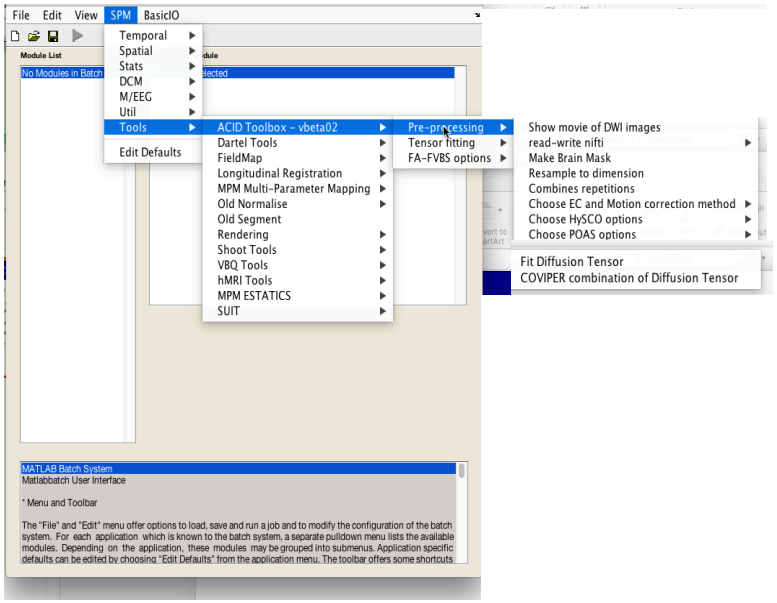
Universitätsklinikum Hamburg-Eppendorf

Artefact Correction In Diffusion MRI

ACID SPM toolbox



Siawoosh Mohammadi

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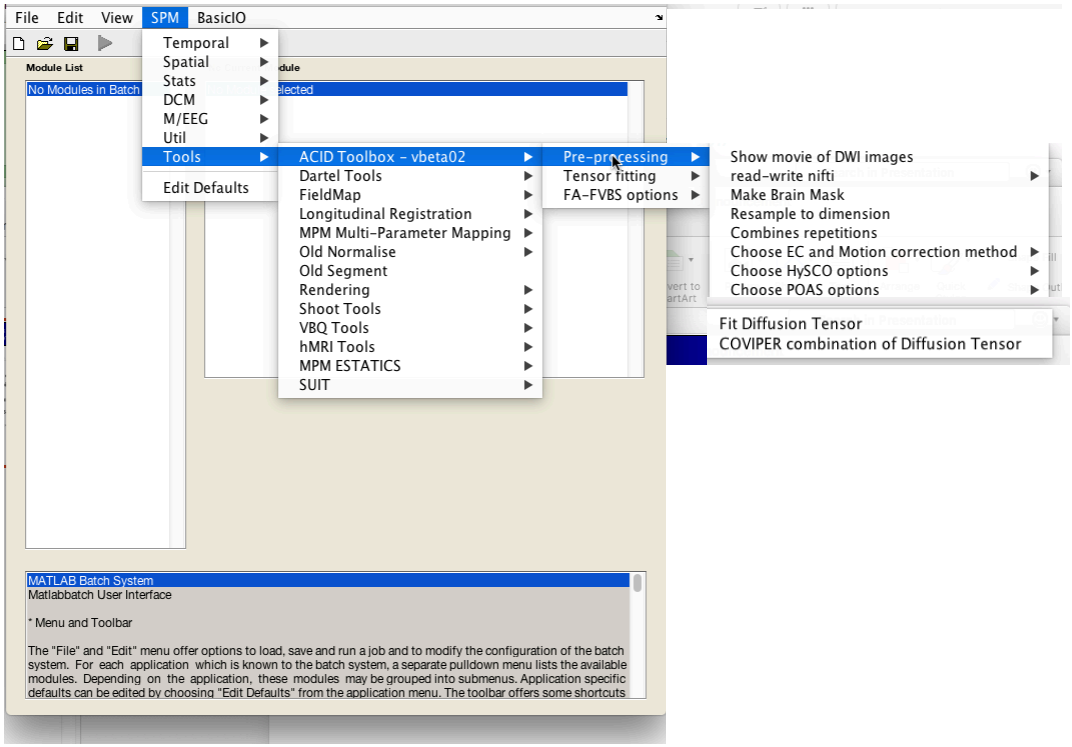
s.mohammadi@uke.de

www.diffusiontools.com

Universitätsklinikum Hamburg-Eppendorf

SPM-ACID Toolbox
DTI, DKI, & NODDI-DTI



Open-Access: www.diffusiontools.com

Questions/queries to Siawoosh Mohammadi
s.mohammadi@uke.de

Preprocessing:

- Eddy current and motion
- HySCO (EPI distortions)
- msPOAS (adaptive smoothing)
- Vibration Artifacts (DTI model)
- Spinal Cord Branch – *in prep*
- Rican Noise Bias Correction – *in prep.*

Signal Models:

- DTI (ols, wols, robust fitting)
- Diffusion Kurtosis Imaging
- NODDI-DTI

Artefact Correction In Diffusion MRI

ACID SPM toolbox

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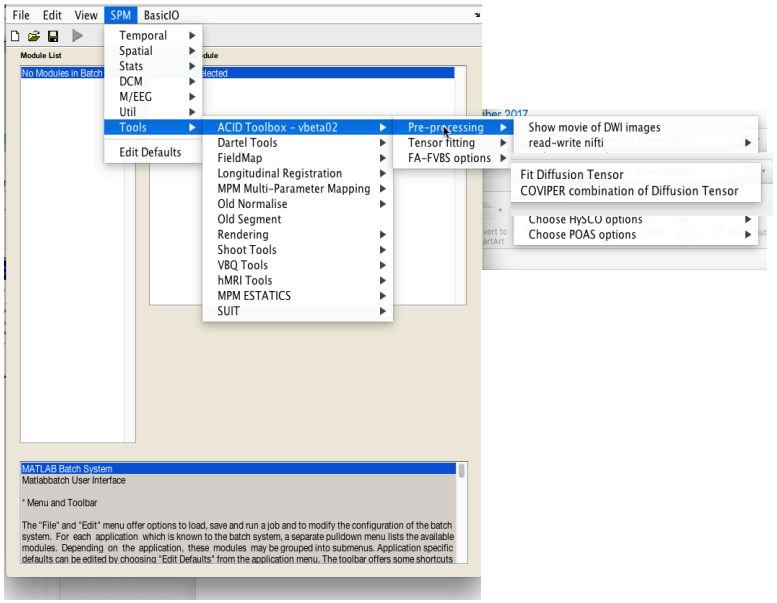

Outline of the ACID course

- 30-60 min intro to ACID toolbox
- hands-on application:
  - Installation,
  - ECMOCO,
  - msPOAS,
  - HySCO,
  - Tensor fitting
- Open discussion

Motivation for ACID toolbox

- One main goal of our group: ”*In-vivo* histology using MRI”
- Standard DTI is sensitive to microstructure but unspecific
- Advanced diffusion MRI might improve specificity
- Diffusion MRI suffers from various artifacts
- Advanced diffusion MRI requires correcting artifacts
- ACID toolbox provides ***principled, model-based, and peer-reviewed correction methods*** to correct artifacts and thus enable advanced diffusion MRI

Outline of this talk

- Diffusion MRI: why, how, and what does it mean?
- Pre-processing steps
  - Eddy current and motion correction
  - Susceptibility artefacts correction
  - Vibration artefact correction
  - Position-orientation adaptive smoothing
- Diffusion models
  - Weighted Ordinary Least Squares, Robust Tensor Fitting
  - Kurtosis Tensor Imaging
  - NODDI-DTI

Outline

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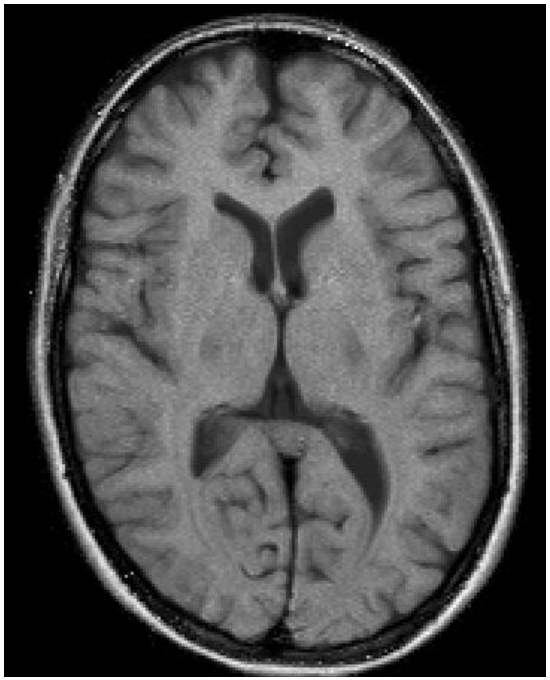
Why is diffusion more interesting than standard structural imaging?

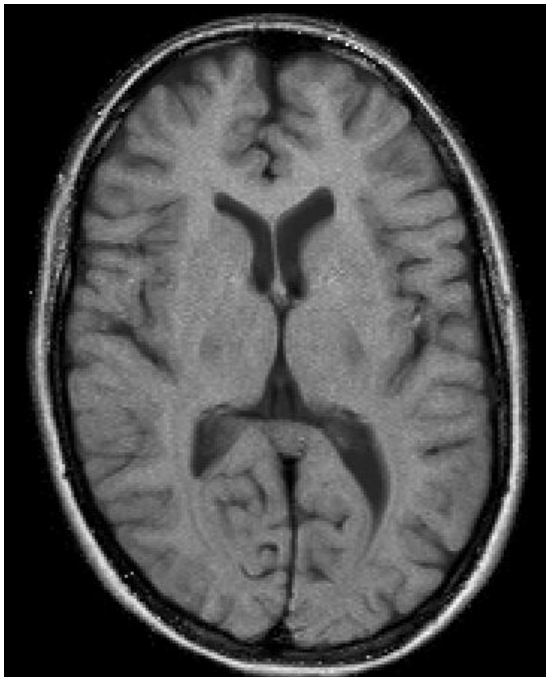
Histology



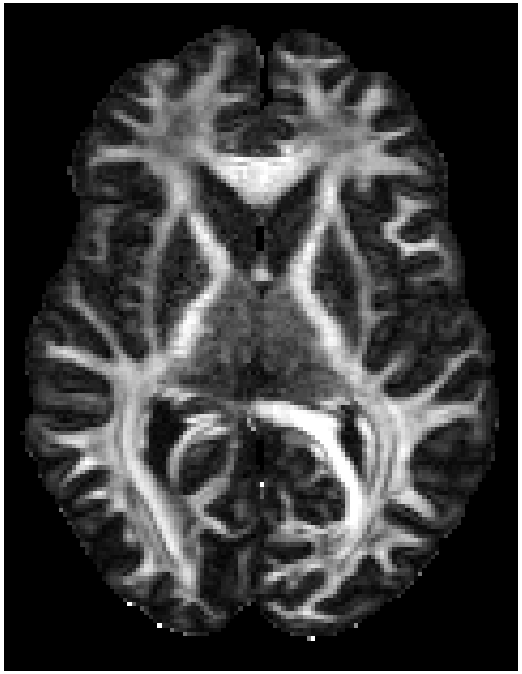
T1w image

Diffusion MRI reveals microstructural information

Histology

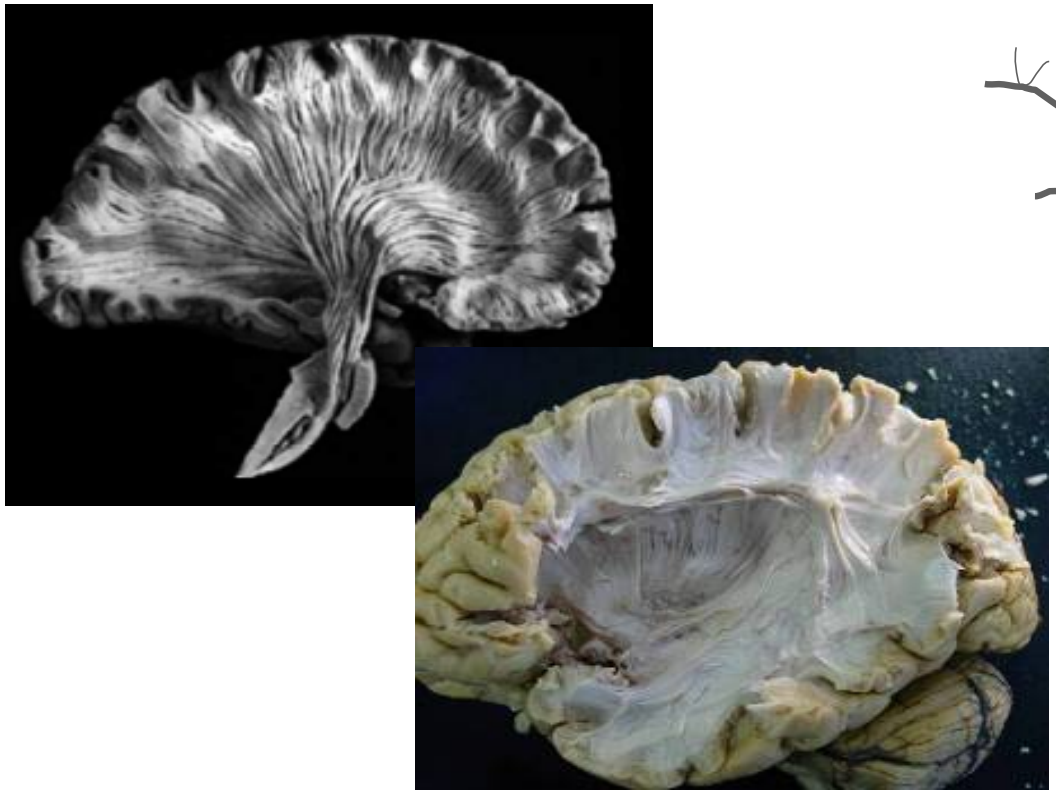


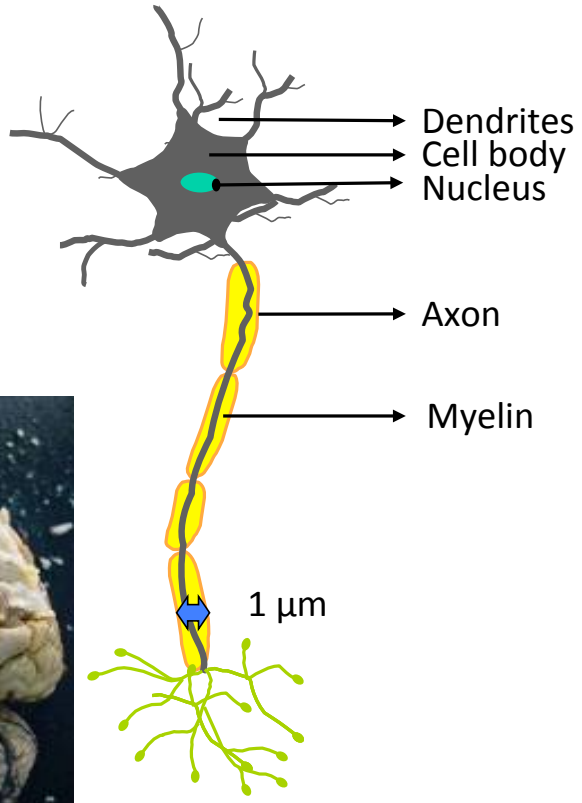
T1w image



DTI index map

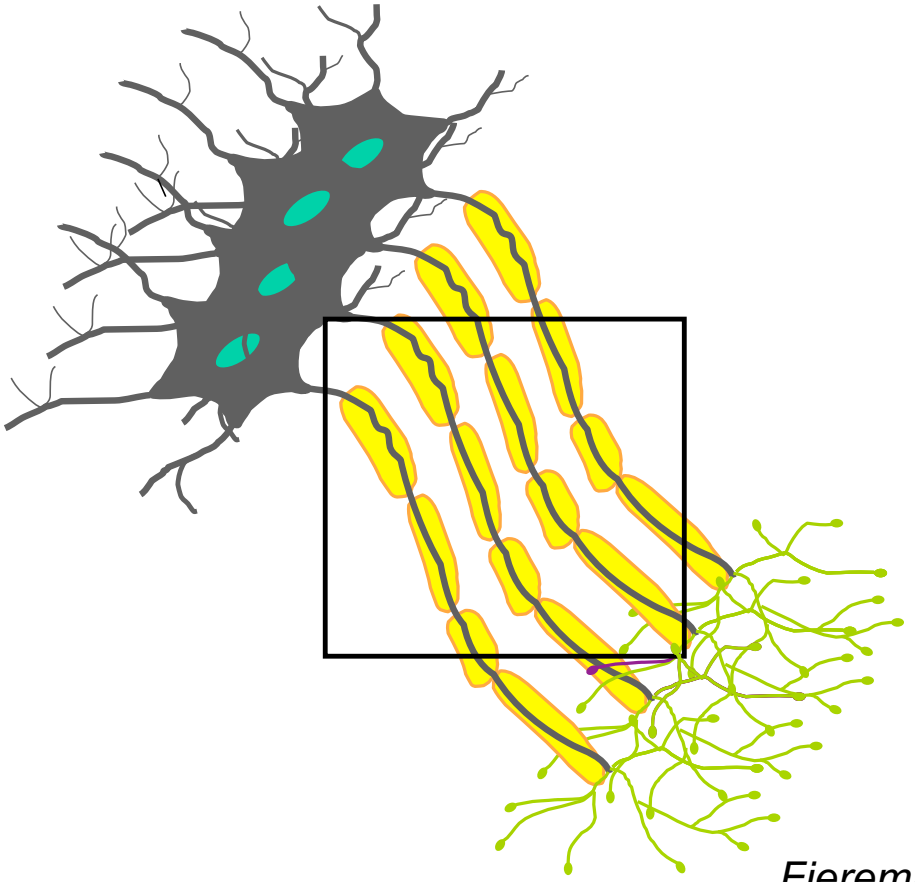
Main features of fibers in the white matter





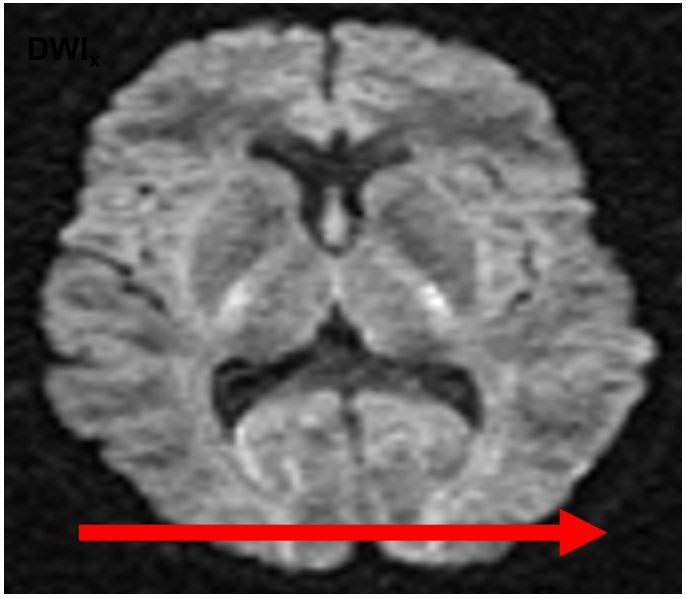
Fieremans, ESMRMB, 2015

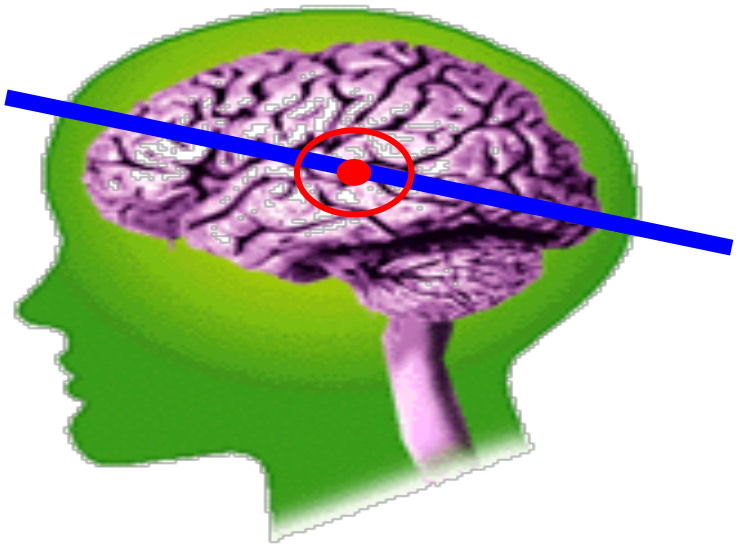
Aligned axons in fiber pathways

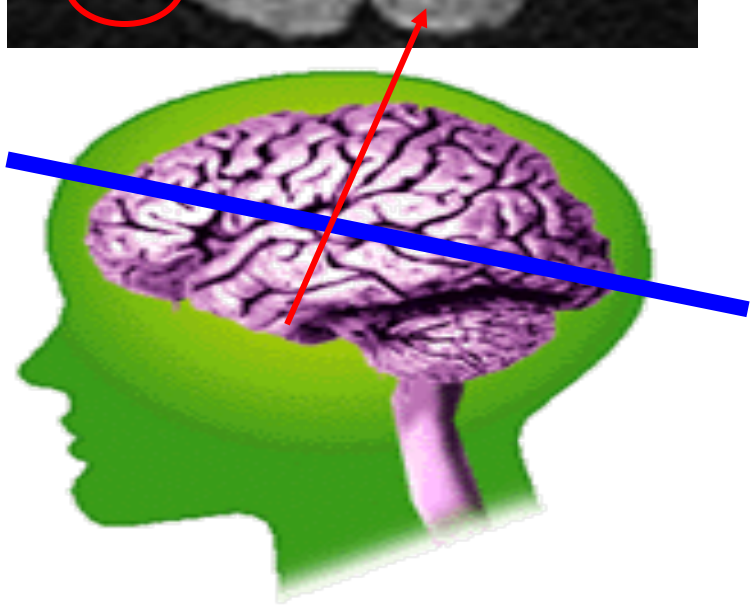


Fieremans, ESMRMB, 2015

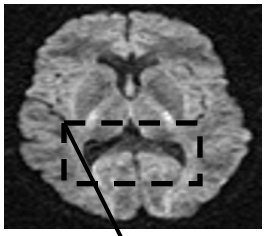
Diffusion weighted images





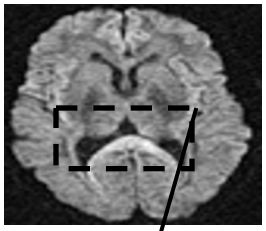


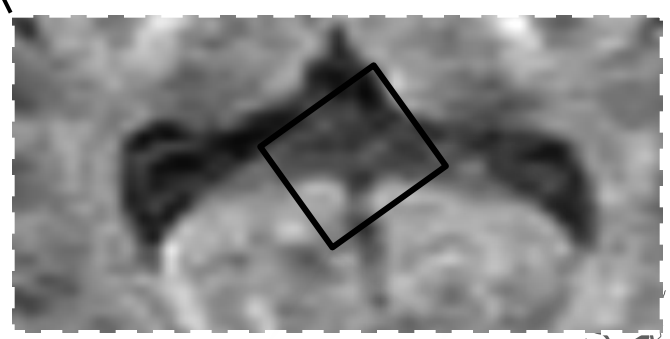
Diffusion weighted images

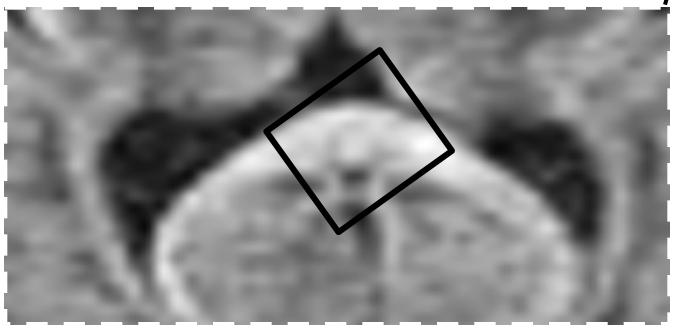


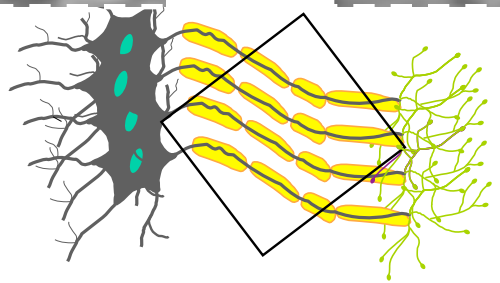
$$\vec{G}^{D} = \begin{pmatrix} G_x & 0 & 0 \end{pmatrix}$$

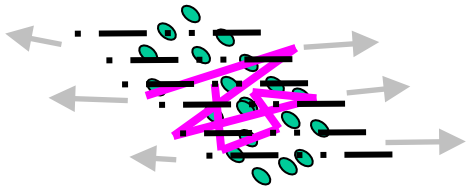
$$\vec{G}^{D} = \begin{pmatrix} 0 & 0 & G_z \end{pmatrix}$$







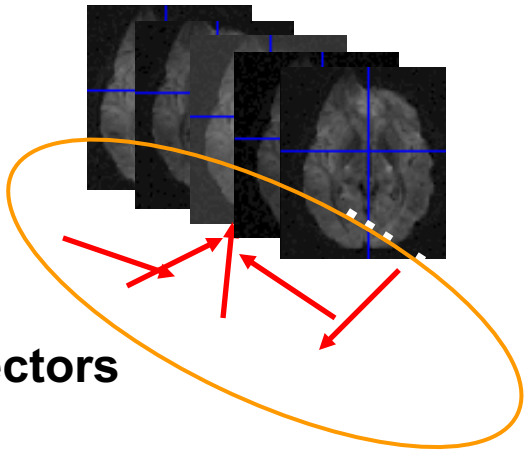




What do we need for diffusion MRI?

Shell 1
(b-value e.g 1000 s/mm²)

***n* DW images**

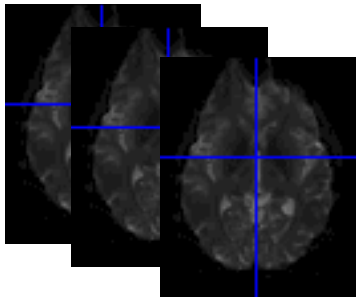


b-vectors

+

Shell 0
(b-value e.g 0 or 100 s/mm²)

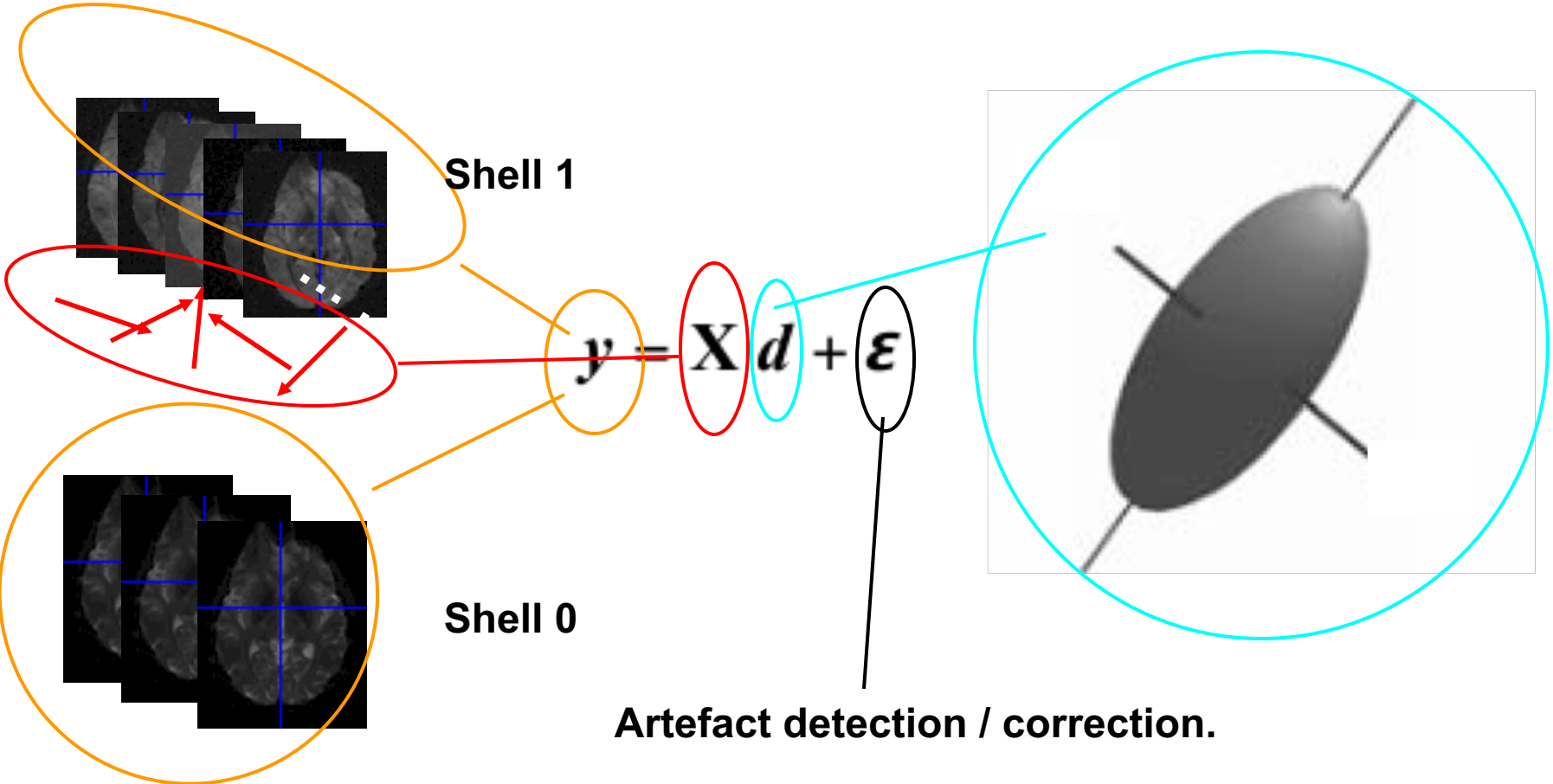
***m* reference images**



+

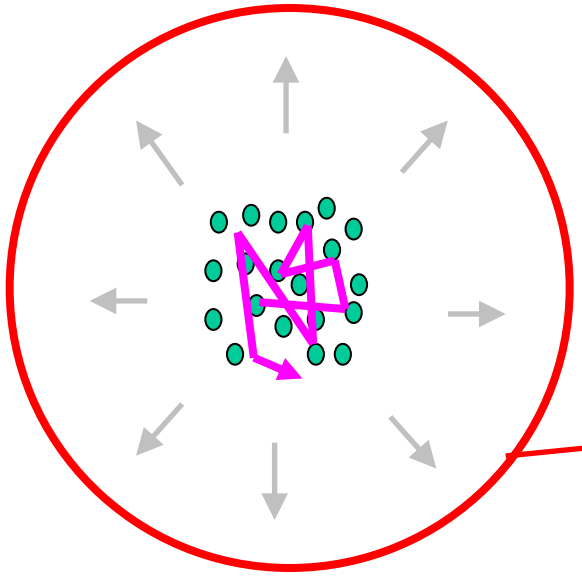
Model

The general linear model framework for diffusion MRI



Diffusion MRI : interpreting fractional anisotropy

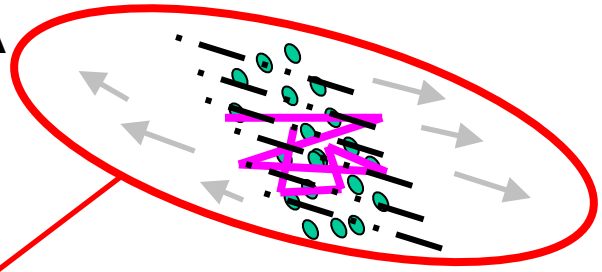
Fractional anisotropy - FA



CSF: Isotropic diffusion

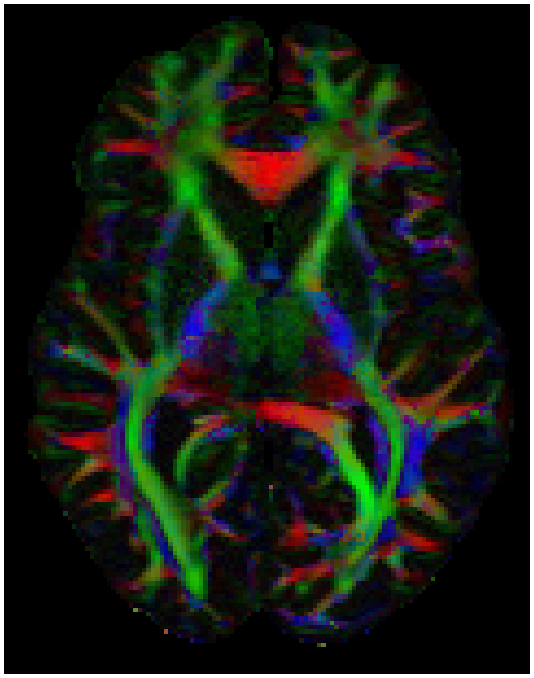
Diffusion MRI : interpreting fractional anisotropy

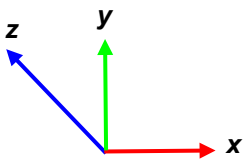
Fractional anisotropy - FA



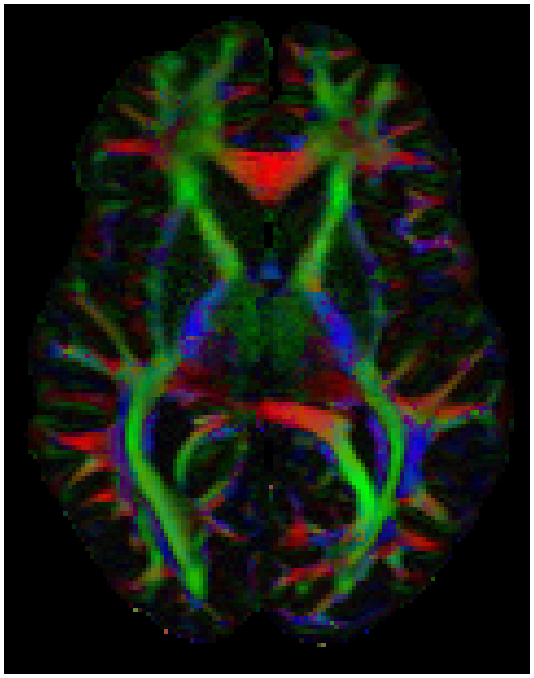
WM: Anisotropic diffusion

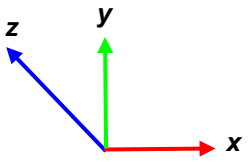
Diffusion MRI reveals orientation information

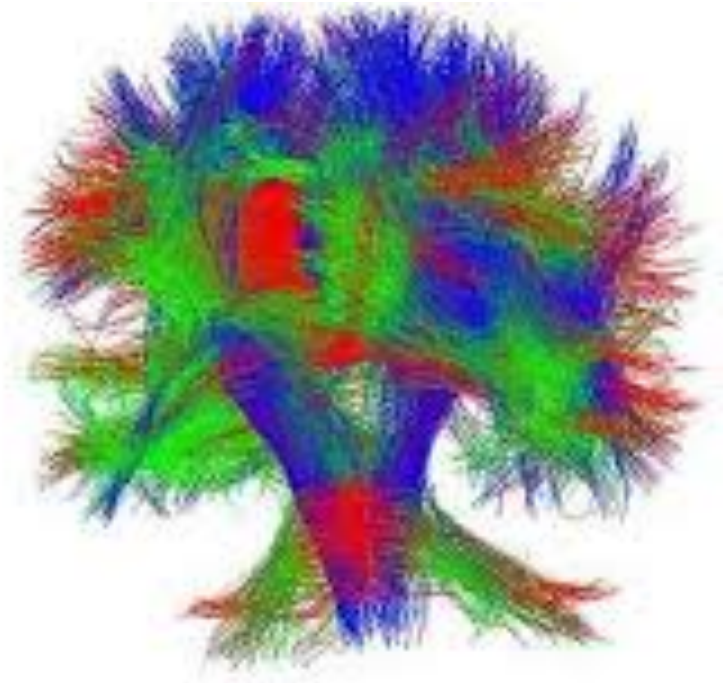




Diffusion MRI reveals orientation information







For tractography in SPM contact Marco Reisert:

https://www.uniklinik-freiburg.de/mr-en/members/current/reisert/

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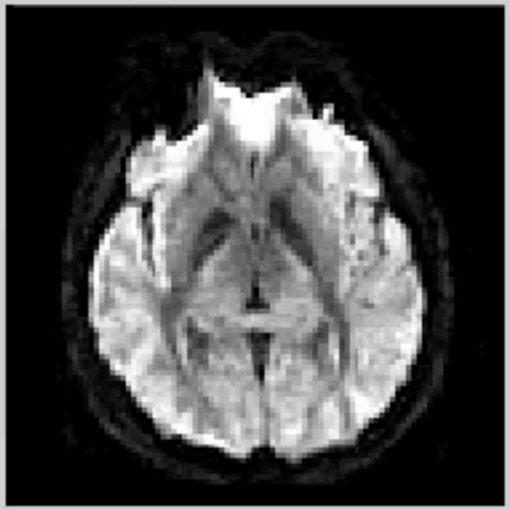
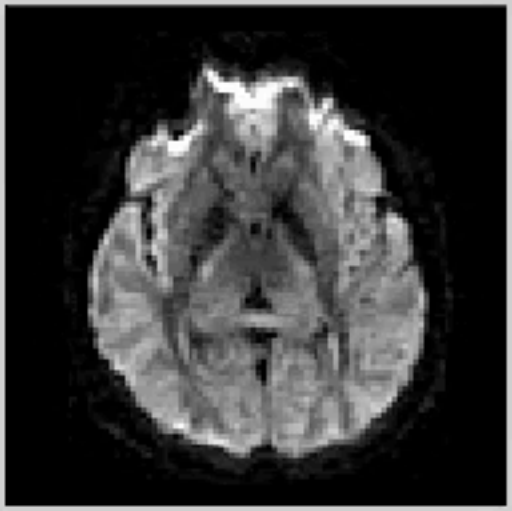
EC and Motion correction

Single spin echo



Double spin echo



Stejskal & Tanner, JCP, 1965

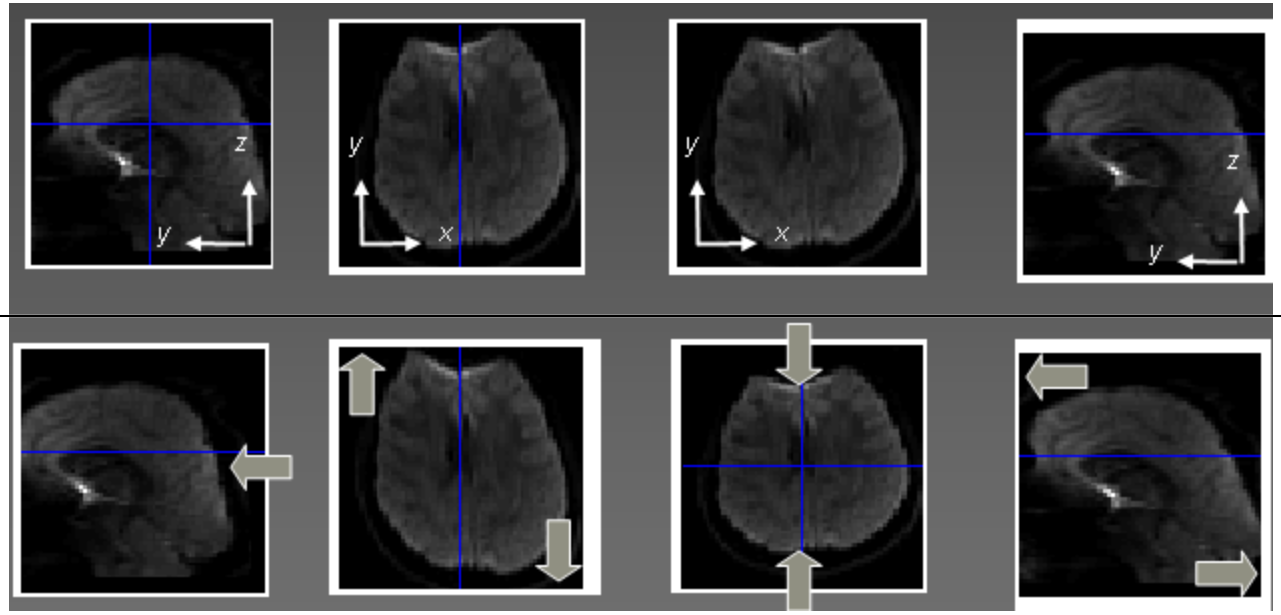
Reese et al., MRM, 2003

Mohammadi et al., Frontiers, 2015

Whole-brain eddy current distortions

original image

distorted image



translation | in-plane shearing | scaling | through-plane shearing

eddy current field components

$$B_0^{EC} \rightarrow \begin{pmatrix} G_x^{EC} \\ 0 \\ 0 \end{pmatrix} \quad \uparrow \begin{pmatrix} 0 \\ G_y^{EC} \\ 0 \end{pmatrix} \quad \uparrow \begin{pmatrix} 0 \\ 0 \\ G_z^{EC} \end{pmatrix}$$

Mohammadi et al., MRM, 2010

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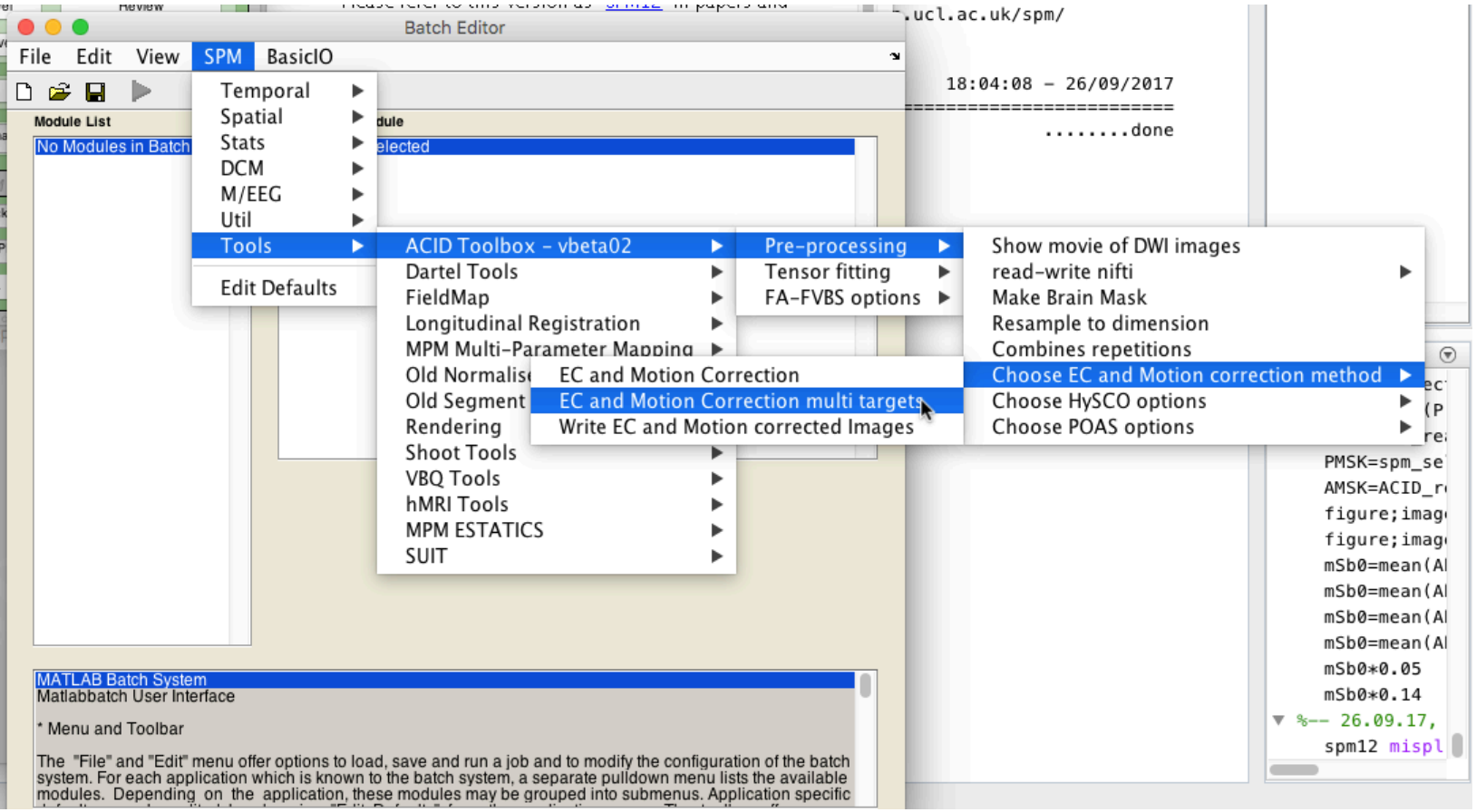
Eddy current and motion correction toolbox



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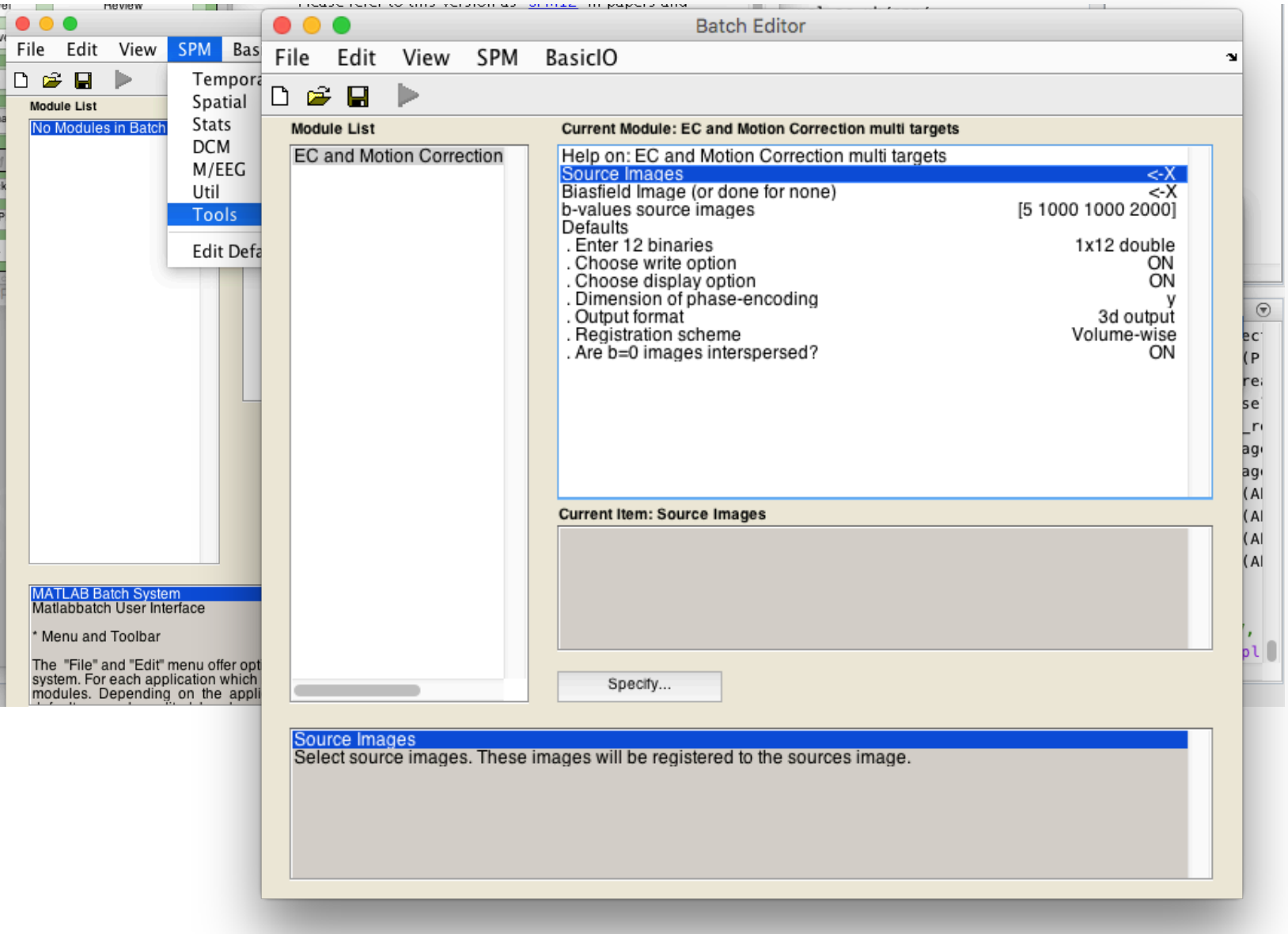

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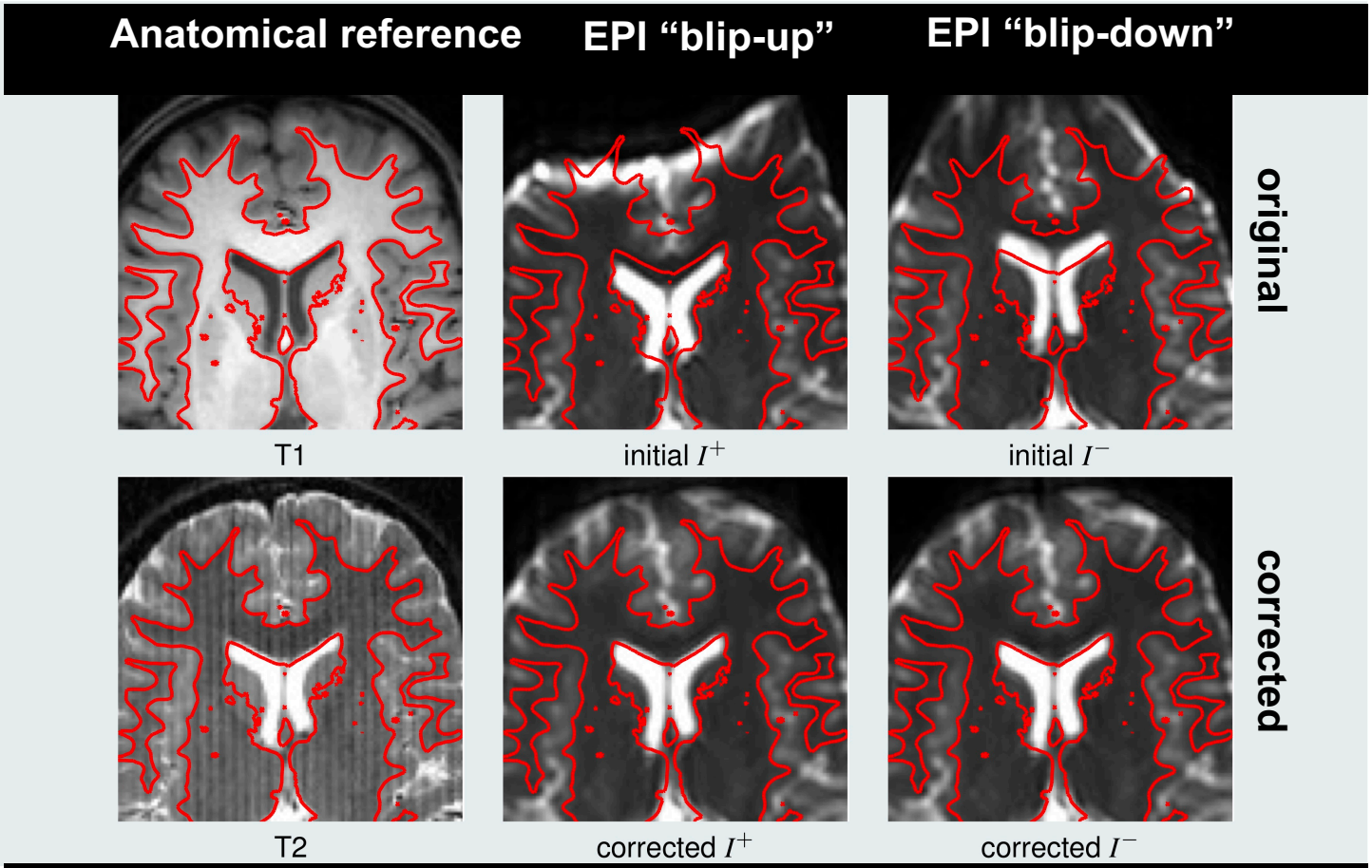
ACID - HYSCO
EPI distortion correction

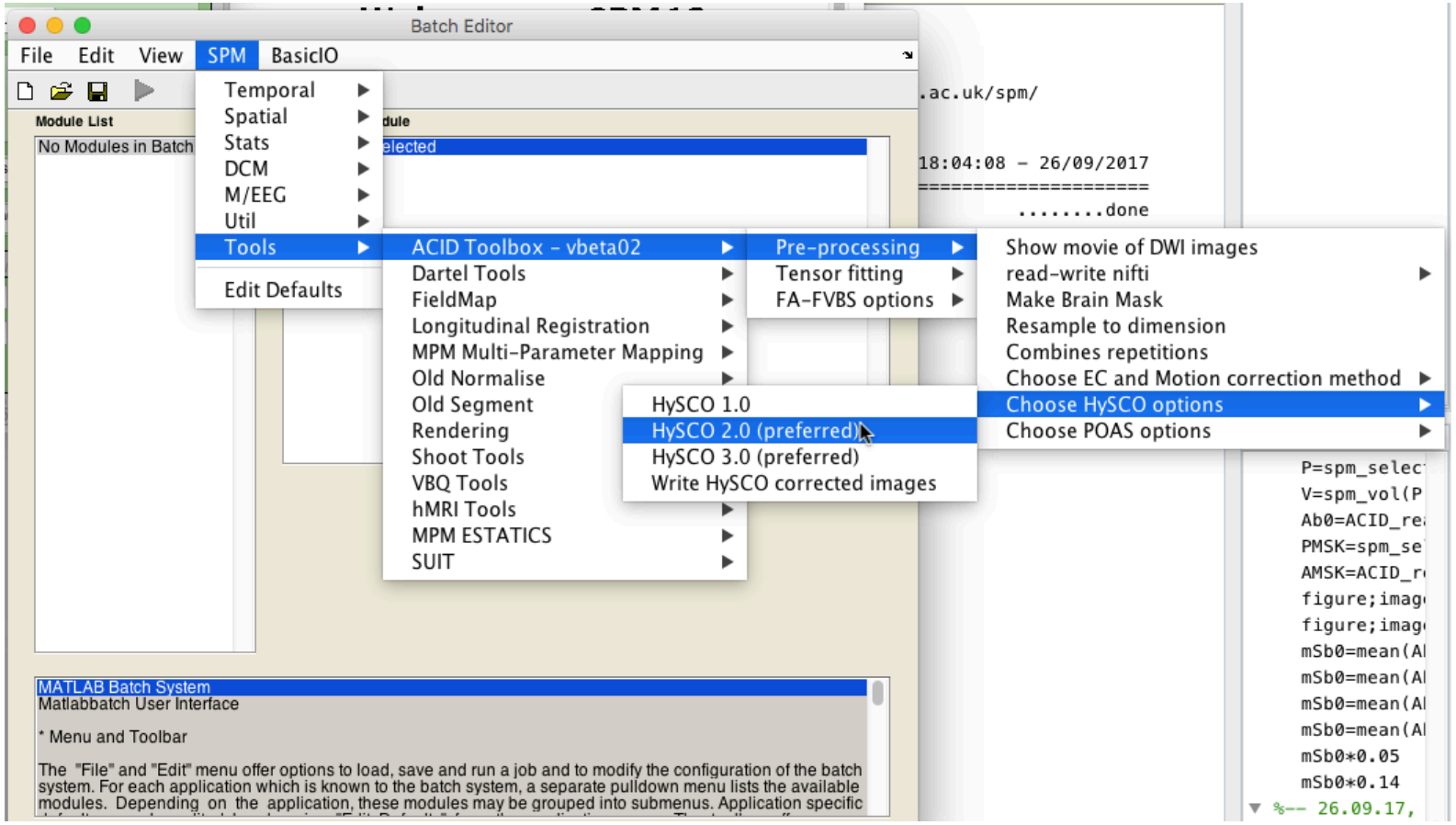
UNIVERSITÄT ZU LÜBECK
INSTITUTE OF MATHEMATICS AND IMAGE COMPUTING

Lars Ruthotto
Susceptibility Artifact Correction



Ruthotto et al., Phys Med Biol, 2012; Ruthotto et al., BVM, 2013

ACID - HYSCO
EPI distortion correction



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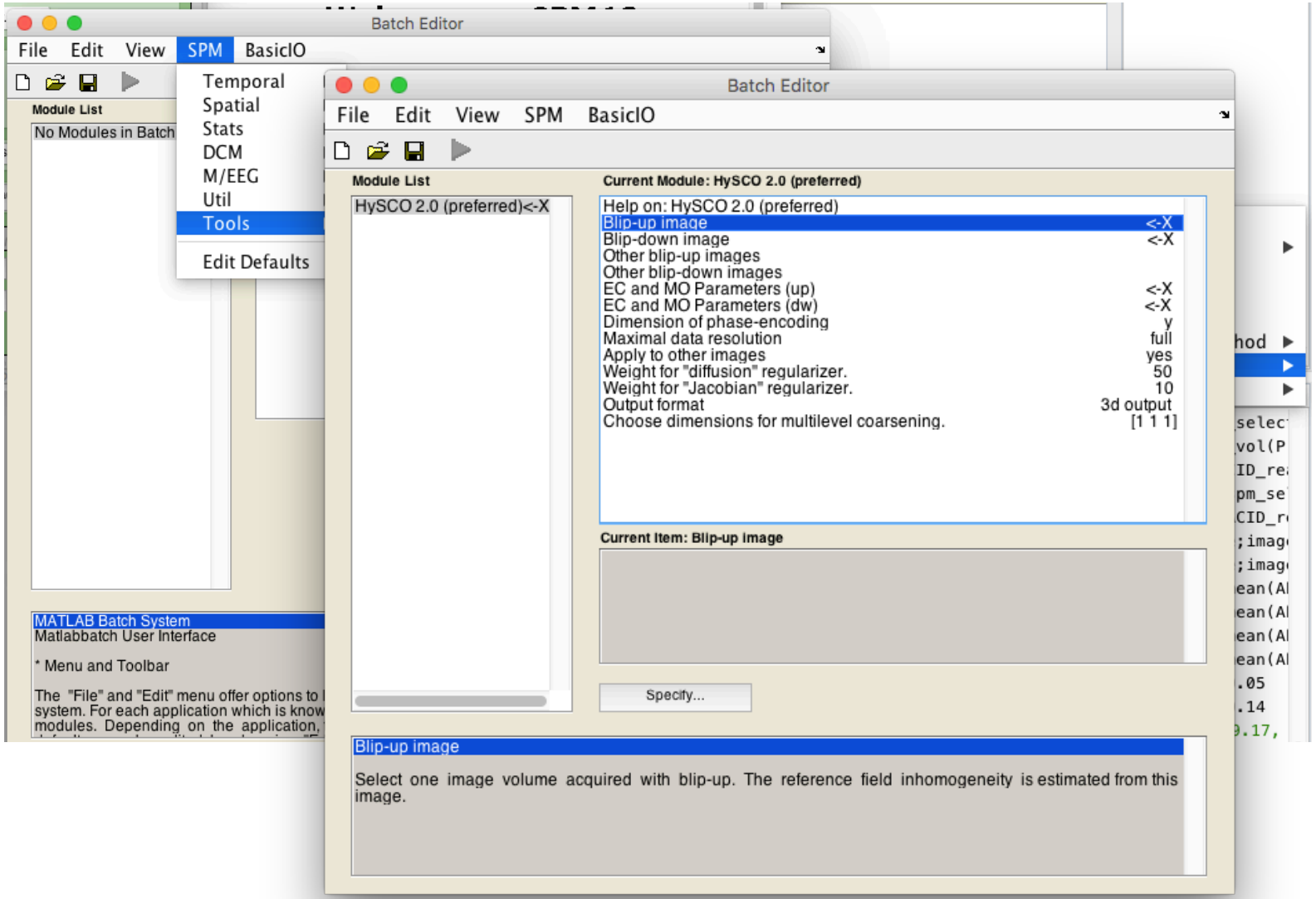
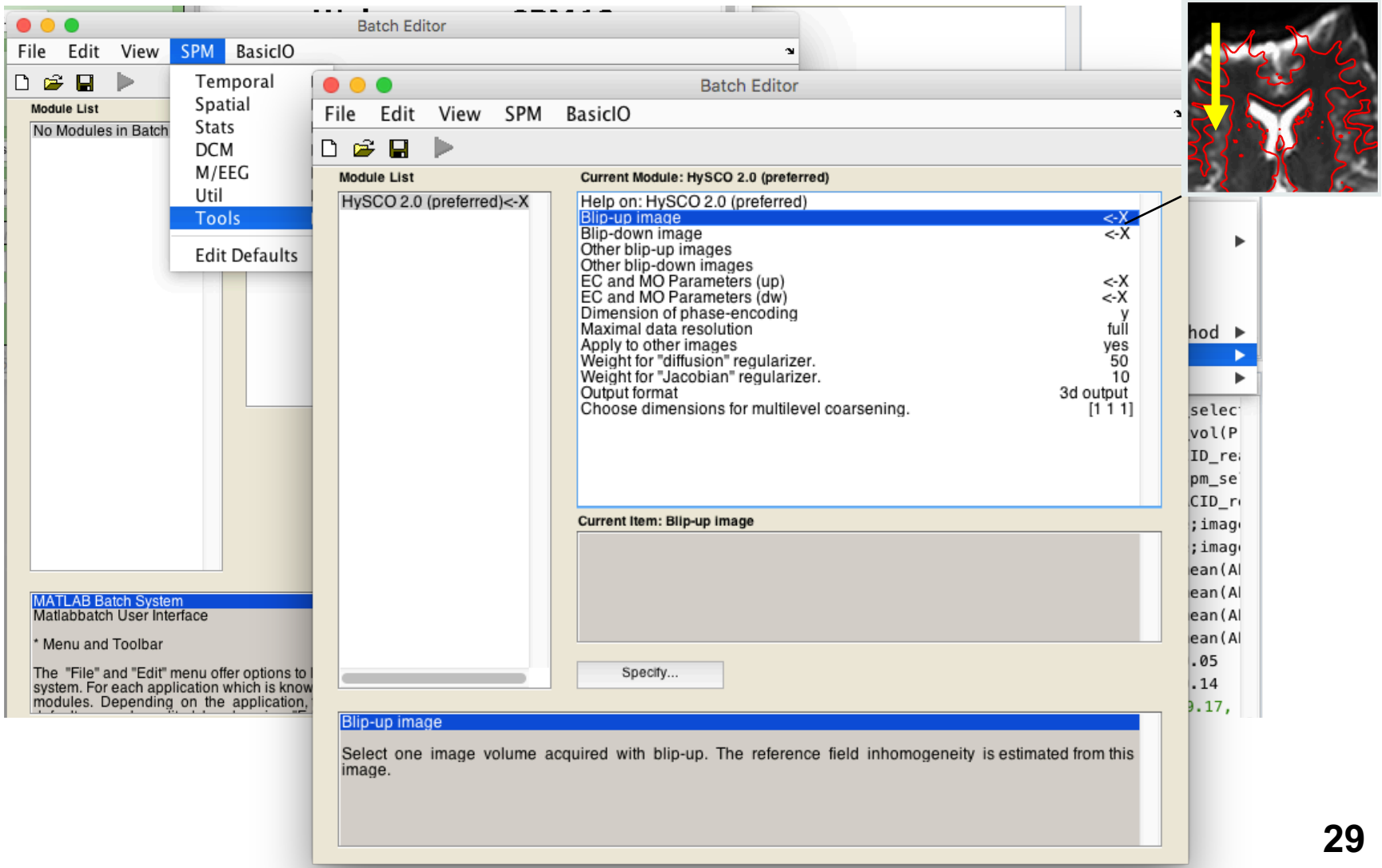
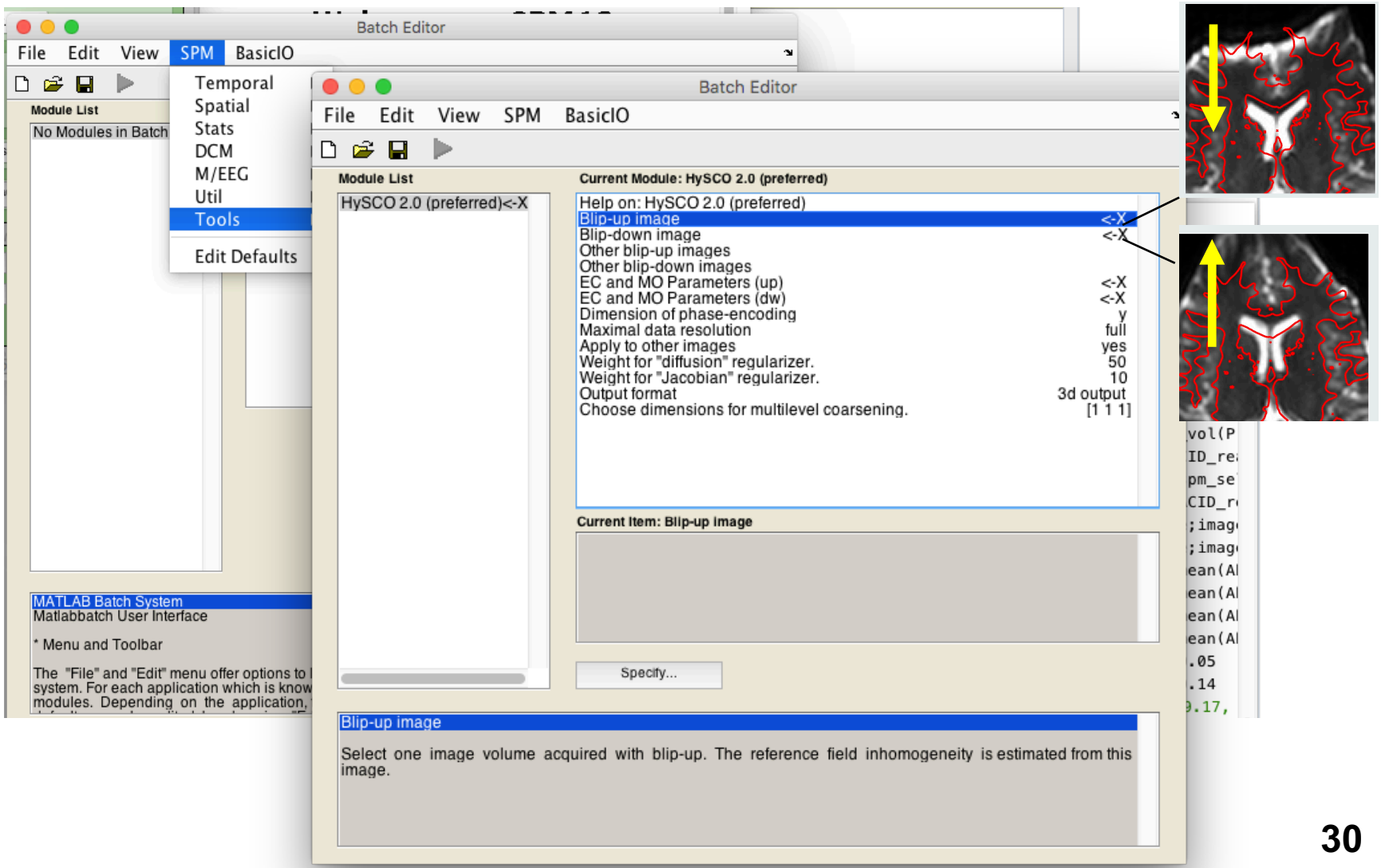
EPI distortion correction



ACID - HYSCO
EPI distortion correction



ACID - HYSCO
EPI distortion correction



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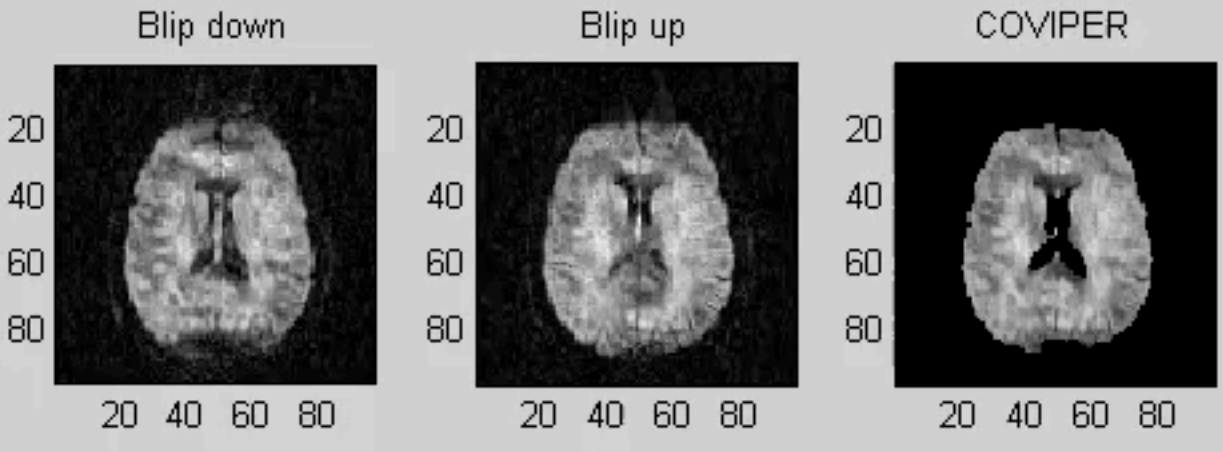
Vibration artifacts and its correction



Correction of Vibration Artifacts in DTI Using Phase-Encoding Reversal (COVIPER)

Mohammadi et al., MRM, 2012

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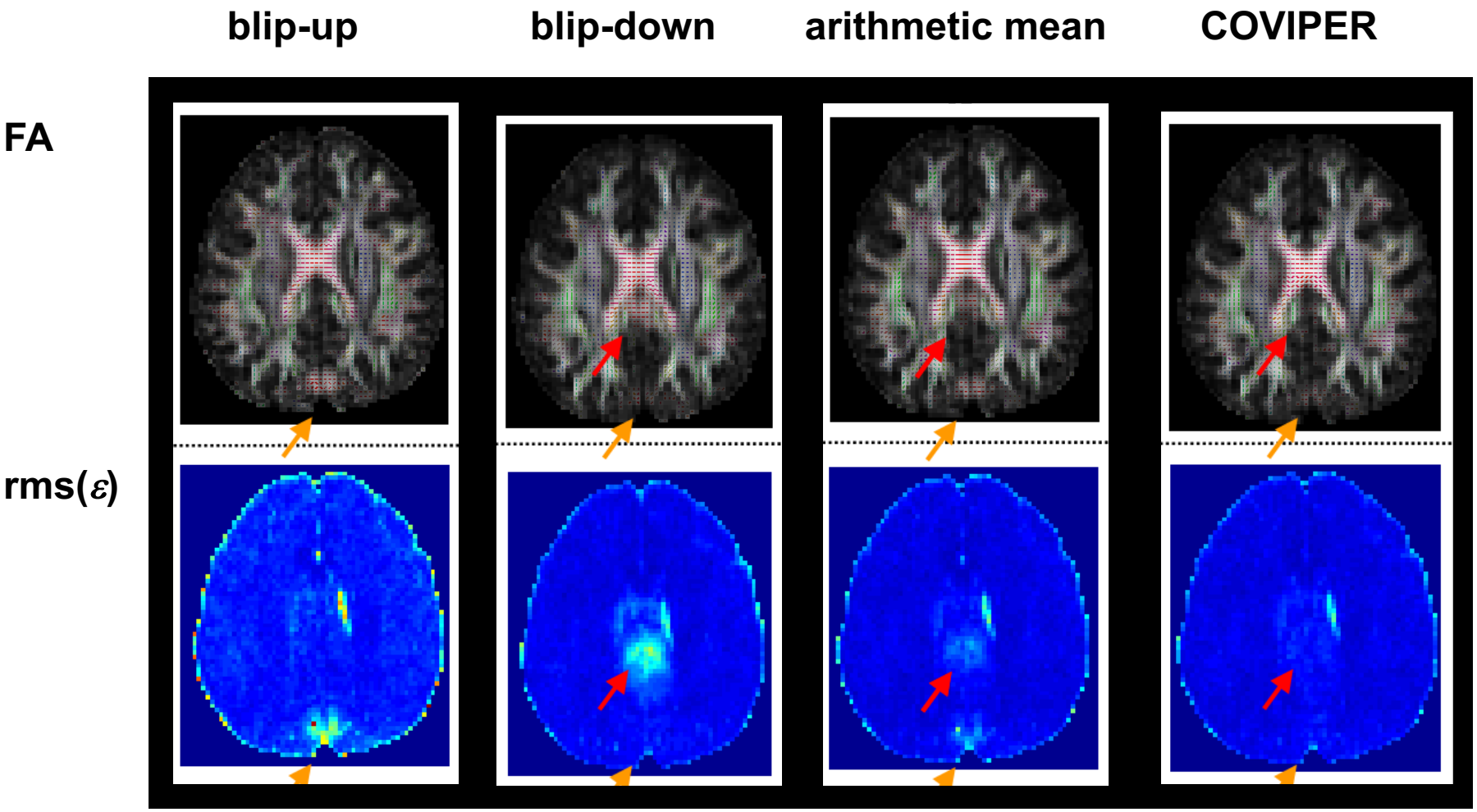
Correction of vibration artefacts in DTI using phase-encoding reversal (COVIPER)



Mohammadi et al., MRM, 2012

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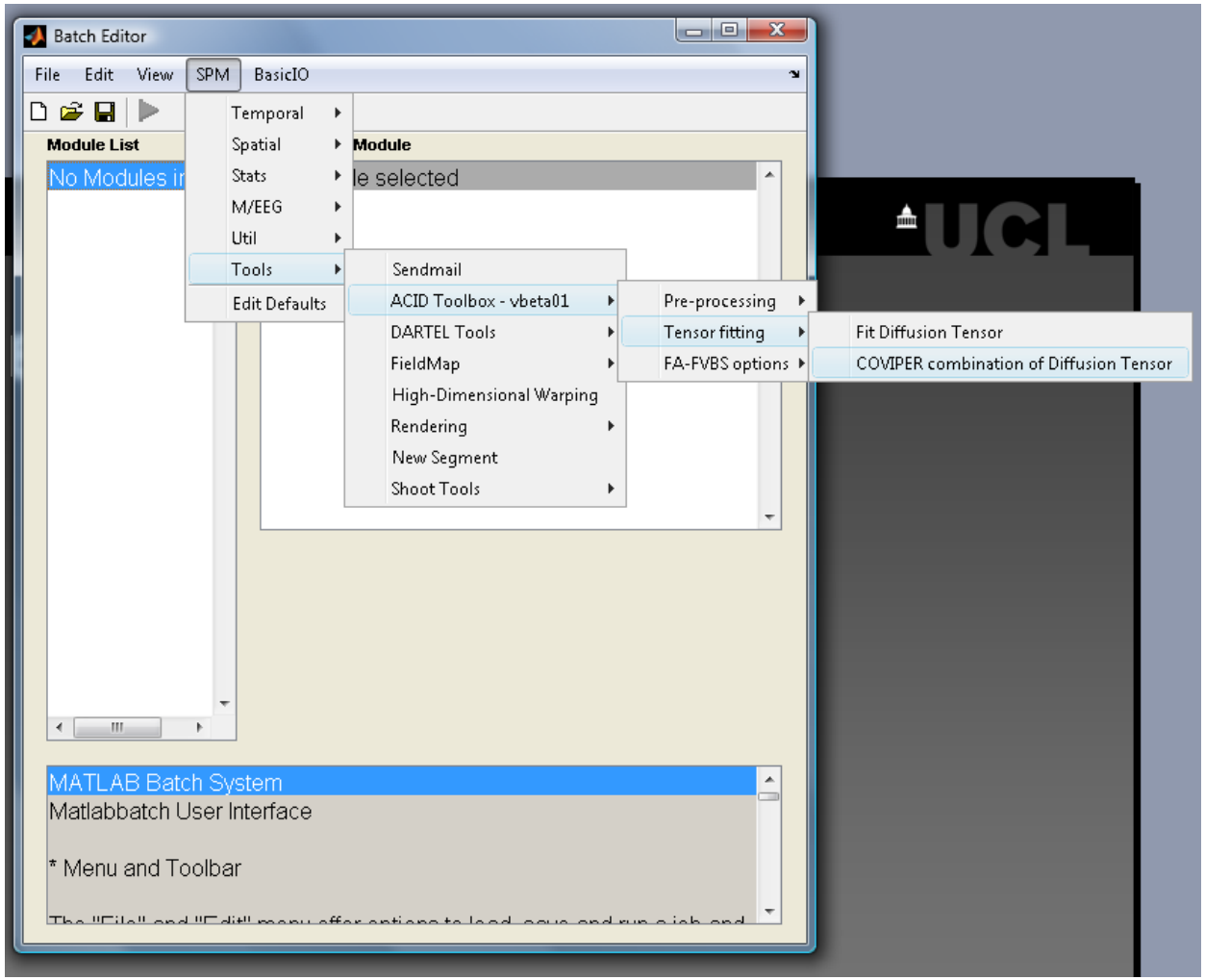
ACID-COVIPER tool
Vibration artefacts



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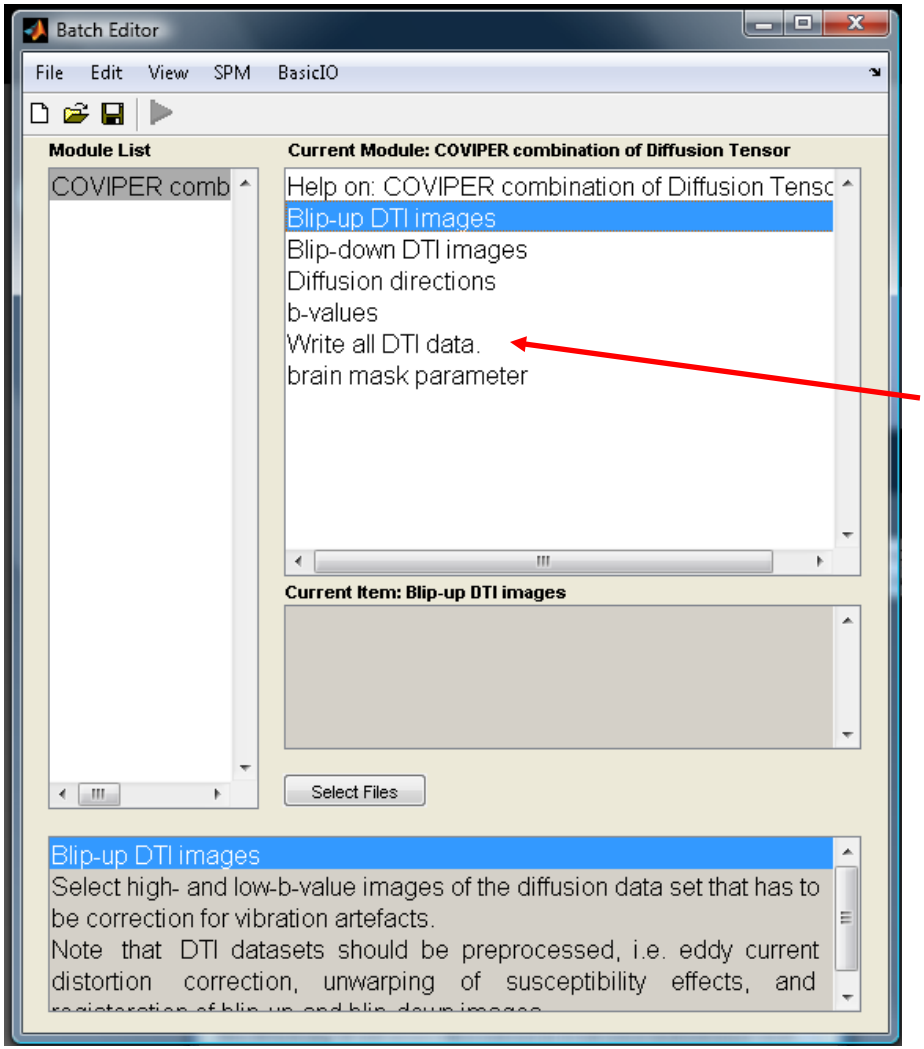
ACID-COVIPER tool
Vibration artefacts



Corrected DTI dataset

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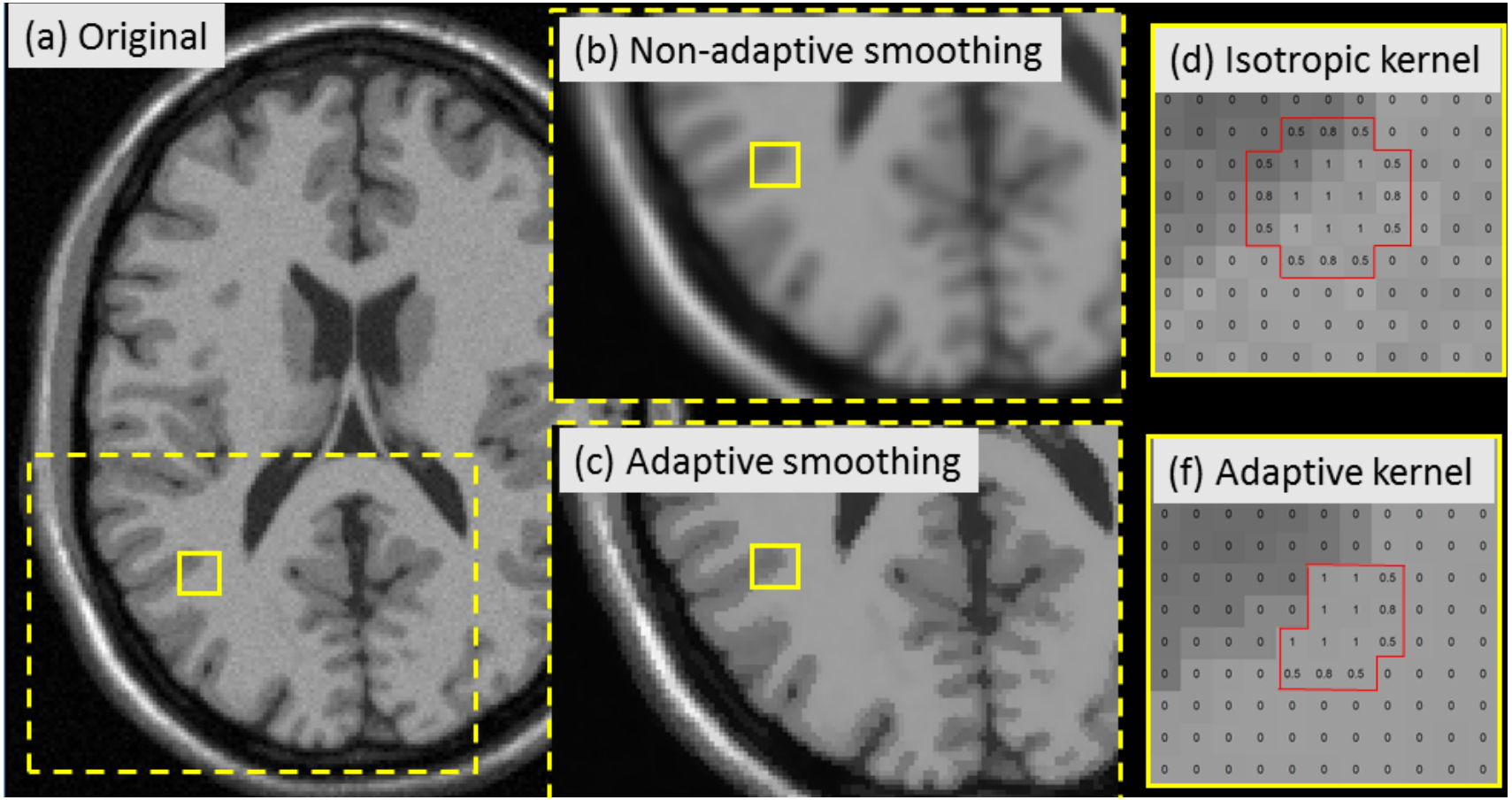
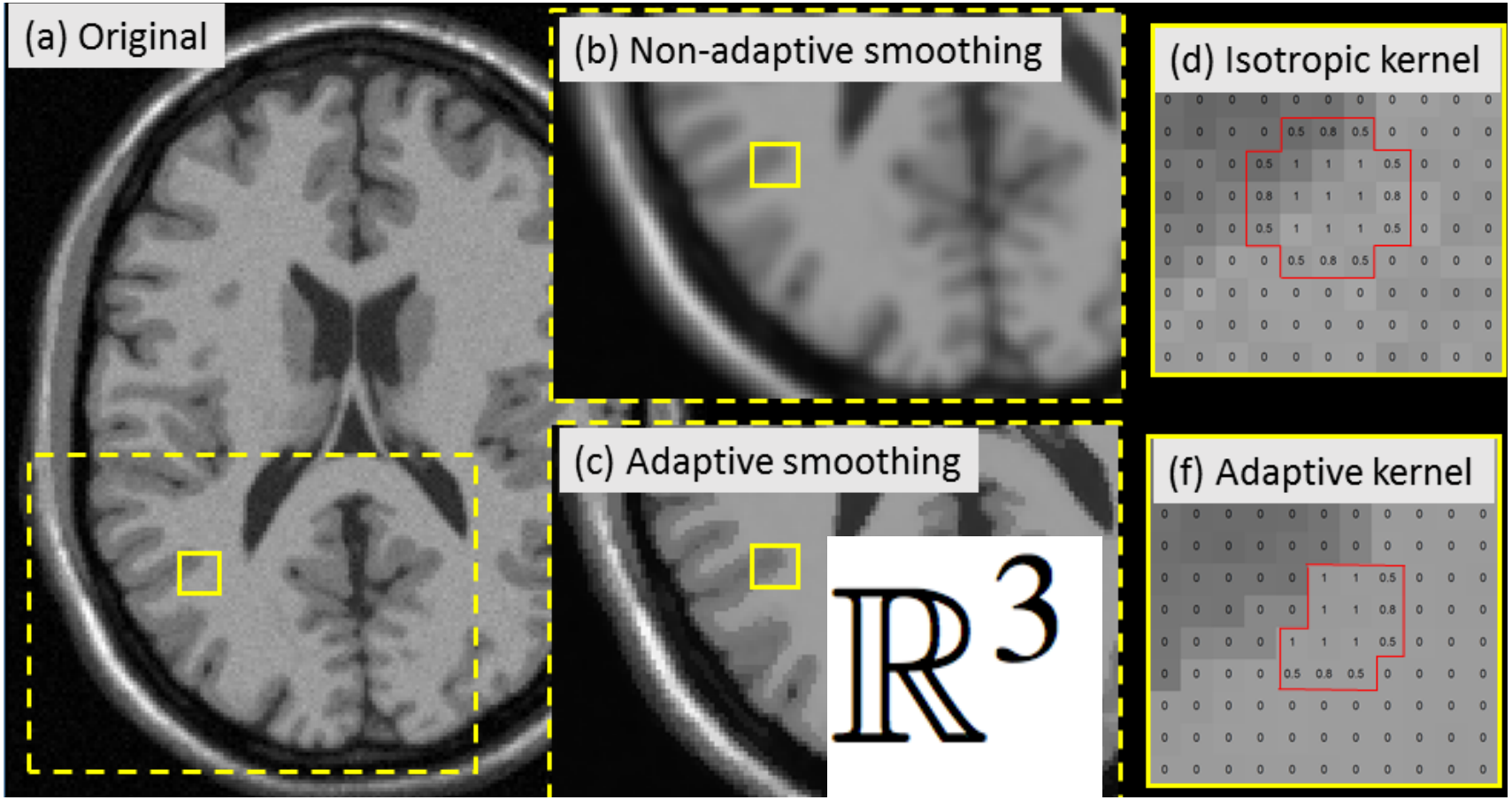
What is adaptive denoising?



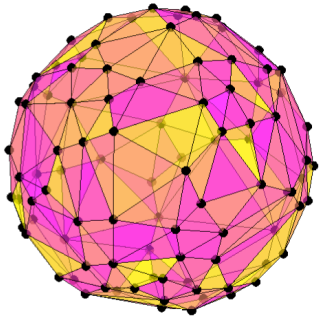
What is adaptive denoising?



Position-orientation adaptive smoothing (POAS)

$\mathbb{R}^3$

$\mathbb{S}^2$

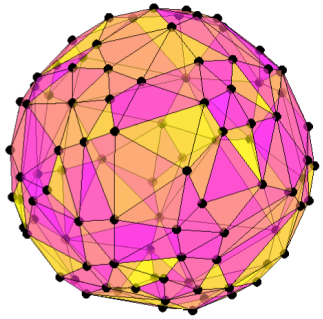


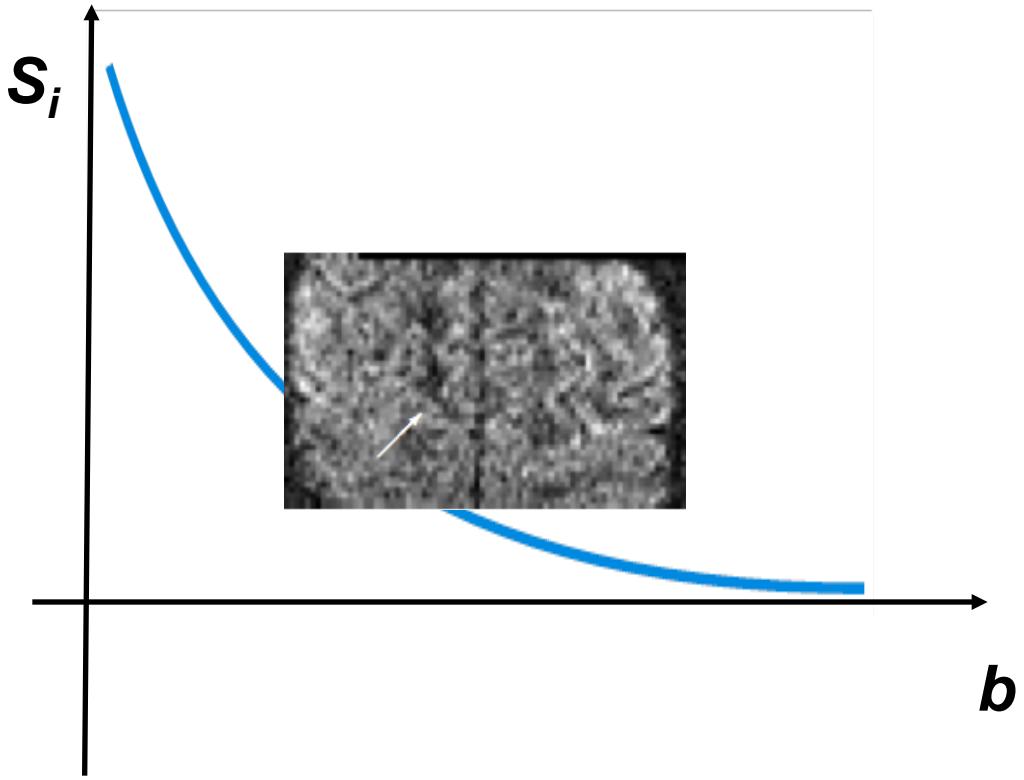
WIAS: Becker et al., 2013

Multi-shell position-orientation adaptive smoothing (msPOAS)

$\mathbb{R}^3$

$\mathbb{S}^2$





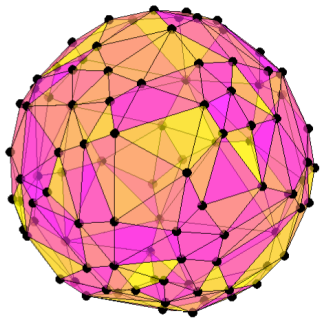
Multiple shells

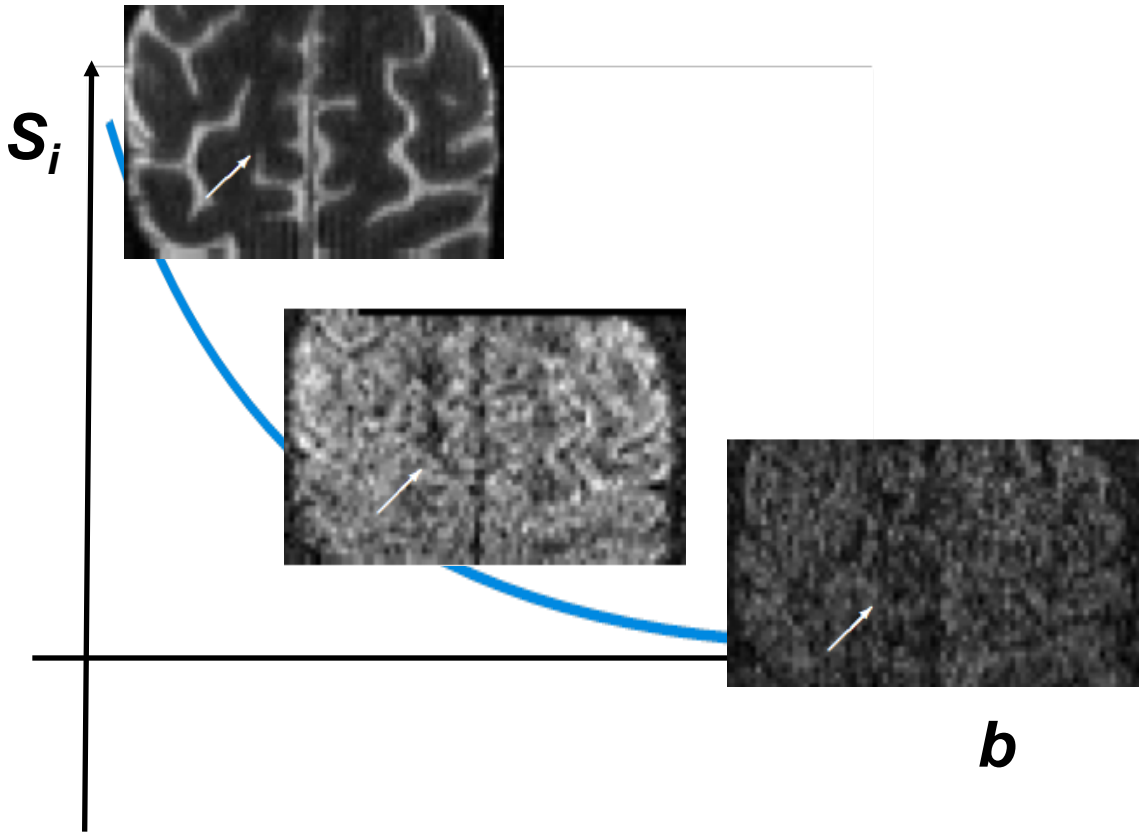
WIAS – Hamburg: Becker et al., 2014; Tabelow/Mohammadi et al., 2015

Multi-shell position-orientation adaptive smoothing (msPOAS)

$\mathbb{R}^3$

$\mathbb{S}^2$

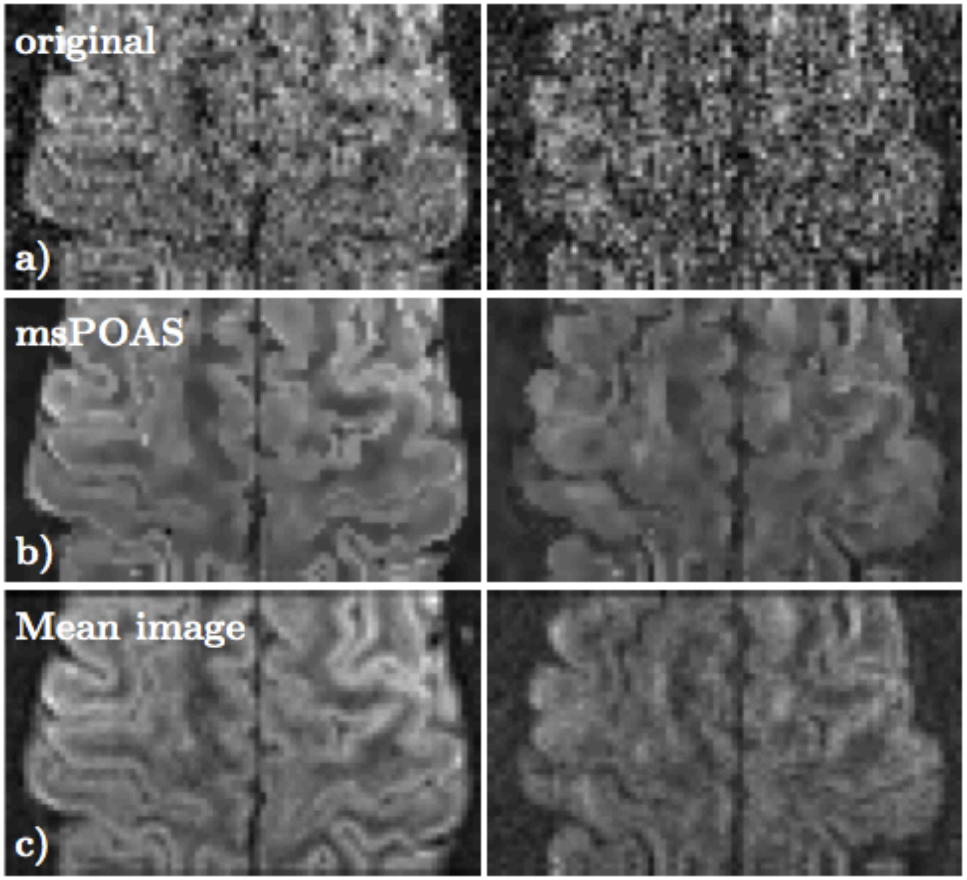




Multiple shells

WIAS – Hamburg: Becker et al., 2014; Tabelow/Mohammadi et al., 2015

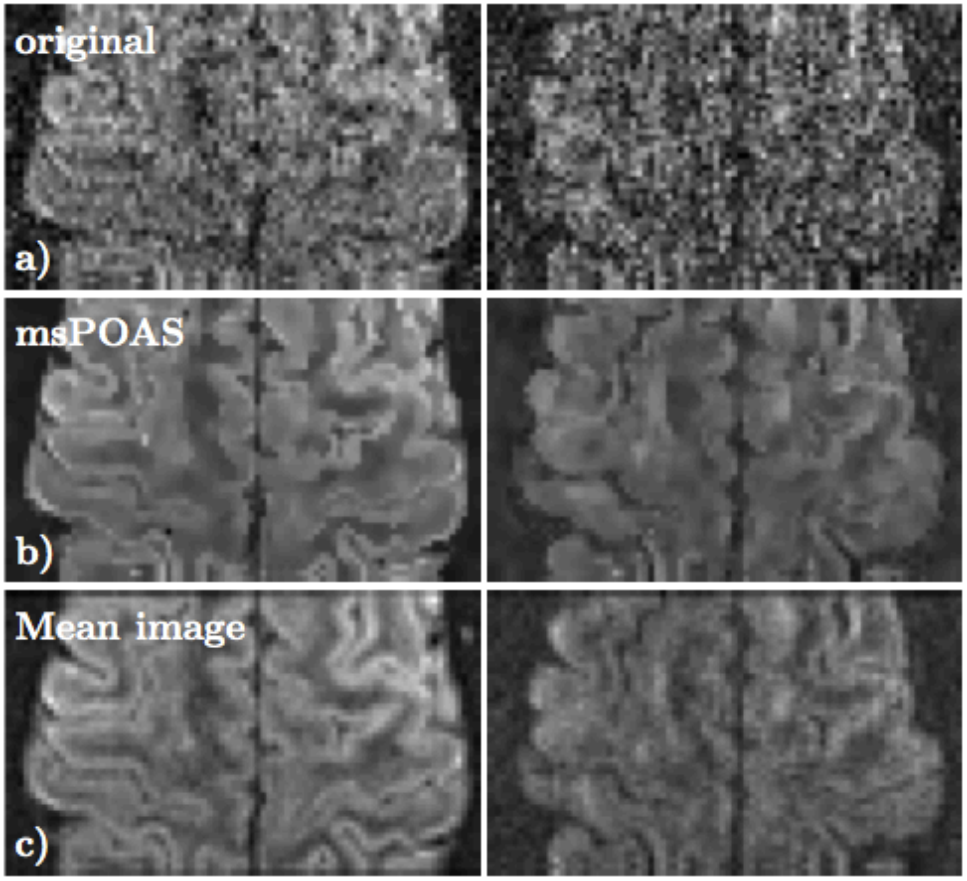
msPOAS in cortex DWI

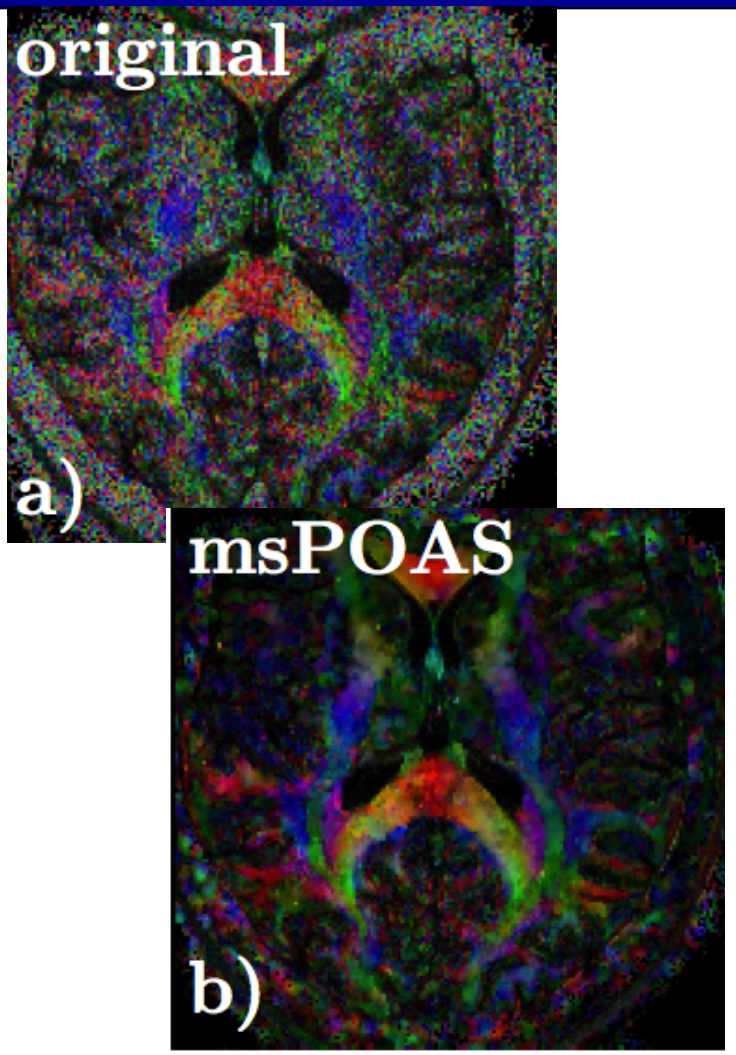


- **Multi-shell dMRI**
- **@1.2 x 1.2 x 1.2 mm^3**
- **@ 3T clinical scanner**

Becker et al., MIA, 2012, Becker et al., 2014

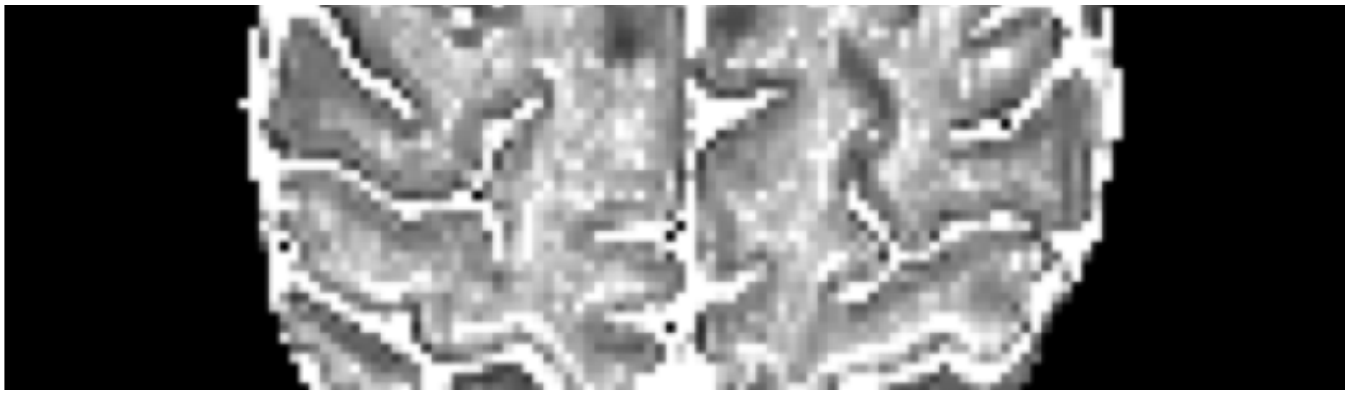
msPOAS in cortex DWI and across brain



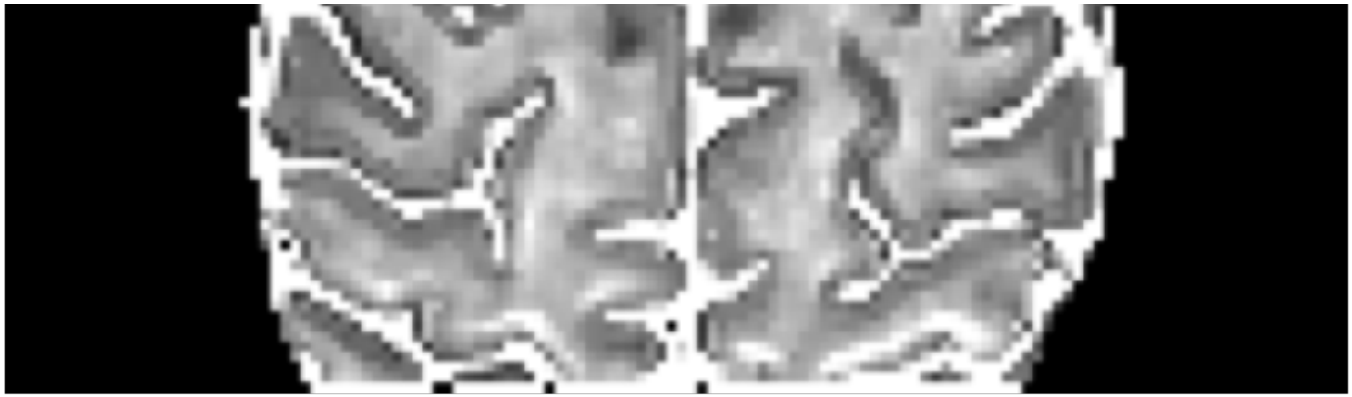


Becker et al., MIA, 2012, Becker et al., 2014

ACID toolbox – msPOAS
NODDI: Intracellular compartment



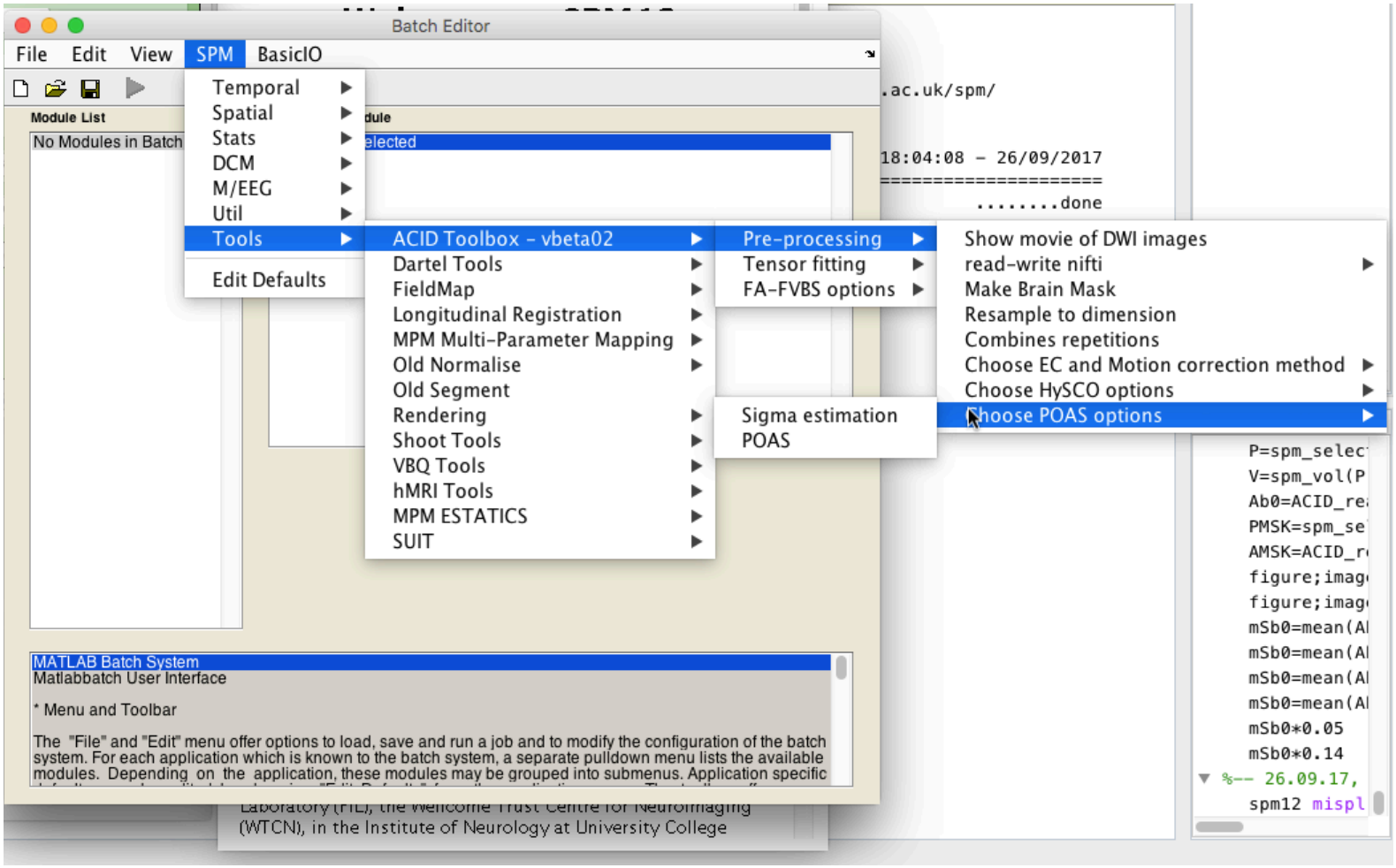
Original



msPOAS

Mohammadi et al., Frontiers in Neuroscience, 2015

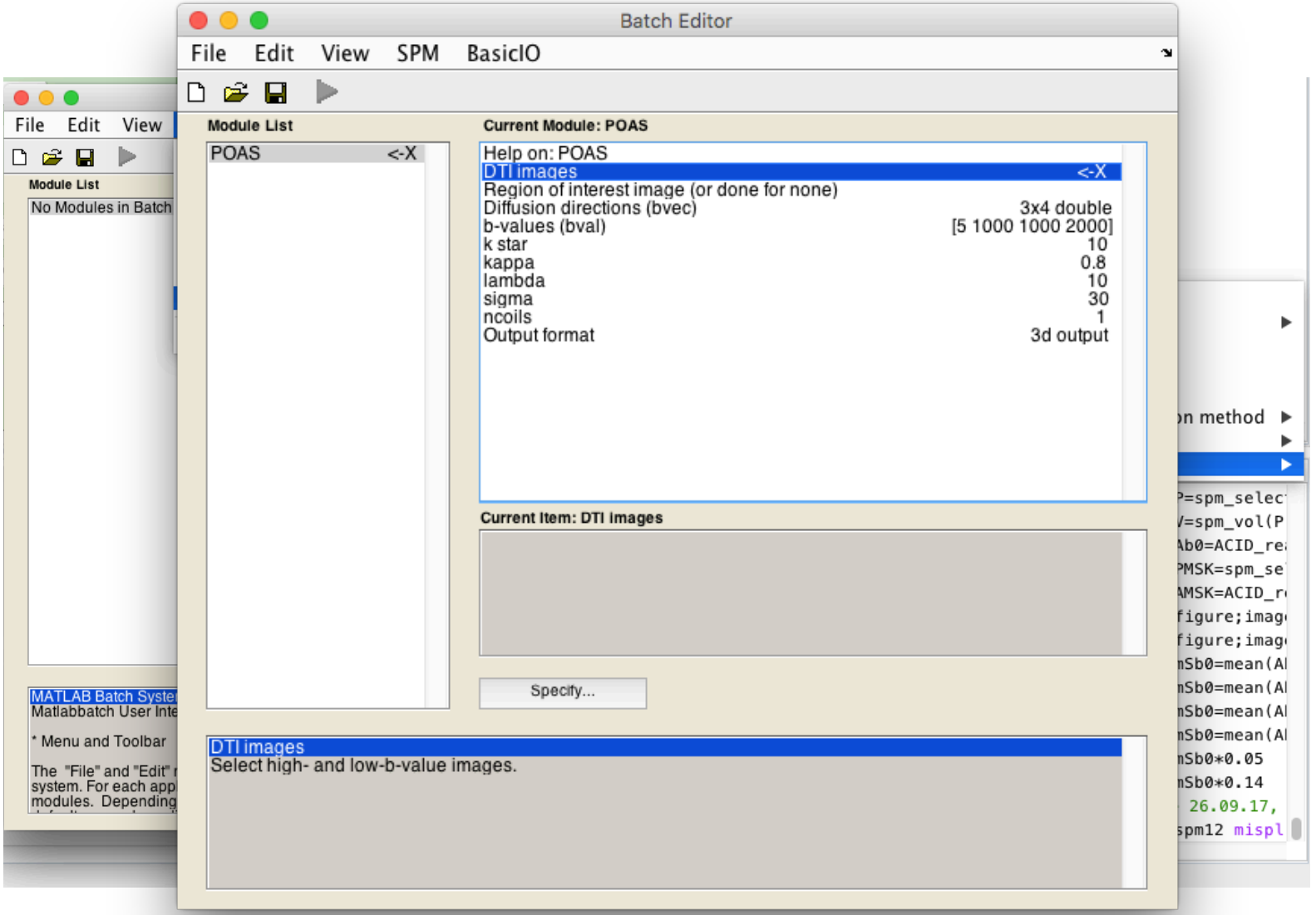
Denoising: multi-shell orientation-position adaptive smoothing (msPOAS)



Tabelow/Mohammadi et al., Neuroinformatics, 2015

Universitätsklinikum Hamburg-Eppendorf

Denoising: multi-shell orientation-position adaptive smoothing (msPOAS)

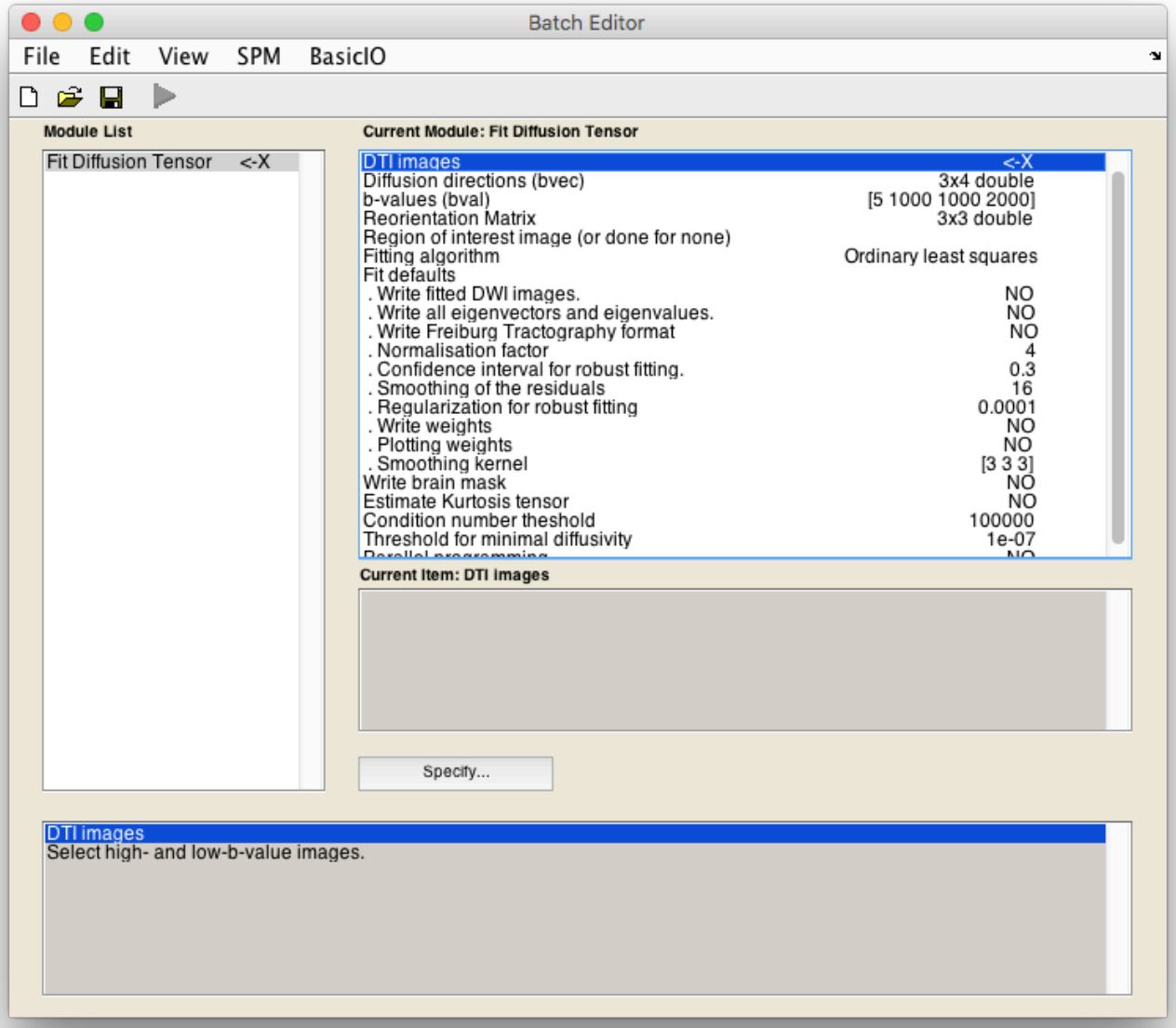


Tabelow/Mohammadi et al., Neuroinformatics, 2015

Outline

- Diffusion MRI: why, how, and what does it mean?
- Pre-processing steps
  - Eddy current and motion correction
  - Susceptibility artefacts correction
  - Vibration artefact correction
  - Position-orientation adaptive smoothing
- Diffusion models
  - Weighted Ordinary Least Squares, Robust Tensor Fitting
  - Kurtosis Tensor Imaging
  - NODDI-DTI

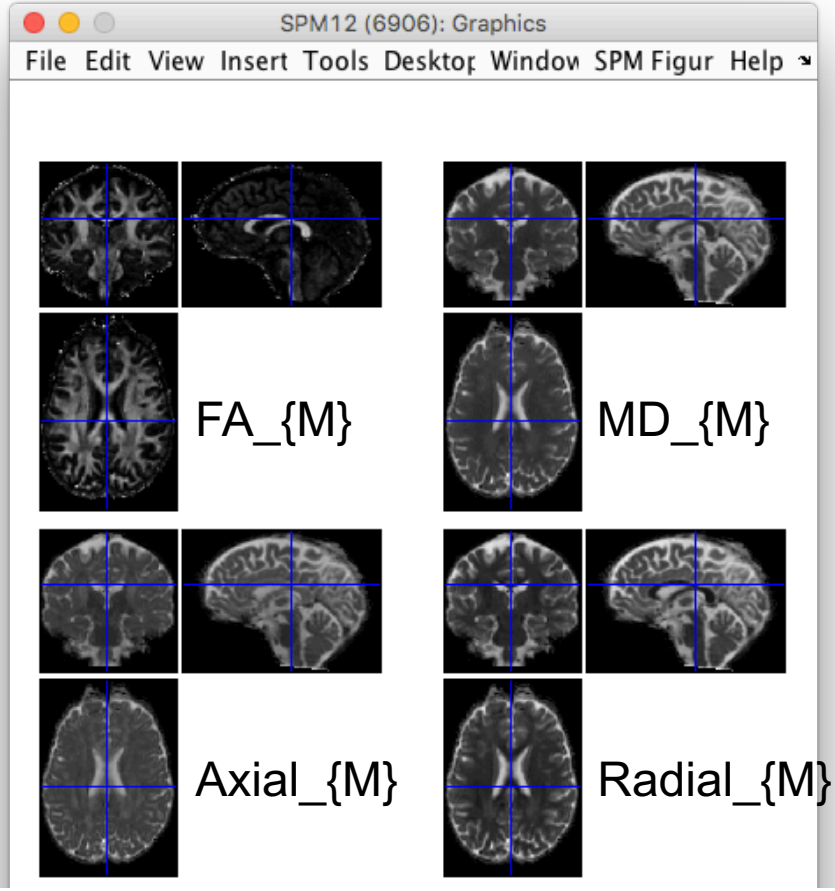
What are the inputs?



Most important

- Diffusoin Data
- b-values
- b-vectors

What are the outputs?



{M} = method:

- ols: ordinary least square
- wls: weighted ordinary least square
- robust: robust fitting
- *More details here:*
  - *Mohammadi et al., MRM, 2012;*
  - *Mohammadi et al., NI, 2013*

More advanced:

- Tensor fit error: RES_{M}
- Eigenvalues and Eigenvectors
- Output for Freiburg Fibertools (Tractography – contact Marco Reisert / Volkmar Glauche)

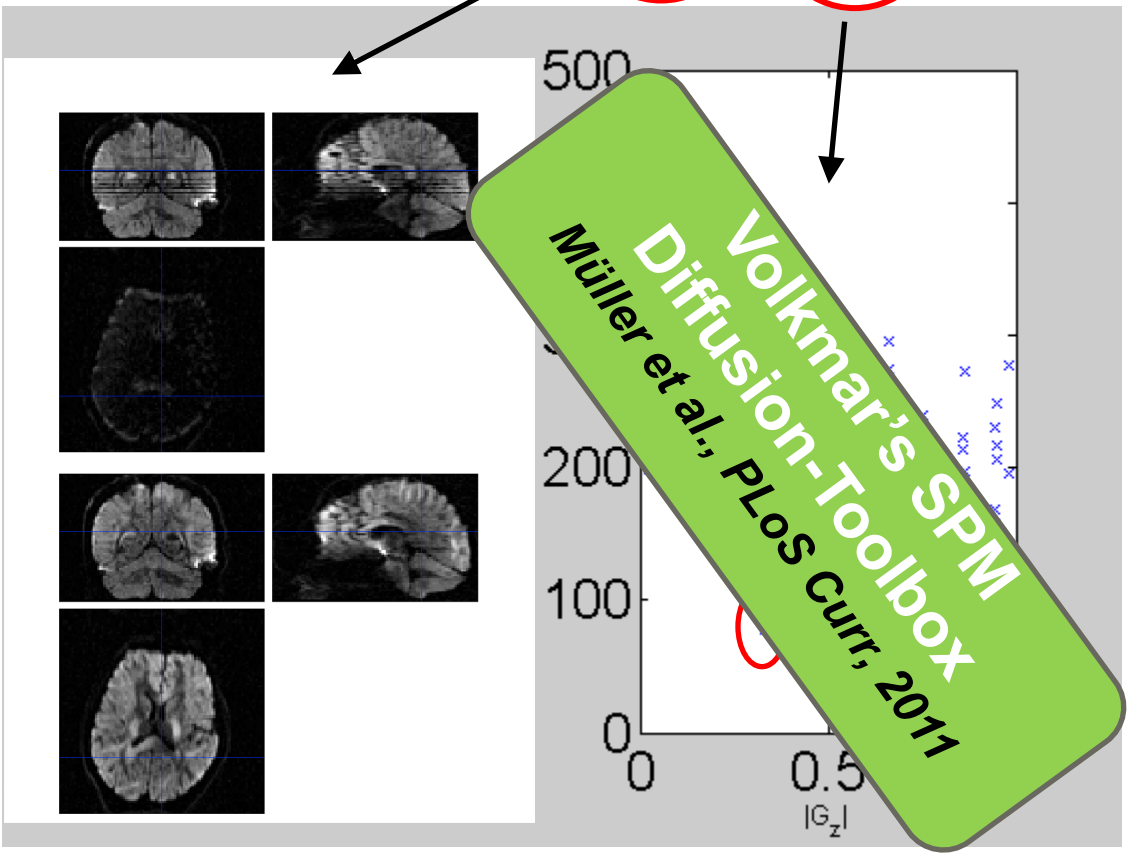
Learn more about the DTI metrics:
Basser et al. 1996; Diffusion MRI…, Ed: H Johansen-Berg & TEJ Behrens, 200?

Robust tensor fitting for spinal cord DTI

Based on Zwiers, NI, 2010

$$y = \mathbf{X}\, d + \varepsilon$$

$$\omega = \omega_{\mathrm{DWI}} \times \omega_{\mathrm{s}} \times \omega_{\mathrm{v}}$$



Mohammadi et al., MRM, 2012
Mohammadi et al., NI, 2013

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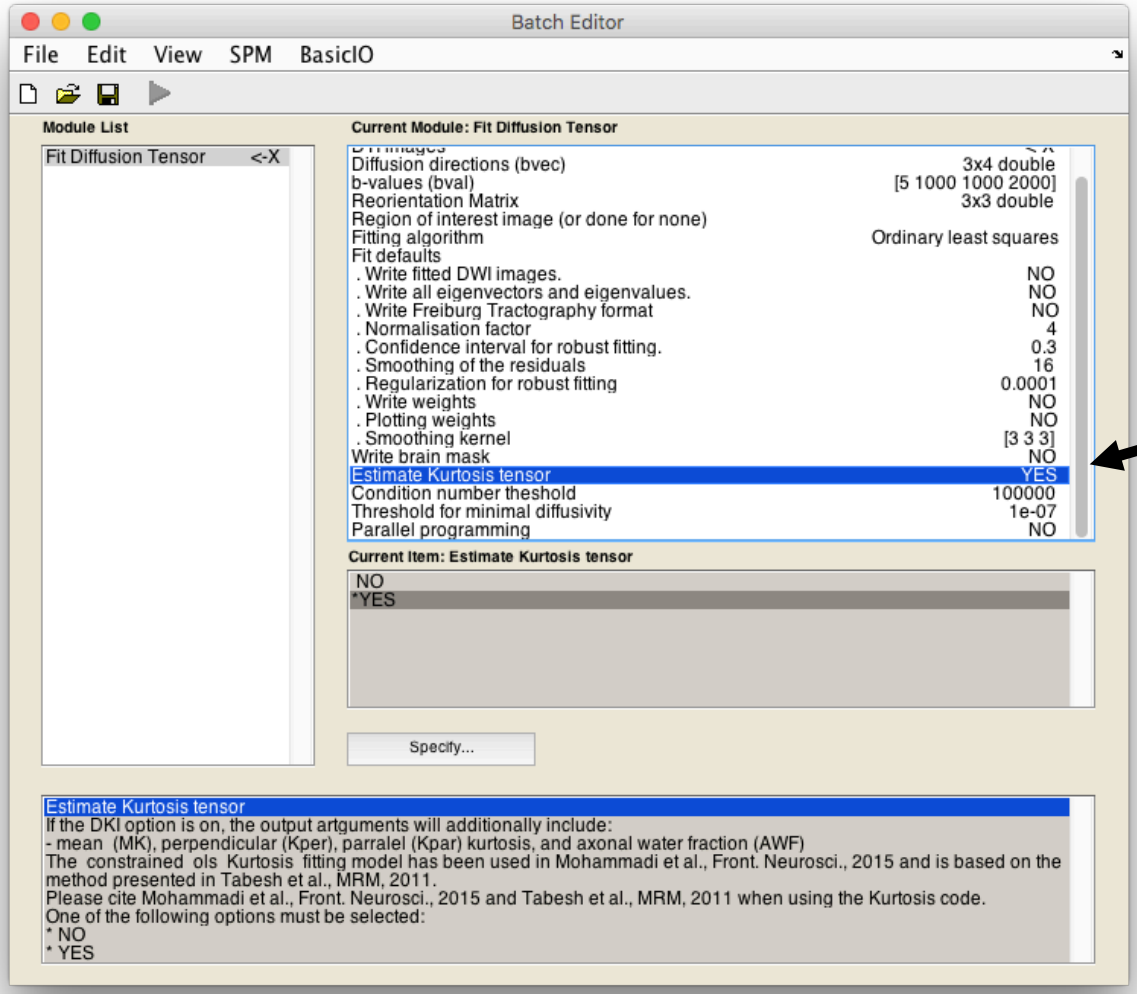
What is the DKI switch?

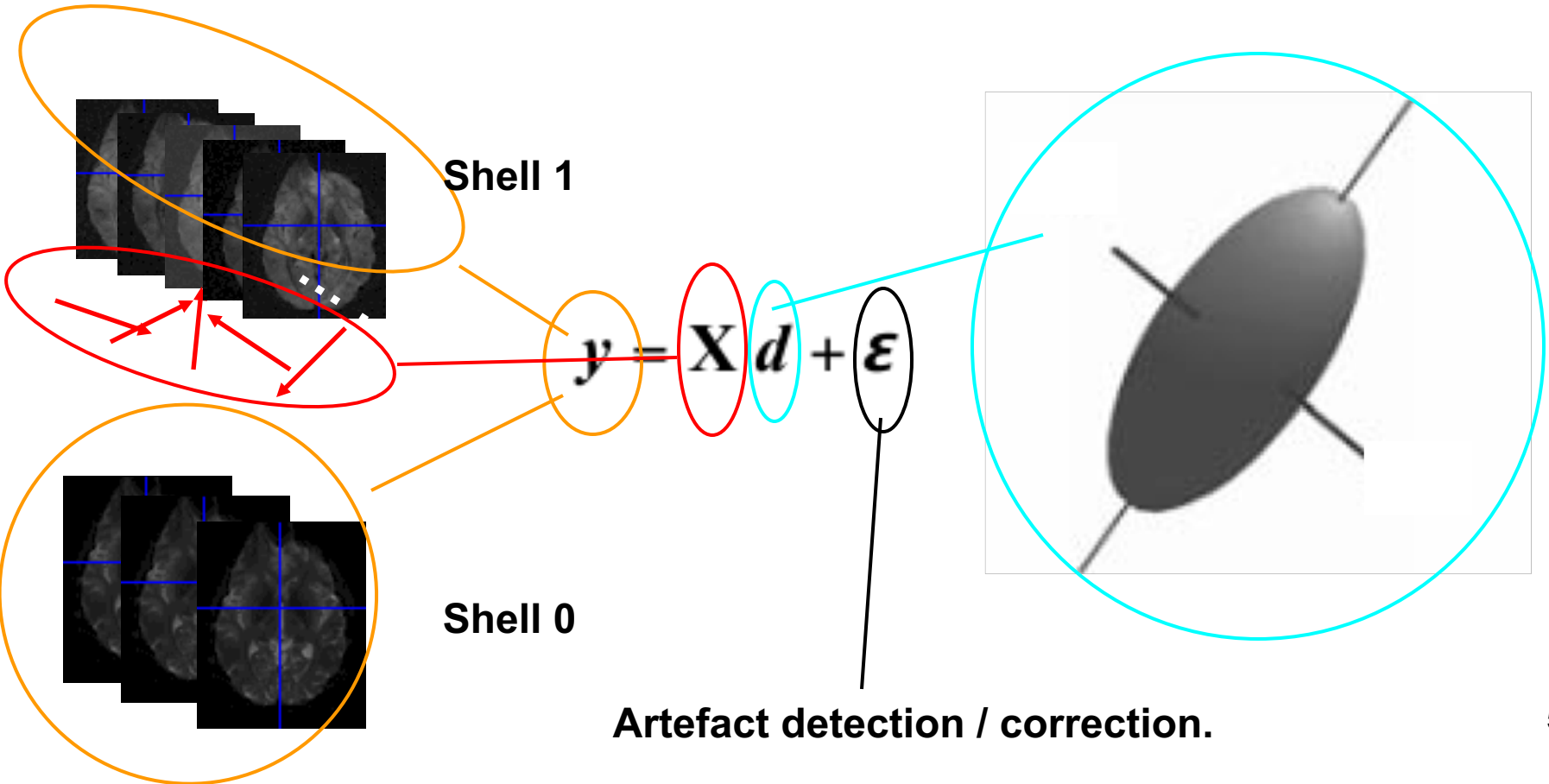


Most important

- Diffusoin Data
- b-values (multi-shell)
- b-vectors

DKI switch

The general linear model framework for diffusion MRI



Diffusion Kurtosis Tensor Imaging

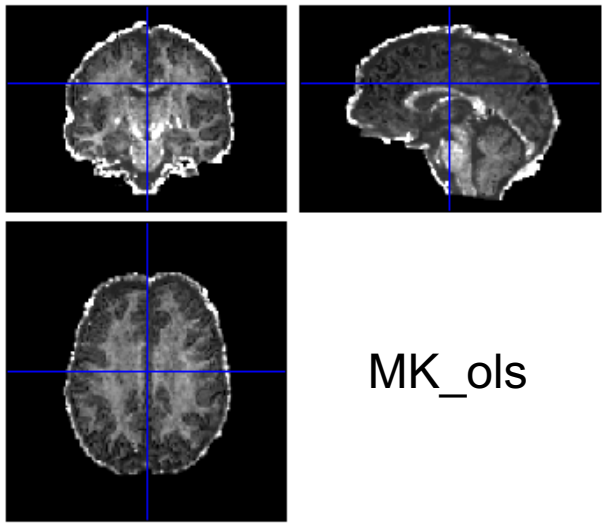
$$\ln\left[\frac{S(\mathbf{n},b)}{S_0}\right] = -b\sum_{i=1}^{3}\sum_{j=1}^{3} n_i n_j D_{ij} + \frac{1}{6}b^2\overline{D}^2\sum_{i=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{l=1}^{3} n_i n_j n_k n_l W_{ijkl},$$

diffusion tensor

kurtosis tensor

The kurtosis tensor is fitted using the constrained least square model suggested by Tabesh et al., 2011. For implementation into ACID, see Mohammadi et al., Frontiers in Neurosci., 2015

What are the outputs?



Maps

- MK – mean kurtosis
- AWF – axonal water fraction

Learn more about MK and AWF:

- *Jensen et al., 2010 (review about DKI);*
- *Fieremans et al., 2011 (biophysical model of AWF)*
- *Jelescu et al., 2015 (comparison to NODDI)*

Learn more about these DKI metrics:
Fieremans et al., NI, 2011

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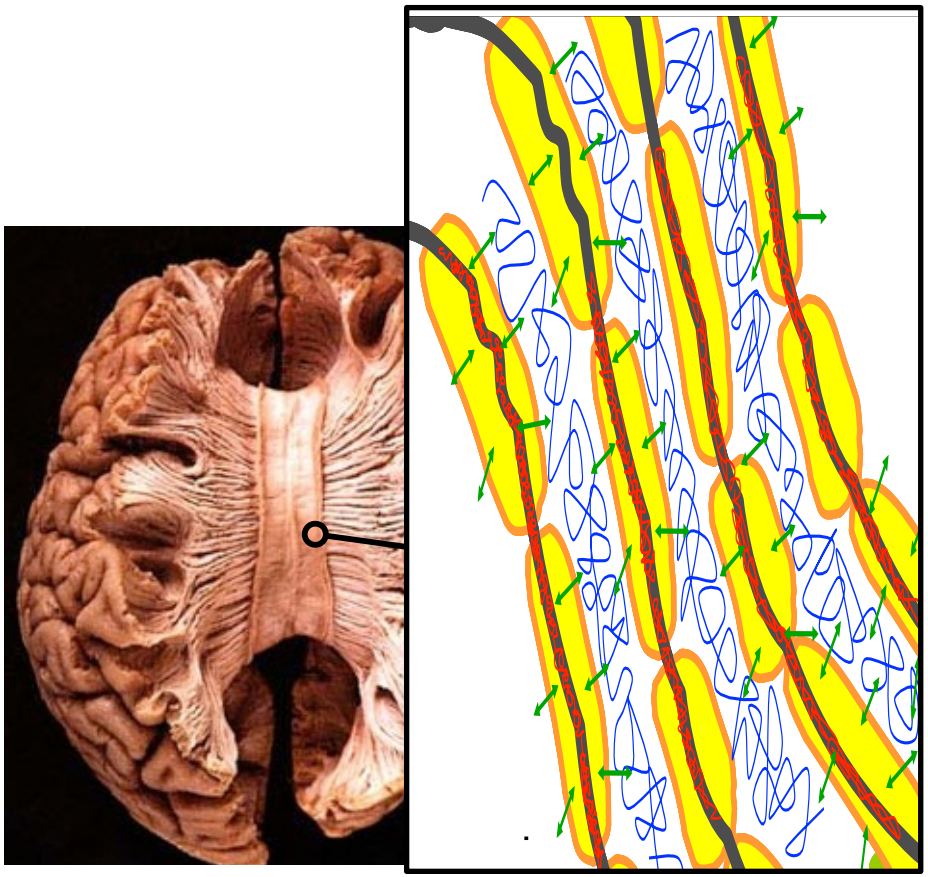
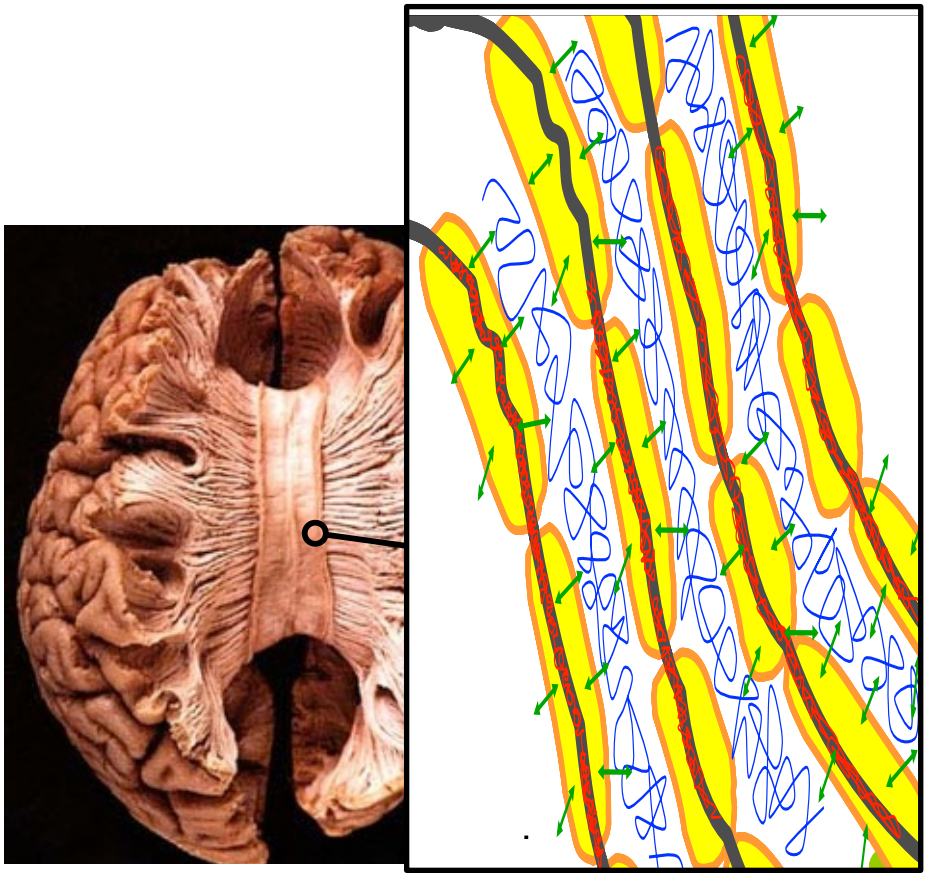
Biophysical model of the diffusion signal



Zhang, OHBM, 2014

Fieremans, ESMRMB, 2015

Biophysical model of the diffusion signal



Zhang, OHBM, 2014

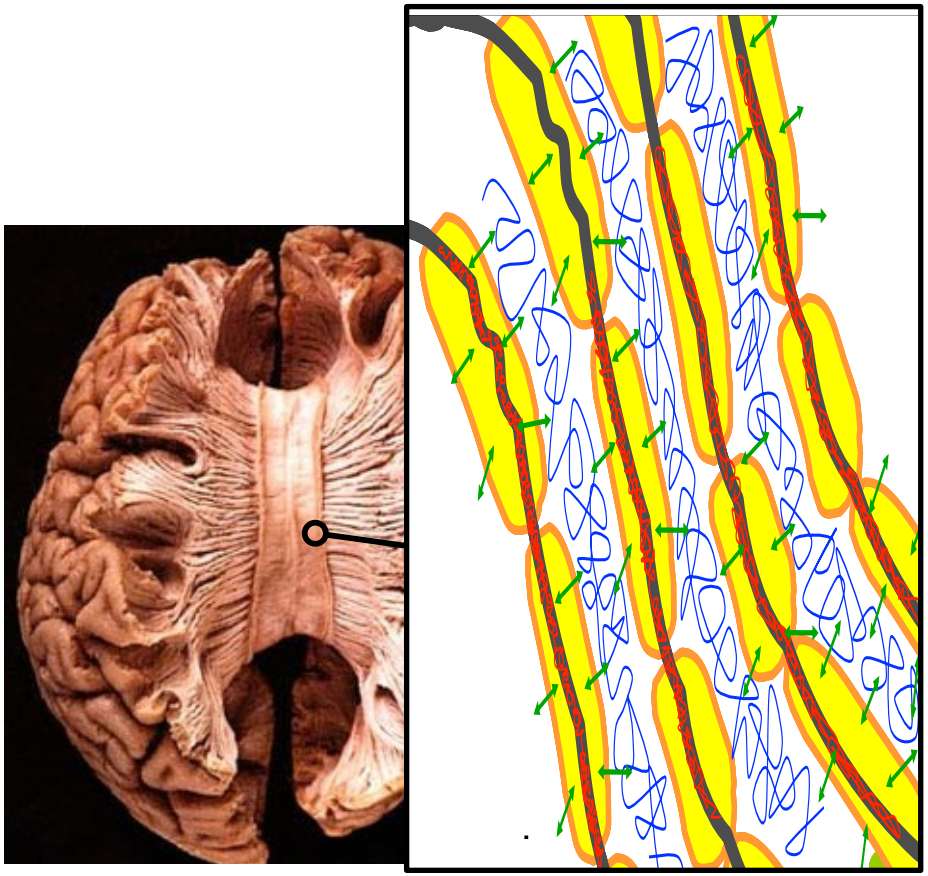
Fieremans, ESMRMB, 2015

Intra-cellular diffusion
=
restricted diffusion

Extra-cellular diffusion
–
restricted diffusion

Exchange

Biophysical model of the diffusion signal



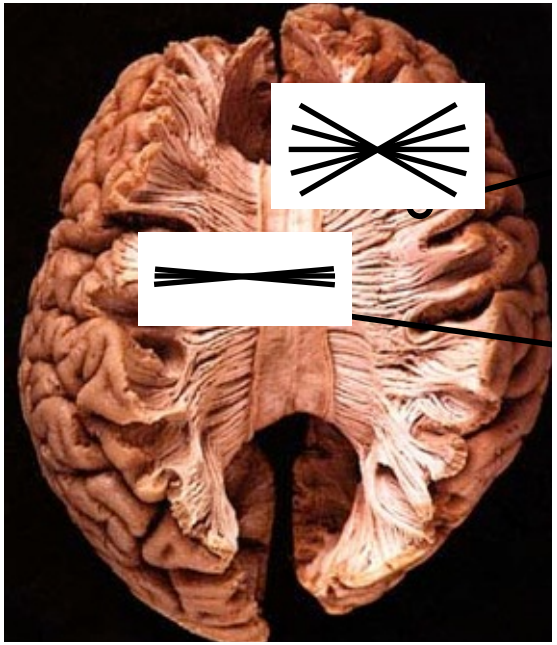
Intra-cellular diffusion
=
restricted diffusion

Extra-cellular diffusion
–
restricted diffusion

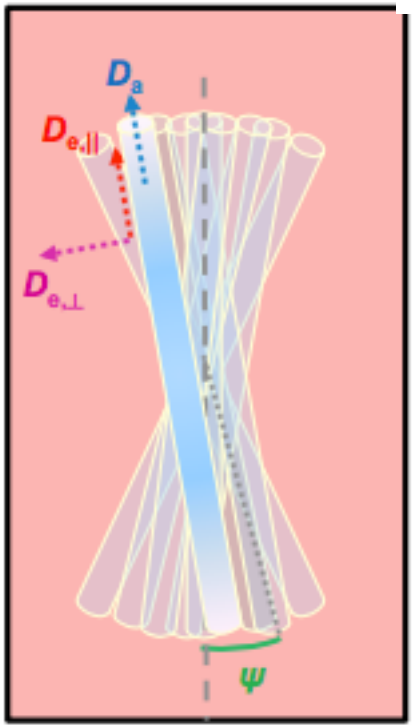
Zhang, OHBM, 2014

Fieremans, ESMRMB, 2015

Biophysical model of the diffusion signal



Zhang, OHBM, 2014



Axonal volume fraction

$= f$

Intra axonal space

D_a

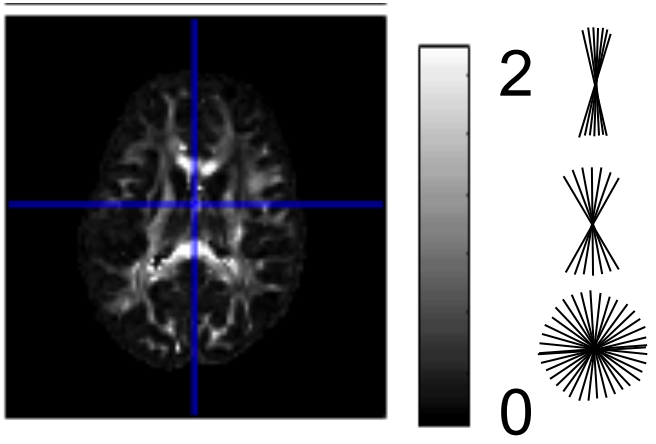
Extra axonal space

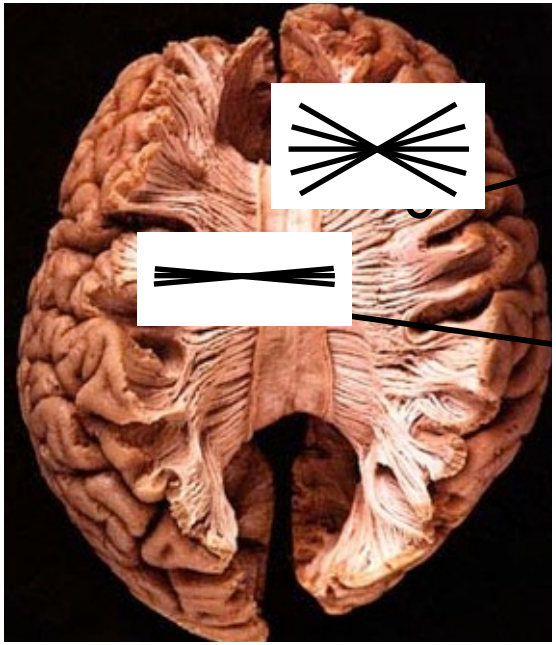
$D_{e,\parallel}, D_{e,\perp}$

Fieremans, ESMRMB, 2015

Biophysical model of the diffusion signal

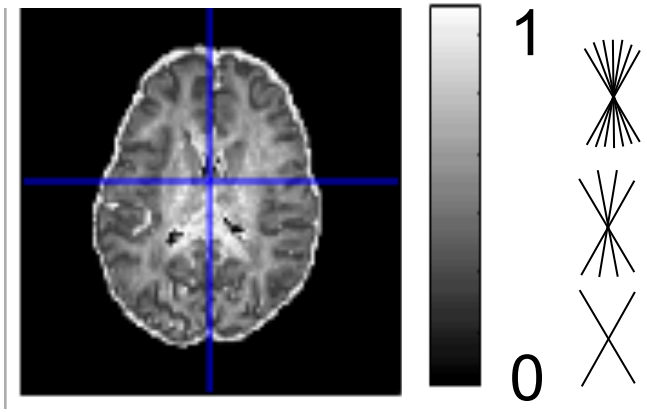
Fiber dispersion “” [a. u.]





Zhang, OHBM, 2014

Fiber density “τ” [a. u.]



NODDI-DTI:

fiber density "ν"

~

mean diffusivity "MD"

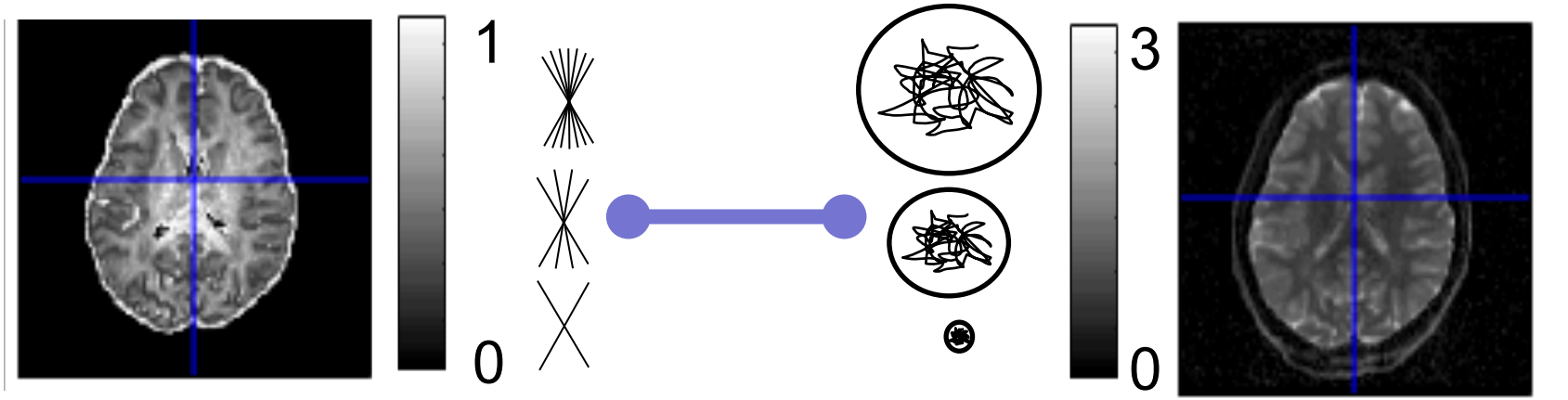
$$\nu = 1 - \sqrt{\frac{1}{2}\left(\frac{3\mathrm{MD}}{d} - 1\right)}$$

Edwards et al., 2017

NODDI-DTI: fiber density "ν"~ mean diffusivity "MD"

Fiber density [a. u.]

Mean diffusivity $\left[\frac{\mathrm{mm}^2}{\mathrm{s}} \times 10^{-3}\right]$



$$\nu = 1 - \sqrt{\frac{1}{2}\left(\frac{3\mathrm{MD}}{d} - 1\right)}$$

Edwards et al., 2017

NODDI-DTI:

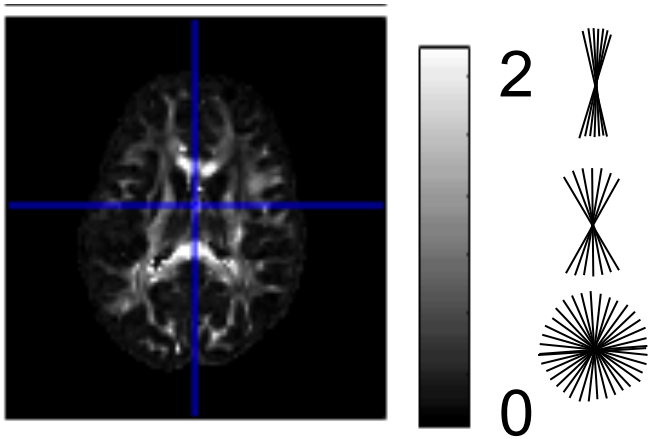
fiber dispersion "τ"

~

mean diffusivity "MD" & fractional anisotropy "FA"

$$\tau = \frac{1}{3}\left(1 + \frac{4}{|d - MD|}\frac{MD \times FA}{\sqrt{3 - 2FA^2}}\right)$$

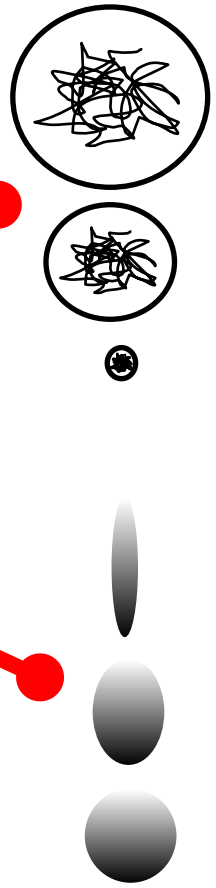
NODDI-DTI: fiber dispersion "τ" ~ mean diffusivity "MD" & fractional anisotropy "FA"



Fiber Dispersion [a. u.]

2

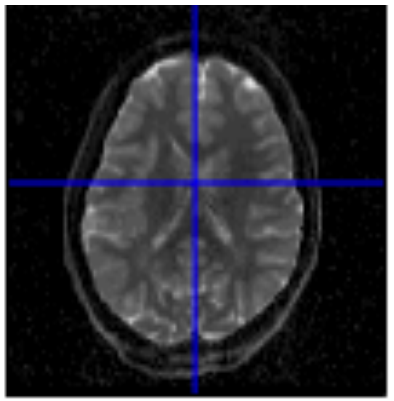
0



3

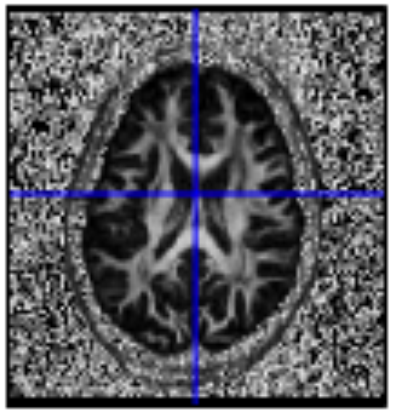
0

Mean Diffusivity $\left[\frac{\mathrm{mm}^2}{\mathrm{s}} \times 10^{-3}\right]$



1

0



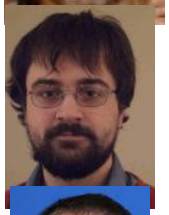
Fractional Anisotropy [a. u.]

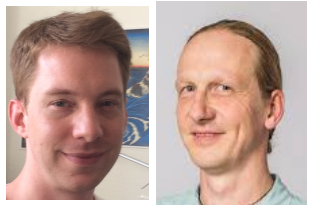
$$\tau = \frac{1}{3}\left(1 + \frac{4}{|d - MD|}\frac{MD \times FA}{\sqrt{3 - 2FA^2}}\right)$$

Edwards et al., 2017

Contributers





- Lars Ruthotto, Emroy University (HySCO and DKI)
- Karsten Tabelow & Jörg Polzehl, WIAS, Berlin (msPOAS and DKI)
- Volkmar Glauche, Universität Freiburg (FA-VBS)
- Luke Edward, MPI-CBS, Leipzig (NODDI-DTI)
- Gergely David, University Zürich (Spinal Cord branch - *in prep.*)
- Jan-Malte Öschger, UKE (Rician noise bias – *in prep.*)