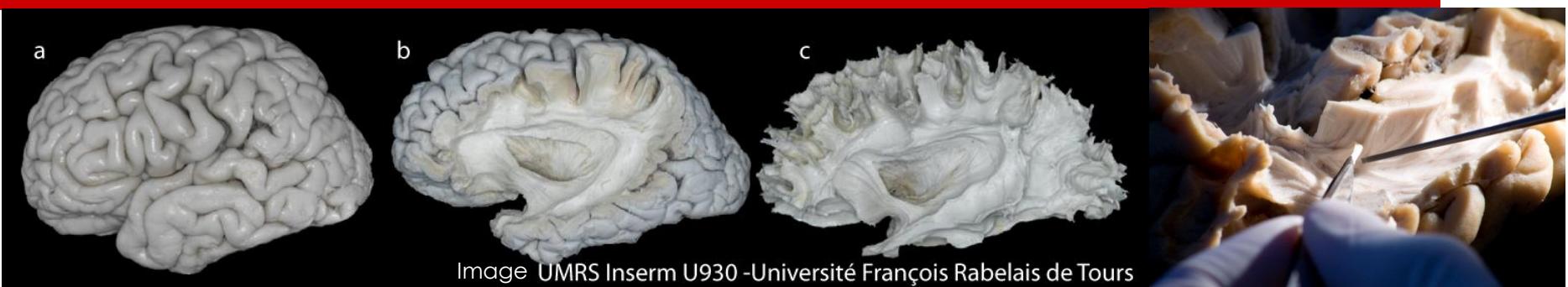


Fig1. Dissection done following the Klingler process [Klingler56].
Laboratoire Anatomie, Tours

- ④ Only done *ex vivo initially*
[Déjerine1895], [Klingler1956]
 - Hemisphere Dissection formalin fixed,
 - Histology
 - References: paper atlases established from dissection data
- ④ With the discover of MR DWI
 - Living subjects image acquisitions,
 - Digital atlases from multiple subjects
 - Clinical use allowed
- ④ Need to go back to *ex vivo* anatomy to validate

[Déjerine1895] J. Déjerine, *Anatomie des centres nerveux*, Paris, 1895

[Klingler1956] Ludwig & Klingler, *Atlas cerebri humani*, Bâle, 1956

How to study White Matter in Human - *in vivo*

MRI diffusion technique [Le Bihan 1985]

- ④ Principle of diffusion
 - Water displacement measurements
 - Preferential diffusion direction
- ④ Diffusion maps

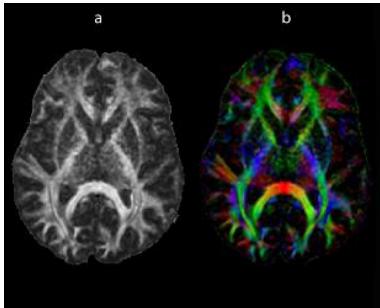


Fig 2. Fractional Anisotropy (FA)
raw map (a) color map (b).

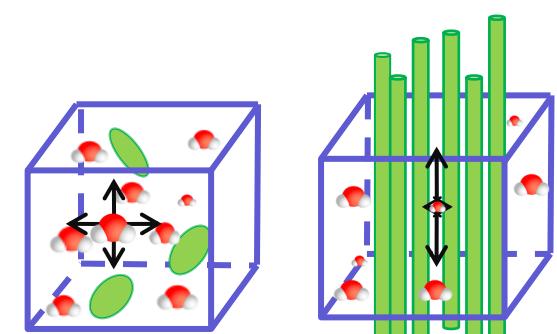


Fig1. Diffusion isotropic

Diffusion anisotropic

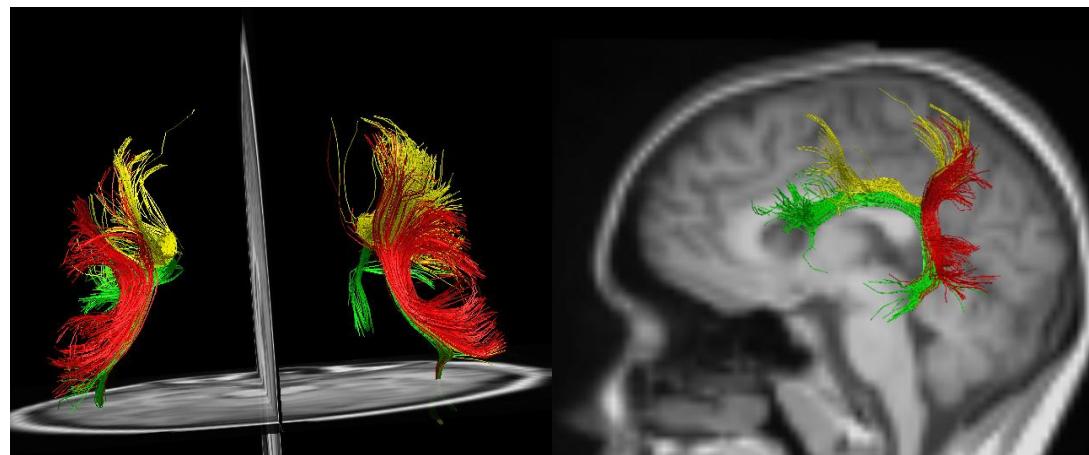


Fig 3. Tractography algorithm results - Laboratoire d'anatomie, Tours

- ④ Bundles Reconstruction
 - Tractography algorithms
 - Probabilistic or deterministic

[Le Bihan et al.1985] D. Le Bihan et al.,*Imagerie de diffusion *in-vivo* par résonance magnétique nucléaire*, Cr.Acac.Sc.(Paris) 301,15, 1109-1112,1985.

Introduction

- ④ FibrAtlas Project (C. Destrieux , 2009)
 - *in vivo* tractography validation from dissection data
 - Online ressource database to be used by neuroscience community

- ④ Thesis scope and objectives
 - Design of a full featured method for dissection
 - From 3D data acquisition
 - To interactive visualization
 - Design a tool to be used by anatomist experts for knowledge extraction purpose
 - Build « ground truth » to be able to quantitatively compare anatomical data.

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State of the art: Validation Problem

« Does tractography really reflects the anatomy? »

④ Existing validations approaches

- Simulated data [Hall&Alexander2009]
 - + Easy to get ground truth, huge amount of data
 - Digital models, oversimplified
- Real data acquisition from test objects (phantoms) [Poupon2008][Fillard2011]
 - + Comparison to ground truth possible
 - Approximate/mimic anatomical structures
- Real data on animals (axonal chemical tractography) [Dauguet2007]
 - + Contrast enhancement
 - Not possible on humans
- Real data on humans (ex vivo) :
 - + Visual comparison of real anatomy specimen to anatomical references
 - Difficulties to achieve quantitative comparisons

State of the art: ex vivo validation approaches

Direct comparison to anatomy

Method	Principle	On Human	Drawbacks
PLI (Polarized Light Imaging) [Axer2011]	-Directional informations of bundles by polarized light reflexion analysis -Thin slices	Yes	- Need for slicing before acquiring : distortions
OCT (Optical Coherency Tomography) [Huang1991]	- Optical Acquisition - Frozen Specimens - Thick slices	Yes	- Complex device setup - Acquisition time for entire brain

[Axer2011] Axer et al., Microstructural Analysis of Human White Matter Architecture Using Polarized Light Imaging: Views from Neuroanatomy, *Front. neuroinformatics*, 2011

[Huang1991] Huang et al., Science 254 , no. 5035 pp. 1178-1181 ,1991

State of the art: ex vivo validation approaches

Direct comparison to anatomy

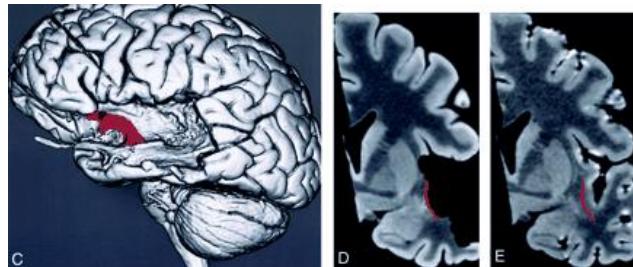


Fig 1 : Illustration from [Kier2004]

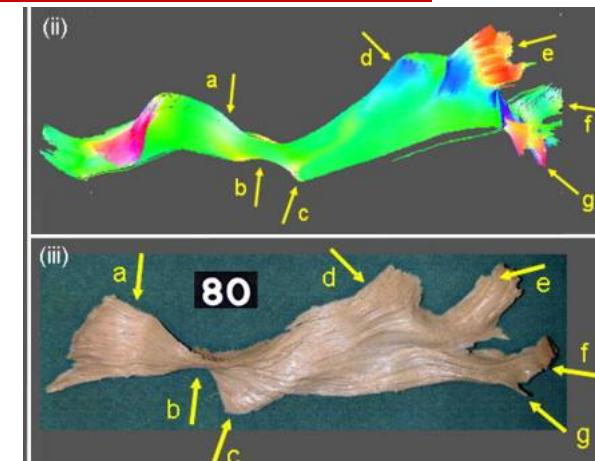


Fig 2 : Illustration from [Nigel2008]

Method	Principle	On Human	Drawbacks
Dissection +MRI [Kier2004]	- T1 MR Acquisition - iteratively during dissection	Yes	- Difficult to set up: too many MR acquisition needed - MR resolution
Dissection visual comparison [Nigel2008]	<p>➡ Need for a method for dissection tracking from anatomical specimen</p> <ul style="list-style-type: none">- Validation from atlases		<ul style="list-style-type: none">- Qualitative comparisons only

[Kier2004] Kier et al., Anatomic dissection tractography: A new method for precise MR localization of white matter tracts. Am J Neuroradiology, 25, 2004, pp 670-676.

[Nigel2008] I. Nigel et al. Atlas-based segmentation of white matter tracts of the human brain using diffusion tensor tractography and comparison with classical dissection, NeuroImage, 39, 2008, Pages 62-79.

Presentation summary

Introduction

State of the art

- Tractography validation
- 3D anatomical data acquisitions
- 3D medical visualisations

Methodology

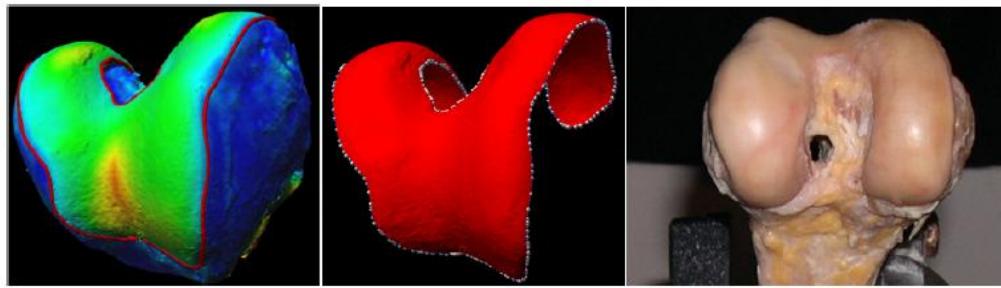
Results & Validations

Conclusion & Future Works

State of the art: 3D anatomy acquisitions

How to build « ground truth »?

- ④ In orthopaedic surgery : 3D laser acquisition knees cartilages [Trinh et al. 2006]
 - 2 acquisitions (laser scanner 3D), before and after dissection



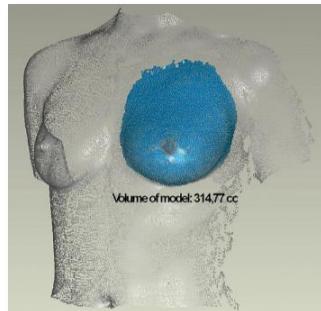
Thickness difference map

Figures issued from [Trinh et al.2006]

Cartilage reconstruction

Anatomical view

- ④ Breast surgery : 3D laser acquisition [Kovacs2006],[Patete2012]



[Trinh et al.2006] Accurate Measurement of Cartilage Morphology Using a 3D Laser Scanner in Computer Vision Approaches to Medical Image Analysis, pp 37-48, Springer, Berlin Heidelberg

[Kovacs2006] Comparison between breast volume measurement using 3D surface imaging and classical techniques, The Breast, 16(2), 2006, pp137-145

[Patete2012] Comparative Assessment of 3D Surface Scanning Systems in Breast Plastic and Reconstructive Surgery, Surgical Innovations, 2012

Plan de la présentation

Introduction

State of the art

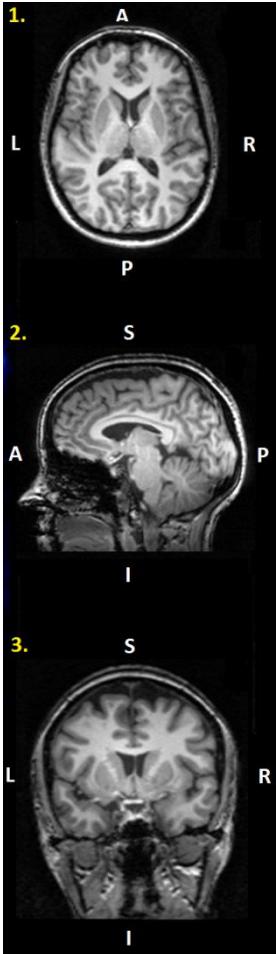
- Tractography validation
- 3D anatomical data
- 3D medical visualizations

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State of the Art: 3D Medical Visualization



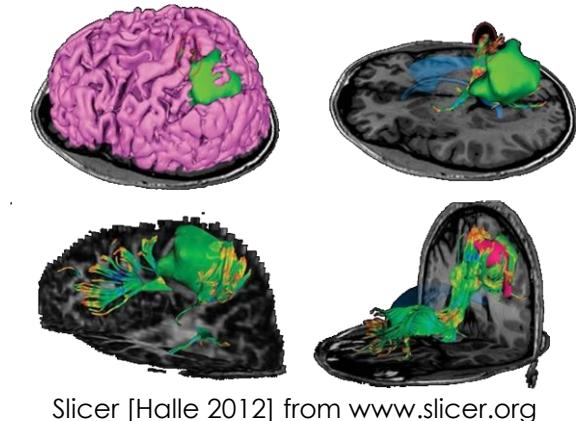
④ Classic medical data visualizations

- 3D volumic data
 - MR images/CT-Scan
 - Visualization by 2D slices
 - Few use of 3D volumic rendering
 - Computation cost
 - Need to involve transfert function setup
- 3D surfacic data
 - Isosurfaces from segmentation
 - Low polygons meshes

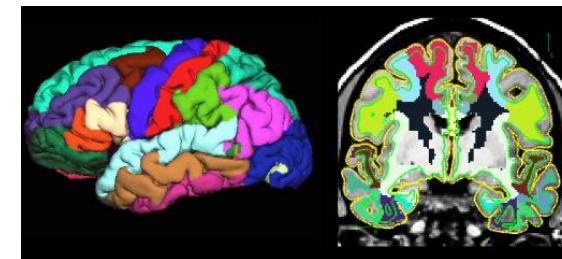
④ Dedicated software for each issue

- Specific needs
 - In term of rendering,
 - In term of data to deals with
 - In term of interactions tools,
 - Users settings

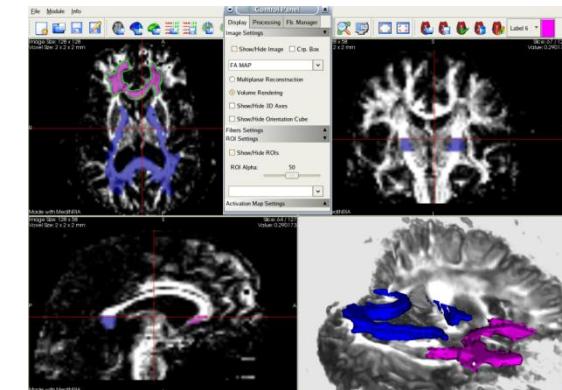
MedINRIA from
<http://wwwsop.inria.fr/asclepios/software/MedINRIA>



Slicer [Halle 2012] from www.slicer.org



Freeview/freesurfer
from «Introduction to freesurfer»
<https://surfer.nmr.mgh.harvard.edu/>



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- Interaction & Visualization
- 3D Reconstruction
- Surfaces/MRI Registration
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Methodology: Overview

A: Specimen Fixation

PVC support
Fiducial points

B: Initial T1 MR acquisition

Volumic

C: Laser iterative acquisitions

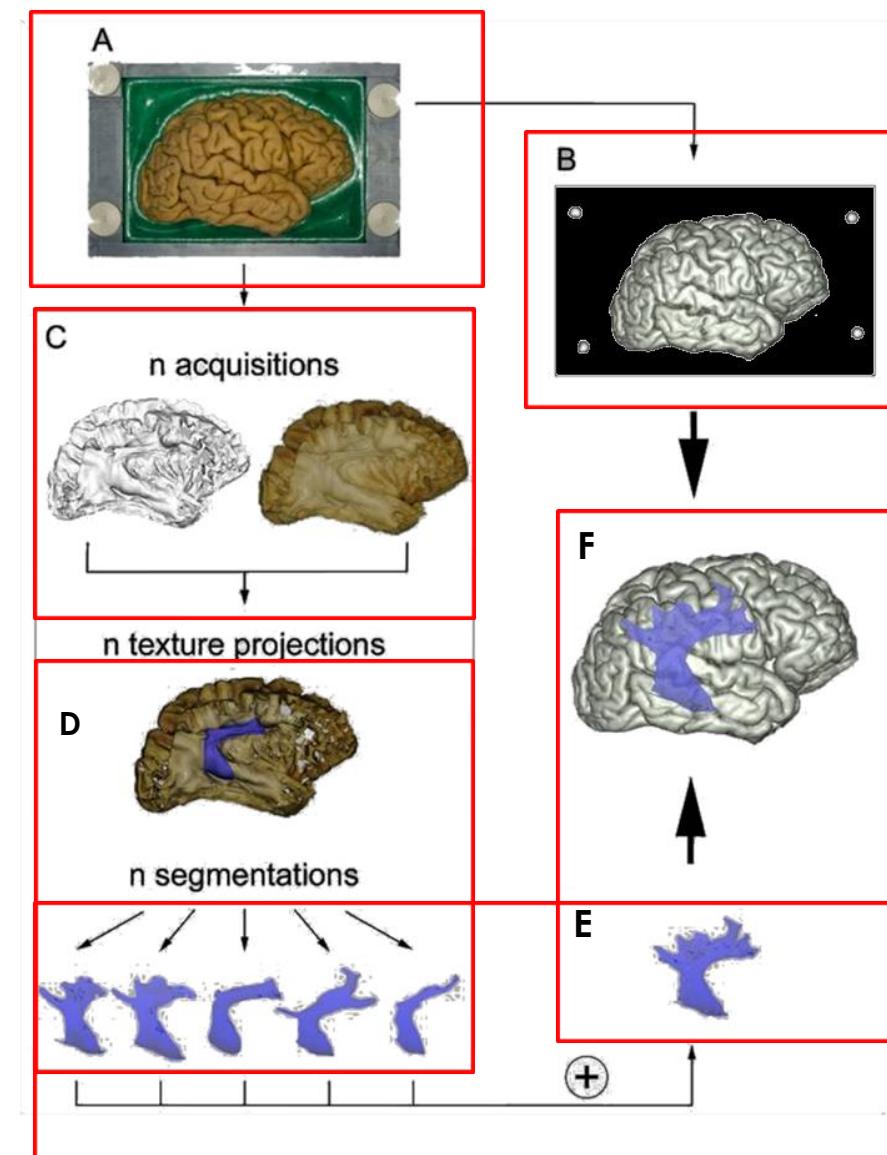
3D surfacic
Colour
Registrations

D: Labelling/ROIs Segmentation

E: 3D Reconstruction

F: 3D Registration & Visualization

Reconstructed object
Visualized inside initial MRI



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3D Acquisition : Volumic data

- Methodology
- **3D Acquisition**
 - 3D Registration
 - Visualization & Interactions
 - Reconstruction
 - Registration surfaces/MRI Comparisons

- ④ MR morphological (T1)
- ④ Objective
 - Get volumic referencial of the specimen
 - Acquire specimen morphology before any dissection takes place
- ④ Material
 - MR machine: 1.5T (GE)
 - Coil type: « head »
- ④ Method
 - T1 Acquisition of the specimen inside its support and with fiducials
 - Isotropic voxels (1mm)

3D Acquisition : Surfacic data

« How acquiring high fidelity specimen surface? »

- ④ Objective
 - Digitalize anatomical specimen
- ④ 3D acquisition technologies
 - Stereoscopy
 - Fringe projections
 - Laser
- ④ Acquisition constraints
 - Physics of the specimen to be acquired
 - Size
 - Accessibility
 - Object complexity (Gyri/Sulci)

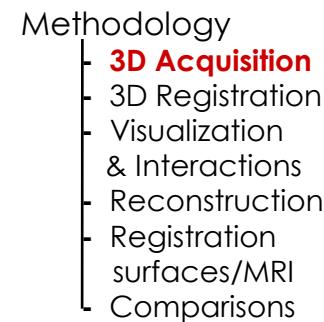


Fig 1. Laser : HDS3000, Leica Geosystems AG (a), FaroArm, FARO GmbH (b) - Projection de franges : Mephisto, 4DDynamics (c)

3D Surfacic Acquisition Device Choice

« How to choose the acquisition device? »

- Methodology
- **3D Acquisition**
 - 3D Registration
 - Visualization & Interactions
 - Reconstruction
 - Registration surfaces/MRI Comparisons

④ 3D Acquisition device final choice: FaroArm

- ✓ 7 DOF
→Flexibility
- ✓ Laser technology
- ✓ Measure repeatability
100 to 150µm
- ✓ High acq. rate:
19000 pts/s
- ✓ Palpation sensor
- ✓ Budget : <50K€

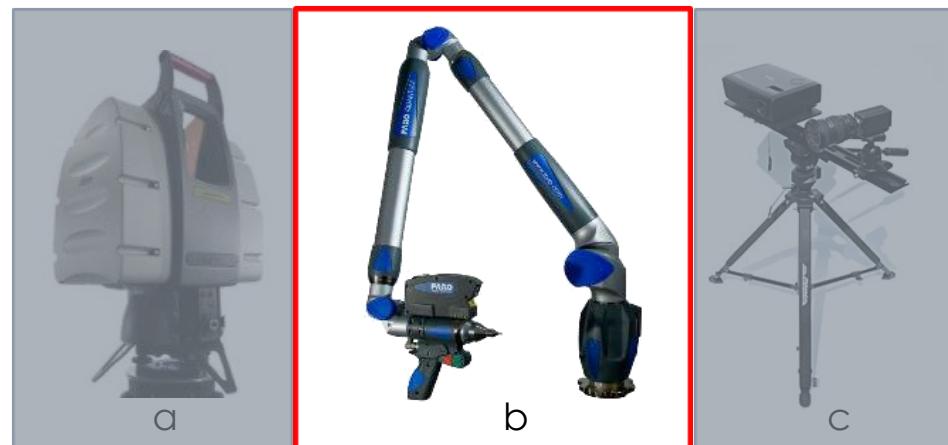


Fig 1. Laser : HDS3000, Leica Geosystems AG (a), FaroArm, FARO GmbH (b) - Projection de franges : Mephisto, 4DDynamics (c)

3D Surfacic Acquisition : Methodology

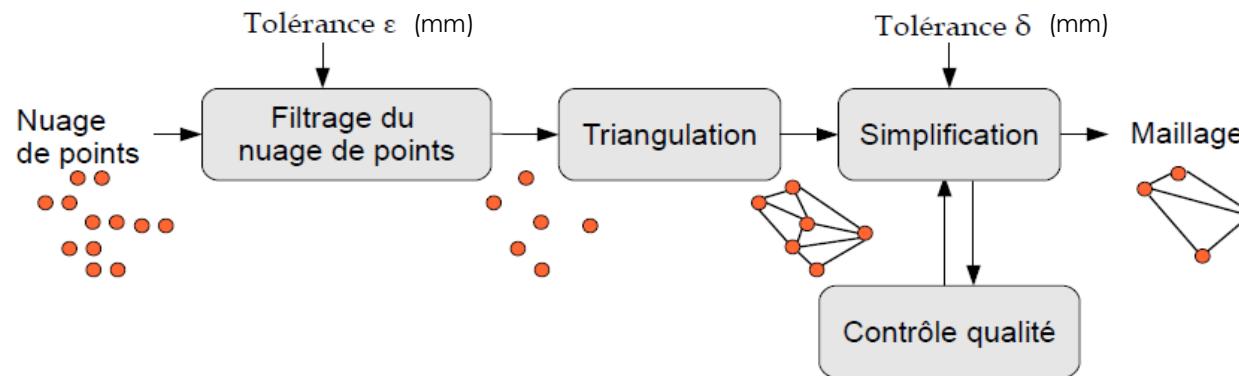
- Methodology
- **3D Acquisition**
 - 3D Registration
 - Visualization & Interactions
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 - Registration surfaces/MRI Comparisons

④ Objectives

- High resolution 3D acquisition, dense meshes
- Keep data size/volume reasonable

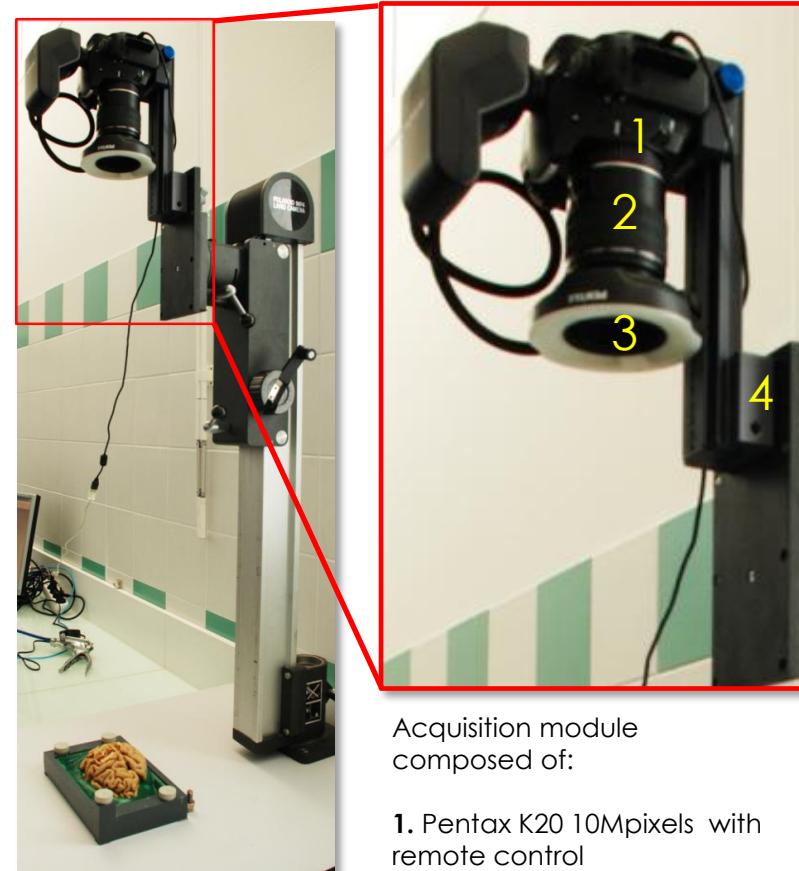
④ Method

- Set up a normalized acquisition protocol
- Set up a post processing tools chain



3D Surfacic Acquisition : Texture

- ⇒ Objective
 - Get color information
- ⇒ Method
 - Orthophotographic acquisition
- ⇒ Results
 - Acquisition system design
 - Support design
 - Lighting conditions



Orthophotographic camera device

Acquisition module composed of:

1. Pentax K20 10Mpixels with remote control
2. Optics 50mm
3. Flash type : annular
4. Millimetric custom support

3D Surfacic Acquisition : Texture

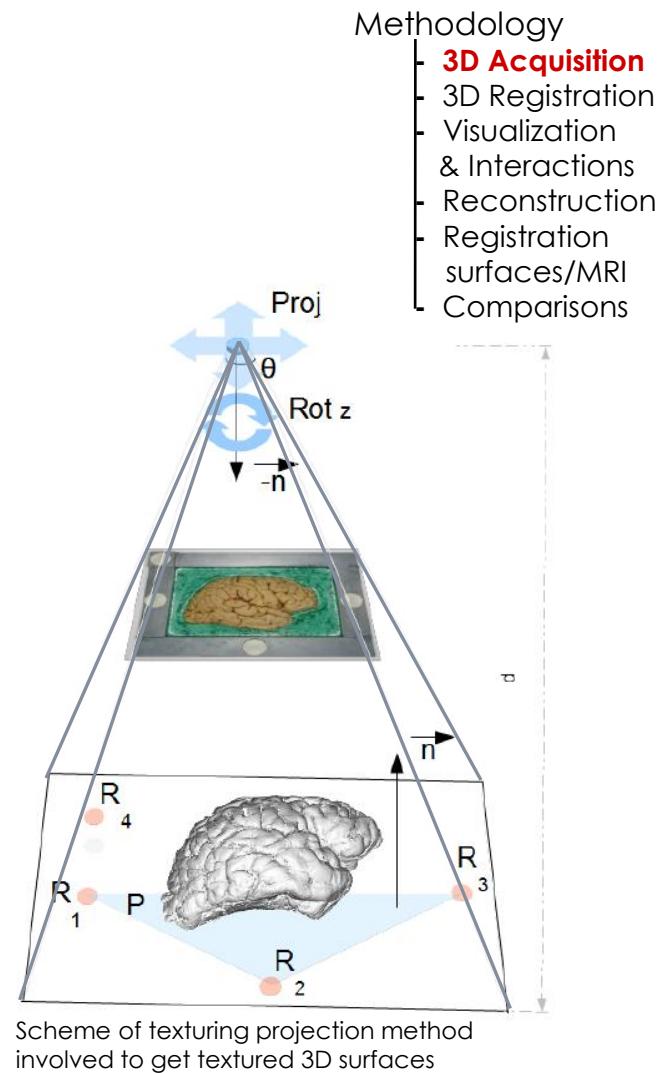
« How to texture 3D surfaces? »

② Objective:

- Build realistic 3D virtual specimen
- Add precious visual information to our triangle meshes

③ Method

- Texturing
 - State of the art technique:
Perspective texturing [Everitt01]
 - Occlusions correction
method used for shadow map
- Semi-interactive texturing
- Qualitative validations
 - on simple scene
 - on brain hemisphere



[Everitt01] C. Everitt, Technical report, Nvidia, 2001

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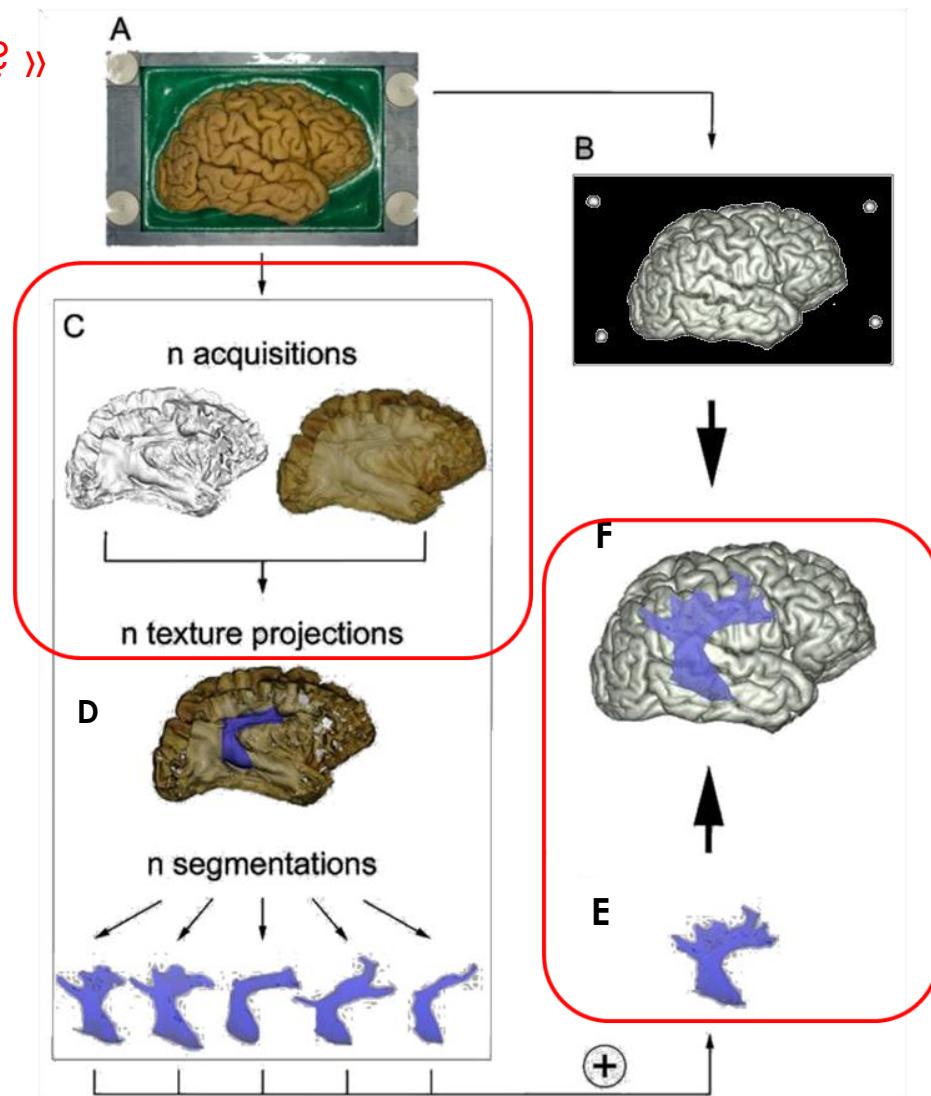
Results & Validations

Conclusion & Future Works

3D Registration

« Why do we need registration? »

- ④ 3D Surfaces registration
 - Each acquisitions have been done in different time
 - Support will be moved between 2 acquisitions
 - All surfaces have to be set in a common frame
- ④ Bundle need to be registered in the initial MR acquisition
 - 2 differents modalities
 - 3D Surfaces / MR



3D Registration

« How do we register? »

④ Linear Alignment Method

- Based on Iterative Closest Point (ICP) from [Besl&Mckay92]
 - Mapping computation between points cloud
 - Transformation Evaluation
 - Iterations until distances between both clouds fall under a given value

④ Method #1:

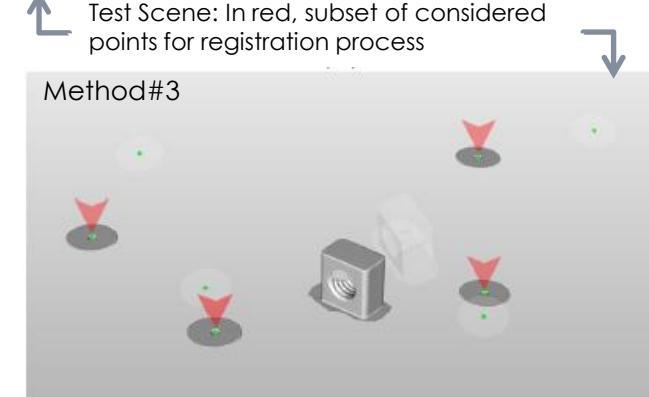
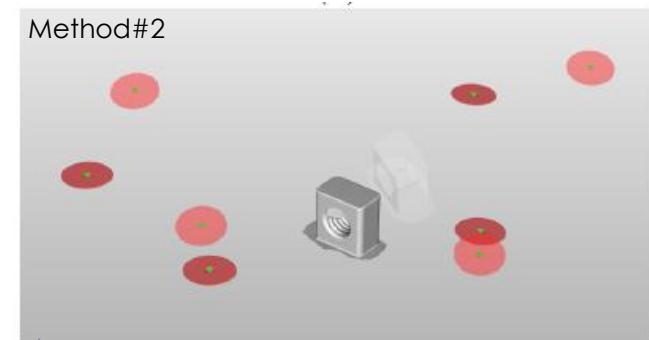
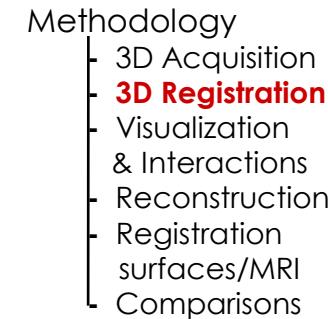
Take into account whole points cloud from both 3D surfaces (meshes)

④ Method #2:

Take into account a subset of both points cloud

④ Method #3:

Based only on fiducial points acquired by palpation



[Besl&Mckay92] : A method for registration of 3-d shapes. IEEE Transactions on Pattern Analysis and Machine Intelligence, 14(2): pp239-256

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3D Visualization

④ Objectives

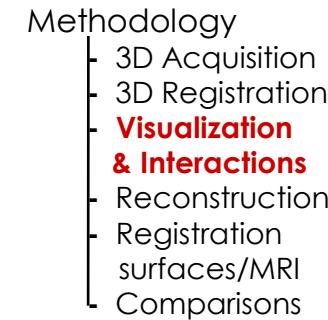
- Visualize heterogenous acquired data
- Allow user to build its own visualization
- Facilitate knowledge extraction

④ Data Visualizations

- 3D surfacic (3D laser surfaces)
- 3D volumic (MR volume)
- Mixed Visualizations

④ Visual Filtering Tools

- Hiding. Showing context
- Cutting Planes
 - View dependant
 - Static
- Transfert Function
 - Volume Rendering



3D Visualization 3D : Tools Overview

Surface Rendering

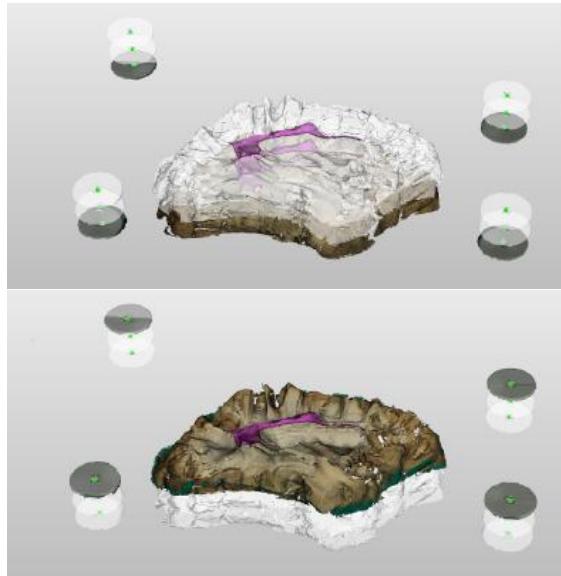


Fig 1. Eclated view of 3 dissection steps.
Segmented FLS part sare visible in purple.

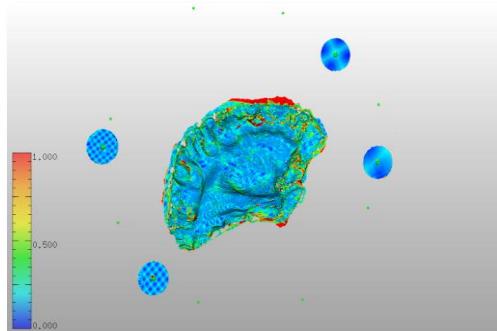


Fig2. Error map visualization tool. Used to check differences between 2 surfaces

Volume Rendering

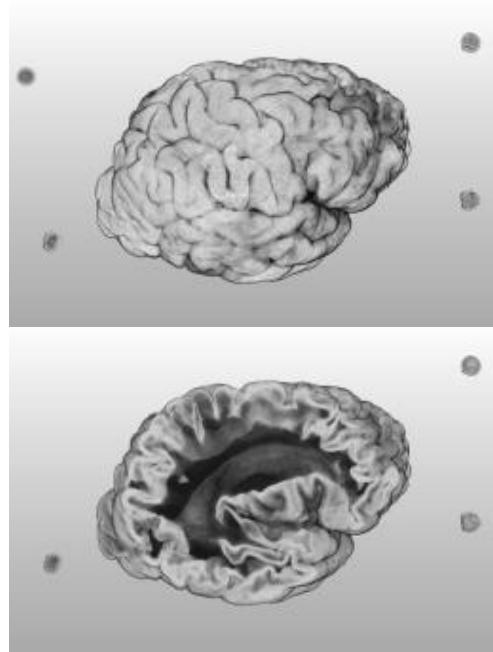


Fig 3. Virtual cutting plane. Make it possible to see internal structures

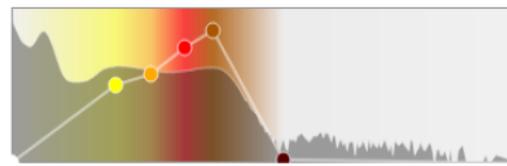


Fig 4. Interactive tool for Volume Rendering management (RGB + alpha)

Mixed

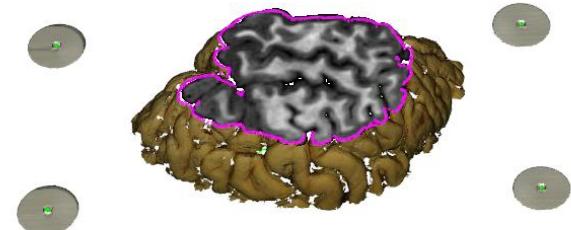
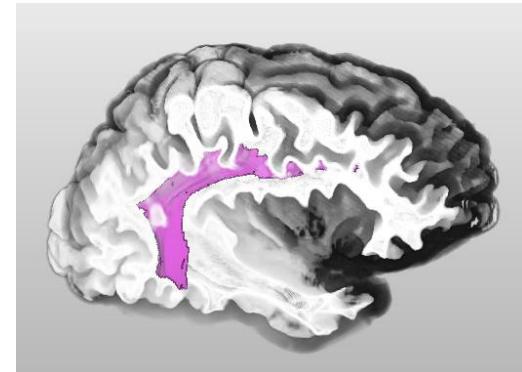


Fig 5. Mixed visulization results allowed with cutting tools

Interactions: Segmentation Tool

④ Objective

- Allow ROI selection directly on 3D meshes

④ Cursor 3D

- « Sliding » cursor onto the surface

④ Tools available to experts

- Rectangle, Line, free hand selection
- Fill in closed selection
- Substractive/Additive selection
- Reverse selection

Methodology

- 3D Acquisition
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Fig. 1 : Sample of triangle selection directly on meshes -

Interactions: Immersive Visualization

« How to improve user performances during segmentation process? »

④ Objective

- Add visual and haptic relief perception

④ Method

- Integrate haptic device
 - Phantom from Sensable
- 3D Stereoscopic Visualization
 - 120Hz Display
 - Synchronised shutter glasses

④ Evaluation

- User study



Phantom Omni



120Hz Display



Synchronized shutter glasses, NVidia

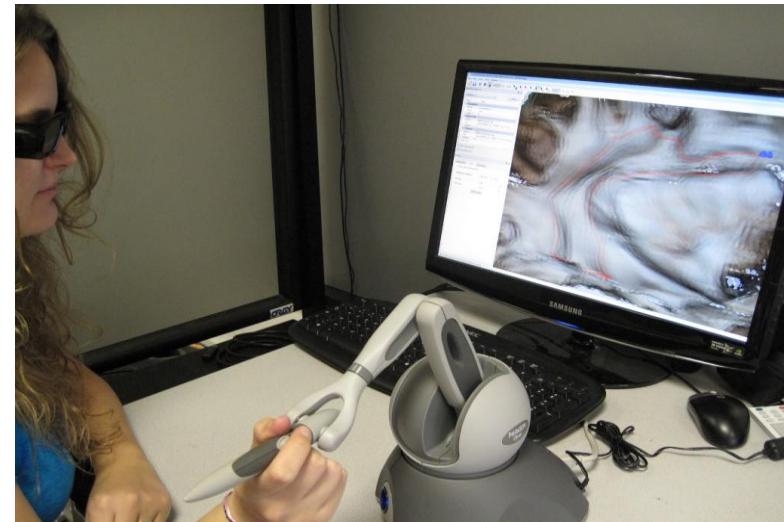
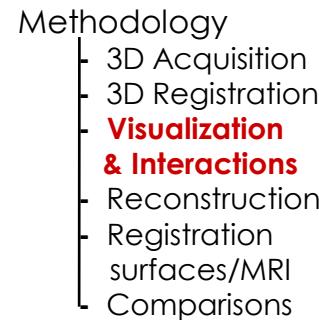


Fig. 1 : Bundle part (ROI) being segmented under stereoscopic and haptic environment



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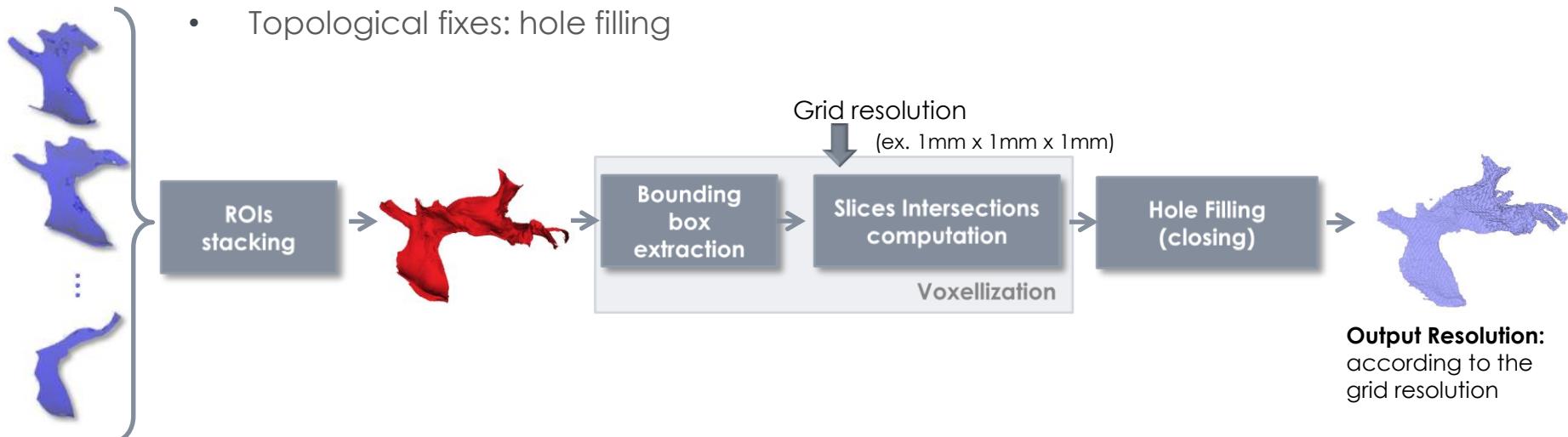
3D Reconstruction: from ROIs to 3D volume

④ Objectives

- Build a «ground truth» in surfacic domain
- Build a «ground truth» in volumic domain

④ Method

- Stacking ROIs of the same labels
- Build binary volume: voxellization
- Topological fixes: hole filling



④ Validations

- Experiment: Egg Yolk Reconstruction

Methodology

- 3D Acquisition
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3D Surfaces registration inside MR image

Methodology

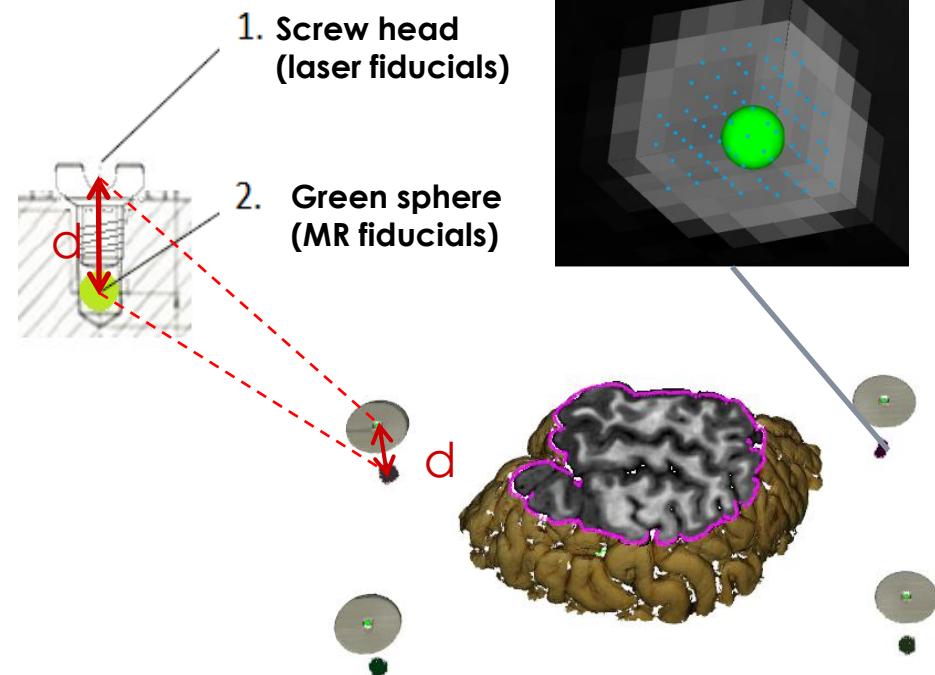
- 3D Acquisition
- 3D Registration
- Visualization & Interactions
- Reconstruction
- **Registration surfaces/MRI**
- Comparisons

④ Objectives

- Get volumic and surfacic data in the same coordinate system
- Merge these data in a common 3D visualization

④ Tasks

- MR image fiducial extraction
 - Thresholding
 - Clustering
 - Isobarycentre
- 3D surfaces registration → MRI
 - Rigid transformation (ICP)



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Voxel Set Comparisons

- Methodology
- 3D Acquisition
 - 3D Registration
 - Visualization & Interactions
 - Reconstruction
 - Registration surfaces/MRI
- Comparisons**

④ Objective:

- Quantify similarity between V and V_{ref}

④ How doing this?

- Indexes from binary segmentation validation studies
 - Accuracy, Recall/Sensitivity,
 - F_α measure,
 - Dice[Dice1945], Jaccard[Jaccard1901] indexes
- Distances
 - Hausdorff and modified Hausdorff distance

④ Indexes established from a confusion matrix

- Let be V and V_{ref} 2 binary voxels set to be compared
- Matrix based on V and V_{ref} voxels counting

	Outside V_{ref}	Inside V_{ref}
Outside V	A	B
Inside V	C	D

Confusion matrix

[Dice1945] Dice L.R. Measures of the amount of ecological associations between species, Ecology, 1945, 26(3) pp 297-302

[Jaccard1901] Distribution de la flore alpine dans le bassin des Dranses et dans quelques régions voisines, Bulletin de la Société Vaudoise de sciences naturelles, 37, pp 241-272

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Introduction

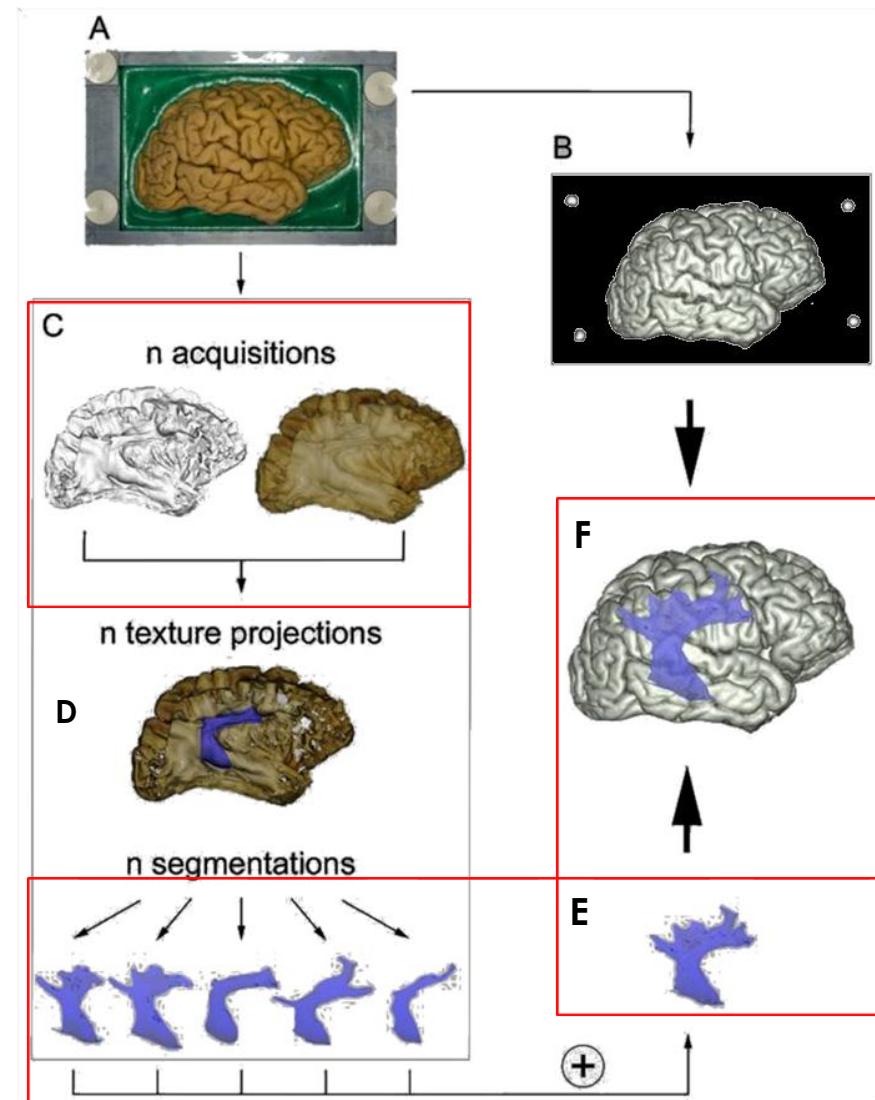
State of the Art

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Results & Validations

- Method Validation
- Experiments

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Results : 3D Surfacic Acquisition

④ 3D Acquisition

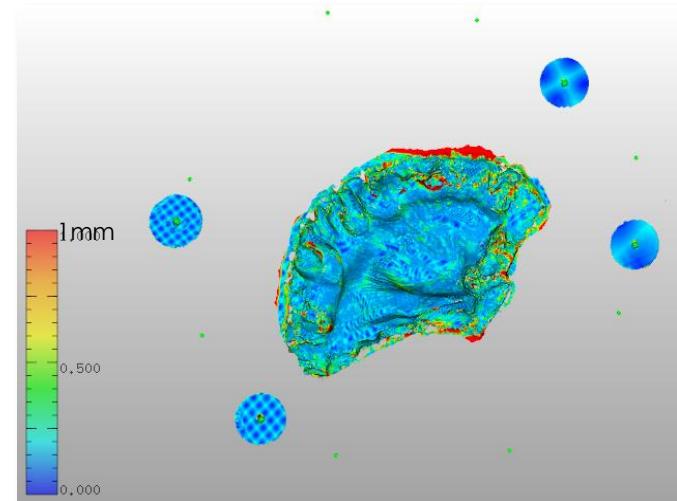
- Advanced dissection step

④ Post processing

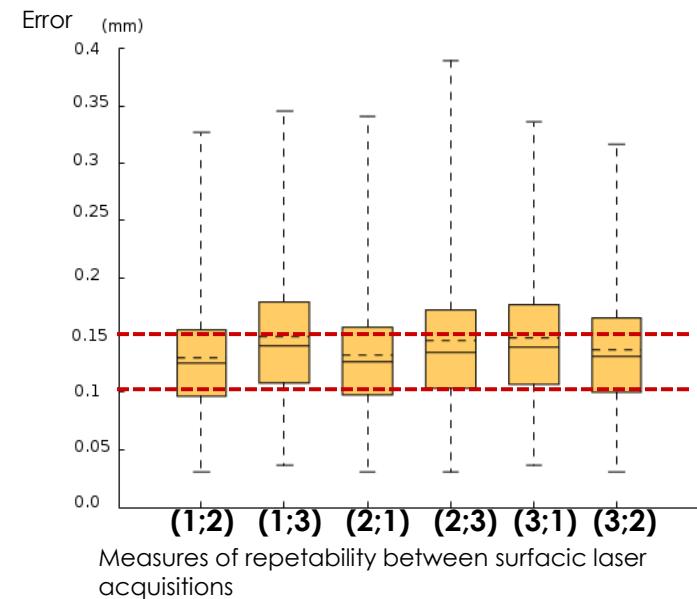
- Cloud Filtering
- Triangulated
- Mesh simplification

④ Repetability validation

- 1 dissection step : 3 different acquisitions
- Two at a time comparisons
- Error measurement for each mesh vertices (nearest neighbors search – euclidian distance)
- Error visualization involving a color map



Color map of error Visualization while comparing 2 acquisition of the same surface



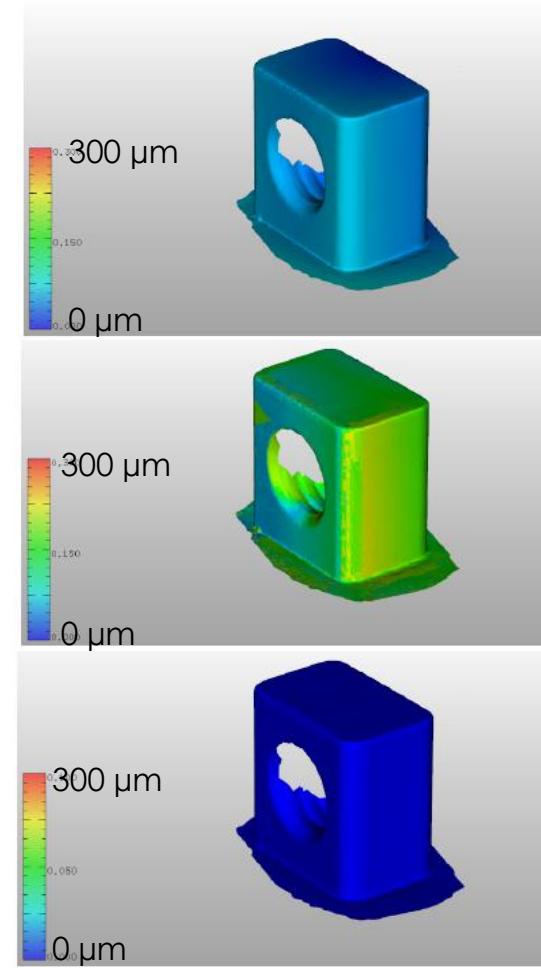
Results: 3D Registration

④ Results

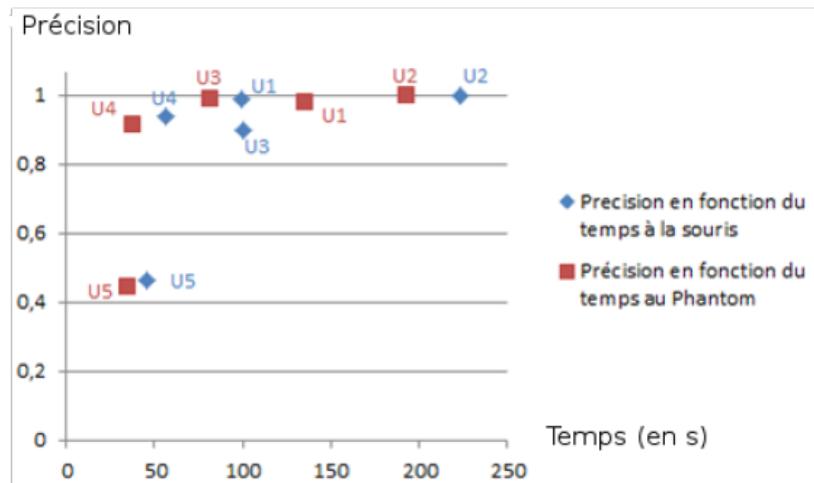
- Comparison of 3 registrations methods
- Same test scene mesh, random transformation
- Registration: accuracy measurement
 - Error visualization: color map
 - In each case, ε values are computed for all vertices of the whole point set

	ε_{\min} (μm)	ε_{\max} (μm)	$\varepsilon_{\text{mean}}$ (μm)	σ (μm)
Whole Cloud registration	1,7	343,6	56,8	40,3
Cloud Subset registration	2,2	800	129	72,4
Fiducial Registration	0	0,2	$5,2 \cdot 10^{-3}$	$1,12 \cdot 10^{-3}$

Table showing measured errors (distance between closest neighbors) with the 3 methods



Evaluation : User Immersive Experiment



④ Experiment goal

- Evaluate gain of productivity
From 2D mouse to Phantom

④ Protocole

- 5 users involved
- 5 simple selection tasks
- Using mouse and Phantom
- Record speed and accuracy

④ Results & Discussion

- Users records show a excellent precision
- Gain in time
- Learning time

Presentation Summary

Introduction

State of the Art

Methodology

Results & Validations

- Methodology Validations
- Experiments
 - Real Bundle Reconstruction: SLF
 - Voxels Set Comparisons

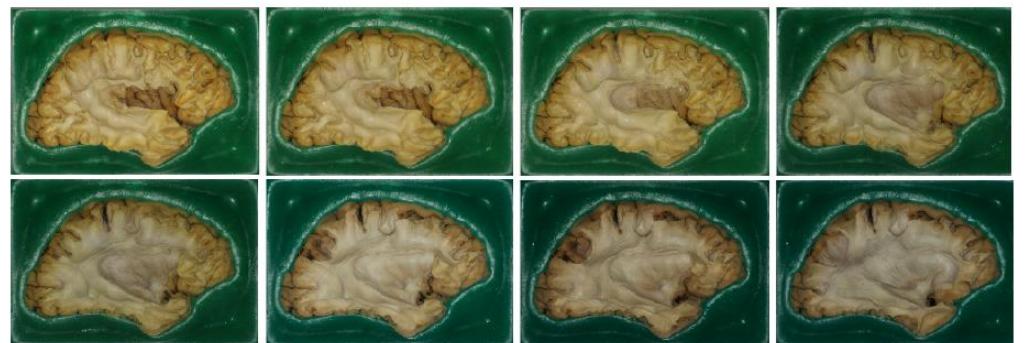
Conclusion & Future Works

3D Acquisition

- ④ 1 brain hemisphere
 - 1 target bundle
 - 33 steps
- ④ Dissection
- ④ 3D Acquisitions
 - Fiducial points
 - Laser points clouds
 - Mesh post processing
- ④ Color Acquisitions
 - Orthophotograph



Setup overview while anatomist is scanning a specimen being dissected



Série d'orthophotographies acquises à chaque instant d'acquisition 3D durant le processus de dissection

ROIs Selection: SLF

- ④ Navigation and immersive visualization
- ④ 3D Registration
 - Rigid transform applied on fiducials
- ④ ROI Segmentation
 - Selections tools on mesh
- ④ ROI Visualization
 - Surfacic rendering
 - Contextual information

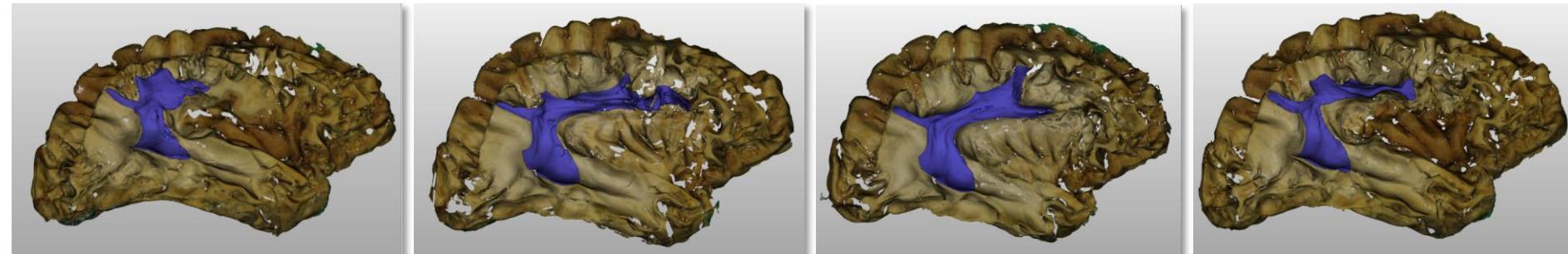
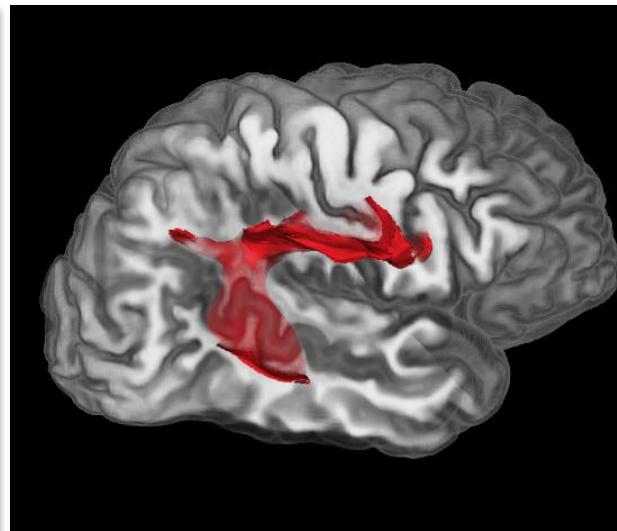
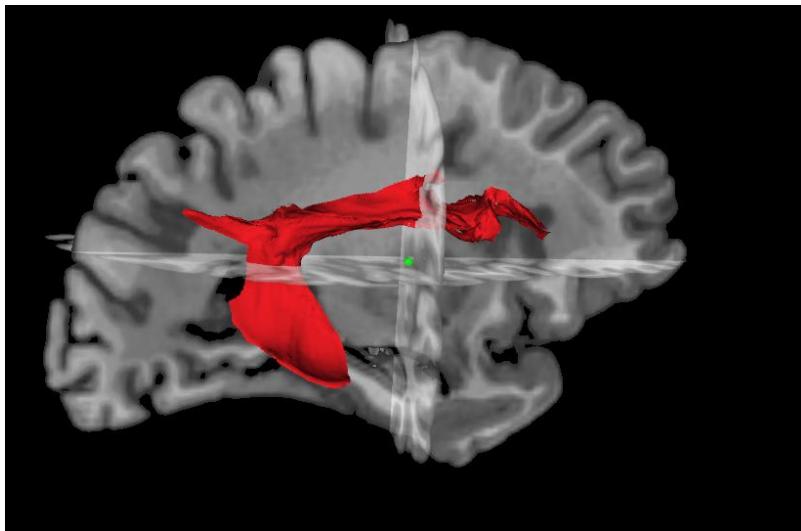


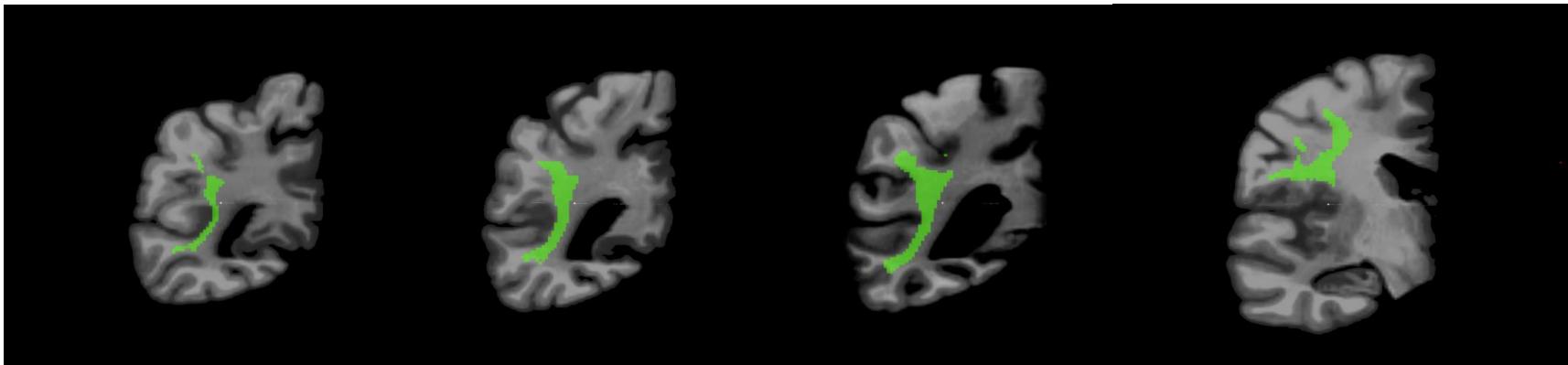
Fig. 1 : Segmentation steps at different dissection states

3D Registration of SLF inside MRI



Surfacic reconstruction of SLF bundle from dissection data. Result is presented inside MR volume image

Views of volumic reconstruction of SLF bundle in initial MR slices



Presentation Summary

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Conclusion & Future Works

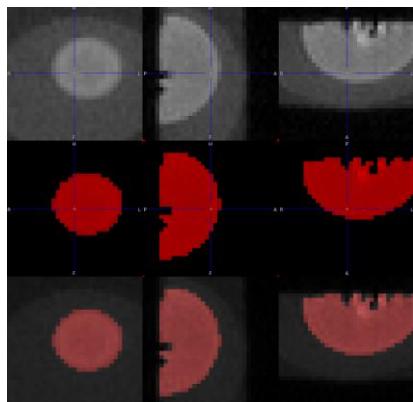
Experiment: egg yolk reconstruction

④ Objective

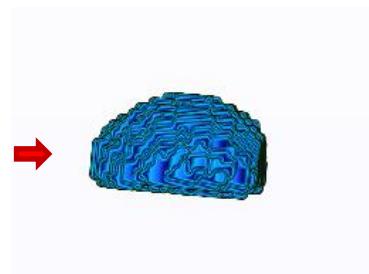
- Validate 3D reconstruction
- Quantitatively compare 2 voxels set from a simple dissecable object

④ V_{ref} : Ground truth building

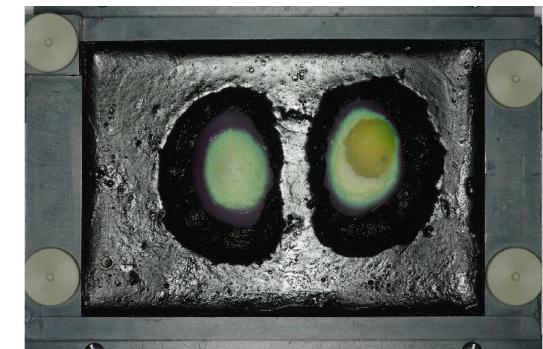
- 3D Volumic Acquisition (T1)
 - Before dissection
 - Egg yolk/albumen good contrast
- Yolk segmentation
- 3D Reconstruction



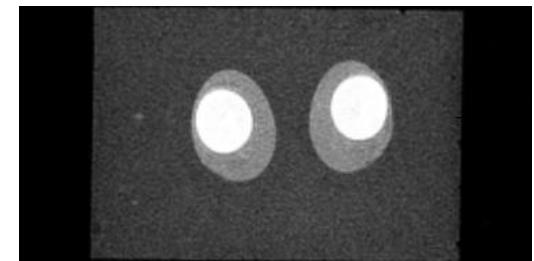
Ground truth: Yolk Segmentation using the Otsu method [Otsu79]



[Otsu79] N.Otsu , "A Threshold Selection Method from Gray-Level Histograms", Transactions on System, Man, and Cybernetics. SMC-9(1), 1979



Dissection support with eggs immersed in gelatin

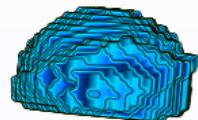


MR T1 Acquisition showing the good yolk/albumen contrast

Experiment : Voxels Set Comparisons

⊕ Protocol

- 3D Successive Acquisitions (11 steps)
- ROIs labelling (egg yolk)
- 3D Reconstruction



Yolk reconstruction results (volumic)

- Computation of indicators of similarity between V et V_{ref}

⊕ Analysis & Discussion

- Two 3D volumes from two different modalities
- Able to quantify similarity
- Good similarity



Labellized yolk part on 2 dissection steps.

Indicators	Computed Value	Optimal Value
Accuracy	86.94%	100%
Recall	97.15%	100%
F-measure ($\alpha=0.5$)	88.81%	100%
Dice	0.918	1.0
Jaccard	0.848	1.0
D hausdorff	1.8	0 (voxels)
<u>D hausdorff</u>	1.04	0 (voxels)

Presentation Summary

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Conclusion

- Presented work allow the following
 - Propose a full operational methodology to keep track of a dissected specimen
 - Rebuild anatomical structures and visualize them inside volume image context
 - Compare and quantify similarity between voxels sets
- Limits
 - Subjectivity of the segmentation process
 - Few bundles per hemisphere
 - Only one viewpoint for texturing
 - Dissection time
- Software design and development
 - Tool has been design with constant users feedback
 - Tool is currently in use
- Pluridisciplinarity
 - Anatomists, Physicists, Computer Scientists
 - Methodology validations through real data experiments

Future Works

- Improvement in automation of acquisition process
- Improvements of quantitative indicators for voxel sets comparisons
 - New metric, Distances map
- Comparisons with data issued from
 - Phantoms (thesis work of I. Filipiak)
 - Ex-vivo tractography results
- Reinforcement of national and international collaborations
 - Neurospin, CEA-saclay, France
 - INRA, plateforme CHIRE « gros animal », Nouzilly, France
 - A.Martinos Center MGH/HMS, Boston (MA) USA

FibrAtlas II Project



Comparison, in the same subjects of Human Brain White Matter reconstruction
by *in-vivo* MR DTI with dissection data:

- ⇒ Validate tractography algorithms
- ⇒ Give neuroanatomist community access to fasciculi « ground truths»

Acknowledgments:

GE Healthcare



SIEMENS

Anatomists Experts:

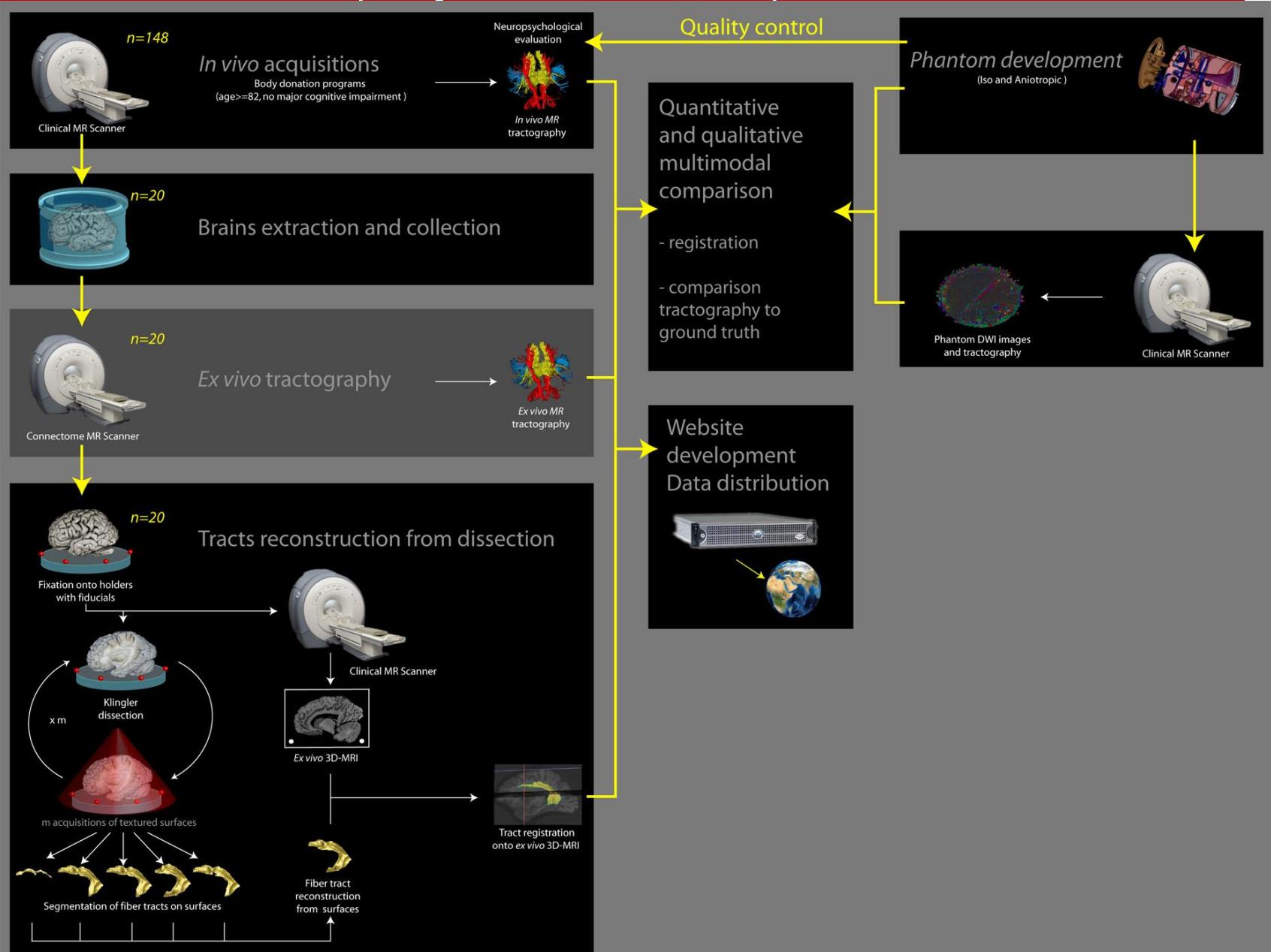
C. Destrieux (PU-PH) U930/Eq5 - project leader
S. Velut (PU-PH) U930-Eq 5
J-P. Cottier (PU-PH) neuroradiologist U930-Eq5
I. Zemmoura (CCA-HU) neurosurgeon U930-Eq5

MR Acquisitions & Post-processing:

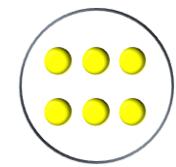
F. Andersson, PhD (IR) U930-Eq5
C. Tauber, PhD (MCU) U930-Eq3
L. Barantin, PhD (IR) U930-Eq5
I. Filipiak, Doctorante, U930-Eq5

3D Acquisitions, Visualization tool and software design:
G. Venturini, Prof. EA6300
B. Serres, PhD student EA6300/U930-Eq5

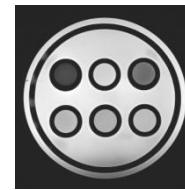
Fibratlas project – follow up



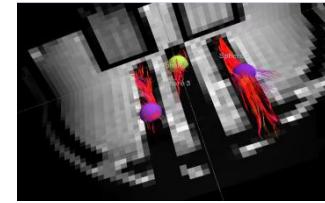
Phantom Tractography: I. Filipiak et al.



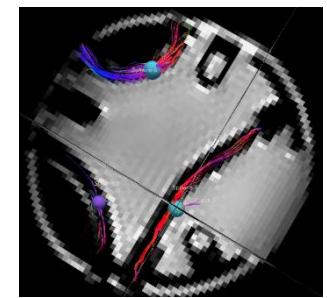
1. Tubes pour diffusion isotrope



2. Fibres longitudinales

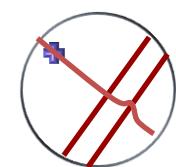
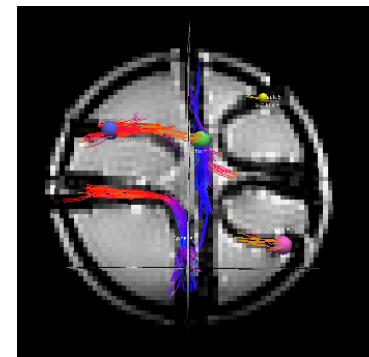


3. Fibres en U



4. Fibres avec des angles

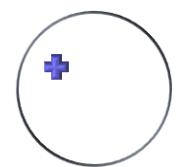
entre 30° et 180°



5. Croisement de fibres



En cours de construction



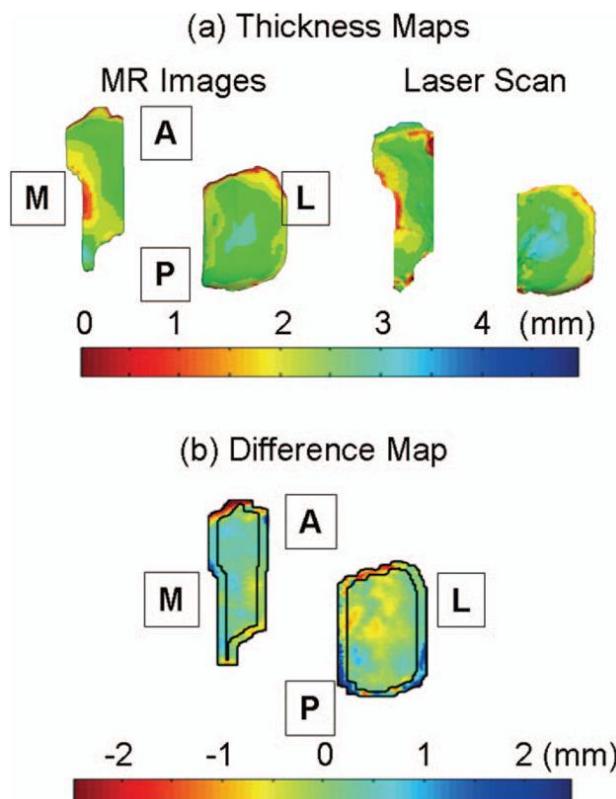
6. Fibre en éventail

Fibre de dyneema



Annexes

Etat de l'art : Acquisitions 3D en anatomie



Carte colorée (a) des mesures d'épaisseurs de cartilage et (b) de leur comparaisons depuis deux acquisitions 3D laser et IRM.

Figure issue de [Koo et al.2009]

- ④ Comparaison de résultats issus d'IRM à une vérité terrain
- Mesure de précision de modèles de cartilages issus d'acquisitions IRM [Koo et al. 2009]
 - Comparaison quantitatives basique
 - Précision milimétrique

[Koo et al. 2009] Accuracy of 3D Cartilage Models Generated From MR Images Is Dependent on Cartilage Thickness: Laser Scanner Based Validation of In Vivo Cartilage – in J Biomech Eng. 2009 ,131(12)

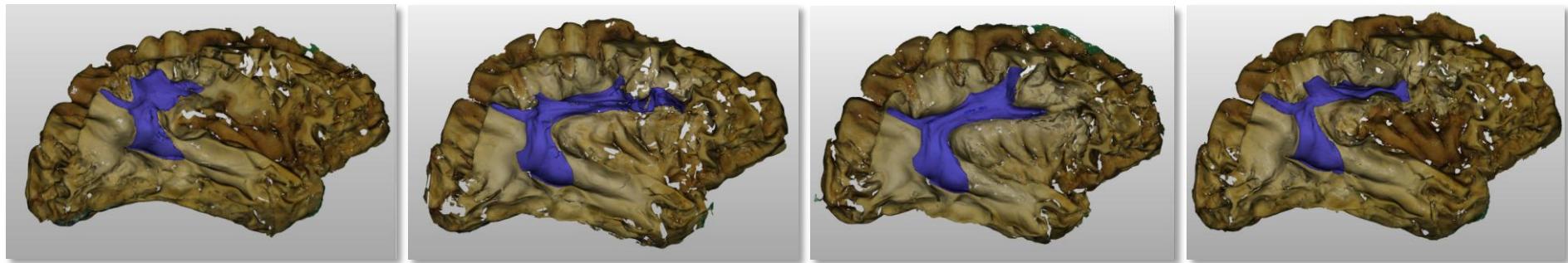
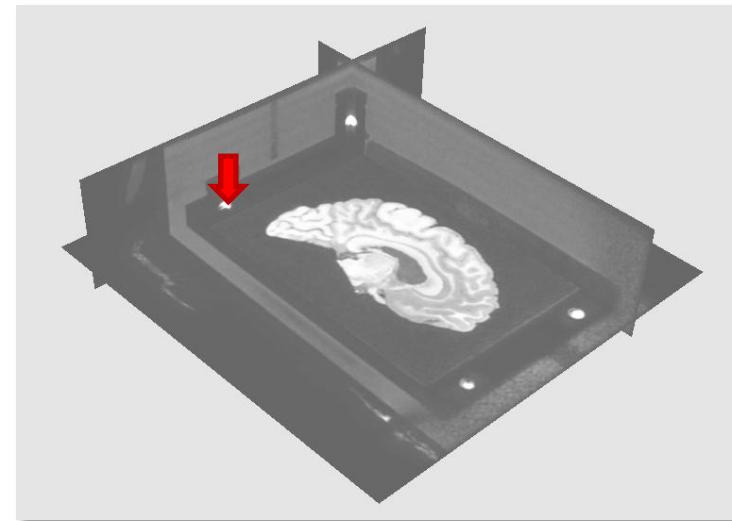


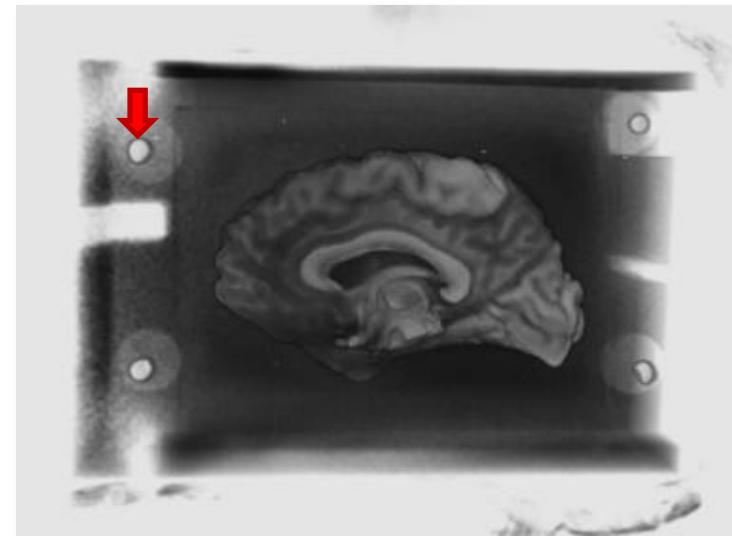
Fig. 1 : Etapes de segmentation des différentes portions visibles du faisceau

Acquisition volumique 3D

- ④ Acquisitions IRM pondérée en T1
 - Choix de la platine visible en hypo-signal IRM
 - 4 points repères non coplanaires visibles en hyper-signal IRM



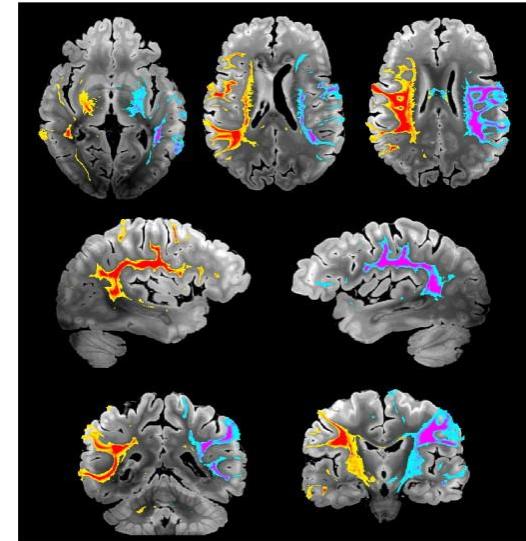
Visualization classique: 3 plans 2D



Visualization 3D en rendu volumique

Future Works

- Enrichissement des indicateurs de mesure quantitatifs de comparaisons volumiques
 - Métriques, Cartes de distances
- Comparaison avec des données issues
 - de fantômes [Filipiak2013]
 - de tractographie ex vivo
- Renforcement des collaborations nationales et internationales
 - Neurospin, CEA-saclay, France
 - A.Martinos Center MGH/HMS, Boston (MA) USA



[Miller2012] Diffusion tractography of post-mortem human brains: Optimization and comparison of spin echo and steady-state free precession techniques, *NeuroImage*, 59, 2012, pp2284-2297