Validating tractography pipelines: the help of simulated phantoms

CoBCoM Winter School Workshop
Juan les Pins, November 20th 2017

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Outline of the lecture

Tractography: main applications and associated challenges

- Identify the main bundles in normal white matter
- Tractography and pathology
- Characterize "strength" of a connection between two regions
- Tractography pipeline

Can we make tractography more reliable: evaluation and validation

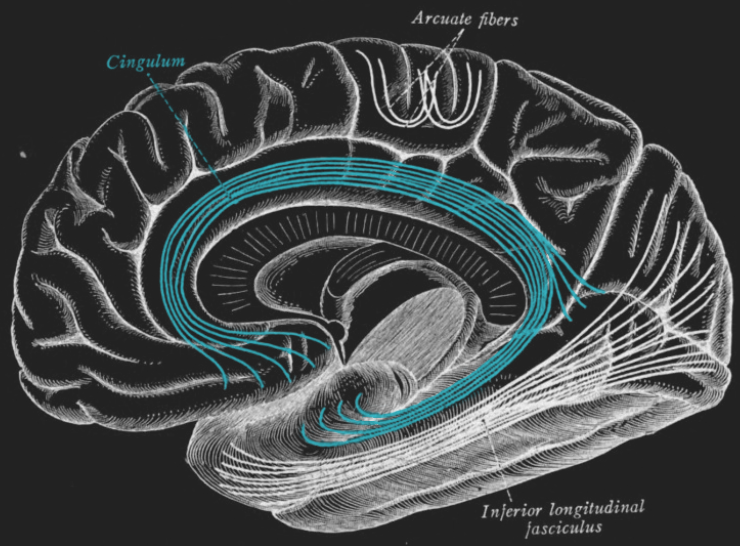
- What can we do *in vivo*?
- Compare to a reference

Generate your own ground truth with Phantomas

- A word on models under the scene
- Hands-on tutorial!

Tractography: main applications, and associated challenges

Identify the main bundles in normal white matter

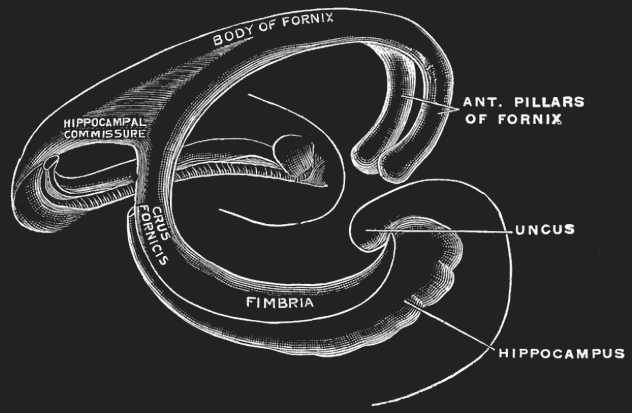


[Gray, 1918]

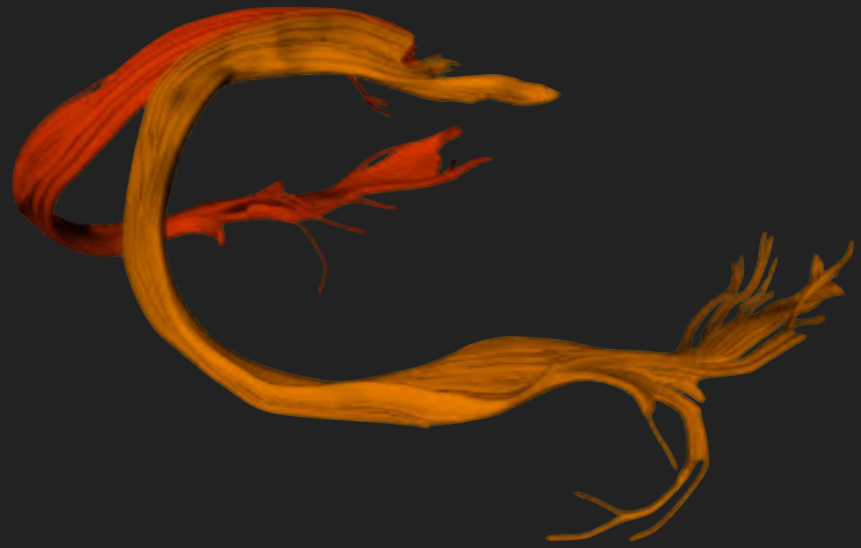
[Fortin et al, Can J Neurol Sci 2012]

Challenge 1: Fiber bending with high curvature

Reconstruction of Fornix



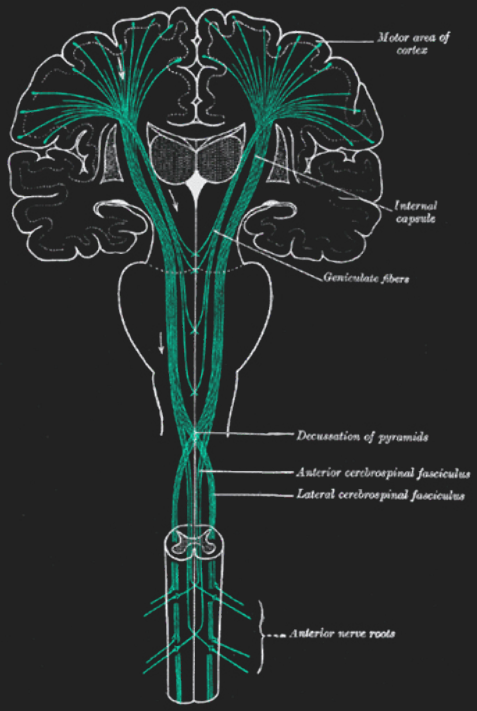
[Gray, 1918]



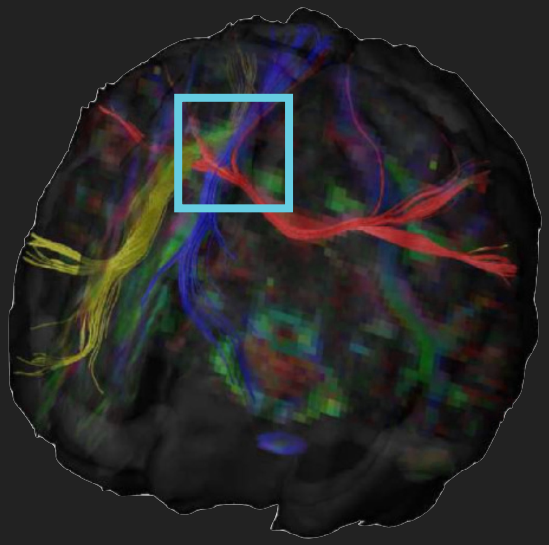
[Garyfallidis et al, Front Neuroinform, 2014]

Challenge 1: Fiber bending with high curvature

Reconstruction of pyramidal tract



Challenge 2: Tracking through complex white matter



Courtesy of M. Descoteaux

Fiber-tractography in patients with brain tumor (1)

Improve surgical planning

- Better characterize white matter around the tumor
- Maximize resection while minimizing patient morbidity

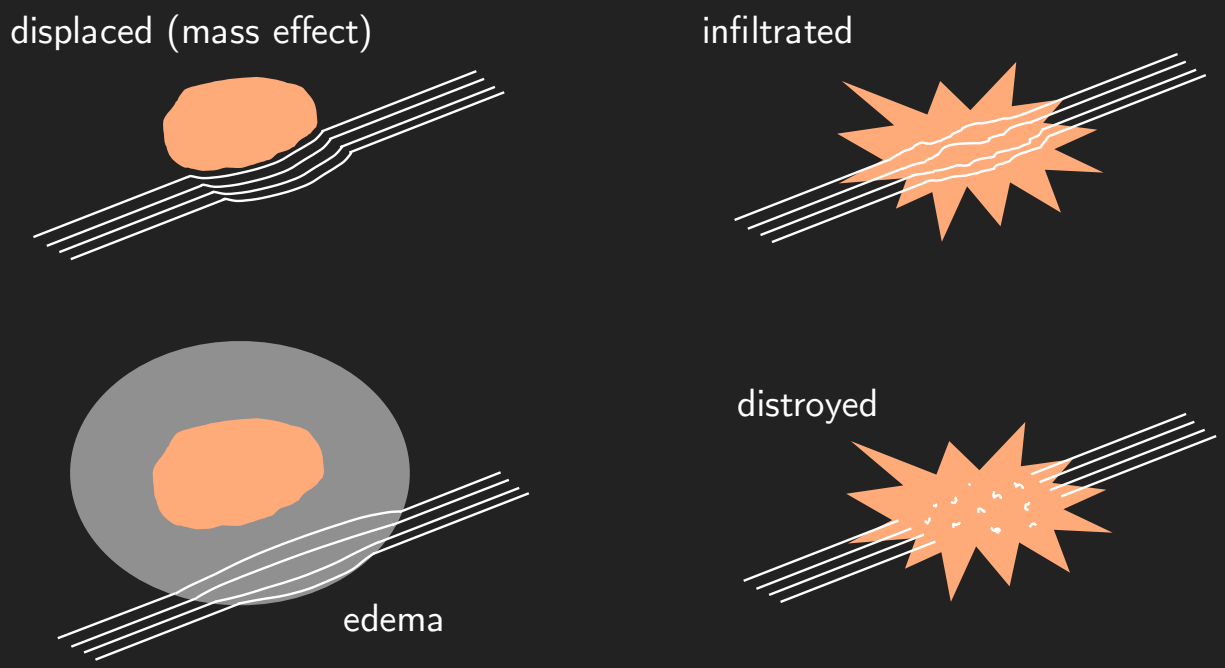
Associated challenges

- Tracts displaced by tumor mass effect (red)
- Fiber tracking impacted by edema (blue)

[courtesy of R. Verma]

Fiber-tractography in patients with brain tumor (2)

Better characterize white matter in/around the tumor

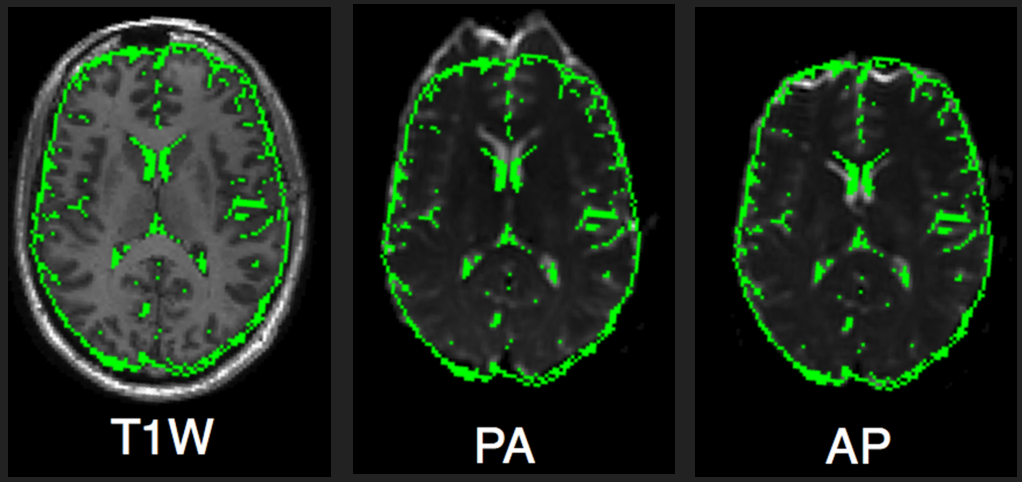


[Courtesy of M Descoteaux]

see Ragini Verma's talk on Friday, 2pm

Robustness of tractography to image distortions (1)

- Fast acquisitions (Echo-planar images) produce many geometric artefacts
- These impact fiber tracking if not properly addressed

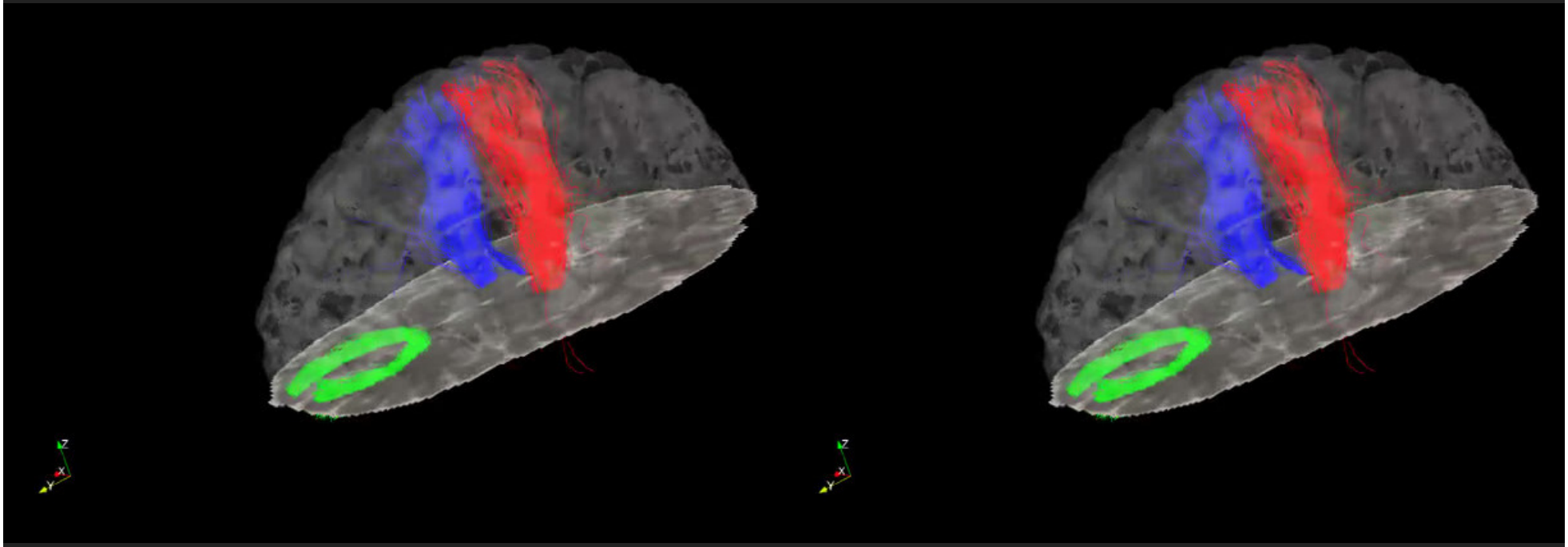


Field inhomogeneity [Treiber et al, PLOS ONE 2016]

Ghosting

Robustness of tractography to image distortions (2)

Example of the impact of correcting for susceptibility-induced distortion



Left: reconstruction without susceptibility distortion

Right: in the presence of susceptibility distortion the forceps minor is lost

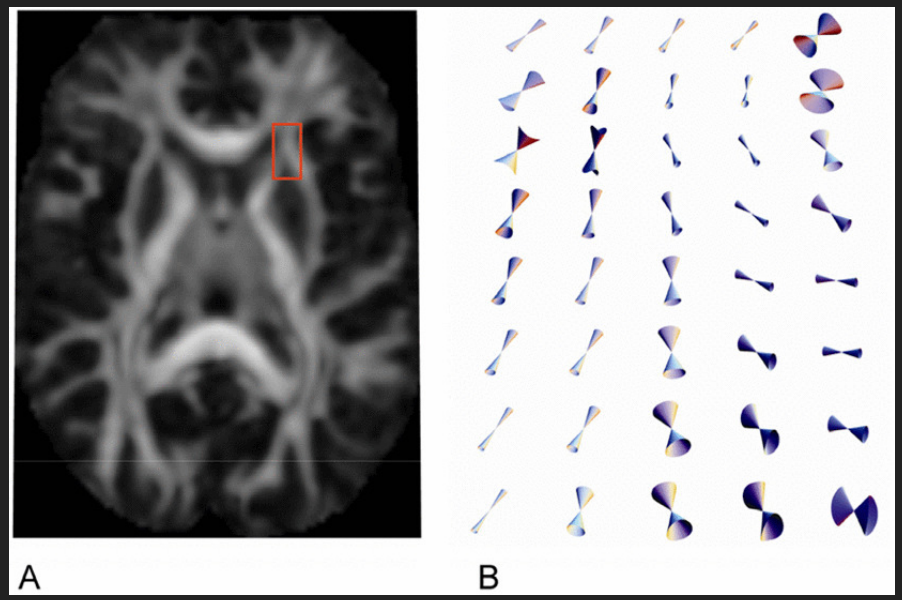
[O Esteban et al, Front Neuroinform 2016]

Noise in DW images: the HARDI paradox

Higher b-value provides better angular contrast

- At the cost of a stronger attenuation
- TE is also increased (so the baseline signal is decreased)

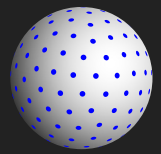
low-SNR DWI



FA map and cone of uncertainty
[CG Koay et al, IEEE Trans Med Imaging. 2008]

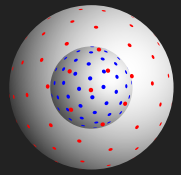
Tractography pipeline: a long road to fibers

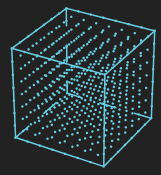
Acquisition design



Single *b*-value
- high/low *b*
- high/low angular resolution

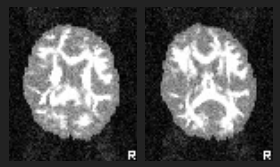
Multishell/DSI



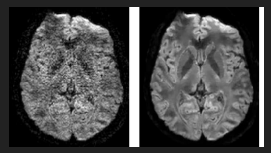


Preprocessing

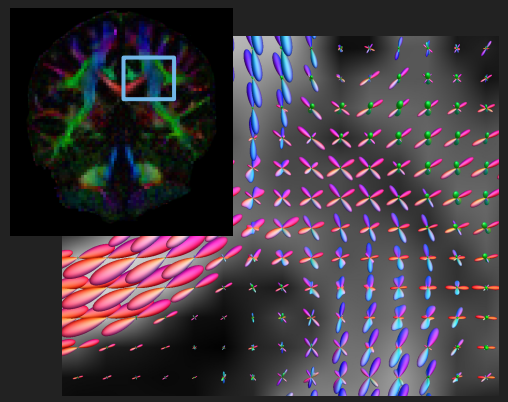
Motion/distortion correction



Denoising/ Resampling

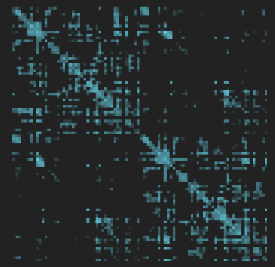


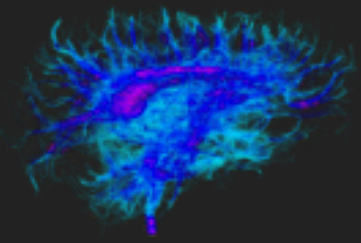
Local reconstruction



Tracking and connectomics

probabilistic/deterministic, ...

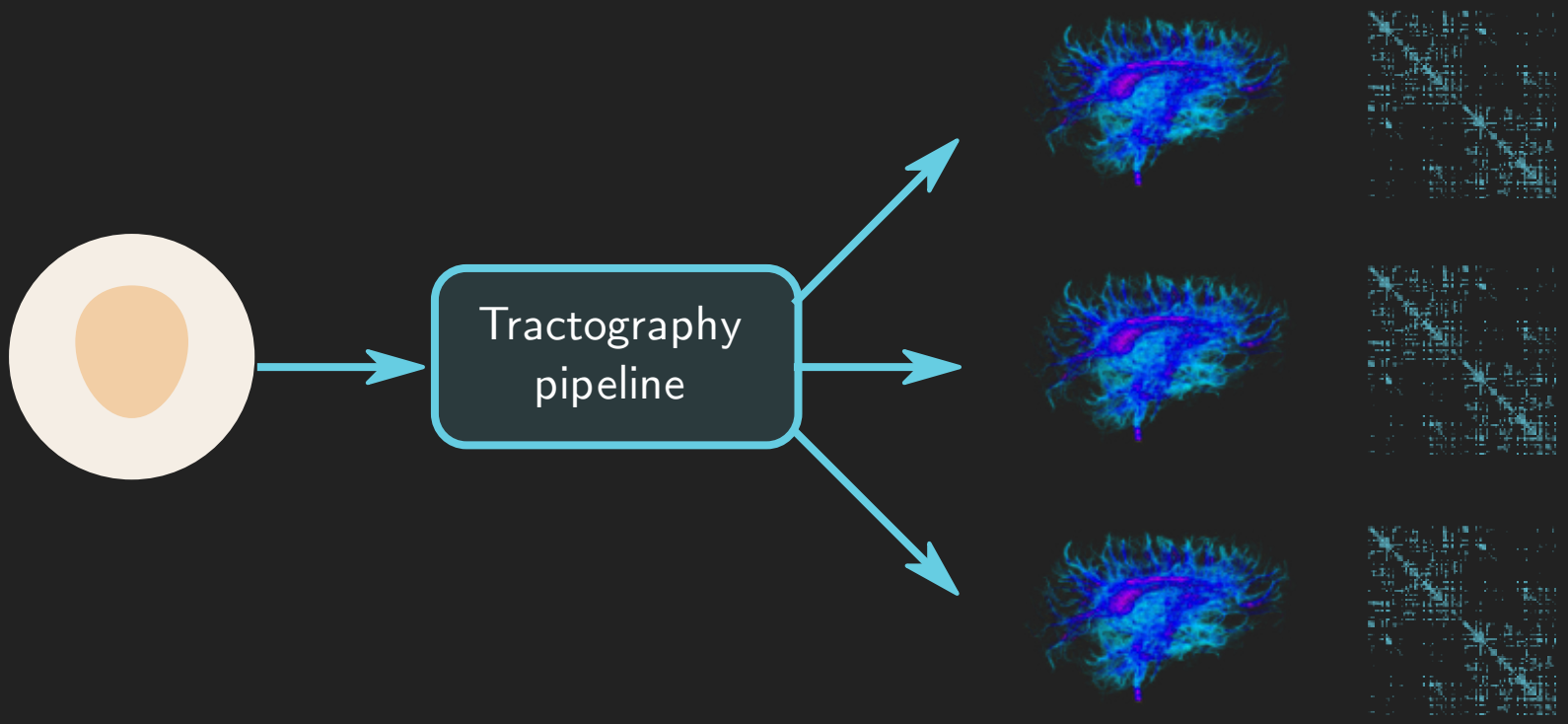




Can we make tractography more reliable: evaluation and validation

Validate a tractography pipeline *in vivo*

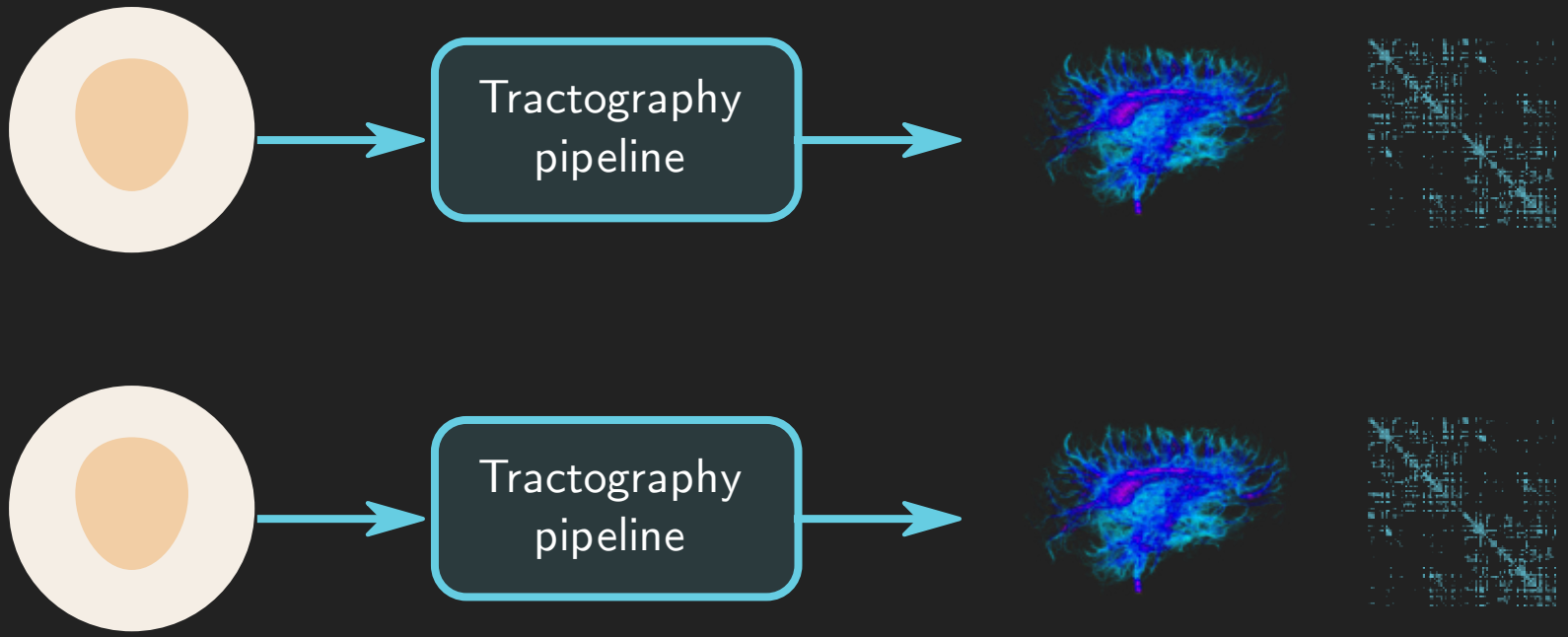
What can we do without a reference?



Tractography results should be **reproducible**

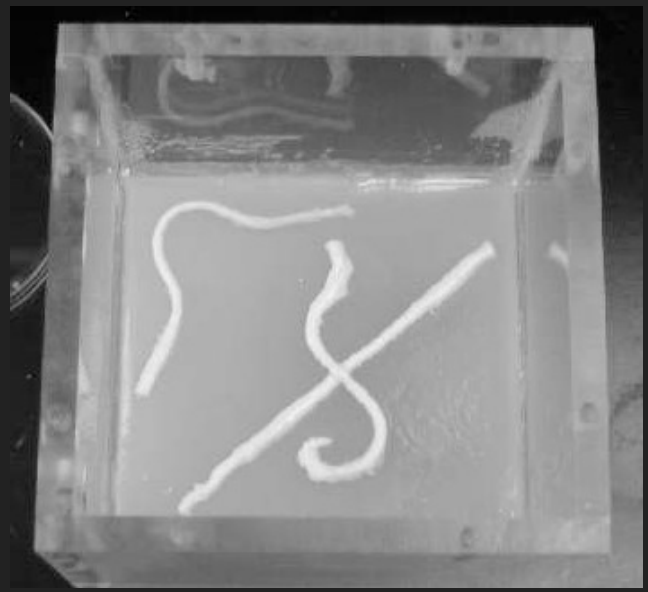
Validate a tractography pipeline *in vivo*

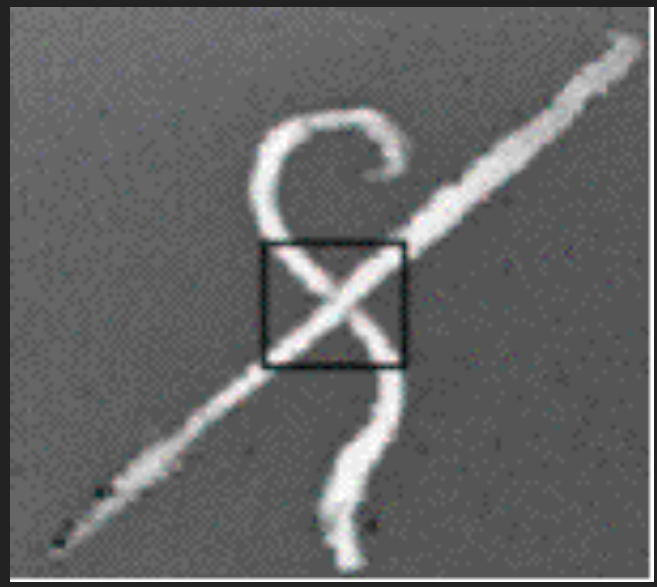
What can we do without a reference?



Tractography should provide **subject-specific information**

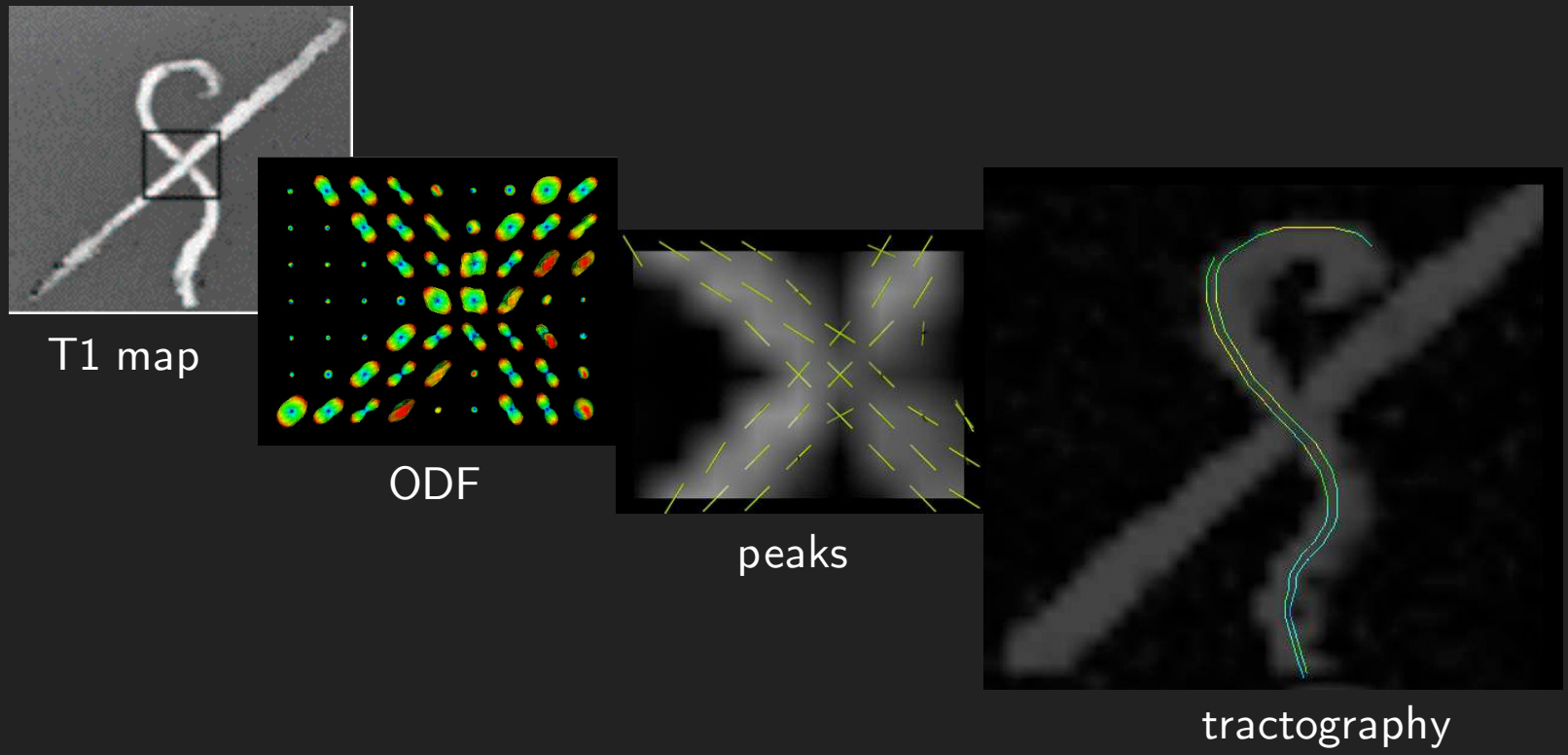
Compare to a reference: biological phantom (1)



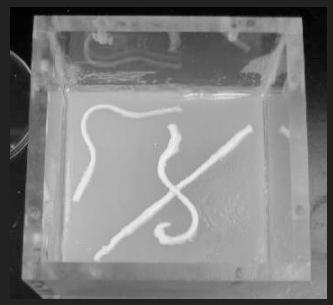


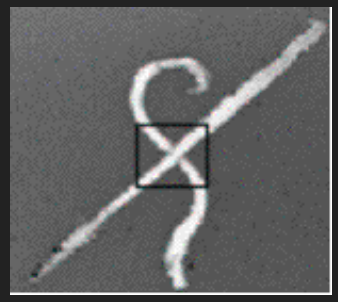
Rat spinal cords [J Campbell, PhD thesis, 2006, McGill University]

Compare to a reference: biological phantom (2)



Compare to a reference: biological phantom (3)





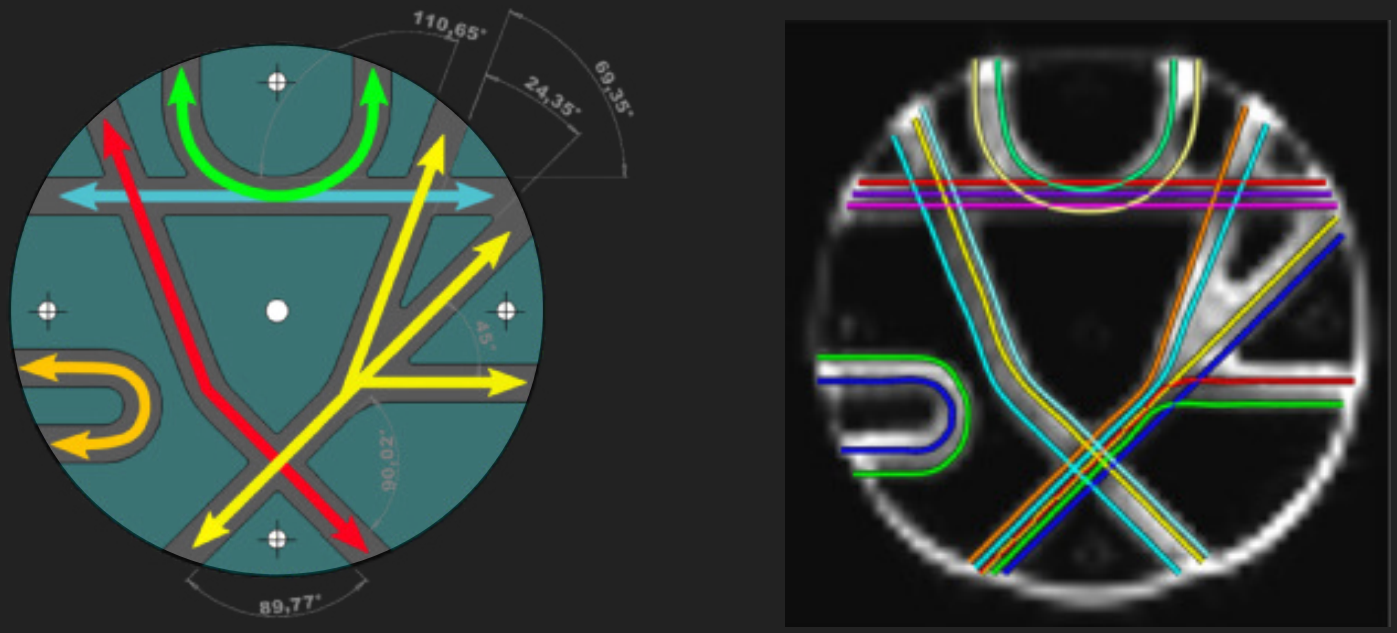
Pros

- A real biological tissue
- A real acquisition (1.5T, $b = 3000$s/mm^2, 90 dirs, 2.8mm iso)
- Fiber crossing modeled by partial volume effect

Cons

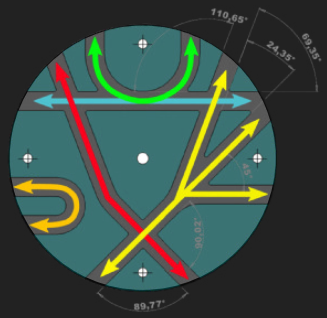
- Hardly reproducible
- Fiber configuration much simpler than a human brain
- Ground truth is not perfectly known either
- Perishable
- *Ex vivo* diffusion is different from *in vivo*

Compare to a reference: hardware phantom (1)



Fiber cup phantom (challenge MICCAI'09) [P Fillard et al, Neuroimage 2011]

Compare to a reference: hardware phantom (2)



Pros

- A real acquisition (3T, b up to 2650s/mm², 64 dirs per shell on 3 shells, 3mm iso and 6mm iso (2 version))
- Phantom mimics a coronal section of the brain
- Ground truth is precisely known

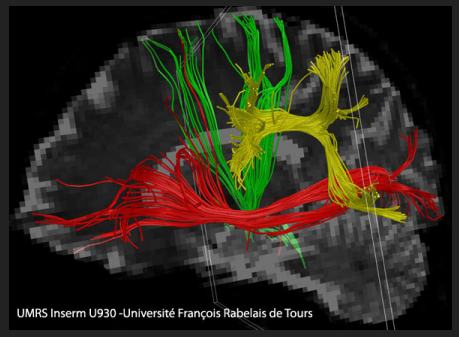
Cons

- Fiber configuration still simpler than a human brain
- Diffusion characteristics far away from *in vivo* brain white matter.

Compare to a reference: post-mortem dissection (1)

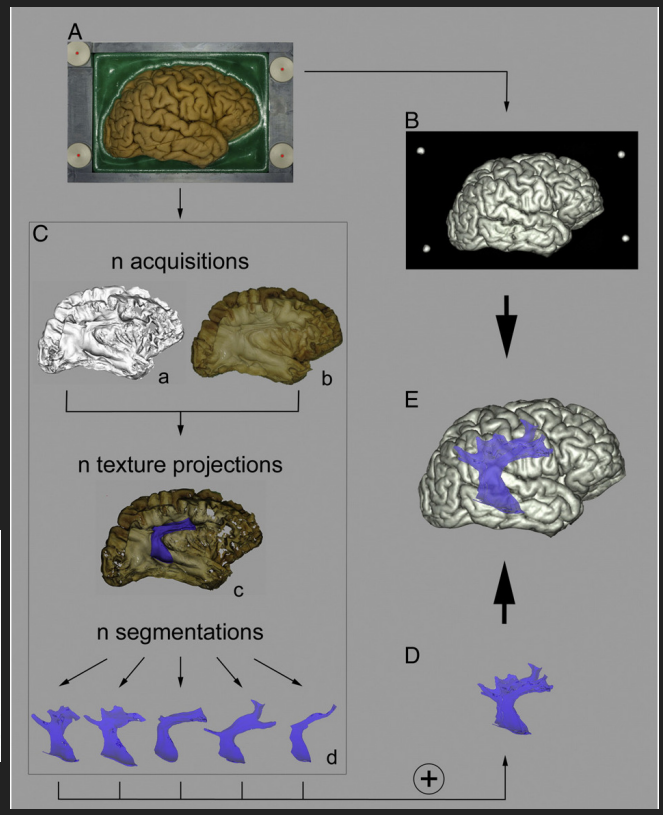
The Fibratlas project

People who donate their body to science are proposed to volunteer for one in vivo MRI



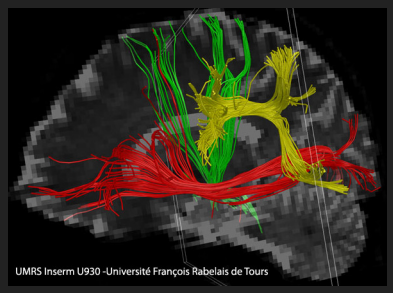
In vivo protocol includes HARDI acquisition

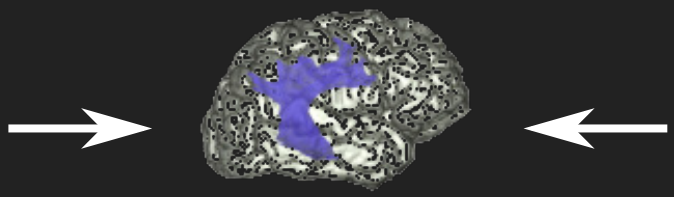
One more ex vivo scan is performed prior to dissection



[Courtesy of C Destrieux, Univ François Rabelais Tours, France]

Compare to a reference: post-mortem dissection (2)





Registration to post-mortem MRI

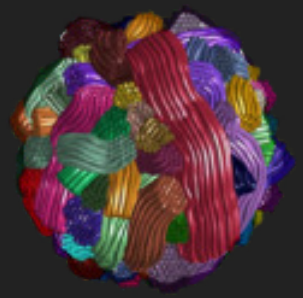
Pros

- Real acquisition of *in vivo* subject
- High resolution capture of the dissection

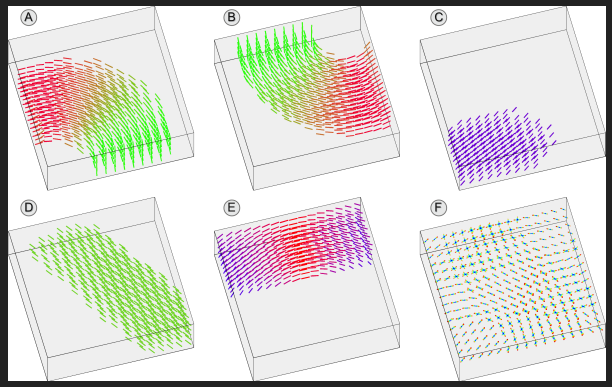
Cons

- Dissection can only focus on a single bundle at a time
- Klinger's method for dissection is destructive and selective
- Data yet to come

Compare to a reference: simulated phantoms (1)



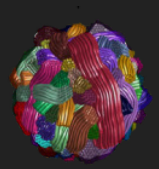
Numerical Fiber Generator
[T Close et al, Neuroimage 2009]



ISBI 2012 HARDI contest
[A Daducci et al, Neuroimage 2013]

ISMRM'15 contest
[K Maier-Hein et al, Nature Comm 2017]

Compare to a reference: simulated phantoms (2)



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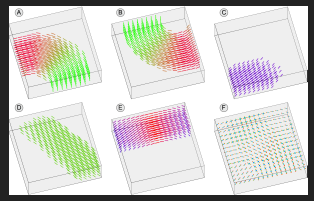

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[A Daducci et al, Neuroimage 2013]

ISMRM'15 contest
[K Maier-Hein et al, Nature Comm 2017]

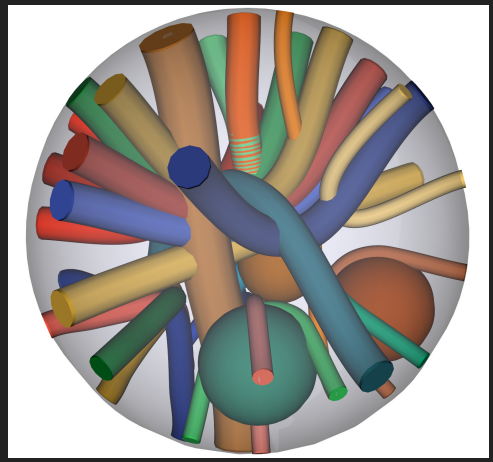
Pros

- Exact (to sub-millimeter accuracy) knownledge of ground-truth
- Cheap (no MR, no hardware required)
- Easy to change acquisition parameters, noise, ...
- Allows to focus on specifics of the pipeline

Cons

- Images as realistic as simulation can be

Generate your own phantoms with Phantomas



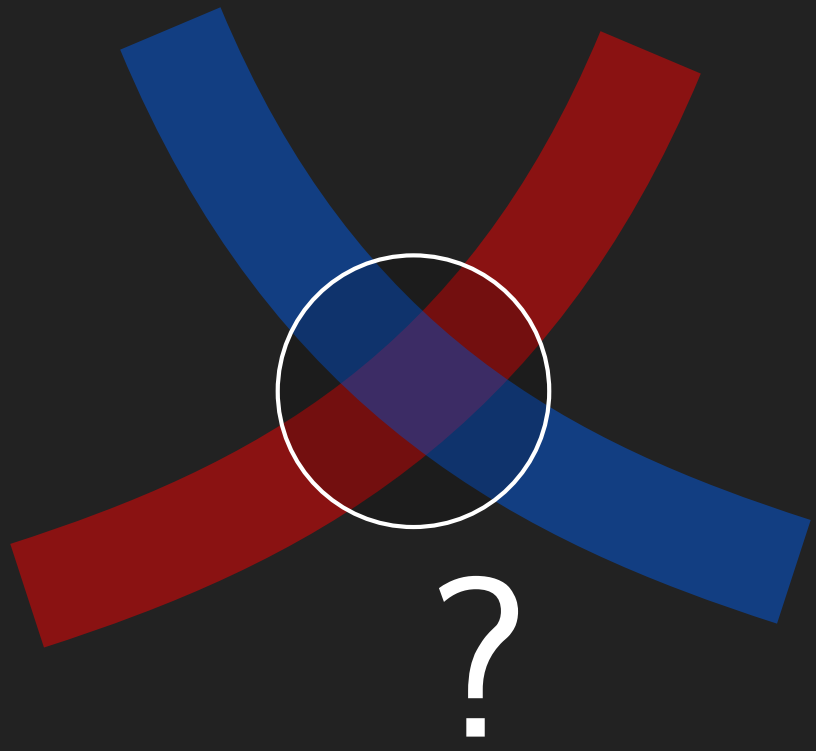
Phantomas: tutorial/demo

emmanuelcaruyer.com/phantomas.php

Phantomas: Open challenges

Diffusion modelling: incorporate microstructure information

- Axonal diameter/density
- What happens in fiber crossings/branching?
- Computational burden of computing realistic microstructure-derived signal



Questions ?

www.emmanuelcaruyer.com