



Université catholique de Louvain



Signal Processing Seminar

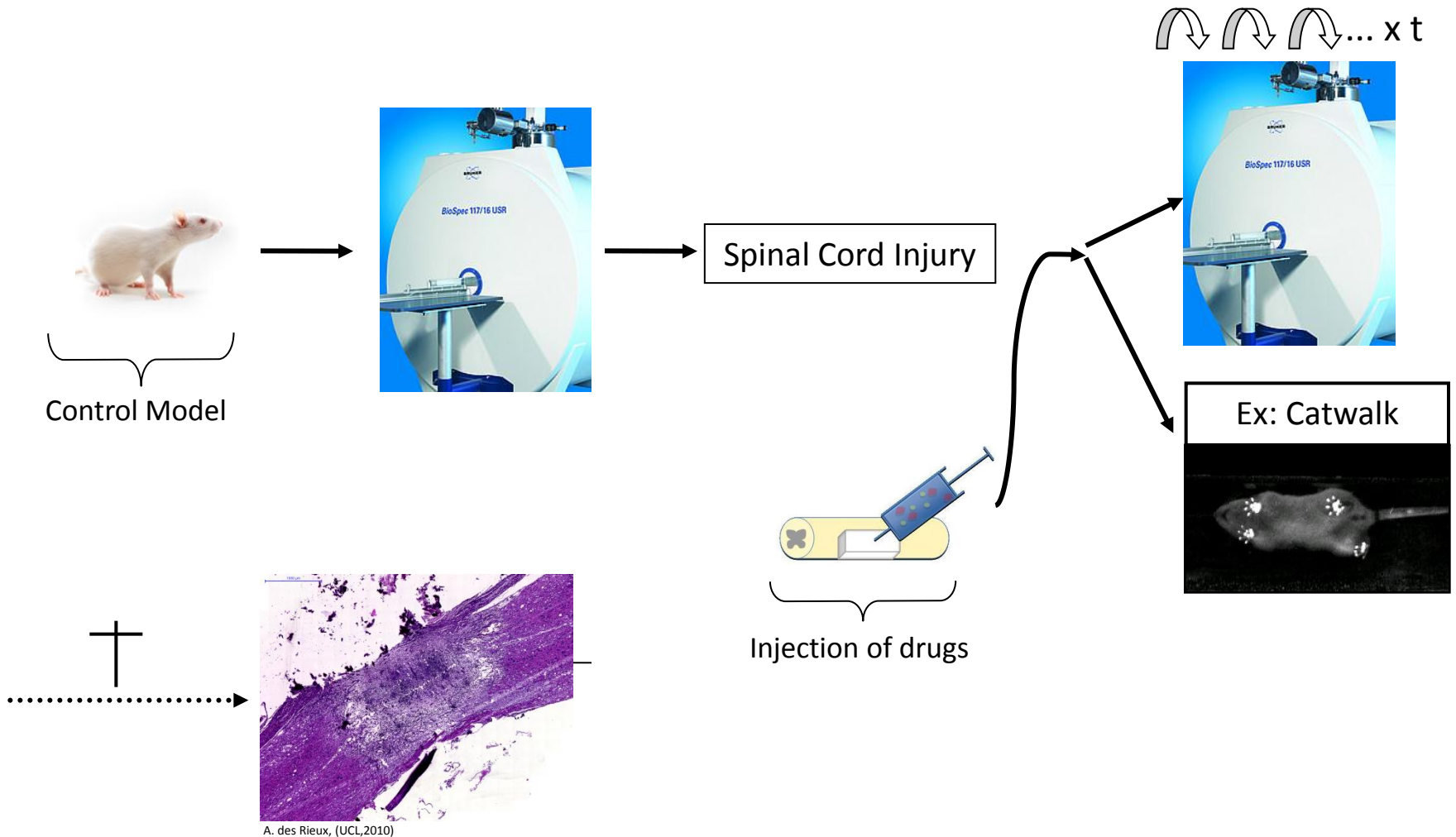
Diffusion Tensor Imaging applied to spinal repair assay: a challenge

Promotor: Benoît Macq

Co-promotors: Bernard Gallez, Véronique Prétat



Evaluate the efficiency of drugs for spinal repair: a large inter-subject variability



Layout

Diffusion Tensor Imaging on spinal cord

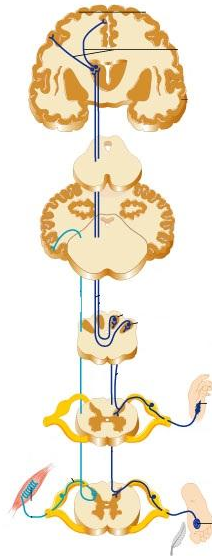
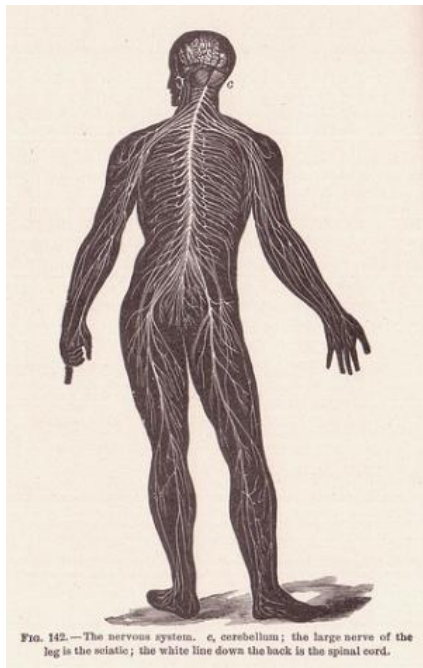
A first study for prove of concept

A second study to evaluate the efficiency of drugs

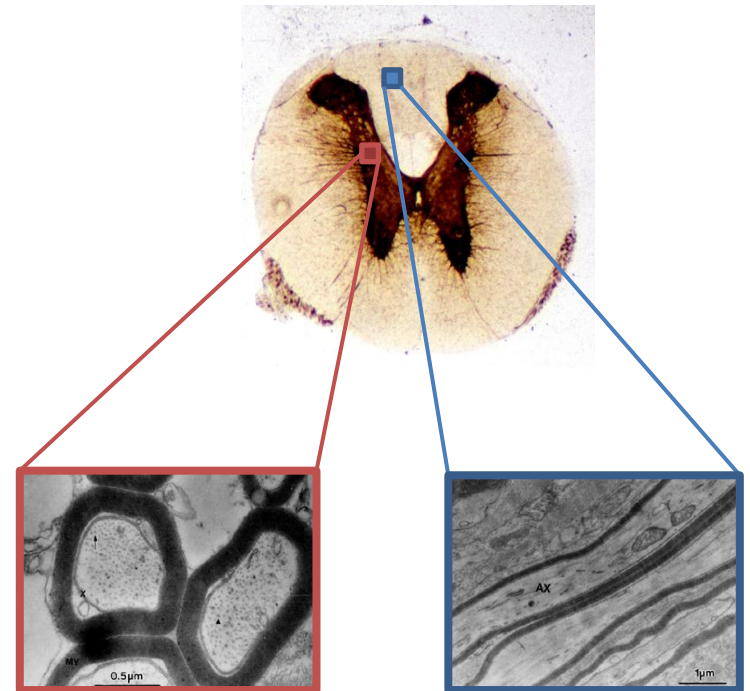
MRI Set-up for spinal cord imaging

Diffusion Tensor Imaging on spinal cord

Purpose: Image the nerve growth in the spinal cord



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Diffusion Tensor Imaging on spinal cord

Purpose: Image the nerve growth in the spinal cord

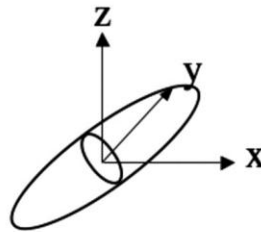
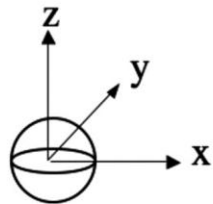
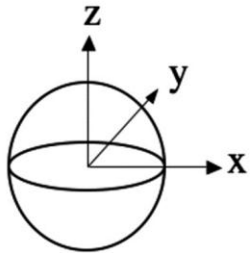
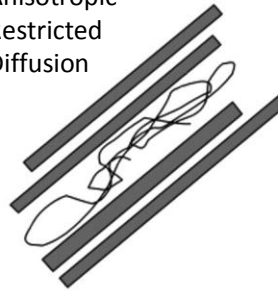
Free Water



Isotropic Restricted Diffusion



Anisotropic Restricted Diffusion



$$\begin{bmatrix} D & 0 & 0 \\ 0 & D & 0 \\ 0 & 0 & D \end{bmatrix}$$

$$\begin{bmatrix} D_{eff} & 0 & 0 \\ 0 & D_{eff} & 0 \\ 0 & 0 & D_{eff} \end{bmatrix}$$

$$\begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{yz} & D_{zz} \end{bmatrix}$$

$$FA = \frac{3}{\sqrt{2}} \frac{\sqrt{Var(\lambda)}}{\sqrt{(\lambda_1)^2 + (\lambda_2)^2 + (\lambda_3)^2}}$$

$$AD = \lambda_1$$

$$RD = \frac{\lambda_2 + \lambda_3}{2}$$

$$MD = \frac{\lambda_1 + \lambda_2 + \lambda_3}{2}$$

Diffusion Tensor Imaging on spinal cord

Purpose: Image the nerve growth in the spinal cord

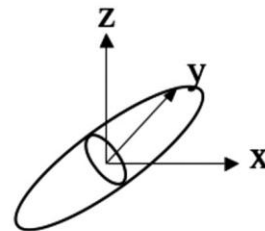
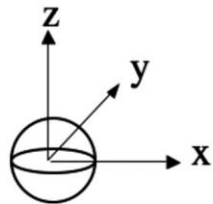
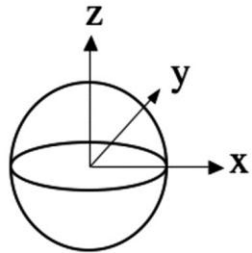
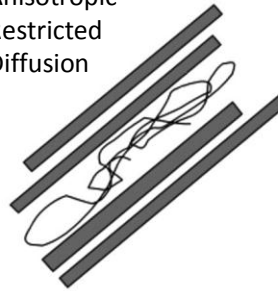
Free Water



Isotropic Restricted Diffusion



Anisotropic Restricted Diffusion

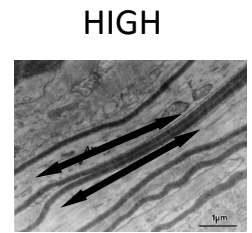
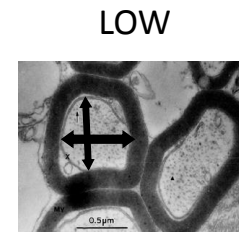


$$\begin{bmatrix} D & 0 & 0 \\ 0 & D & 0 \\ 0 & 0 & D \end{bmatrix}$$

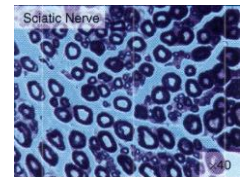
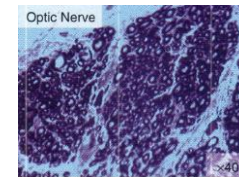
$$\begin{bmatrix} D_{eff} & 0 & 0 \\ 0 & D_{eff} & 0 \\ 0 & 0 & D_{eff} \end{bmatrix}$$

$$\begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$$

FA



MD



Layout

Diffusion Tensor Imaging on spinal cord

A first study for prove of concept

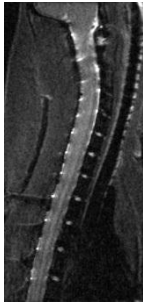
A second study to evaluate the efficiency of drugs

MRI Set-up for spinal cord imaging

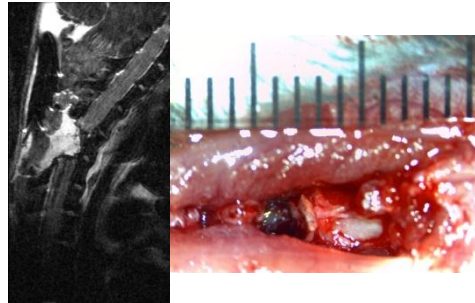
A first study for prove of concept

3 models of injury (9 rats, Long Evans) :

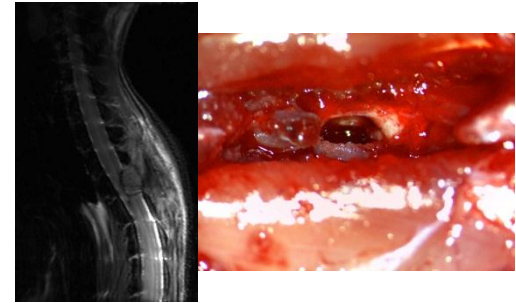
Control



total section



hemisection



MRI acquisition:

Multi-Shot Echo Planar Imaging

4-channel surface coil

3 shots

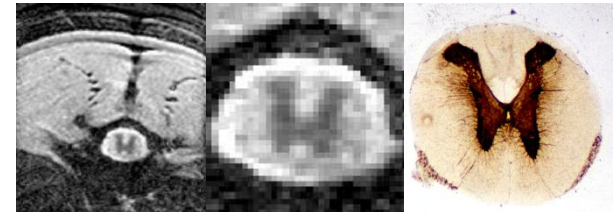
b-value: 670 s/mm^2

$\delta = 3 \text{ ms}, \Delta = 10 \text{ ms}$

TE: 17-20 ms

TR: 250 ms

Trigger per Slice



FOV: $12 \times 15 \text{ mm}^2$

Voxel: $0.11 \times 0.11 \times 1 \text{ mm}^3$

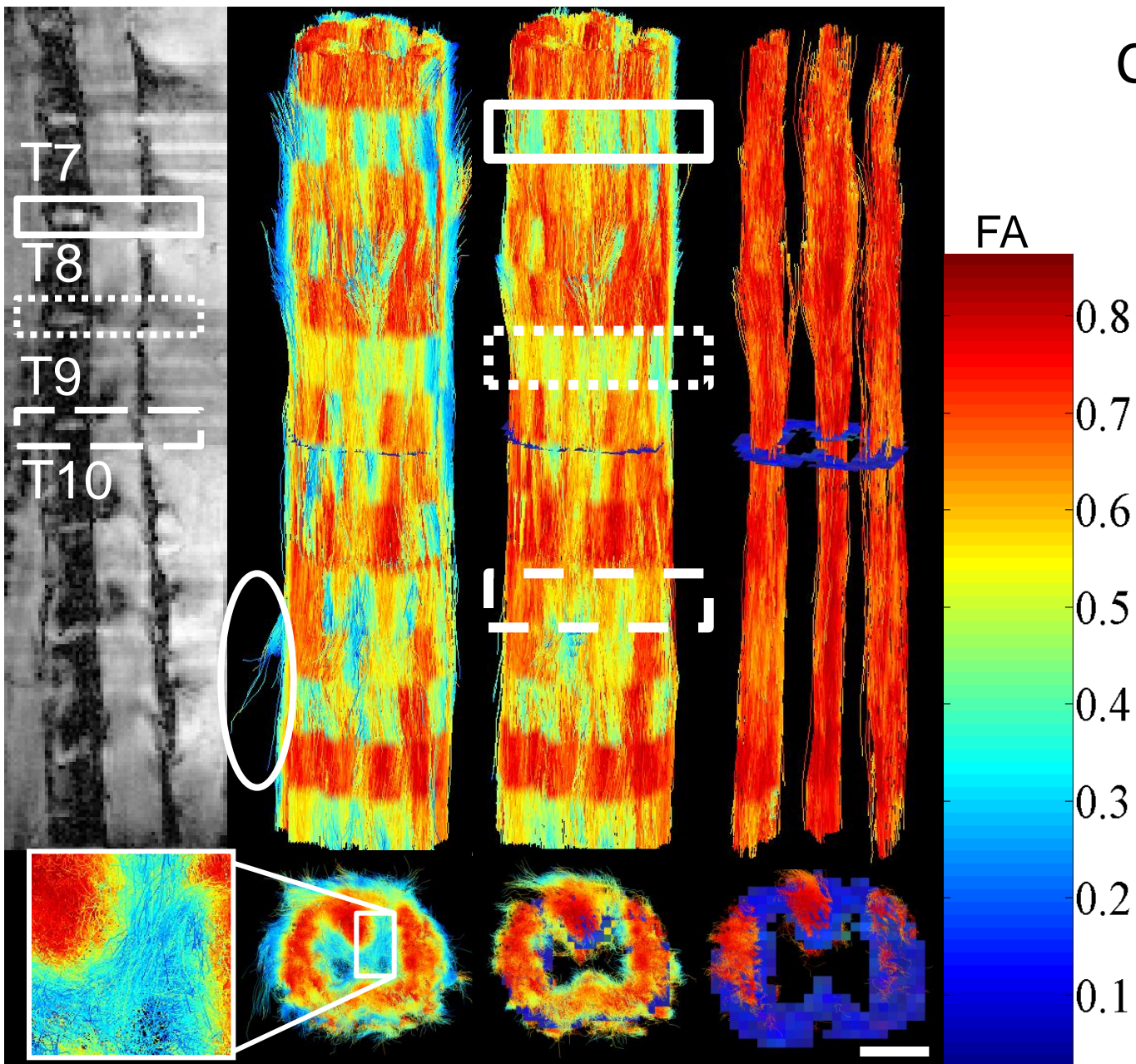
FA treshold

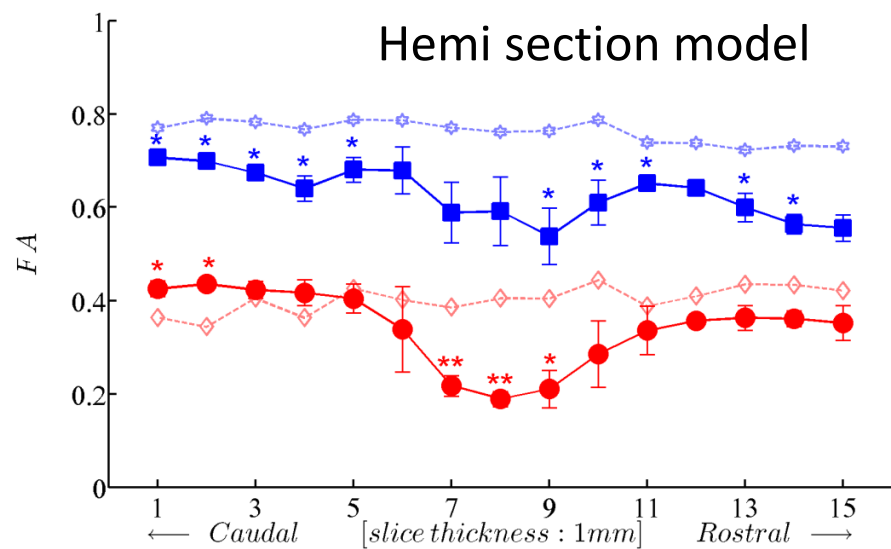
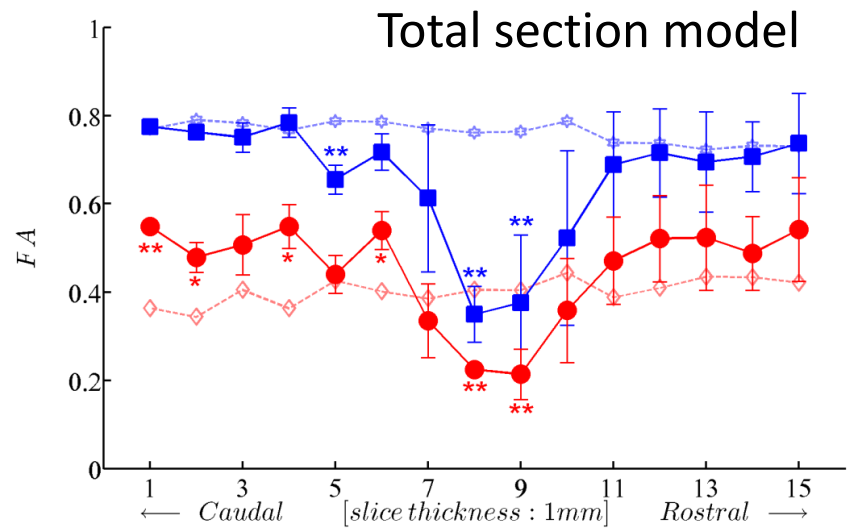
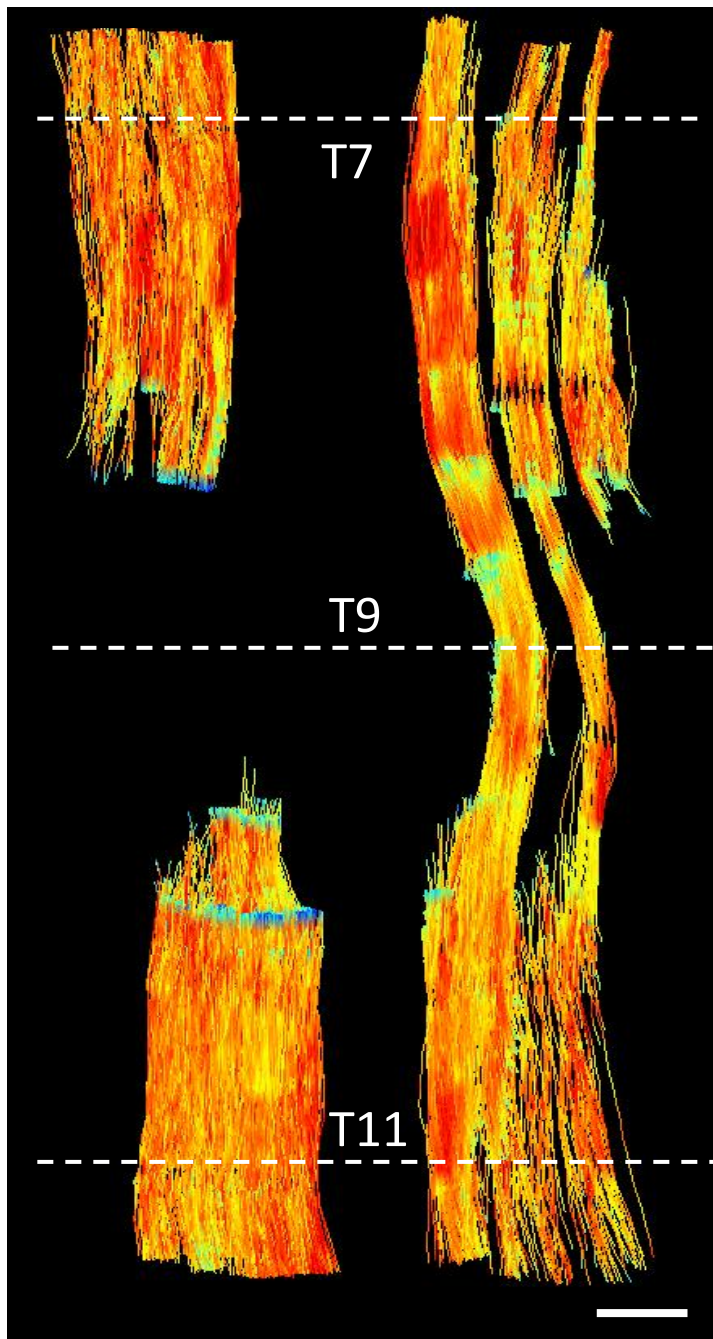
0.2

0.4

0.7

Control Model





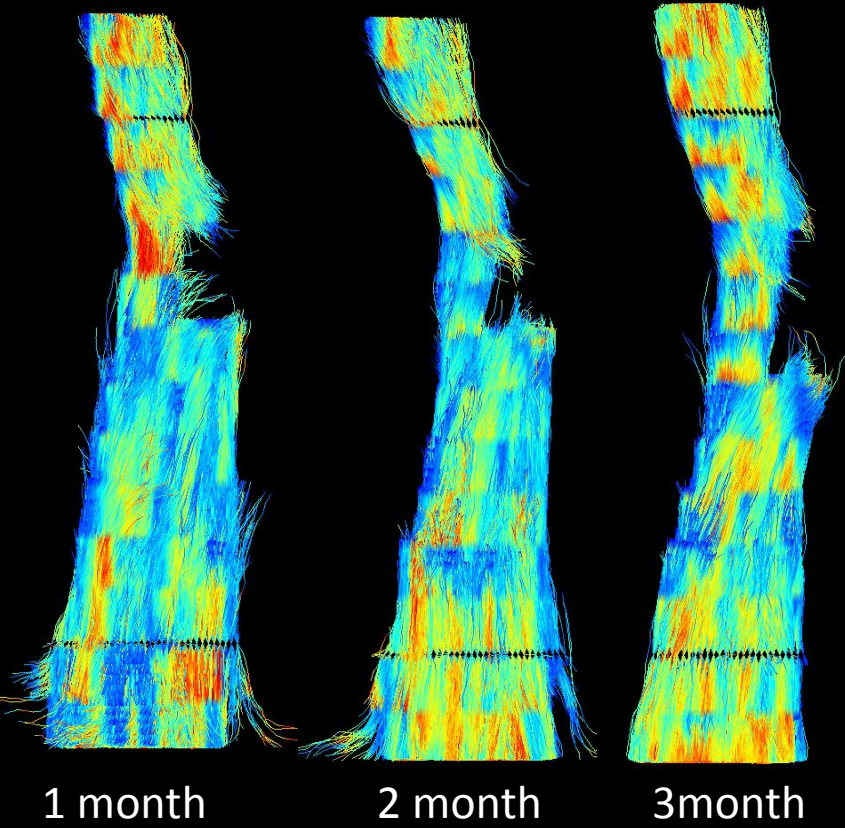
Layout

Diffusion Tensor Imaging on spinal cord

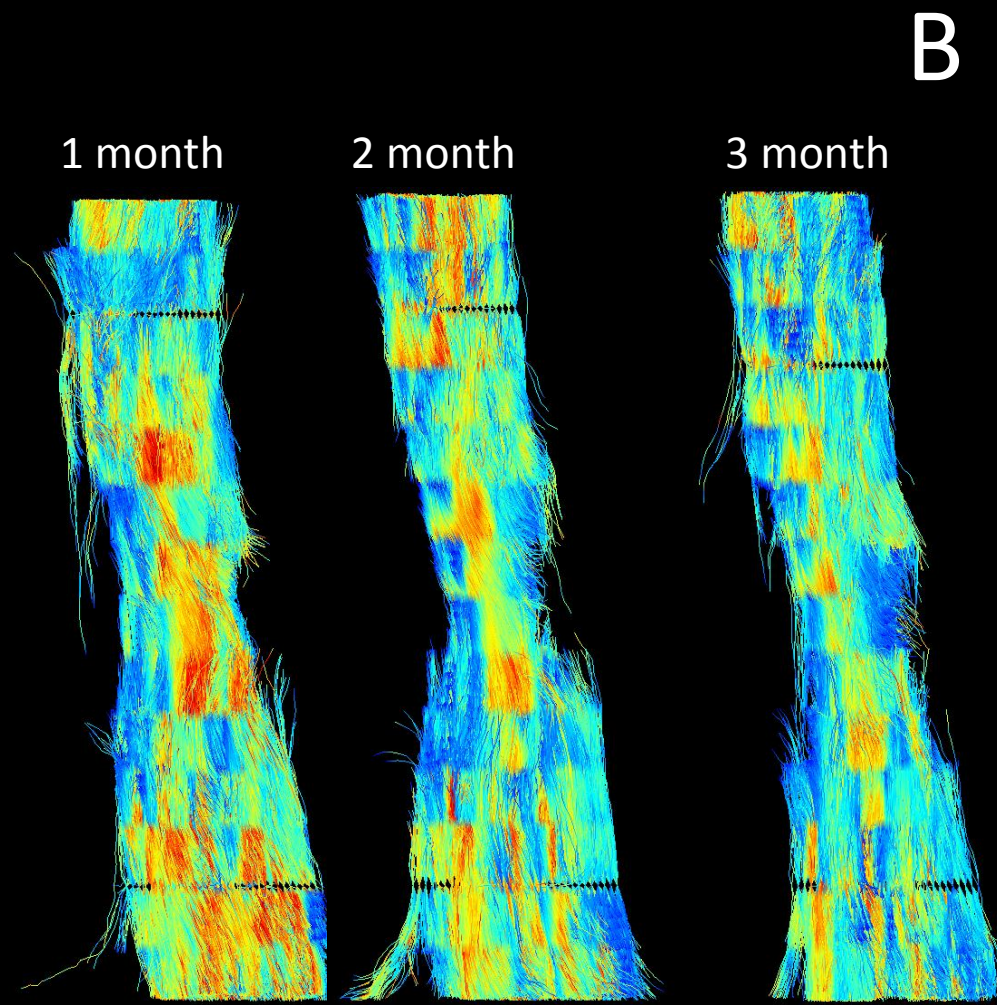
A first study for prove of concept

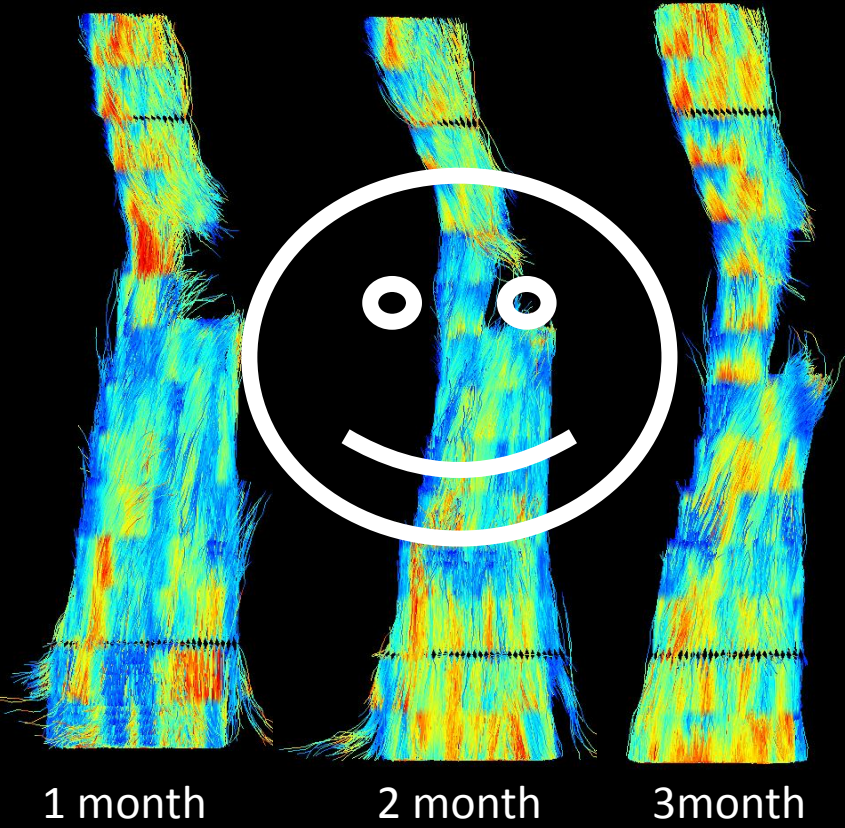
A second study to evaluate the efficiency of drugs

MRI Set-up for spinal cord imaging

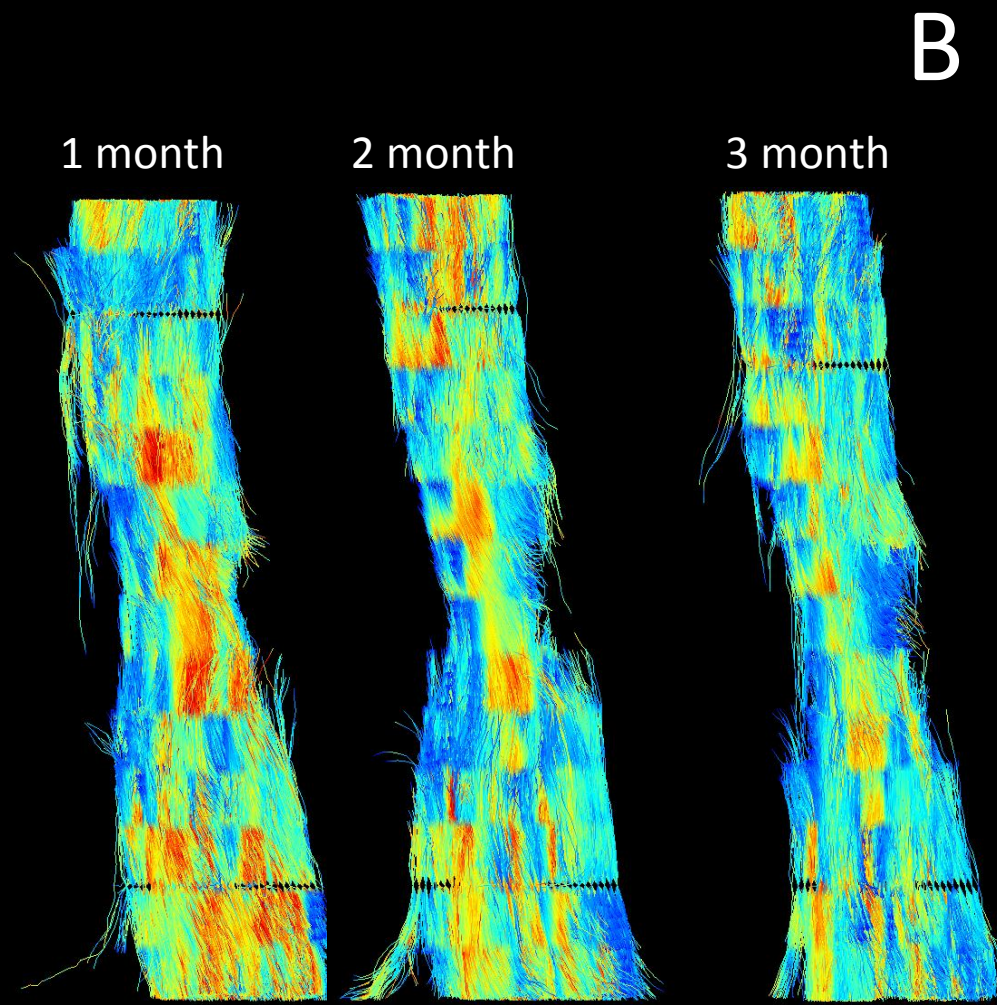


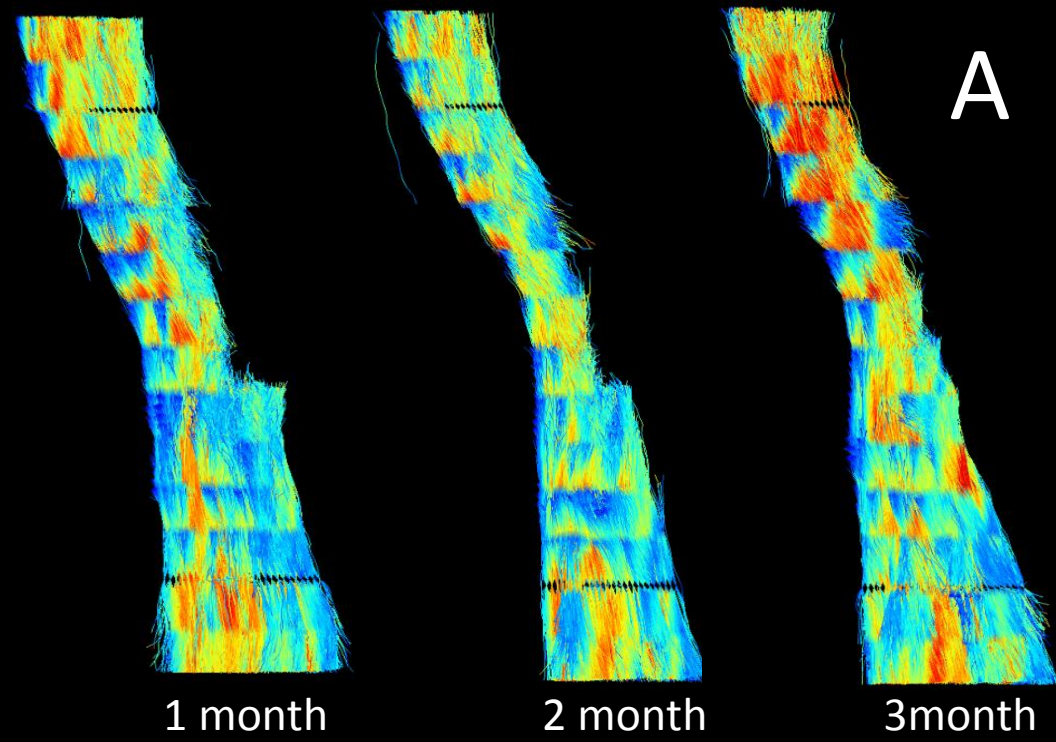
Which rat has received the drug?



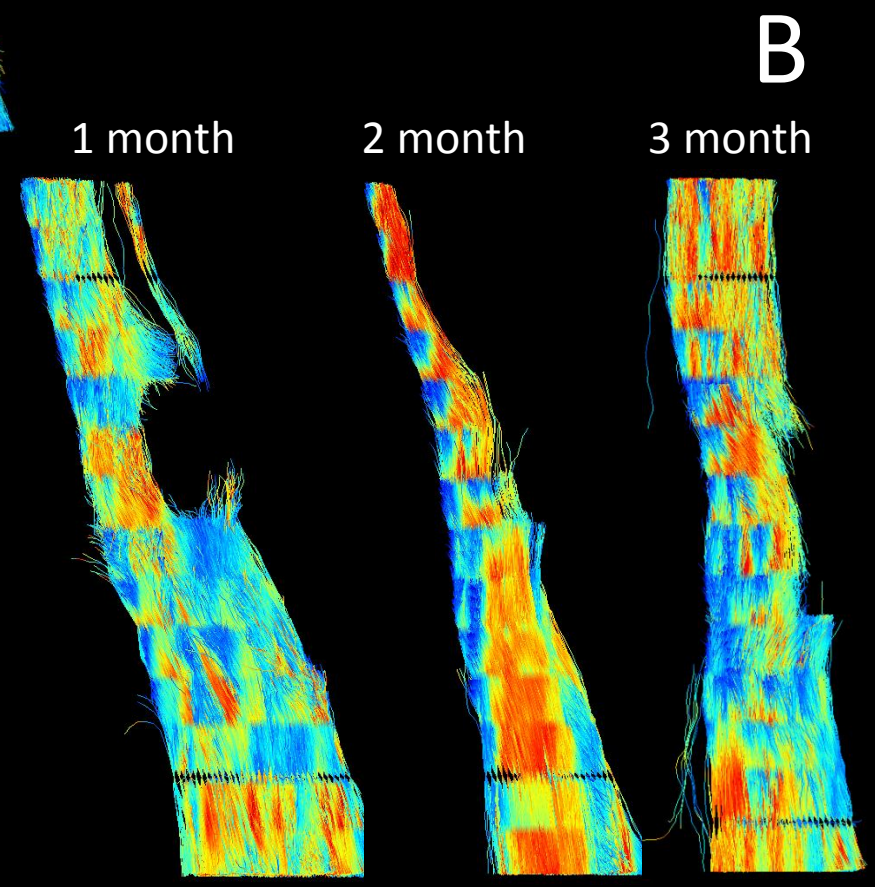


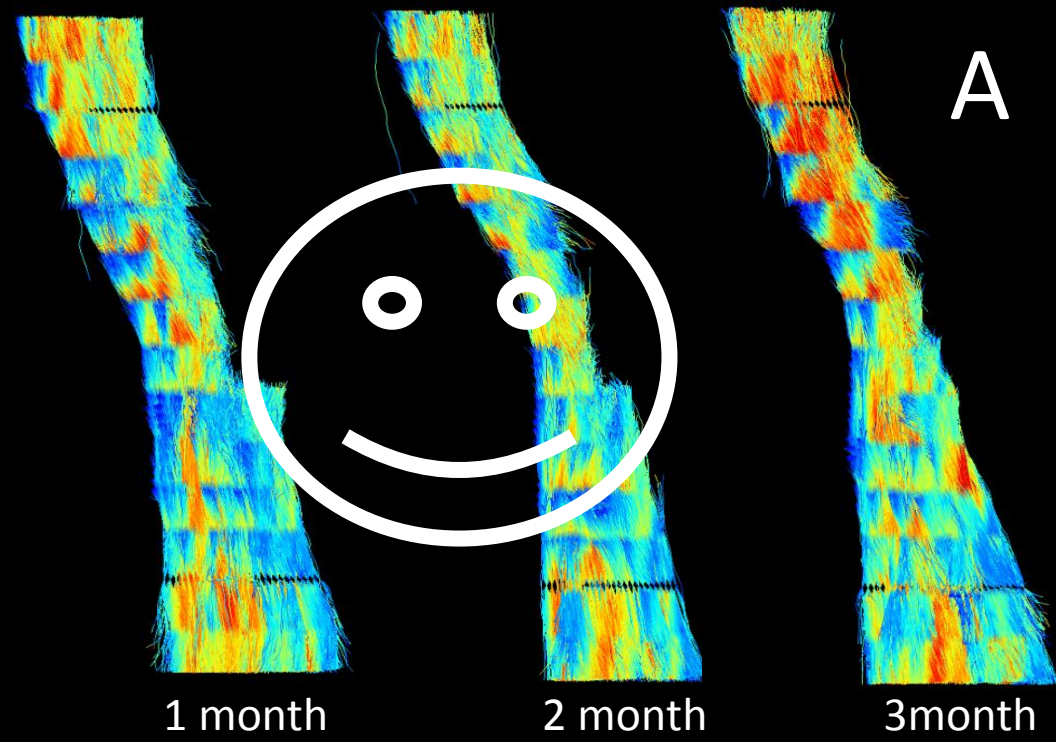
Which rat has received the drug?



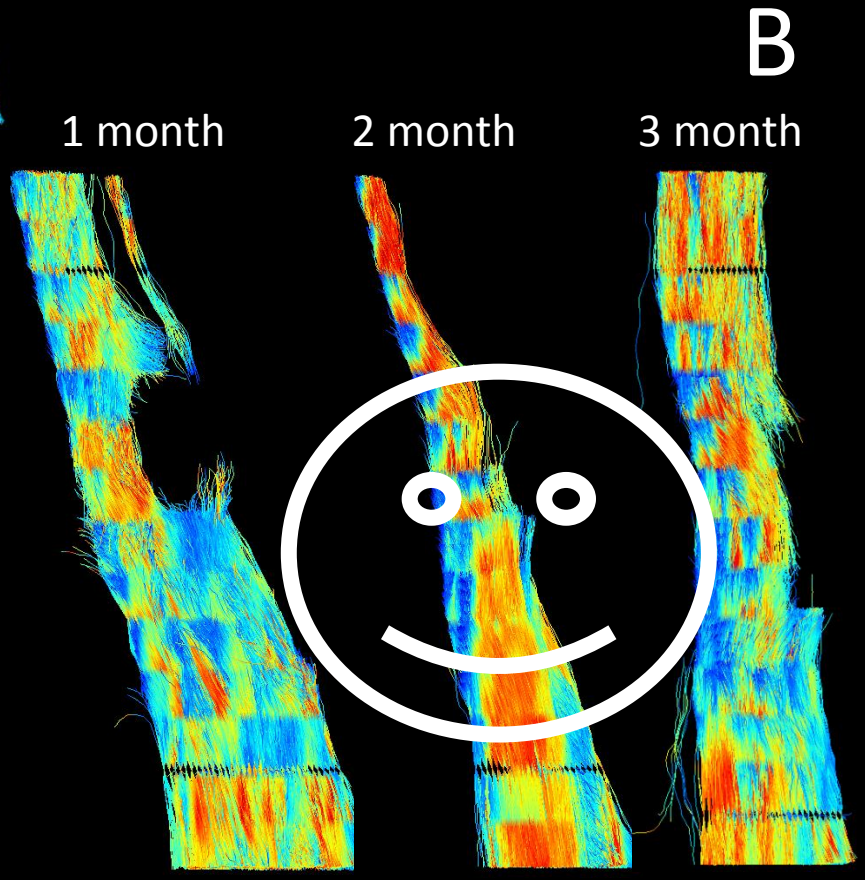


Which rat has received the drug?

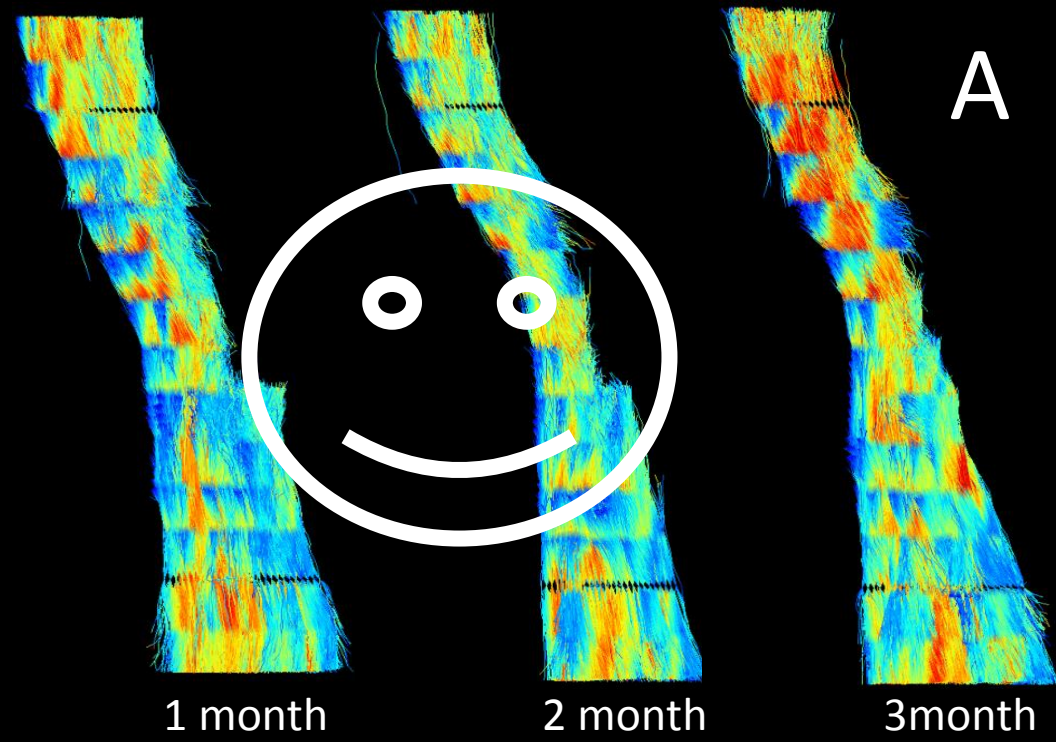




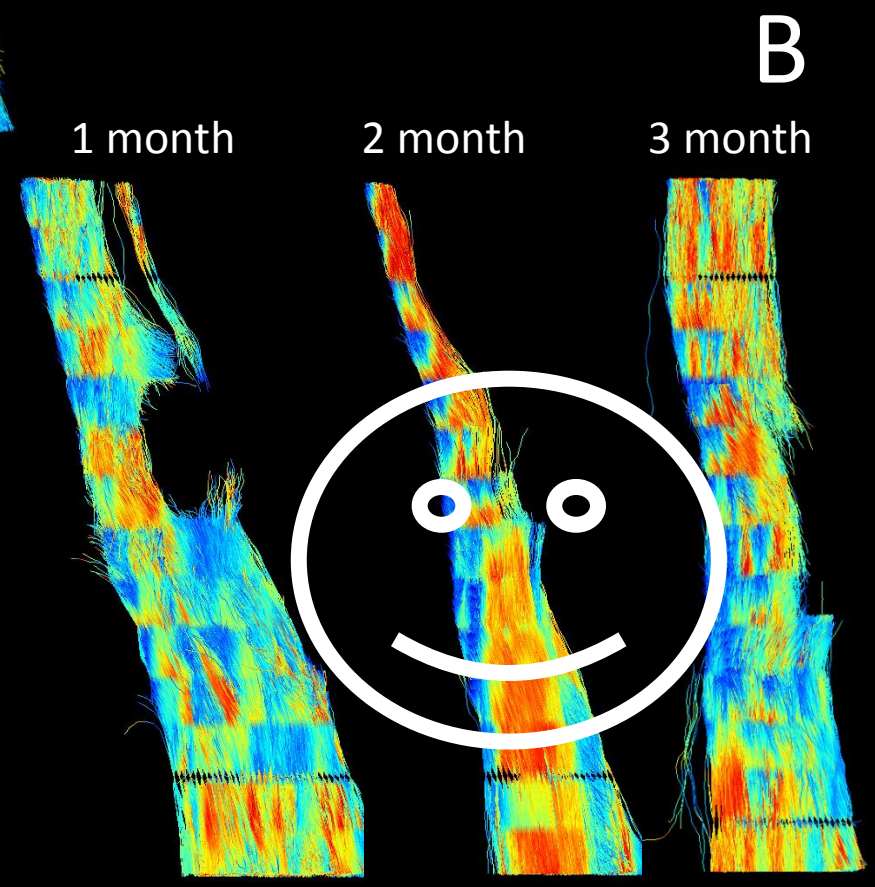
Which rat has received the drug?



Why this variability?



Which rat has received the drug?



Why this variability?



- Surgery

Layout

Diffusion Tensor Imaging on spinal cord

A first study for prove of concept

A second study to evaluate the efficiency of drugs

MRI Set-up for spinal cord imaging

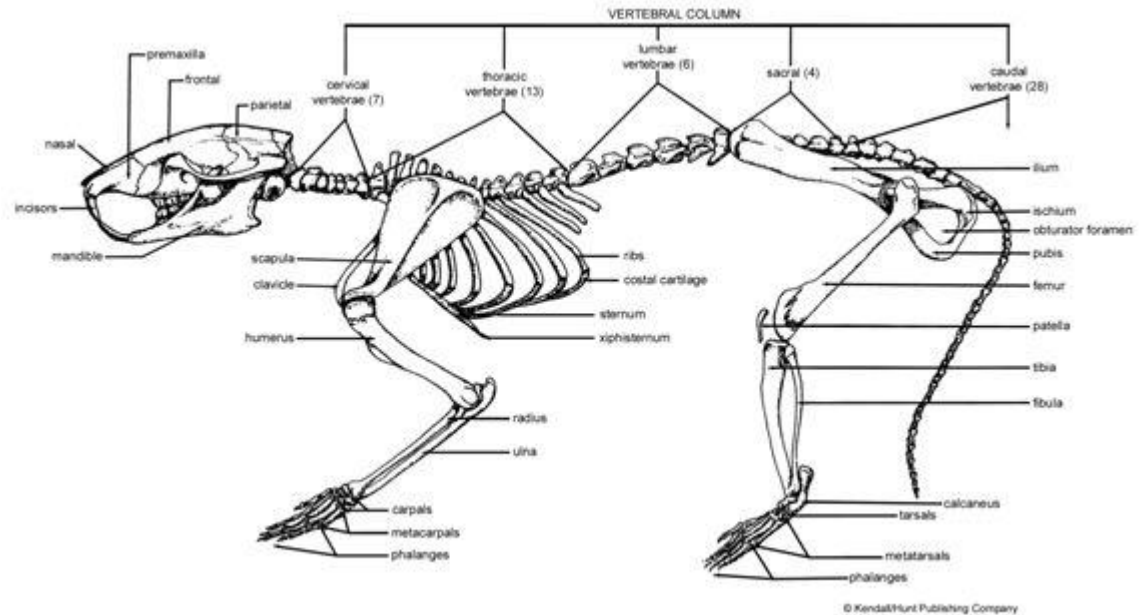
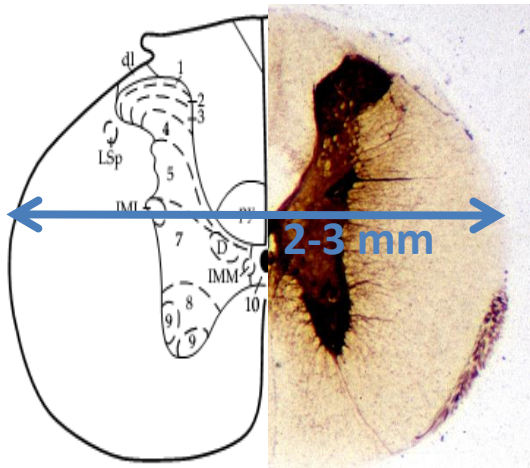
MRI Set-up for spinal cord imaging

Physiological et anatomical environment

volume (3mm)

bone/water/fat

Respiration/Support



MRI Set-up for spinal cord imaging

volume (3mm)



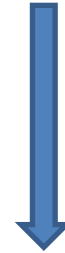
high SNR

bone/water/fat



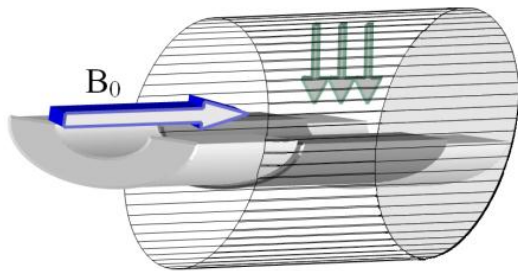
short TE and $B_0 \sim \text{cst}$

Respiration/Support



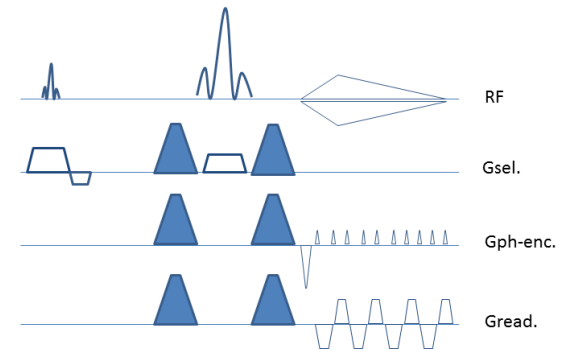
$TR < T \text{ respiration}$

Set-up



Multi-shot sequence

Bandwidth



Anesthesia

MRI Set-up for spinal cord imaging

volume (3mm)



high SNR

bone/water/fat



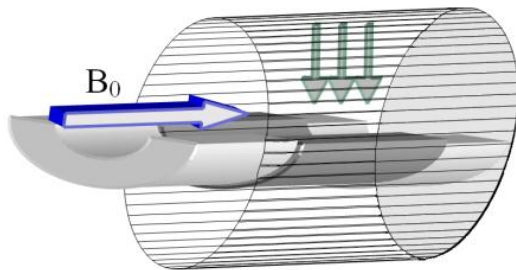
short TE and $B_0 \sim \text{cst}$

Respiration/Support

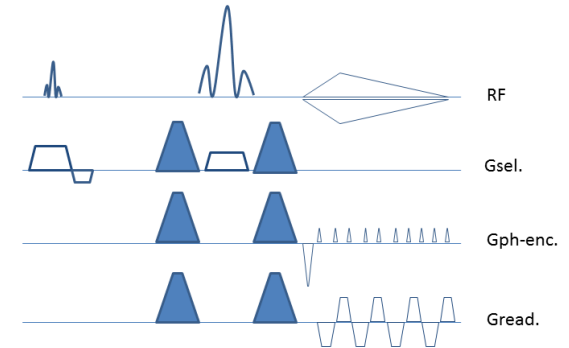


$TR < T \text{ respiration}$

Set-up



Multi-shot sequence

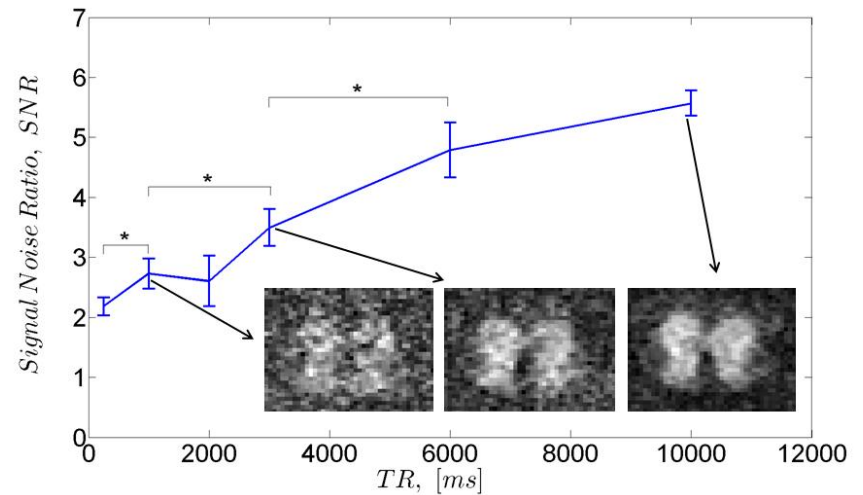
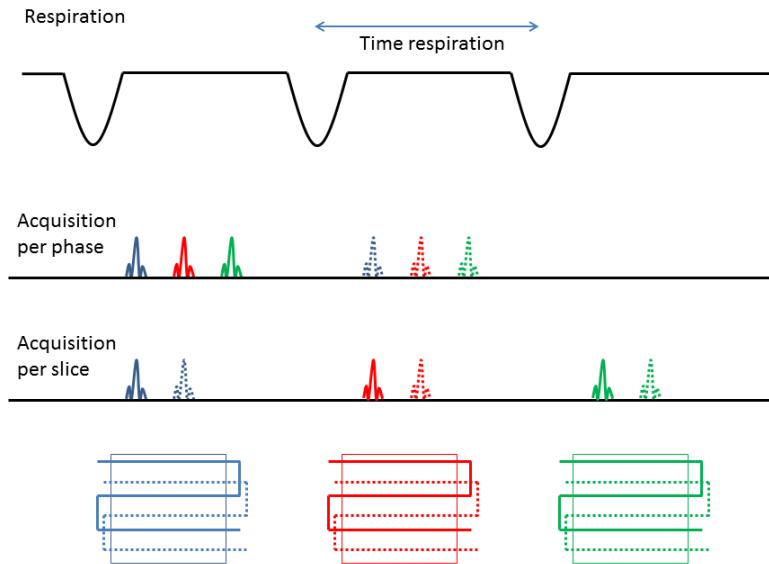


MRI Set-up for spinal cord imaging

Physiological et anatomical environment

1. $TR < T_{resp} \sim 1500$ ms

2. $TR_{perGradient} > 5 * T_1 \sim 10$ sec

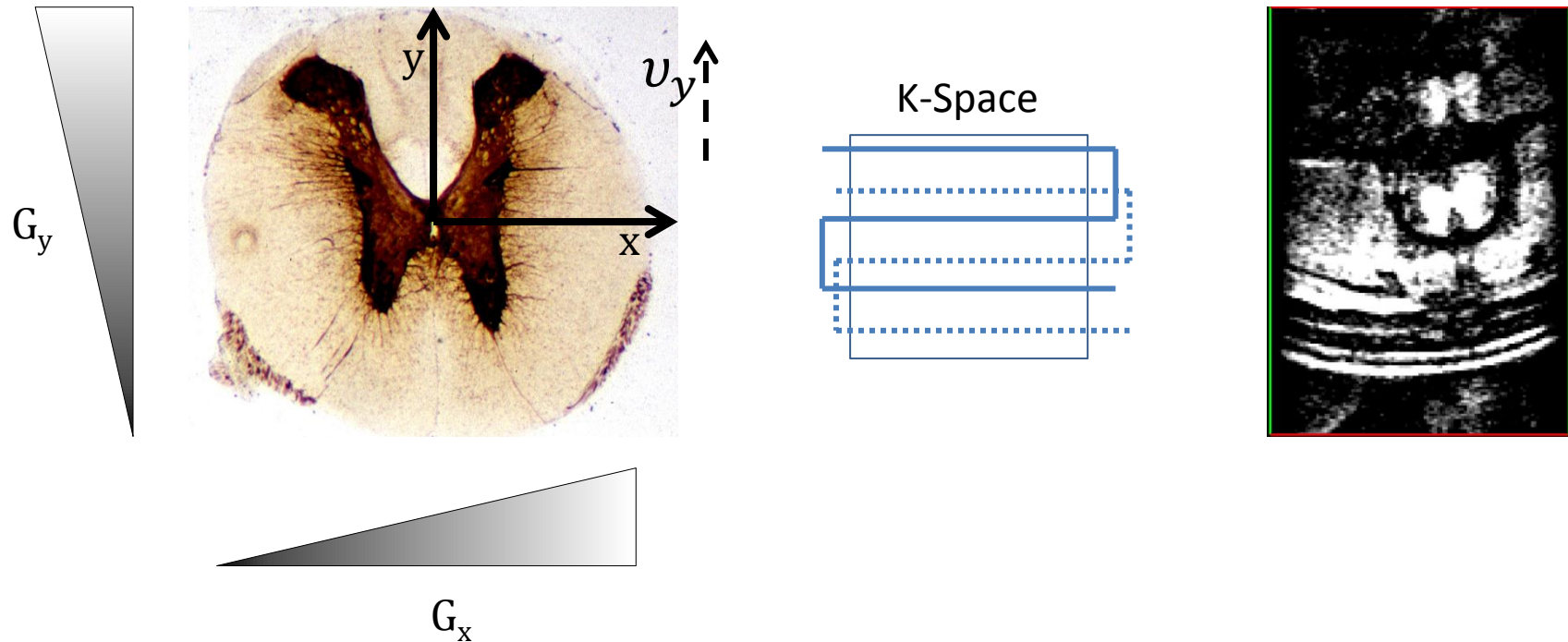


T_1 : ~ 1000 ms at 4.7 T

T_1 : ~ 2000 ms at 11.7 T

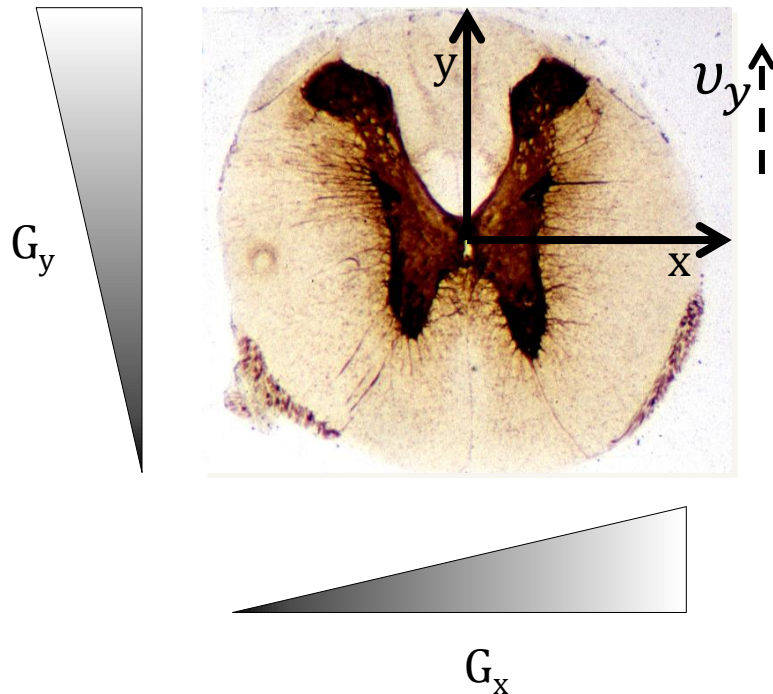
Phase errors in diffusion-weighted imaging

Linear phase error due to multi-shot acquisition



Phase errors in diffusion-weighted imaging

Linear phase error due to multi-shot acquisition



$$S(t) = \iint_{-\infty}^{+\infty} \rho(x, y) e^{-i(\phi(x, y, t))} dx dy$$

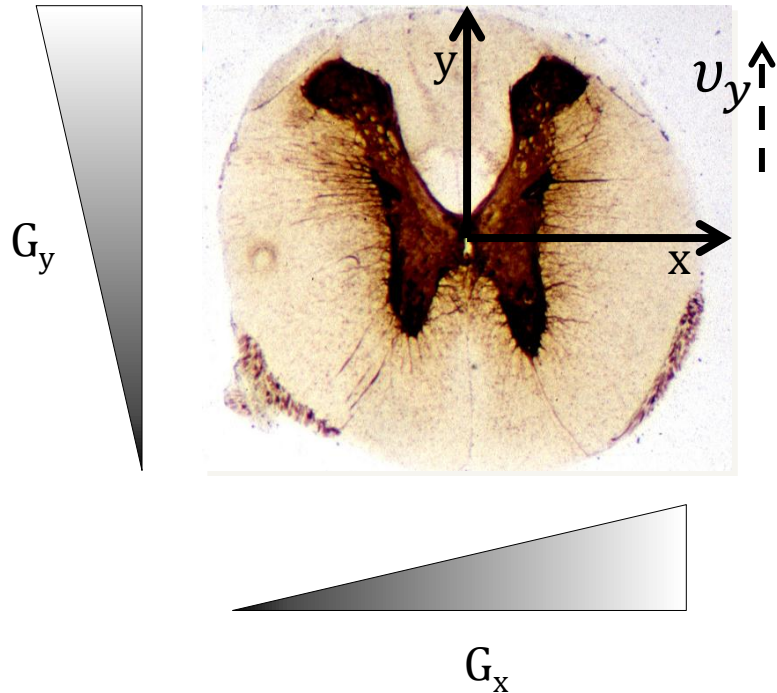
$$\Phi_{motion}(y, t) = \gamma \int_0^t G_y \left(y_0 + v_y \tau + \frac{1}{2} a_y \tau^2 \right) d\tau$$

$$k_y(t) = \gamma \int_0^t G_y d\tau = \gamma G_y t$$

$$\Phi_{motion}(y, t) = 2\pi k_y \left(y_0 + v_y \frac{t}{2} \right)$$

Phase errors in diffusion-weighted imaging

Linear phase error due to multi-shot acquisition



$$S(t) = \iint_{-\infty}^{+\infty} \rho(x, y) e^{-i(\phi(x, y, t))} dx dy$$

$$\Phi_{motion}(y, t) = 2\pi \gamma \int_0^t G_y \left(y_0 + v_y \tau + \frac{1}{2} a_y \tau^2 \right) d\tau$$

$$k_y(t) = \gamma \int_0^t G_y d\tau = \gamma G_y t$$

$$\Phi_{motion}(y, t) = 2\pi k_y \left(y_0 + v_y \frac{t}{2} \right)$$

Phase errors in diffusion-weighted imaging

Generalized Signal Equation for acquisition of κ k-space

$$S(t) = \iint_{-\infty}^{+\infty} \rho(x, y) e^{-i(\phi(x, y, t))} dx dy$$

$$m(t_i) = \sum_{u=1}^{N \times N} \rho(\mathbf{r}_u) \exp(-j\mathbf{k}(t_i) \cdot \mathbf{r}_u) \quad \text{with } i = 1 \dots k.$$

Diagram illustrating the decomposition of the signal equation into matrix form:

- The signal vector \mathbf{m} is defined as $[m(t_1) \ m(t_2) \ \dots \ m(t_k)]$.
- The density vector \mathbf{v} is defined as $[\rho(\mathbf{r}_1) \ \rho(\mathbf{r}_2) \ \dots \ \rho(\mathbf{r}_{N^2})]$.
- The encoding matrix \mathbf{E} is defined as $\begin{pmatrix} e^{-j\mathbf{k}_1 \mathbf{r}_1} & \dots & e^{-j\mathbf{k}_1 \mathbf{r}_{N^2}} \\ \vdots & \ddots & \vdots \\ e^{-j\mathbf{k}_\kappa \mathbf{r}_1} & \dots & e^{-j\mathbf{k}_\kappa \mathbf{r}_{N^2}} \end{pmatrix}$.

Phase errors in diffusion-weighted imaging

Generalized Signal Equation for acquisition of κ k-space

$$S(t) = \iint_{-\infty}^{+\infty} \rho(x, y) e^{-i(\phi(x, y, t))} dx dy$$

$$m(t_i) = \sum_{u=1}^{N \times N} \rho(\mathbf{r}_u) \exp(-j\mathbf{k}(t_i) \cdot \mathbf{r}_u) \quad \text{with } i = 1 \dots k.$$

Diagram illustrating the mapping of the signal equation to matrix notation:

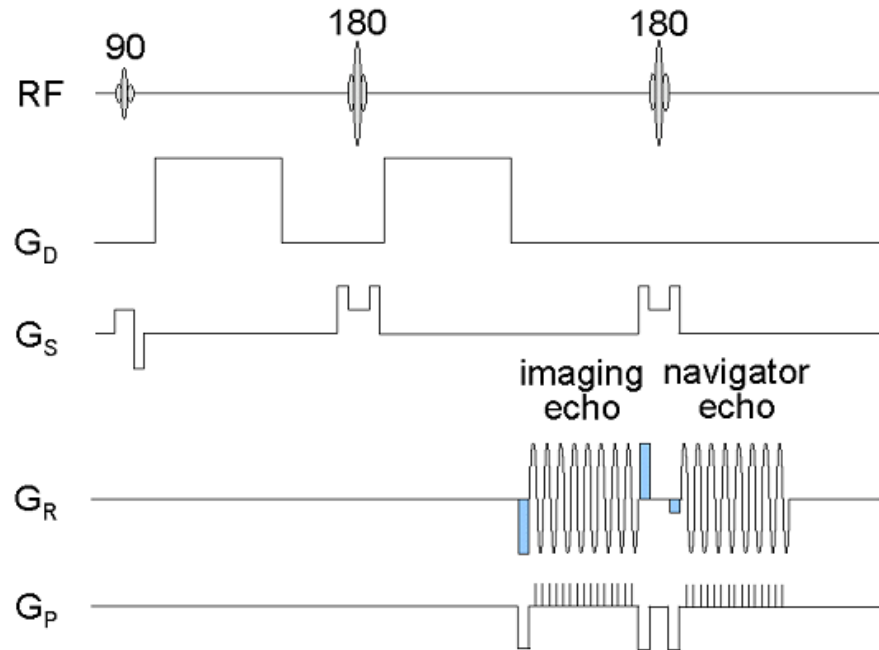
- The signal vector \mathbf{m} is represented as $[m(t_1) \ m(t_2) \ \dots \ m(t_k)]$.
- The density vector \mathbf{v} is represented as $[\rho(\mathbf{r}_1) \ \rho(\mathbf{r}_2) \ \dots \ \rho(\mathbf{r}_{N^2})]$.
- The phase matrix \mathbf{E} is represented as a matrix with elements $e^{-j\mathbf{k}_i \cdot \mathbf{r}_u}$.

The vectors \mathbf{m} , \mathbf{v} , and the matrix \mathbf{E} are circled in red, indicating they are the focus of the diagram.

Solving phase errors requires a navigator

To determine this term \mathbf{E}

$$\begin{pmatrix} e^{-j \mathbf{k}_1 \mathbf{r}_1} & \dots & e^{-j \mathbf{k}_1 \mathbf{r}_{N^2}} \\ \vdots & \ddots & \vdots \\ e^{-j \mathbf{k}_K \mathbf{r}_1} & \dots & e^{-j \mathbf{k}_K \mathbf{r}_{N^2}} \end{pmatrix}$$

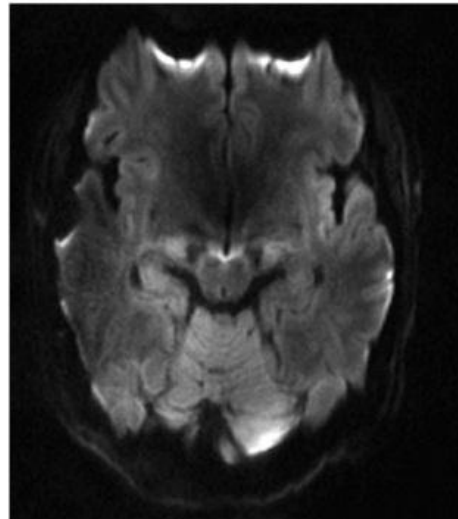


Phase error correction is an inverse problem

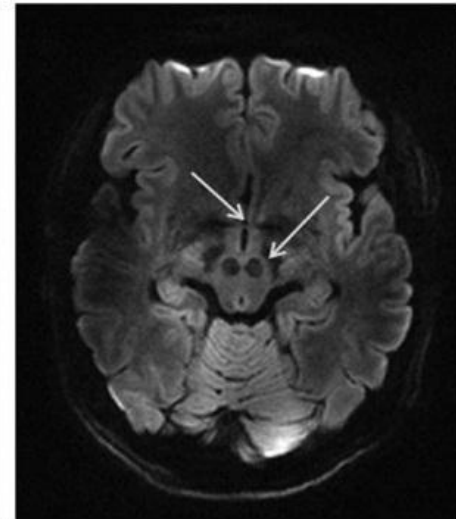
$$[m(t_1) \ m(t_2) \ \dots \ m(t_k)]^T = \begin{pmatrix} e^{-j \mathbf{k}_1 \mathbf{r}_1} & \dots & e^{-j \mathbf{k}_1 \mathbf{r}_{N^2}} \\ \vdots & \ddots & \vdots \\ e^{-j \mathbf{k}_k \mathbf{r}_1} & \dots & e^{-j \mathbf{k}_k \mathbf{r}_{N^2}} \end{pmatrix} [\rho(\mathbf{r}_1) \ \rho(\mathbf{r}_2) \ \dots \ \rho(\mathbf{r}_{N^2})]^T$$

$$\mathbf{M} = \mathbf{E}\mathbf{V}$$

Without correction



With correction



Study of Heidemann *et al.* at 7 T

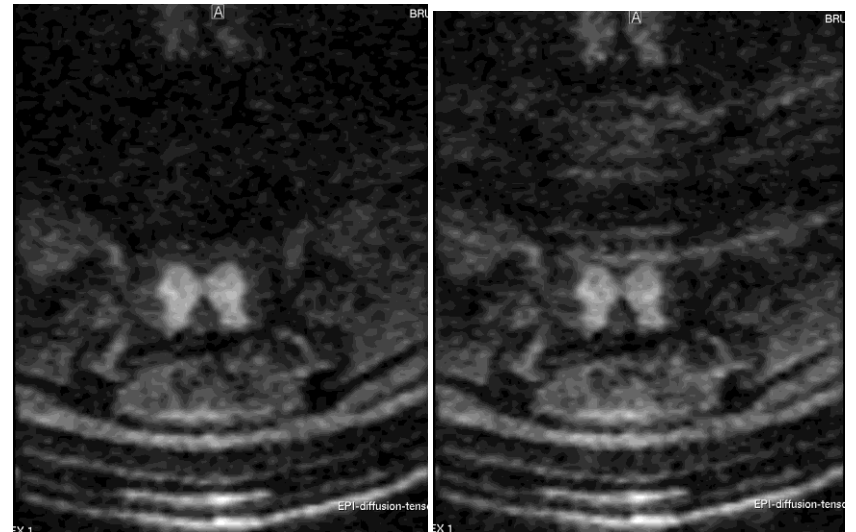
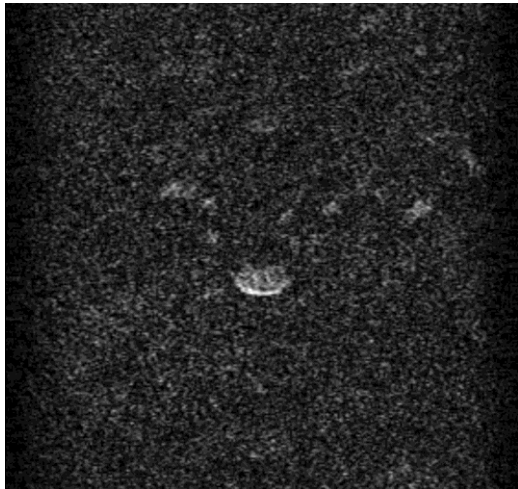
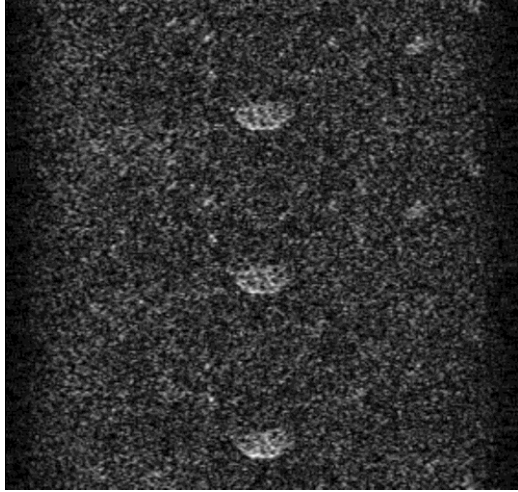
Study on the navigator implemented by Bruker

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RecoUserUpdate	<input type="text" value="Yes"/>	No_Nav_Data Auto_Nav_Mode Manual_Nav_Mode Derive_Nav_Mode Mixed_Nav_Mode
RECO: input reordering	<input type="text" value="NO_REORDERING"/>	
RECO: Number of input channels	<input type="text" value="4"/>	
RECO: reconstruction size	<input type="text" value="0-1"/> < 2 <input type="text" value="128"/> <input type="text" value="128"/>	
RECO: field of view	<input type="text" value="0-1"/> < 2 <input type="text" value="1.5100 cm"/> <input type="text" value="1.5100 cm"/>	NeNoInterleave NeInterleavePerPeStep NeInterleavePerImagePeStep NeInterleavePerScan
RECO: output size	<input type="text" value="0-1"/> < 2 <input type="text" value="128"/> <input type="text" value="128"/>	
RECO: regrid mode	<input type="text" value="NO_REGRID"/>	
RECO: navigation mode	<input type="text" value="AUTO_NAV_MODE"/>	NeCorrPerExp NeCorrPerImage NeCorrPerPeStep NeCorrNiPerPeStep NeCorrPhasFacPerPeStep NeCorrPerScan
RECO: nav. interleaving	<input type="text" value="NeNoInterleave"/>	
RECO: nav. echo density	<input type="text" value="NeCorrPerScan"/>	
RECO: navigation type	<input type="text" value="NAV_PHASE"/>	Nav_Phase Nav_Phase_Diff Nav_Hi_Phase_Diff
RECO: BC mode	<input type="text" value="0-1"/> < 2 <input type="text" value="AUTO_OFFSET_BC"/> <input type="text" value="NO_BC"/>	
RECO: BC start	<input type="text" value="0-1"/> < 2	



It's like a big black box

Do you observe the effect of navigator ?



Acknowledgments

Labo REMA
Labo FARG

UCL St-Luc
Frank Peeters
Prof. Cosnard
Technologues

EPL
Laurent Jacques
Jonathan Orban
Guillaume Janssens
Guillaume Bernard
Maxime Taquet

UCL CHU Mont-Godinne
Dr. Jankovski
Béatrice De Coene

LabVision Antwerp
Ben Jeurissen
Johan Van Audekerke

Atelier
Louis Pirsoul

Comment mesurer D avec l'IRM?

L'aimantation du voxel est influencée par la diffusion:

$$\frac{\partial \mathbf{M}}{\partial t} = D \nabla^2 \mathbf{M}$$

Ajout d'un terme dans l'équation de Bloch:

$$\frac{\partial \mathbf{M}}{\partial t} = \gamma \mathbf{M} \times \mathbf{B} - \frac{M_z - M_0}{T_1} \mathbf{u}_z \frac{M_x \mathbf{u}_x + M_y \mathbf{u}_y}{T_2} - D \nabla^2 \mathbf{M}$$

Quelle atténuation à l'amplitude de l'écho sera mesurée?

Quelle atténuation à l'amplitude de l'écho sera mesurée?

$$\frac{S(g)}{S(0)} = e^{-\gamma^2 g^2 \delta^2 (\Delta - \delta/3)}$$



Signal sans pondération de gradient

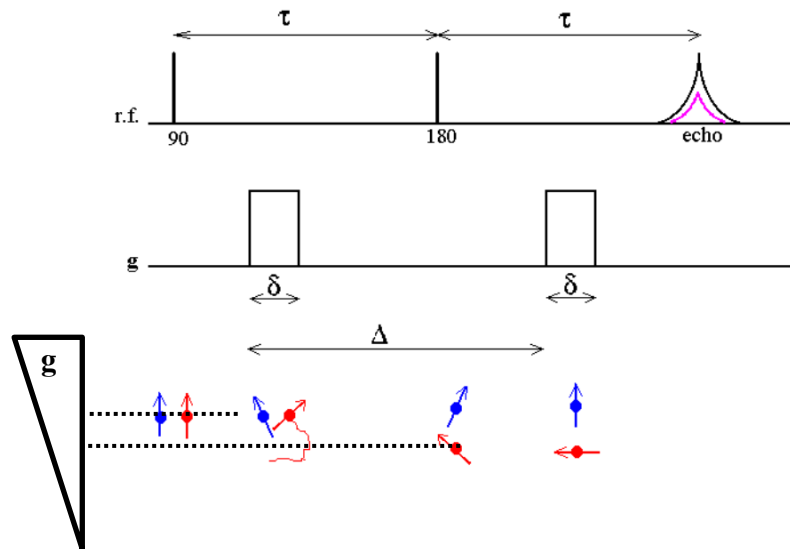
$$\frac{S(b)}{S(0)} = e^{-bD}$$

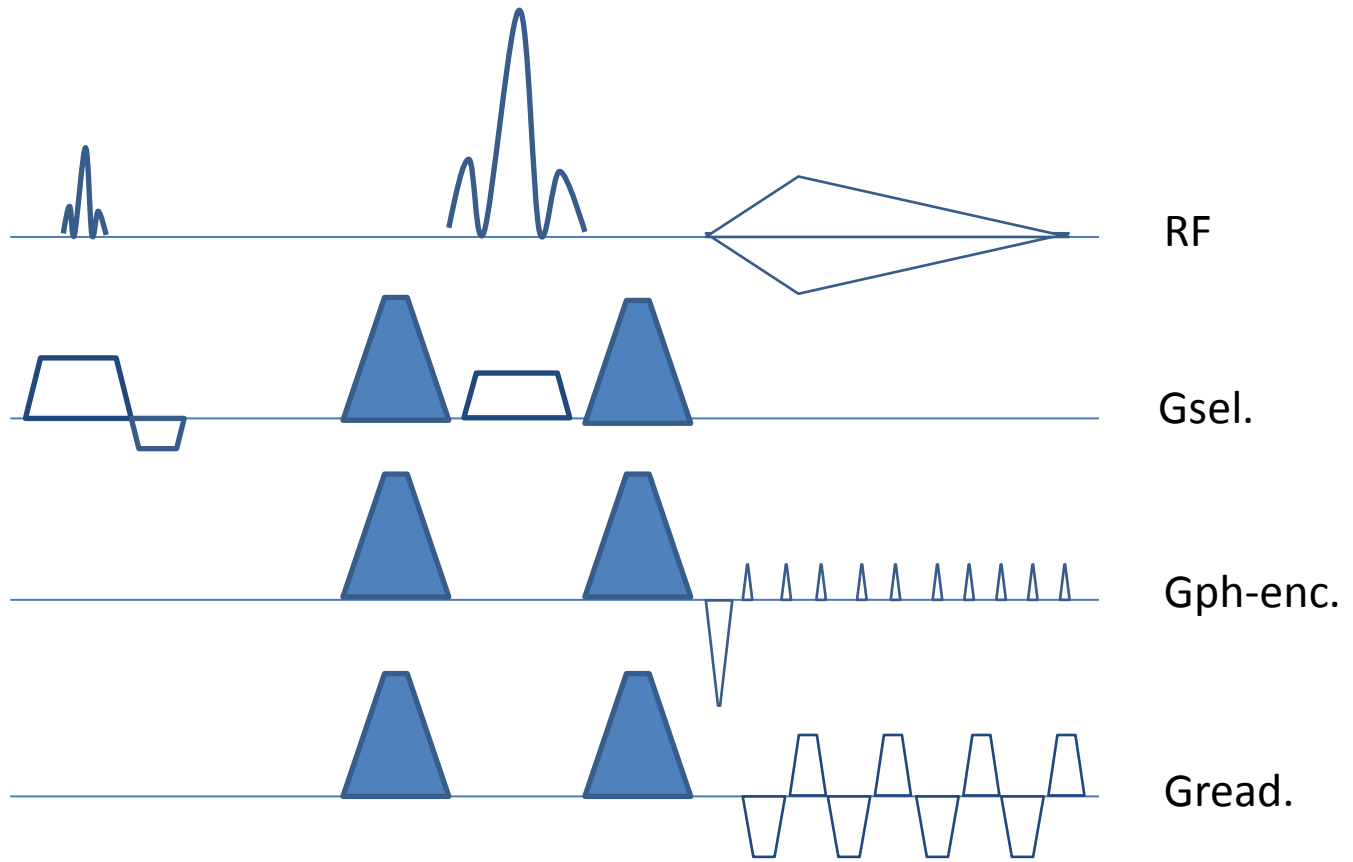
b-value qui dépend de g

Pulsed Gradient Spin Echo (PGSE):

$$\omega(\mathbf{r}) = \gamma B_0 + \gamma \mathbf{g} \cdot \mathbf{r}$$

-  Spin fixe
-  Spin mobile





$$m(t_i) = \sum_{u=1}^{N^2} \rho(\mathbf{r}_u) \exp(-j\mathbf{k}(t_i) \cdot \mathbf{r}_u).$$

$$\begin{pmatrix} m(t_1) \\ m(t_2) \\ \vdots \\ m(t_K) \end{pmatrix} = \begin{pmatrix} e^{-j\mathbf{k}_1 \cdot \mathbf{r}_1} & e^{-j\mathbf{k}_1 \cdot \mathbf{r}_2} & \dots & e^{-j\mathbf{k}_1 \cdot \mathbf{r}_{N^2}} \\ e^{-j\mathbf{k}_2 \cdot \mathbf{r}_1} & e^{-j\mathbf{k}_2 \cdot \mathbf{r}_2} & \dots & e^{-j\mathbf{k}_2 \cdot \mathbf{r}_{N^2}} \\ \vdots & \vdots & \ddots & \vdots \\ e^{-j\mathbf{k}_K \cdot \mathbf{r}_1} & e^{-j\mathbf{k}_K \cdot \mathbf{r}_2} & \dots & e^{-j\mathbf{k}_K \cdot \mathbf{r}_{N^2}} \end{pmatrix} \cdot \begin{pmatrix} \rho(\mathbf{r}_1) \\ \rho(\mathbf{r}_2) \\ \vdots \\ \rho(\mathbf{r}_{N^2}) \\ ? \end{pmatrix}$$

$\mathbf{m} = \mathbf{E}\mathbf{v},$

$$\mathbf{E}^+ \mathbf{m} = \mathbf{v} = (\mathbf{E}^H \mathbf{E})^{-1} \mathbf{E}^H \mathbf{m}. \quad \longrightarrow \quad \text{Moore-Penrose inverse of E}$$

$$\mathbf{v} = \underset{\mathbf{v}'}{\operatorname{argmin}} \|(\mathbf{E}^H \mathbf{E})\mathbf{v}' - \mathbf{E}^H \mathbf{m}\|_2^2, \quad \longrightarrow \quad \text{Least square method}$$