UCL Université catholique de Louvain

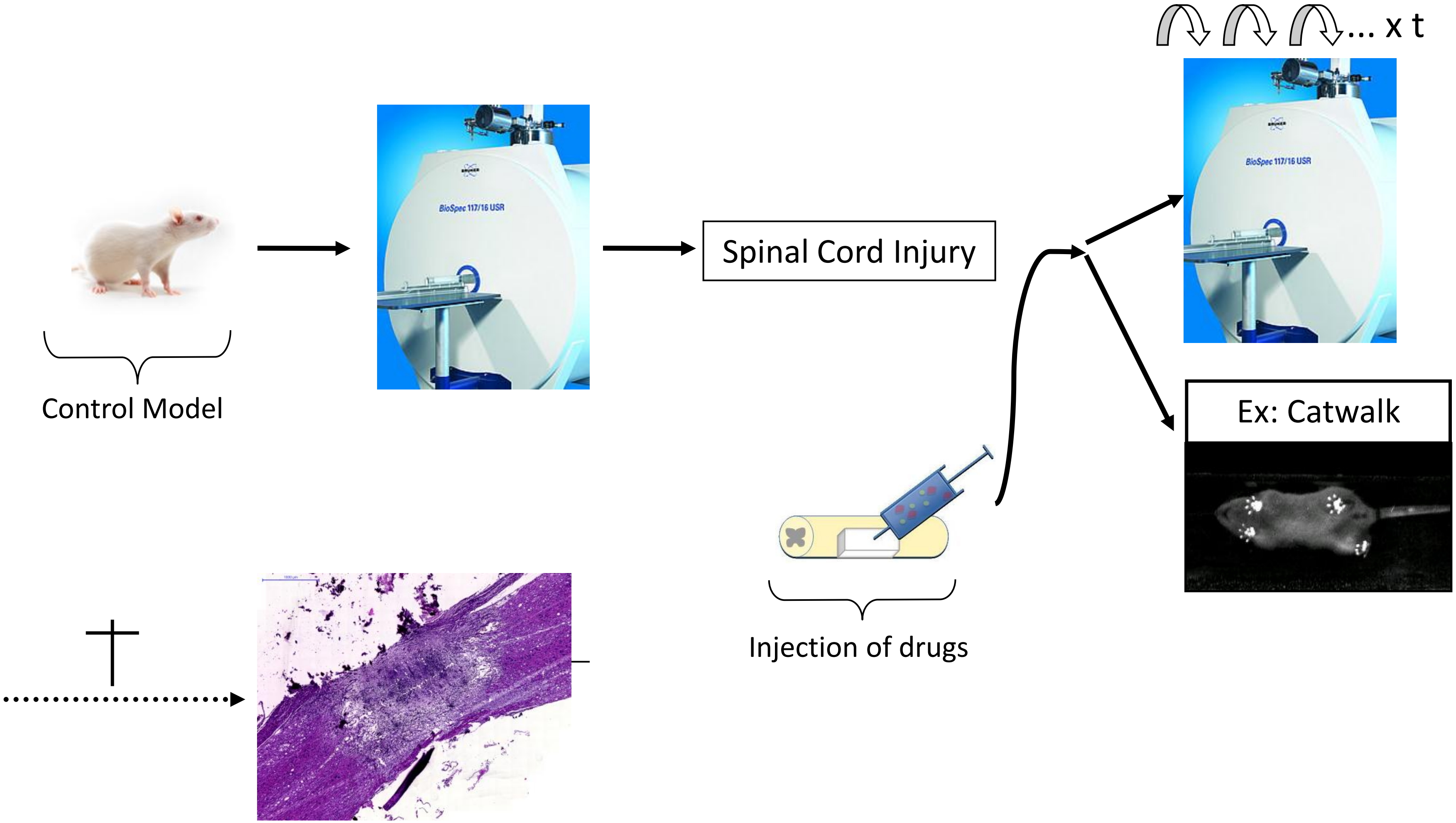
Signal Processing Seminar

Diffusion Tensor Imaging applied to spinal repair assay: a challenge

Promotor: Benoît Macq

Co-promotors: Bernard Gallez, Véronique Préat

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



A. des Rieux, (UCL,2010)

Layout

Diffusion Tensor Imaging on spinal cord

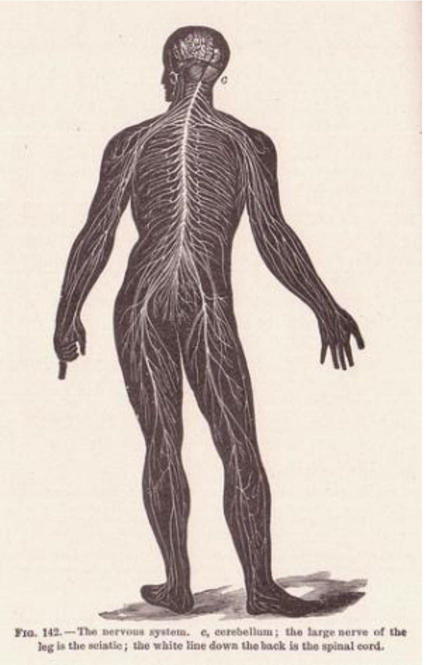
A first study for prove of concept

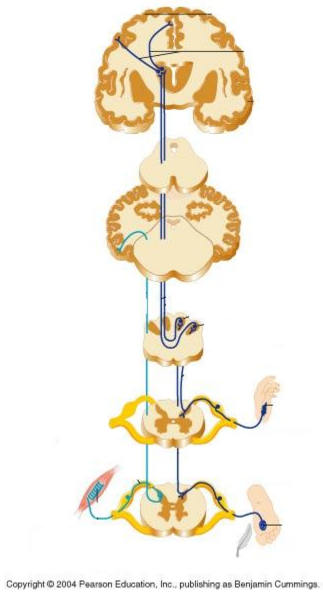
A second study to evaluate the efficiency of drugs

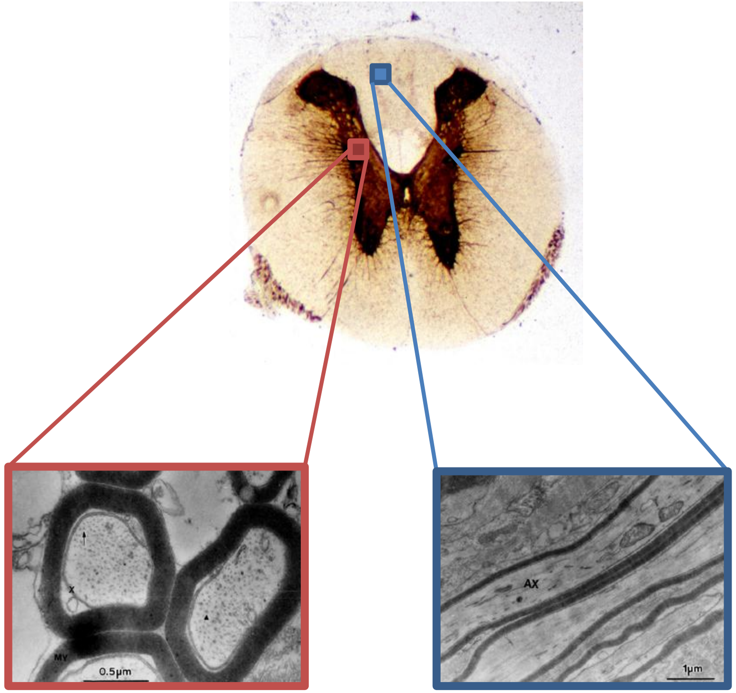
MRI Set-up for spinal cord imaging

Diffusion Tensor Imaging on spinal cord

Purpose: Image the nerve growth in the spinal cord







Diffusion Tensor Imaging on spinal cord

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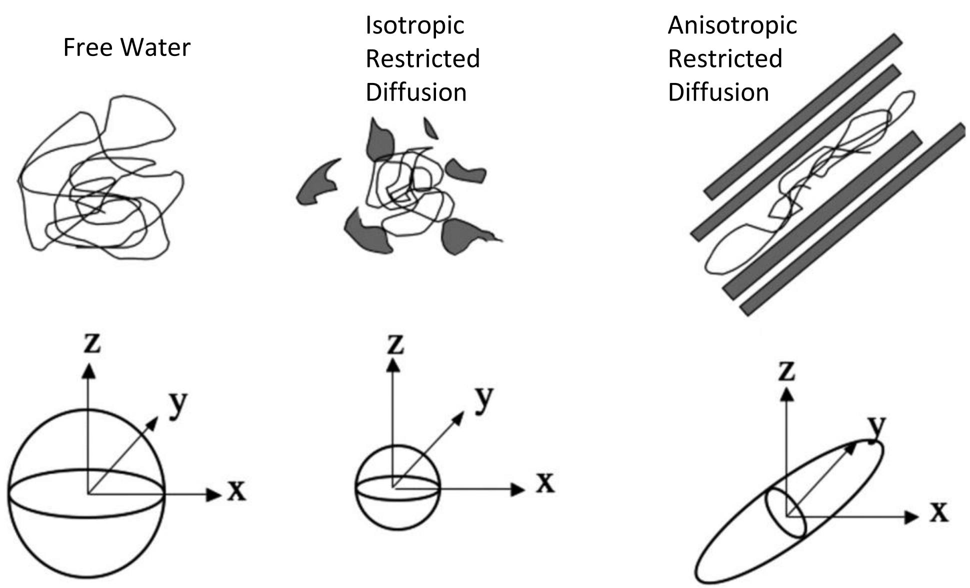


$$\begin{bmatrix} D & 0 & 0 \\ 0 & D & 0 \\ 0 & 0 & D \end{bmatrix} \quad \begin{bmatrix} D_{eff} & 0 & 0 \\ 0 & D_{eff} & 0 \\ 0 & 0 & D_{eff} \end{bmatrix} \quad \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$$

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

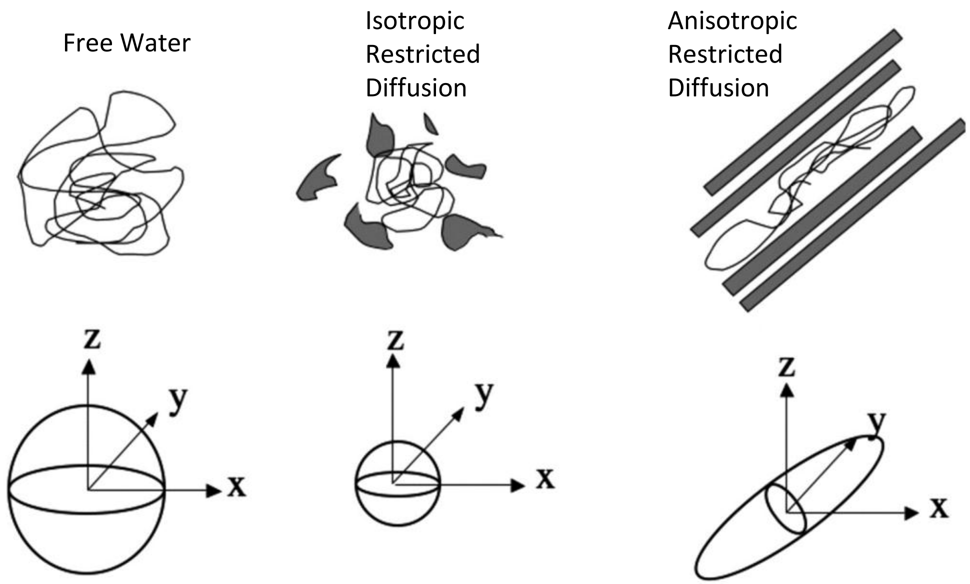
$$AD = \lambda_1$$

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

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

Diffusion Tensor Imaging on spinal cord

Purpose: Image the nerve growth in the spinal cord



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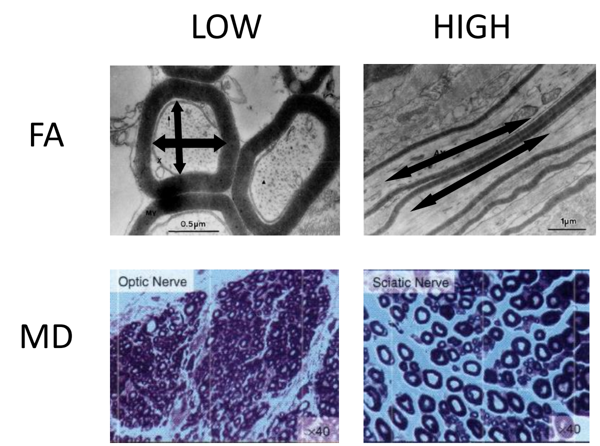


Layout

Diffusion Tensor Imaging on spinal cord

A first study for prove of concept

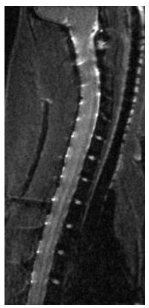
A second study to evaluate the efficiency of drugs

MRI Set-up for spinal cord imaging

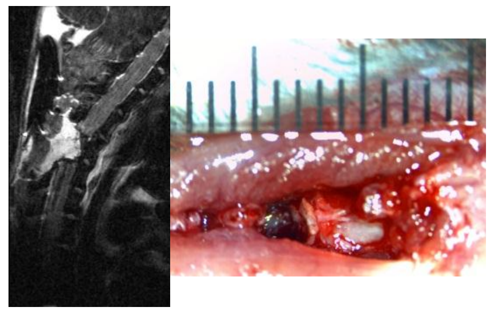
A first study for prove of concept

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

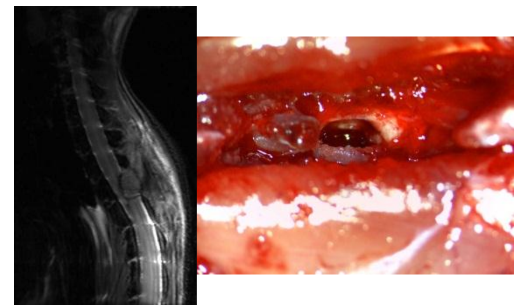
Control



total section



hemisection



MRI acquisition: *Multi-Shot Echo Planar Imaging*

4-channel surface coil

3 shots

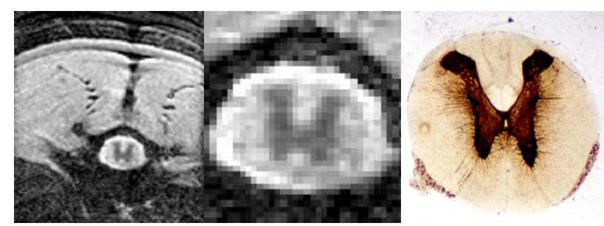
b-value: 670 s/mm^2

$\delta = 3\ ms, \Delta = 10\ ms$

TE: 17-20 ms

TR: 250 ms

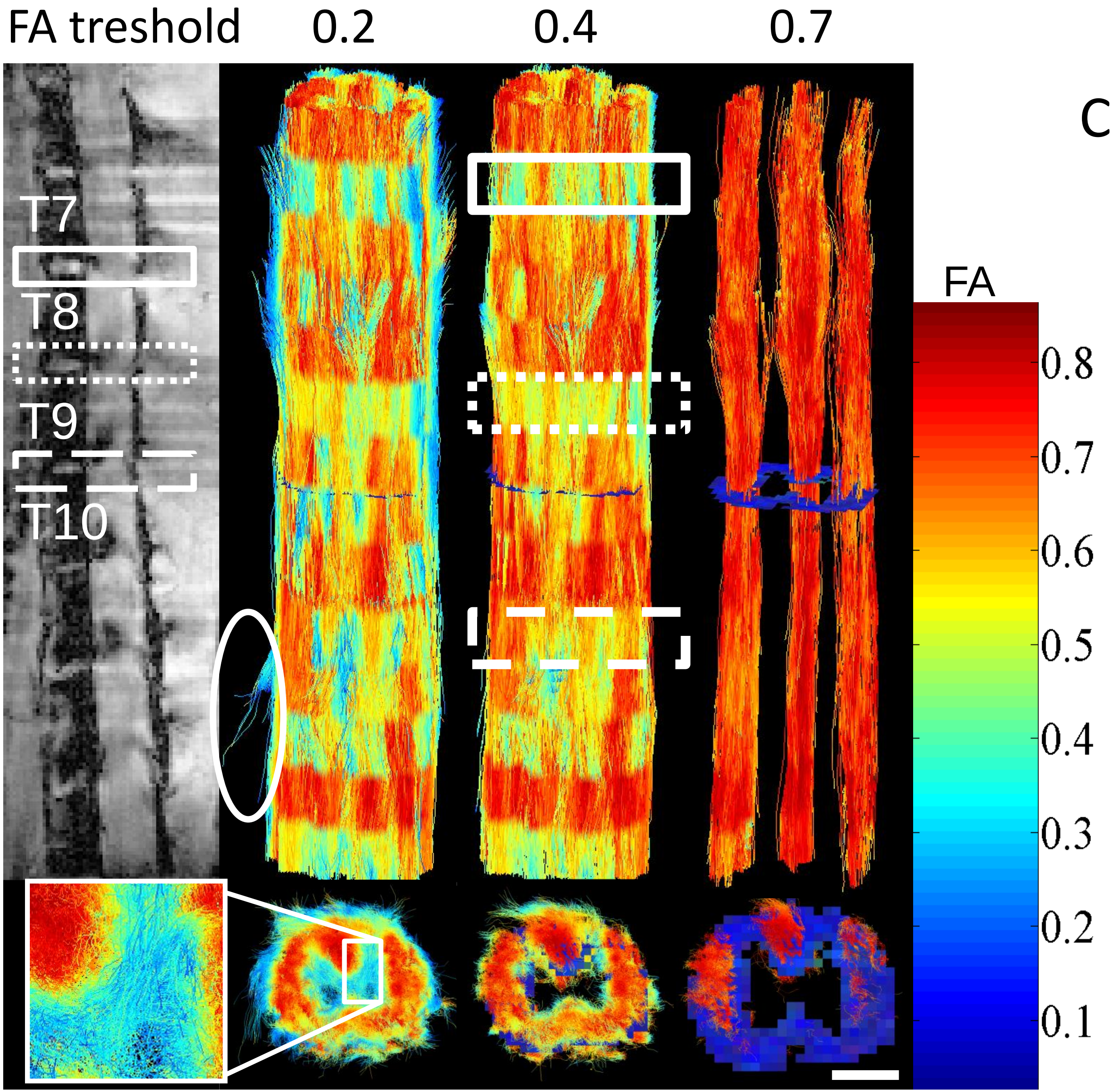
Trigger per Slice

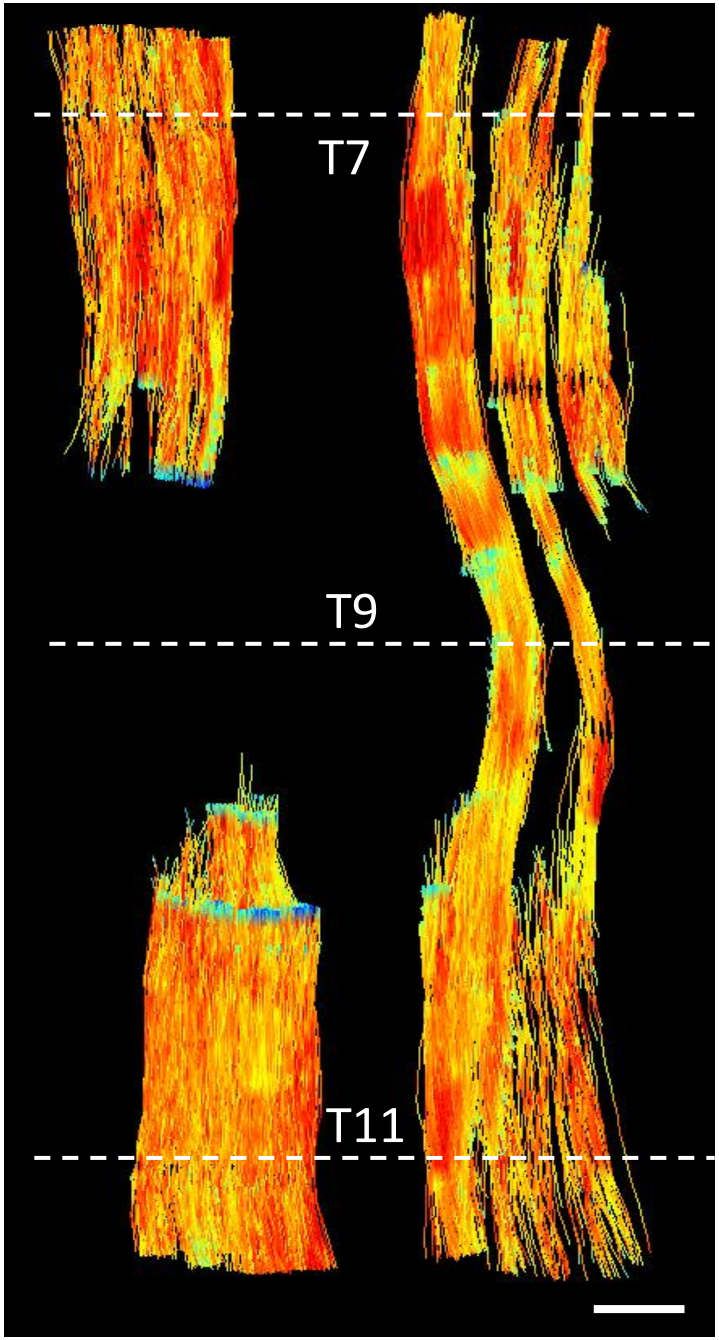


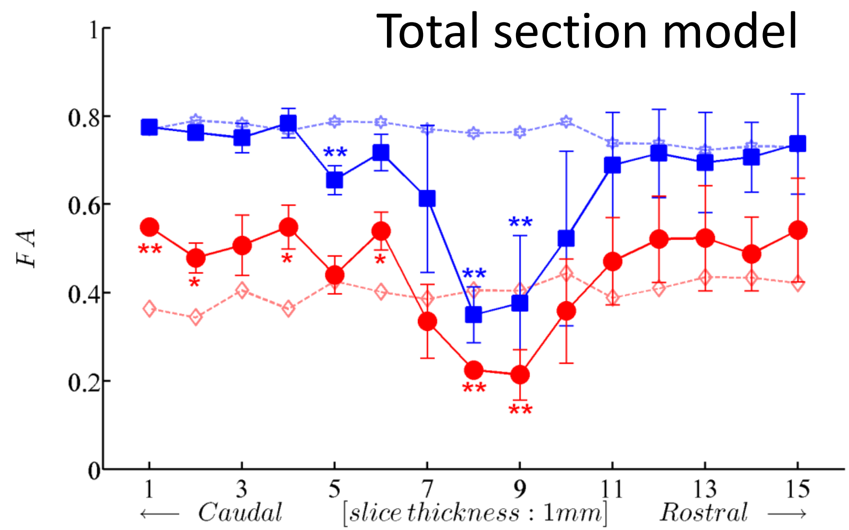
FOV: 12x15 mm^2

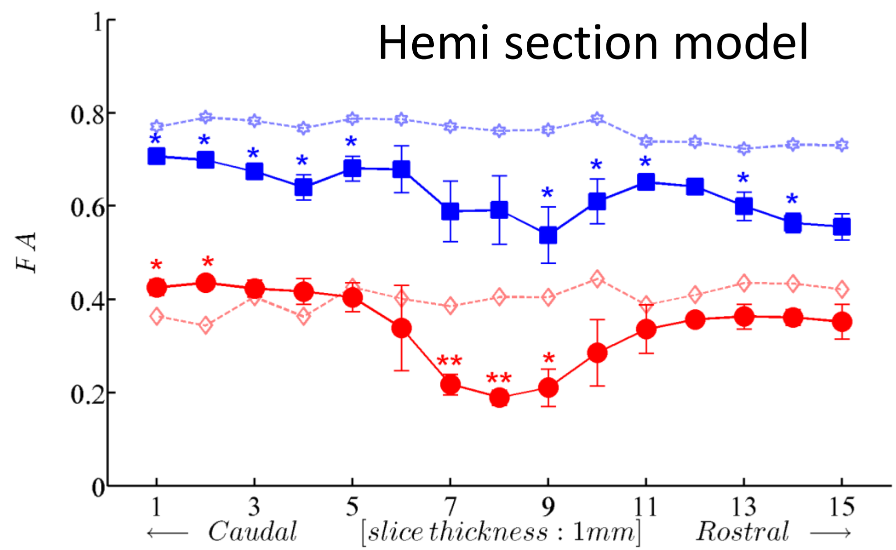
Voxel: 0.11x0.11x1 mm^3

Control Model




T7
T9
T11


Total section model
FA
← Caudal
[slice thickness : 1mm]
Rostral →


Hemi section model
FA
← Caudal
[slice thickness : 1mm]
Rostral →

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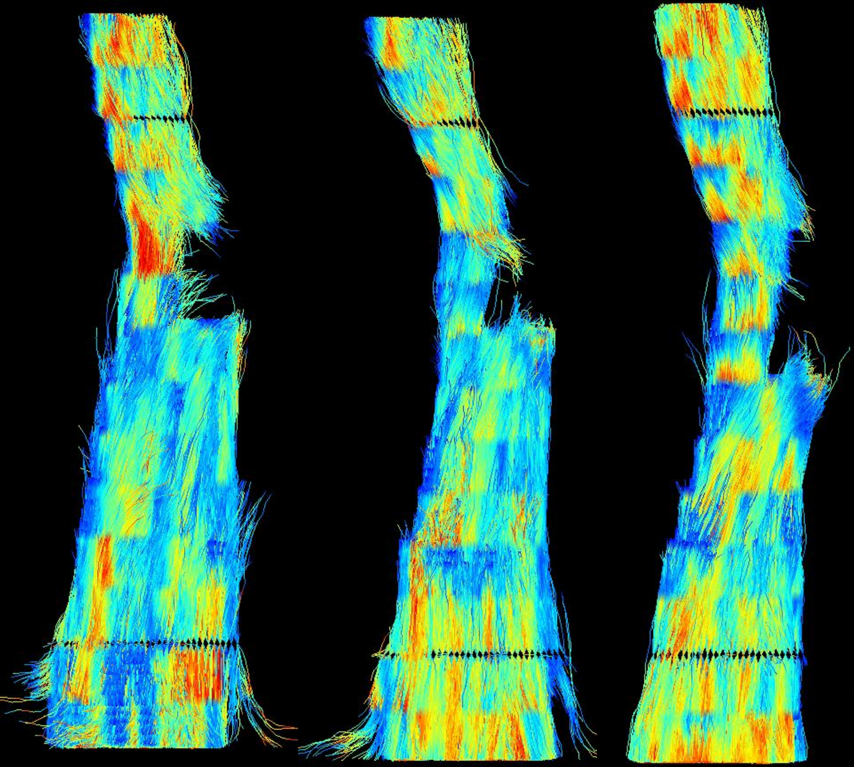
A

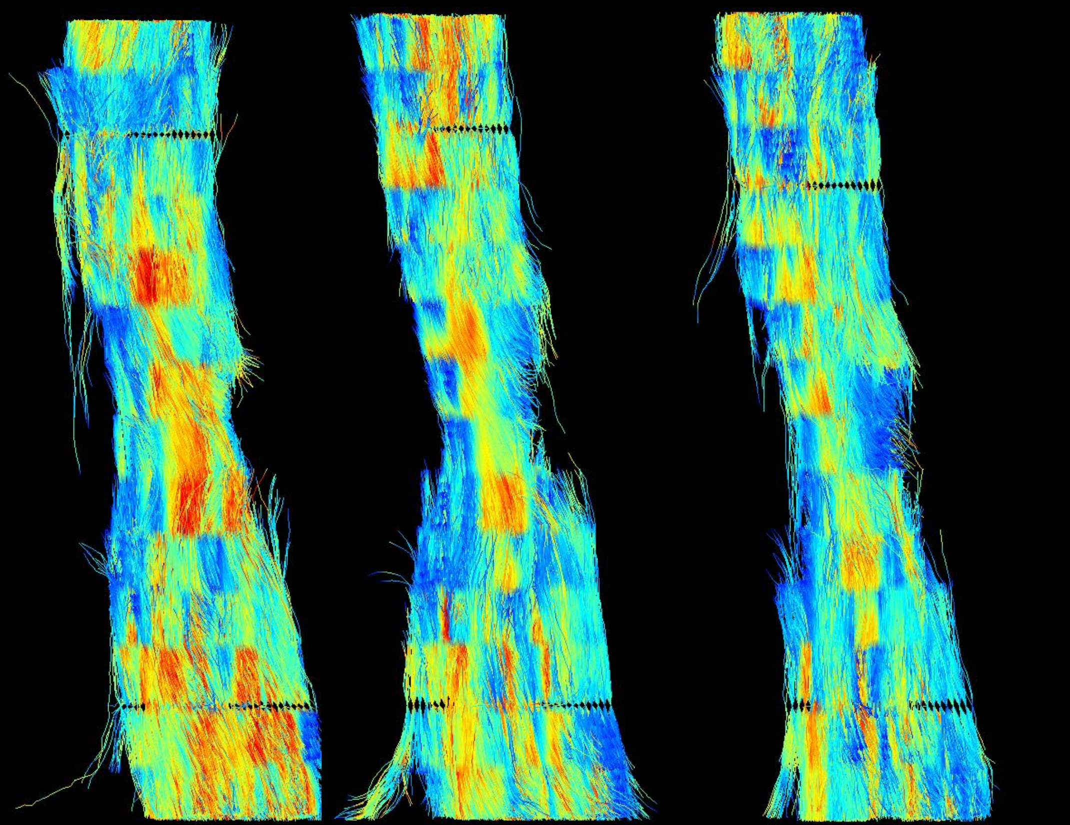


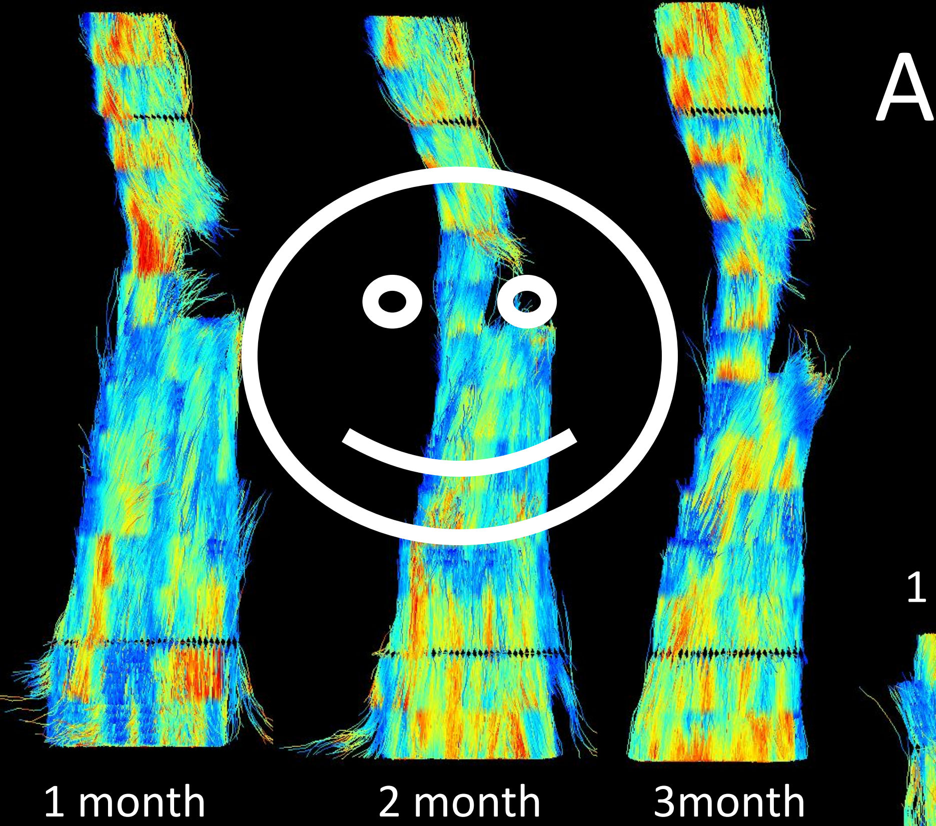
1 month 2 month 3month

Which rat has received the drug?

B

1 month 2 month 3 month





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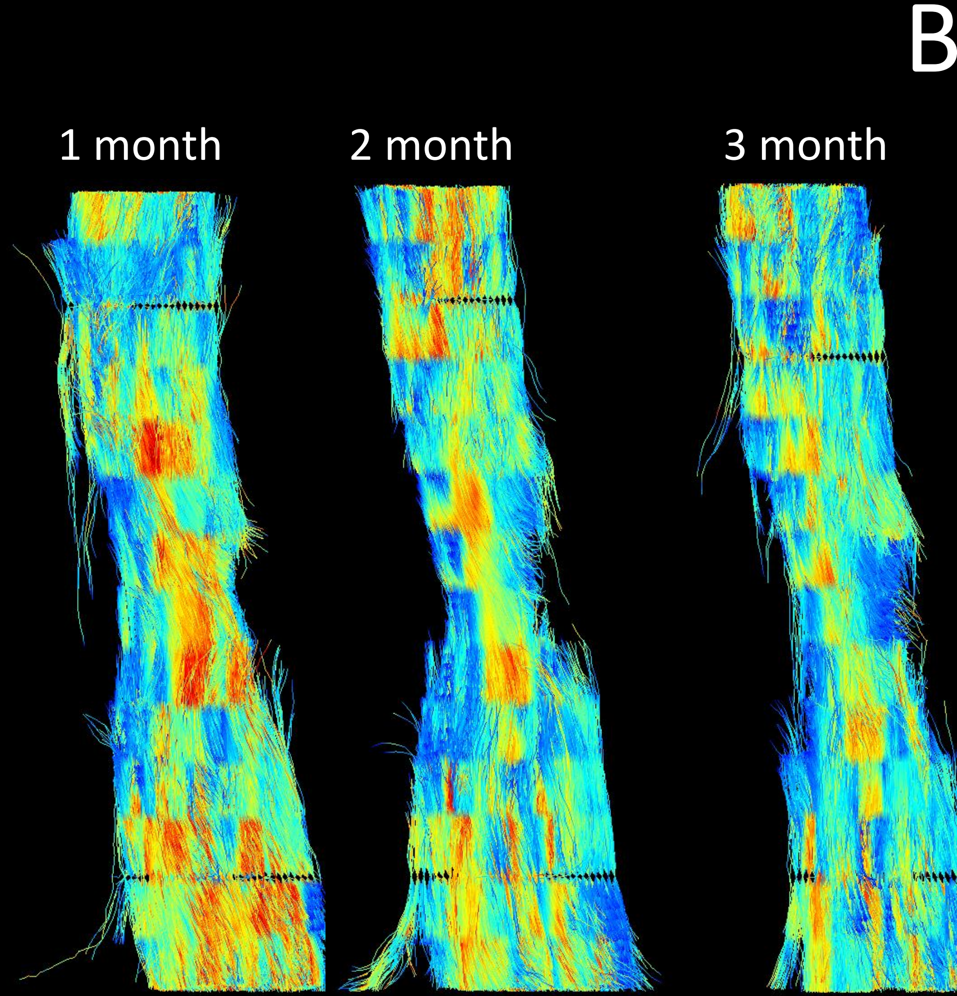
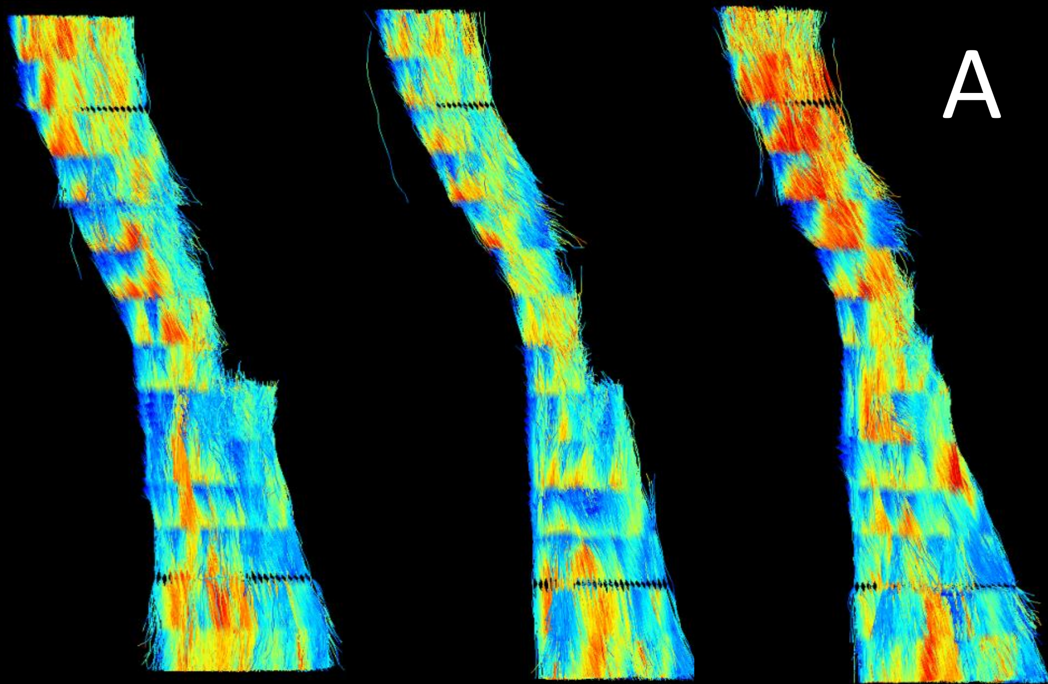


A



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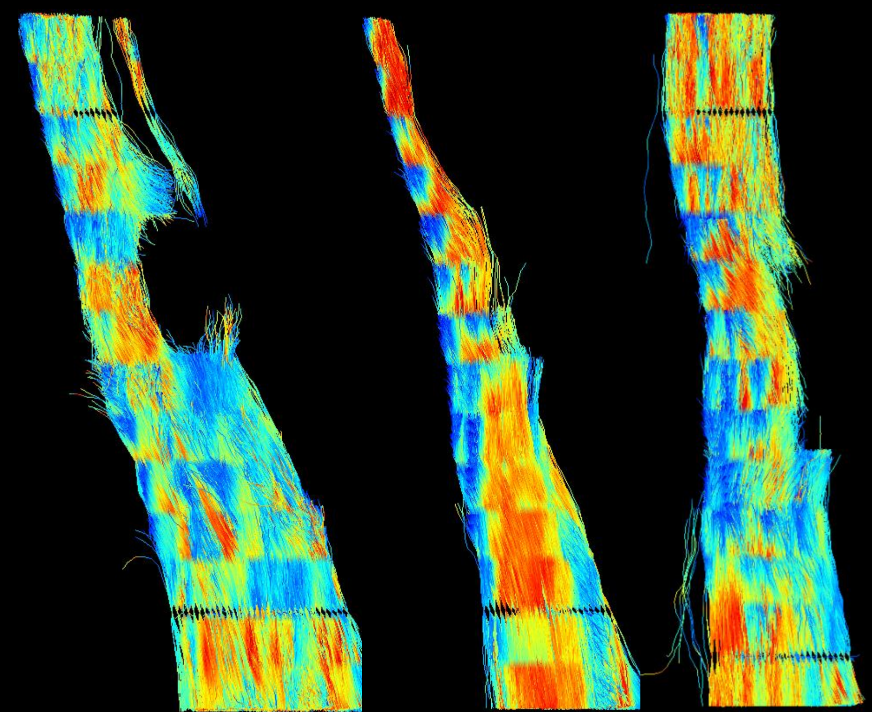
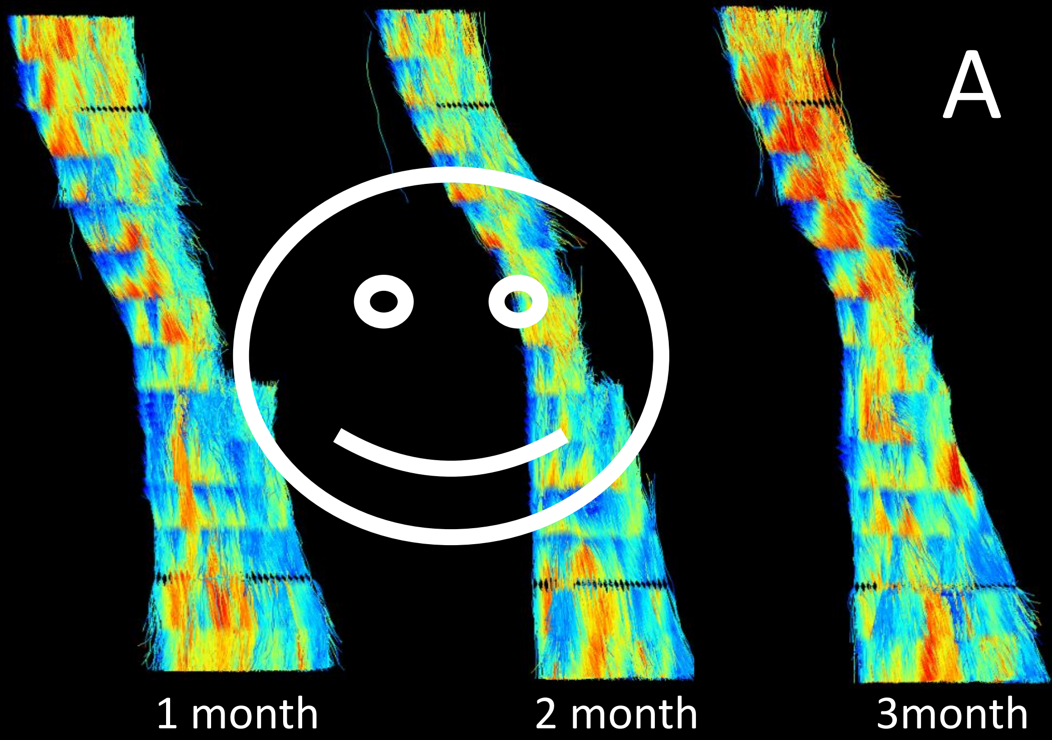
B





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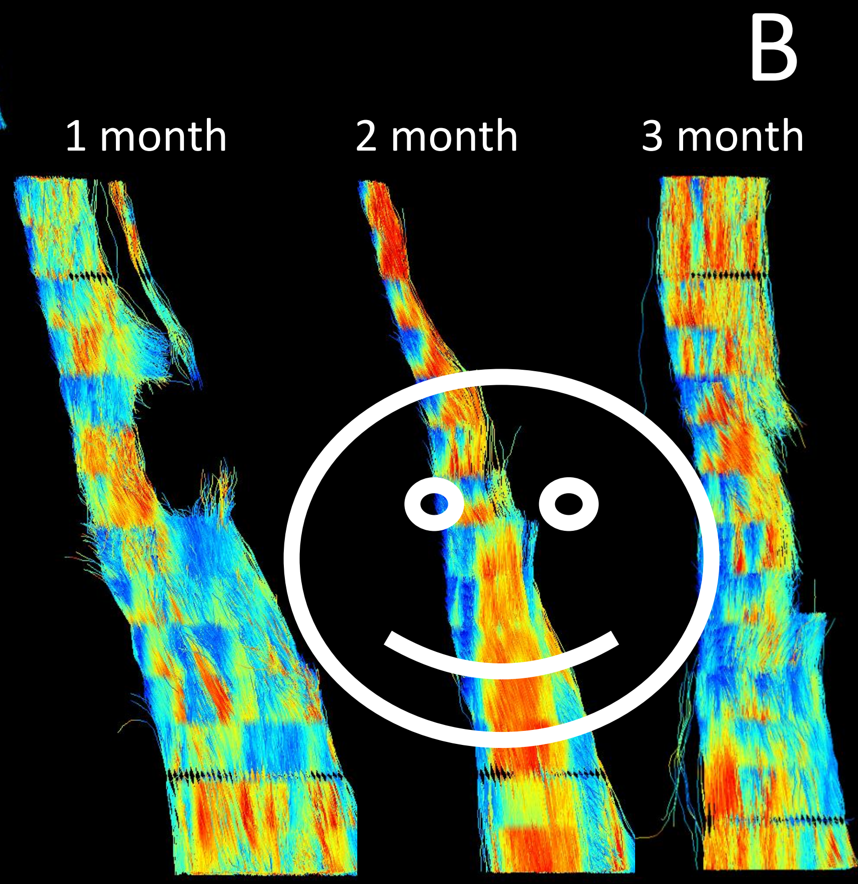
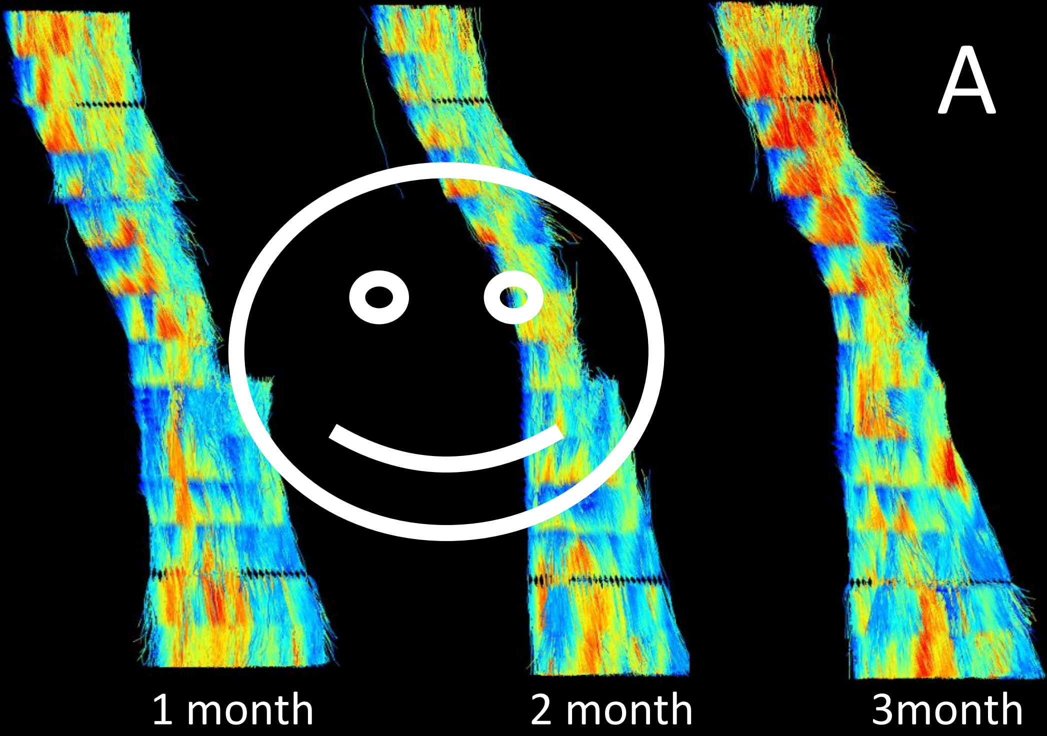


Why this variability?



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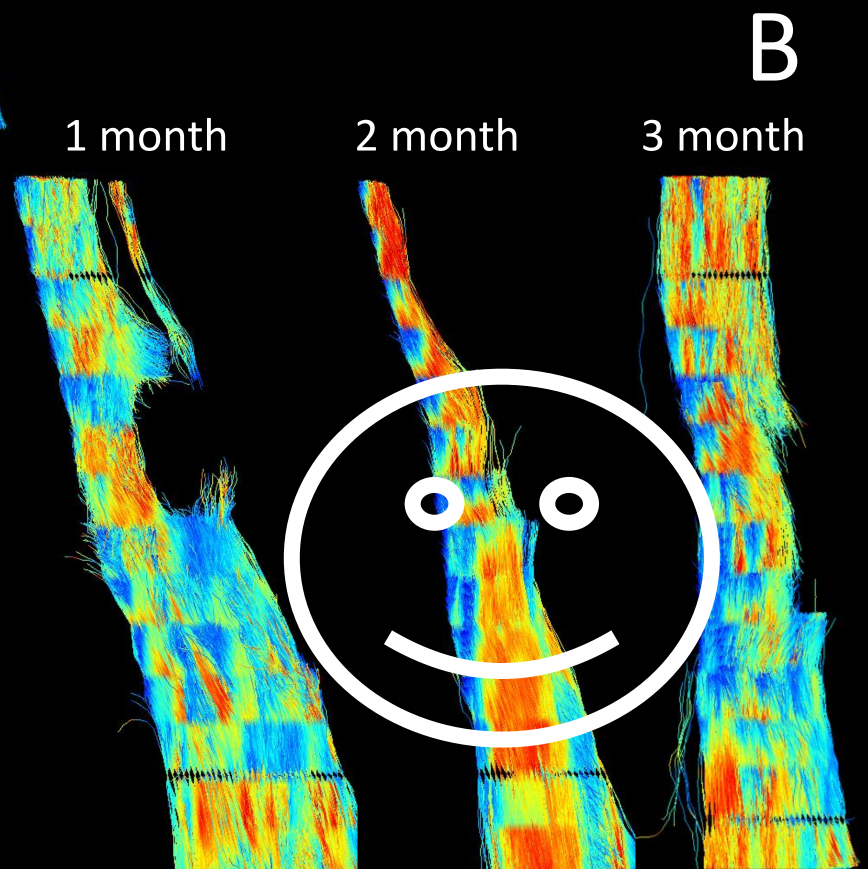

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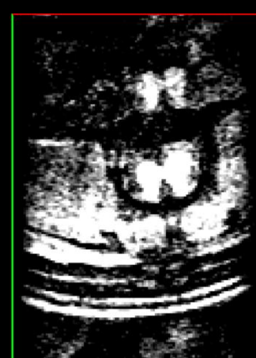

- Surgery

Layout

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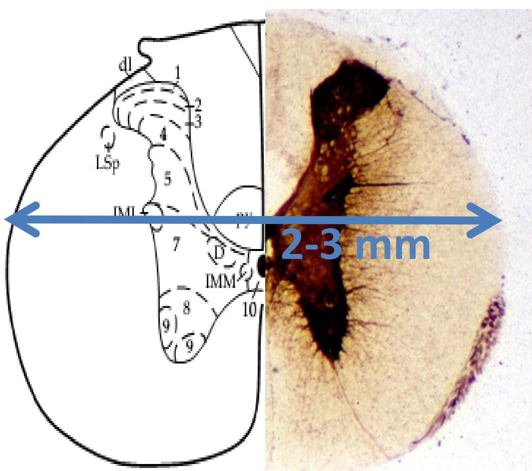
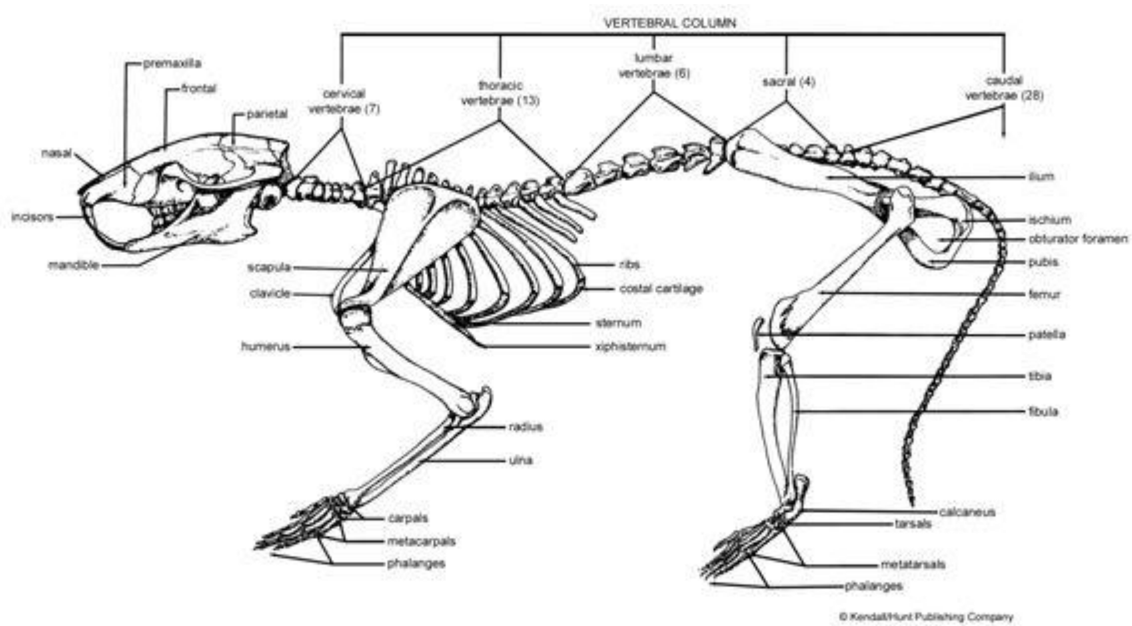
MRI Set-up for spinal cord imaging

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

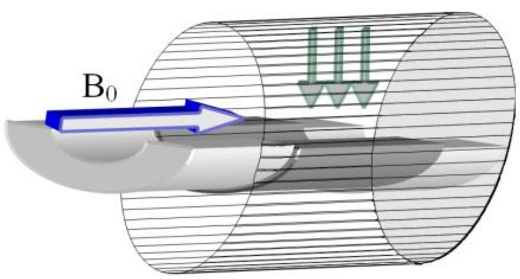
bone/water/fat

short TE and B_0~cst

Respiration/Support

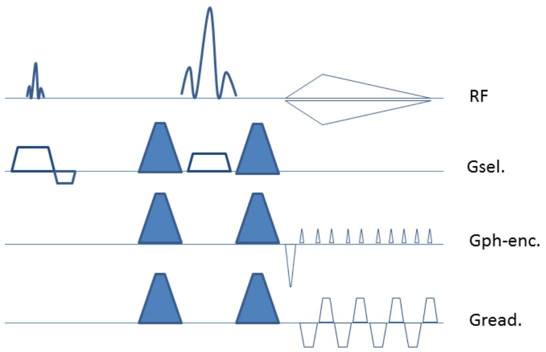
TR < T respiration

Set-up



Multi-shot sequence

Bandwidth



Anesthesia

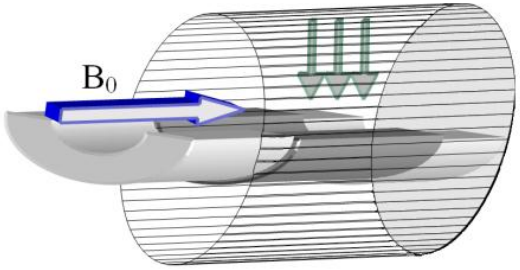
MRI Set-up for spinal cord imaging

volume (3mm) → high SNR

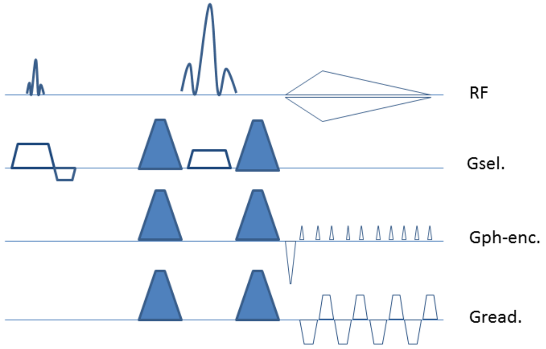
bone/water/fat → short TE and B_0~cst

Respiration/Support → TR < T respiration

Set-up



Multi-shot sequence

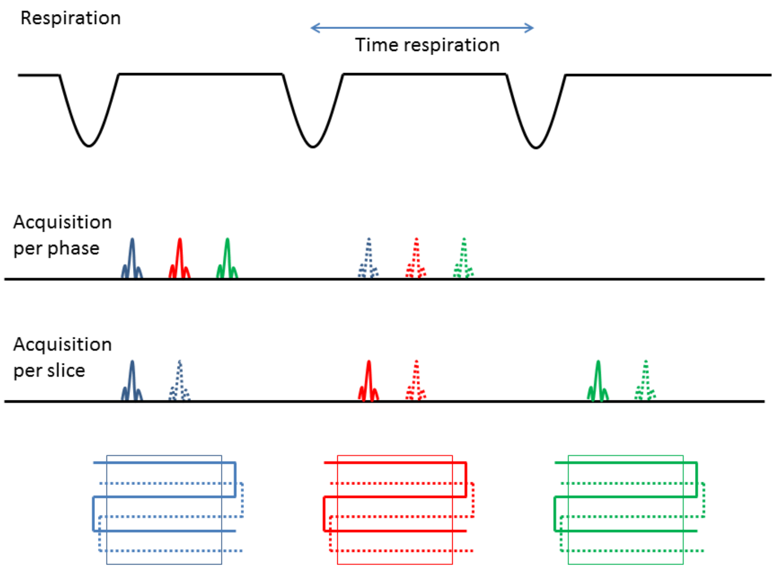


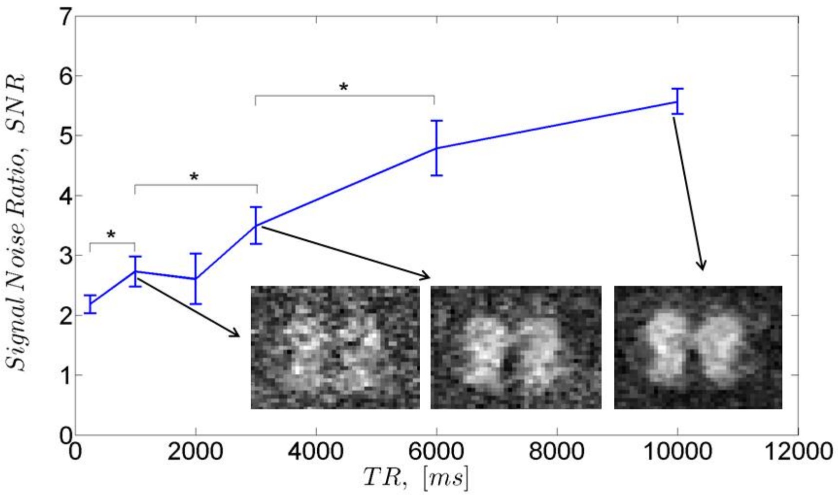
MRI Set-up for spinal cord imaging

Physiological et anatomical environment

1. TR < T resp ~1500 ms

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



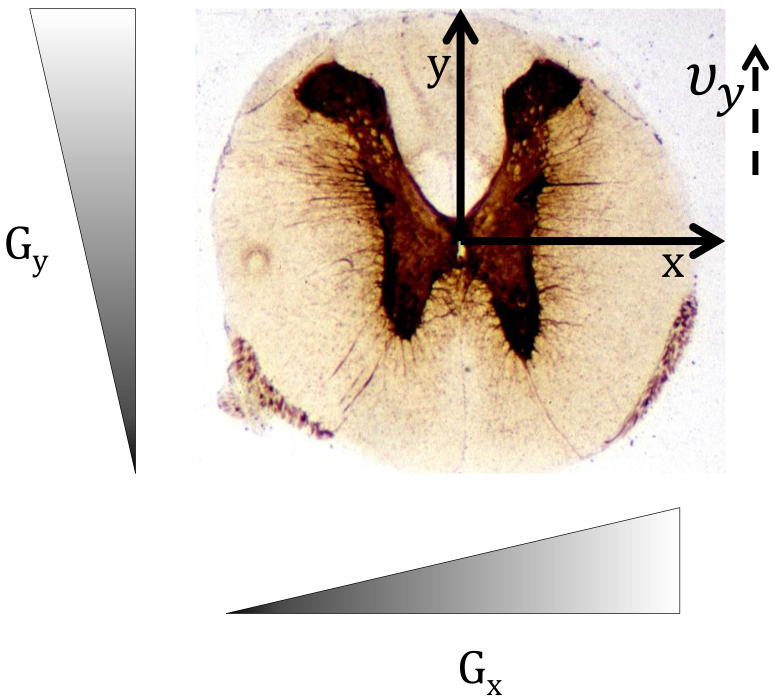


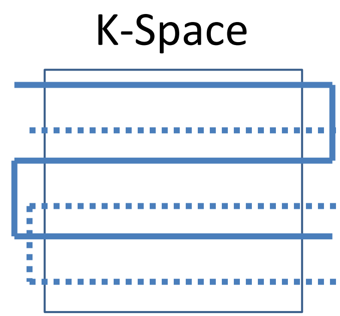
T_1: ~1000 ms at 4.7 T

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

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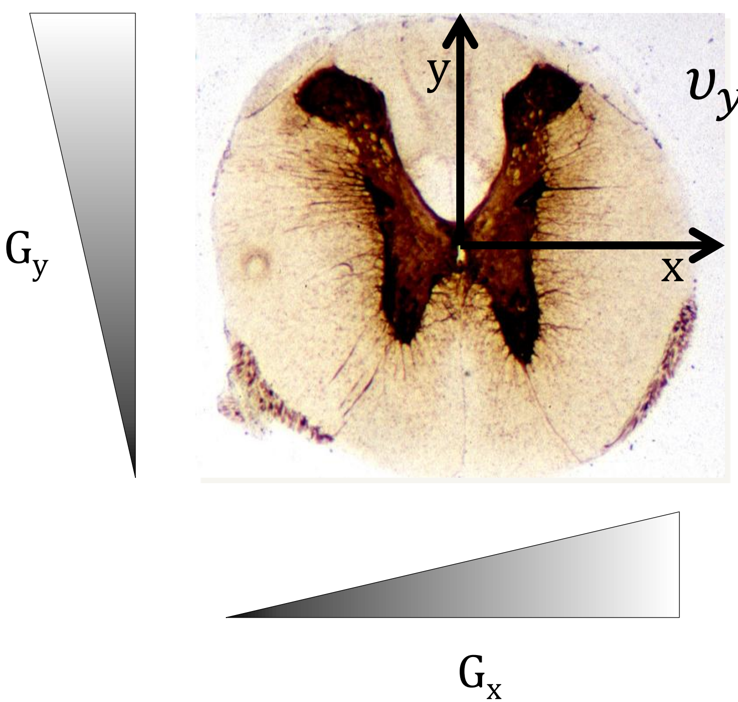


$$S(t) = \iint_{-\infty}^{+\infty} \rho(x,y) e^{-i(\phi(x,y,t))}\, dx\, dy$$

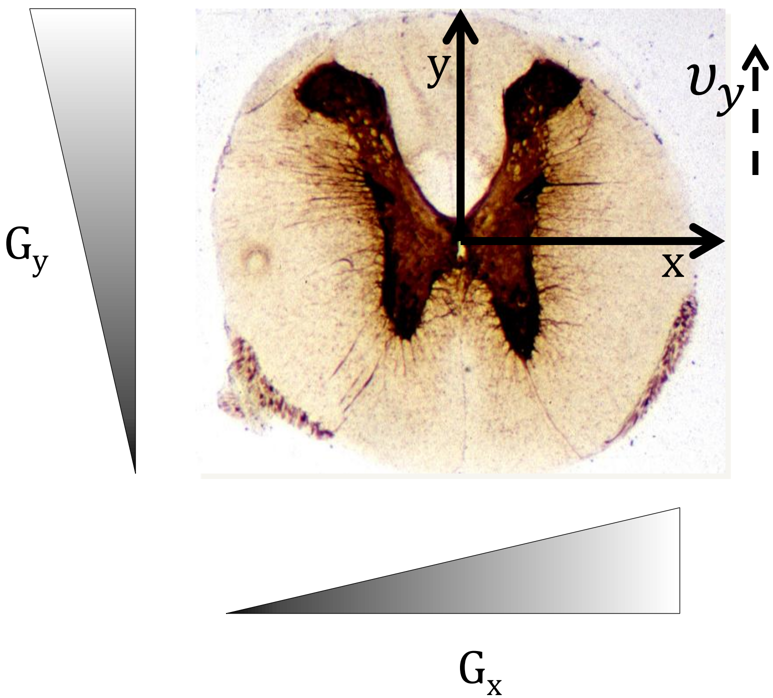
$$\Phi_{motion}(y,t) = \gamma \int_0^t G_y \left(y_0 + \upsilon_y \tau + \frac{1}{2} a_y \tau^2 \right) d\tau$$

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

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

Phase errors in diffusion-weighted imaging

Linear phase error due to multi-shot acquisition



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?

Phase errors in diffusion-weighted imaging

Generalized Signal Equation for acquisition of κ k-space

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

$$m(t_i) = \sum_{u=1}^{NXN} \rho(\boldsymbol{r}_u)\ exp(-j\boldsymbol{k}(t_i)\cdot\boldsymbol{r}_u) \quad with\ i = 1 \ldots\ k.$$

$$\underbrace{[m(t_1)\ \ m(t_2)\ \ \ldots m(t_k)]}_{\mathbf{m}}$$

$$\underbrace{[\rho(\boldsymbol{r}_1)\ \ \rho(\boldsymbol{r}_2)\ \ \ldots\ \ \rho(\boldsymbol{r}_{N^2})]}_{\mathbf{v}}$$

$$\underbrace{\begin{pmatrix} e^{-j\,\boldsymbol{k}_1\boldsymbol{r}_1} & \cdots & e^{-j\,\boldsymbol{k}_1\boldsymbol{r}_{N^2}} \\ \vdots & \ddots & \vdots \\ e^{-j\,\boldsymbol{k}_\kappa\boldsymbol{r}_1} & \cdots & e^{-j\,\boldsymbol{k}_\kappa\boldsymbol{r}_{N^2}} \end{pmatrix}}_{\mathbf{E}}$$

Phase errors in diffusion-weighted imaging

Generalized Signal Equation for acquisition of κ k-space

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$$\underbrace{[m(t_1)\ \ m(t_2)\ \ \ldots m(t_k)]}_{\mathbf{m}} \qquad \underbrace{[\rho(\boldsymbol{r}_1)\ \ \rho(\boldsymbol{r}_2)\ \ \ldots\ \ \rho(\boldsymbol{r}_{N^2})]}_{\mathbf{v}} \qquad \underbrace{\begin{pmatrix} e^{-j\,\boldsymbol{k}_1\boldsymbol{r}_1} & \cdots & e^{-j\,\boldsymbol{k}_1\boldsymbol{r}_{N^2}} \\ \vdots & \ddots & \vdots \\ e^{-j\,\boldsymbol{k}_\kappa\boldsymbol{r}_1} & \cdots & e^{-j\,\boldsymbol{k}_\kappa\boldsymbol{r}_{N^2}} \end{pmatrix}}_{\mathbf{E}}$$

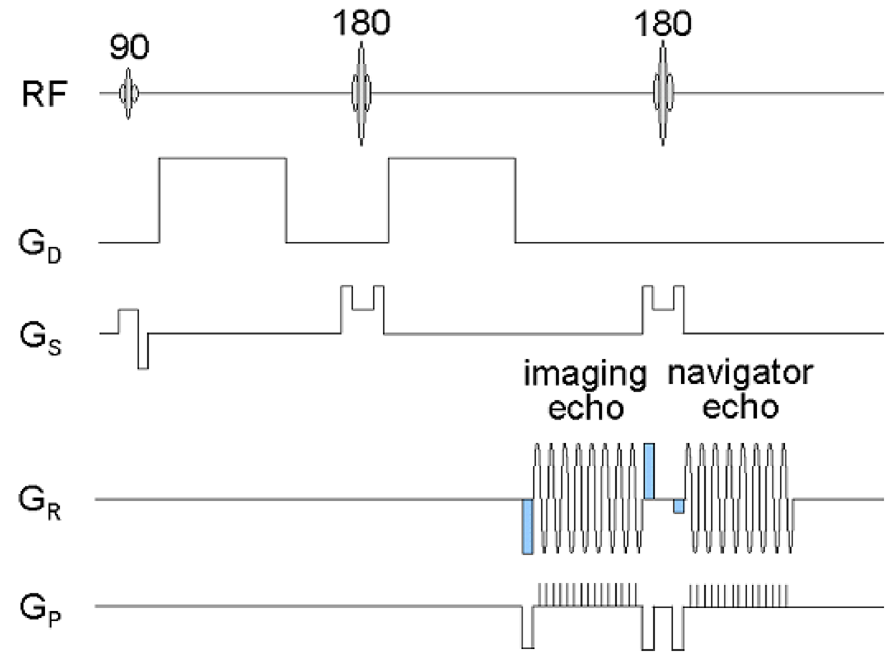
v ?

E ?

Solving phase errors requires a navigator

To determine this term $\mathbf{E}$

$$\begin{pmatrix} e^{-j\,\boldsymbol{k}_1\boldsymbol{r}_1} & \cdots & e^{-j\,\boldsymbol{k}_1\boldsymbol{r}_{N^2}} \\ \vdots & \ddots & \vdots \\ e^{-j\,\boldsymbol{k}_\kappa\boldsymbol{r}_1} & \cdots & e^{-j\,\boldsymbol{k}_\kappa\boldsymbol{r}_{N^2}} \end{pmatrix}$$

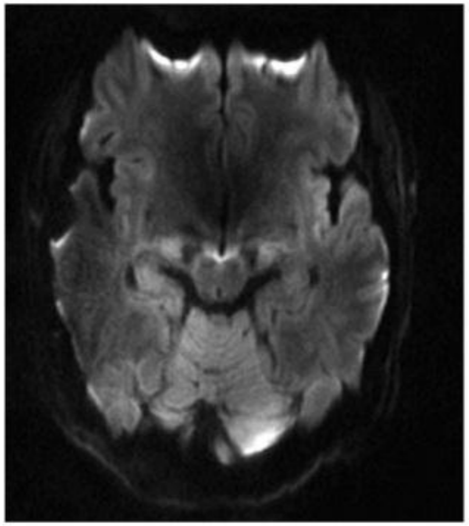


Phase error correction is an inverse problem

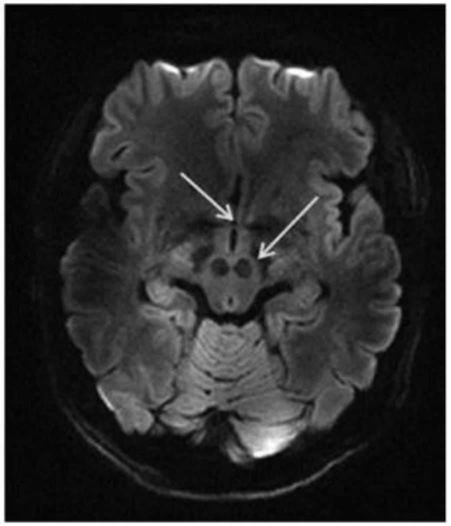
$$[m(t_1)\ \ m(t_2)\ \ \dots m(t_k)]^T = \begin{pmatrix} e^{-j\,\boldsymbol{k}_1\boldsymbol{r}_1} & \cdots & e^{-j\,\boldsymbol{k}_1\boldsymbol{r}_{N^2}} \\ \vdots & \ddots & \vdots \\ e^{-j\,\boldsymbol{k}_\kappa\boldsymbol{r}_1} & \cdots & e^{-j\,\boldsymbol{k}_\kappa\boldsymbol{r}_{N^2}} \end{pmatrix}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

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

Without correction

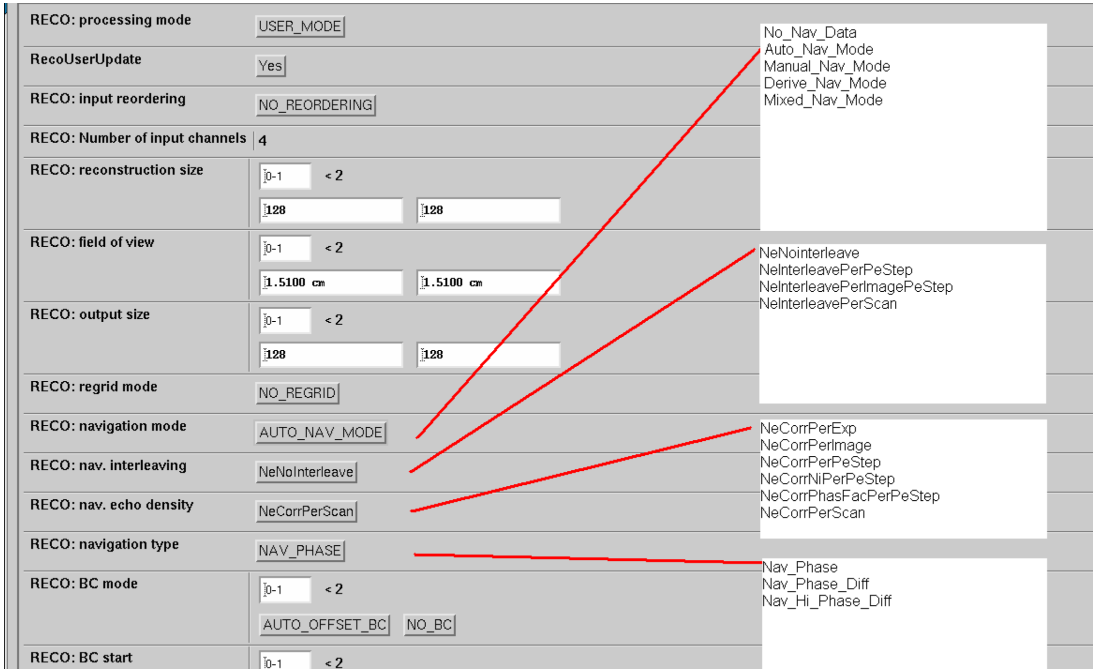


With correction



Study of Heidemann *et al.* at 7 T

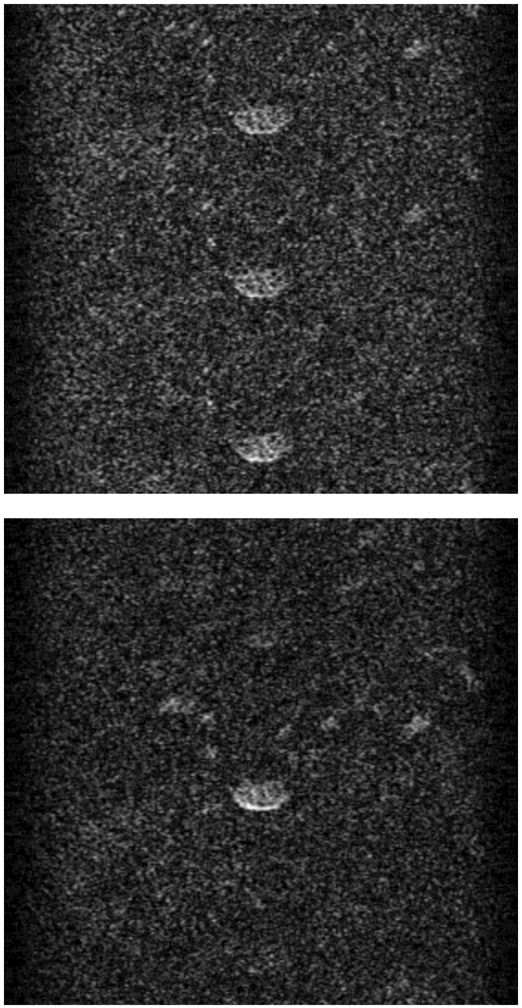
Study on the navigator implemented by Bruker

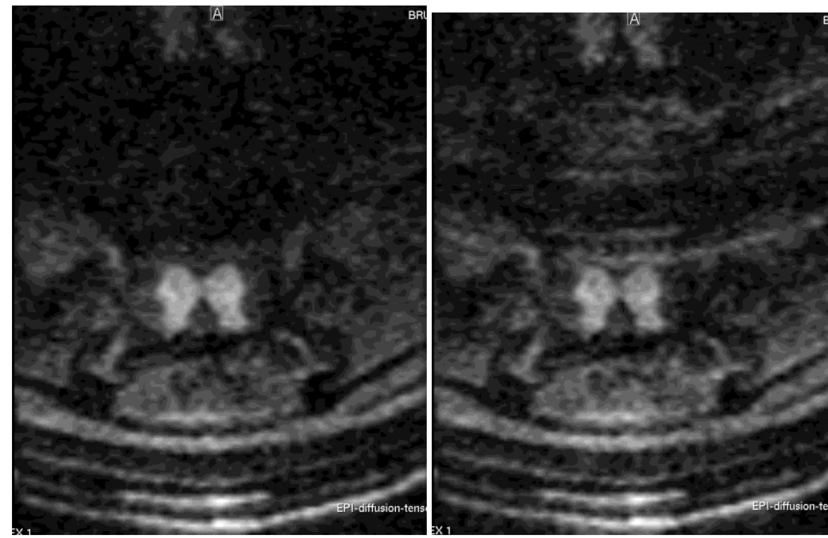


?

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:

$$\frac{\partial \mathbf{M}}{\partial t} = \gamma \mathbf{M} \times \mathbf{B} - \frac{M_z - M_0}{T1}\mathbf{u}_z \frac{M_x\mathbf{u}_x + M_y\mathbf{u}_y}{T2} - D\nabla^2\mathbf{M}$$

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

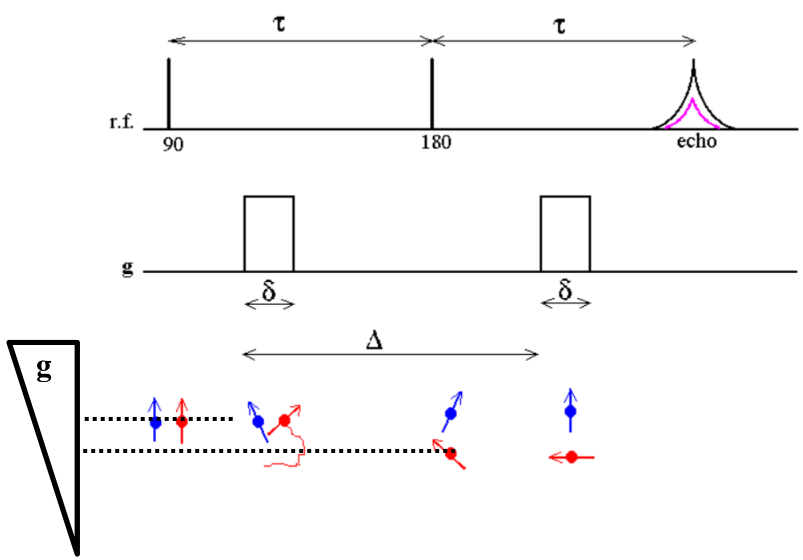
$$\frac{S(b)}{S(0)} = e^{-bD}$$

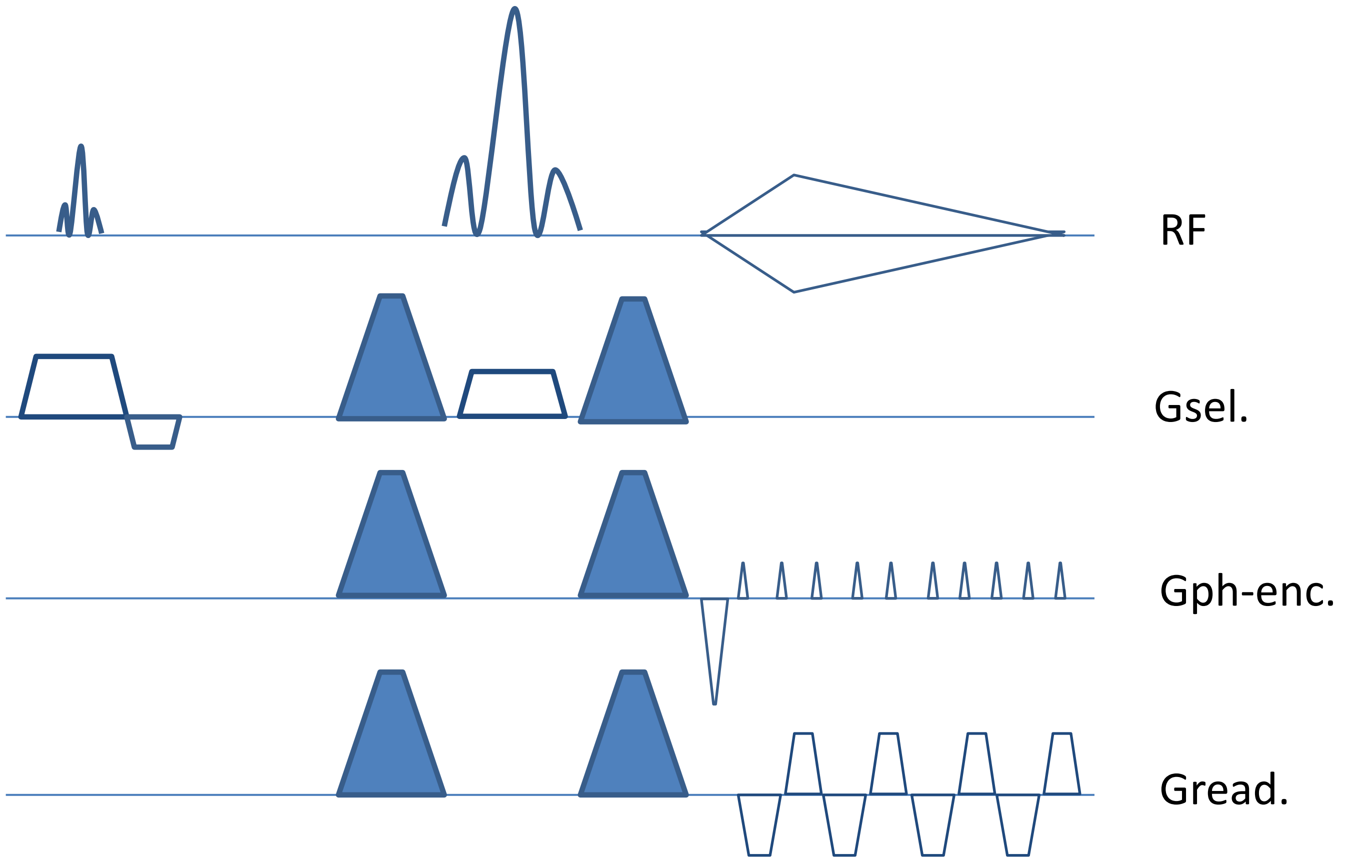
b-value qui dépend de **g**

Pulsed Gradient Spin Echo (PGSE): $\omega(\boldsymbol{r}) = \gamma B_0 + \gamma \boldsymbol{g} \cdot \boldsymbol{r}$

Spin fixe

Spin mobile




RF
Gsel.
Gph-enc.
Gread.

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

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

?

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

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

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