Slide 1

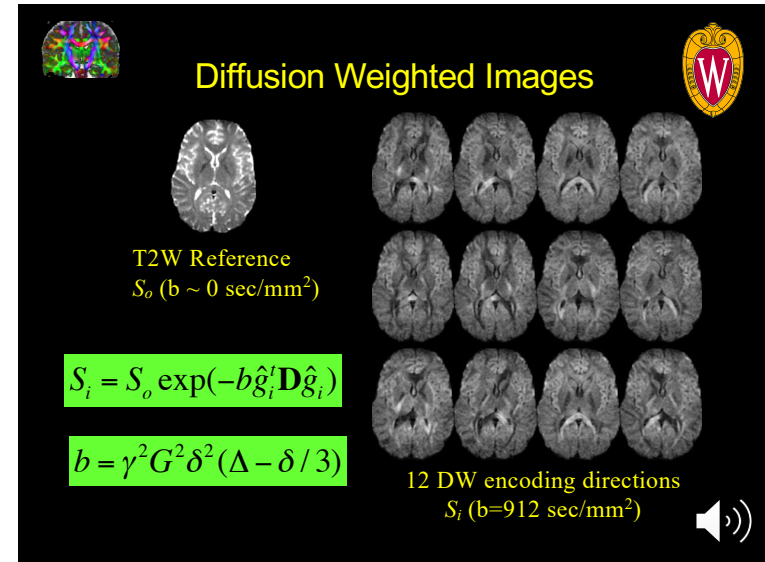# DTI Processing

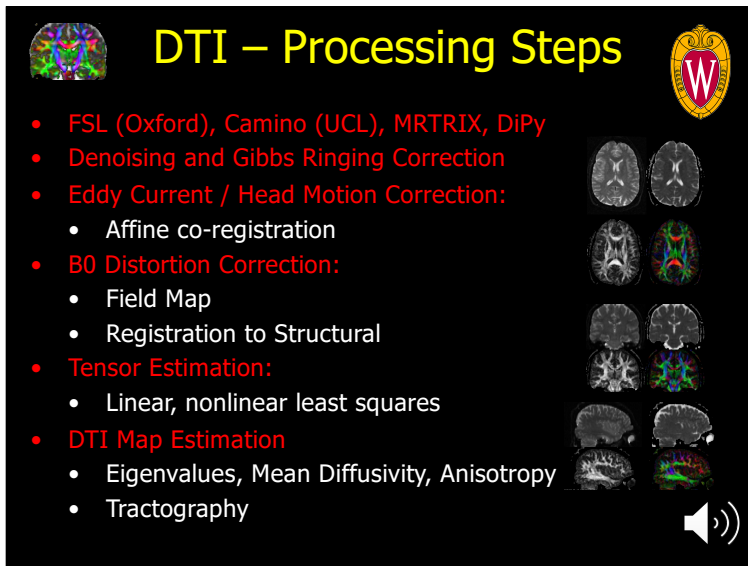MP/NTP 651

Fall 2020

Slide 2

Diffusion Weighted Images

T2W Reference
S_o (b ~ 0 sec/mm^2)

$$S_i = S_o \exp(-b\hat{g}_i^t \mathbf{D} \hat{g}_i)$$

$$b = \gamma^2 G^2 \delta^2 (\Delta - \delta / 3)$$

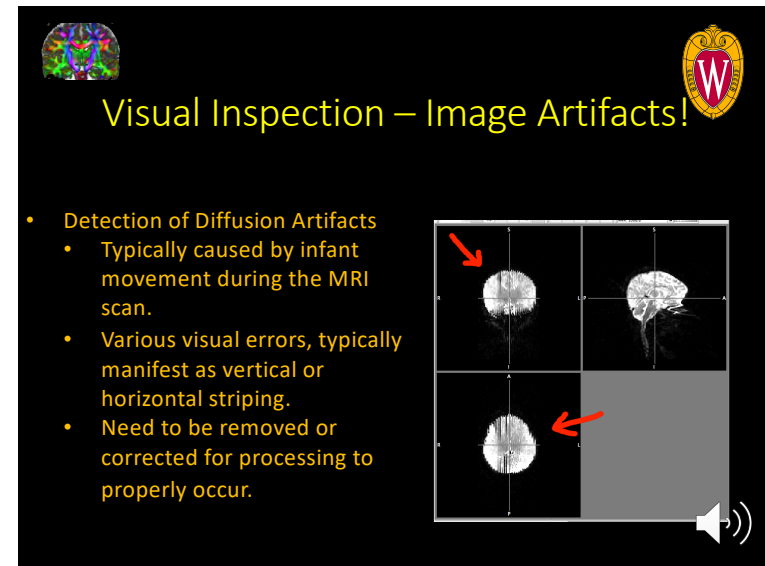12 DW encoding directions
S_i (b=912 sec/mm^2)

Slide 3

DTI – Processing Steps

- FSL (Oxford), Camino (UCL), MRTRIX, DiPy
- Denoising and Gibbs Ringing Correction
- Eddy Current / Head Motion Correction:
  - Affine co-registration
- B0 Distortion Correction:
  - Field Map
  - Registration to Structural
- Tensor Estimation:
  - Linear, nonlinear least squares
- DTI Map Estimation
 - Eigenvalues, Mean Diffusivity, Anisotropy
  - Tractography

Slide 4

Visual Inspection – Image Artifacts!

- Detection of Diffusion Artifacts
  - Typically caused by infant movement during the MRI scan.
  - Various visual errors, typically manifest as vertical or horizontal striping.
  - Need to be removed or corrected for processing to properly occur.
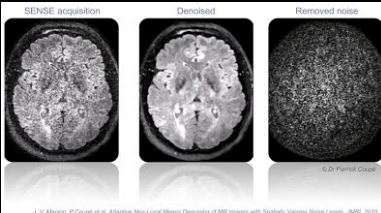
Denoising

- DTI data can be noisy
  - Small voxels
  - Diffusion-weighting – noisy images
  - Rician Noise Distribution
- Denoising
  - Attempt to reduce noise while preserving structure
- MRTRIX: *dwidenoise*

SENSE acquisition   Denoised   Removed noise
© Dr Pierrick Coupé
J. V. Manjon, P Coupé et al. Adaptive Non-Local Means Denoising of MR Images with Spatially Varying Noise Levels, JMRI, 2010

Veraart J, et al. Denoising of diffusion MRI using random matrix theory. Neuroimage. 2016. 142:394-406.
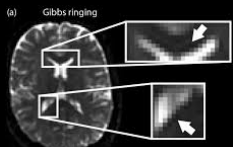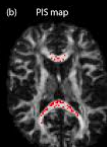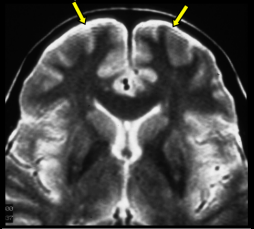
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Gibbs Ringing Removal

- Truncation of High Spatial Frequencies – Edge of k-space
- Ringing artifacts
- Prominent at brain edges and around ventricles
- MRTRIX - *mrdegibbs*

(a) Gibbs ringing   (b) PIS map
Chantal Tax PhD Dissertation   mriquestions.com

Kellner, E et al. Gibbs-ringing artifact removal based on local subvoxel-shifts. Magnetic Resonance in Medicine, 2016, 76, 1574–1581.
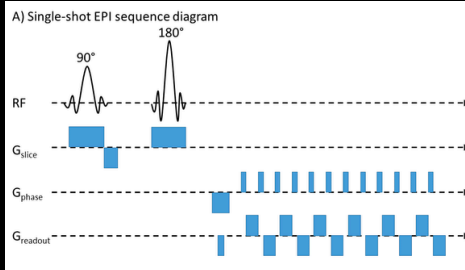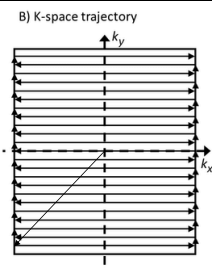
6

Echo Planar Imaging

A) Single-shot EPI sequence diagram   B) K-space trajectory
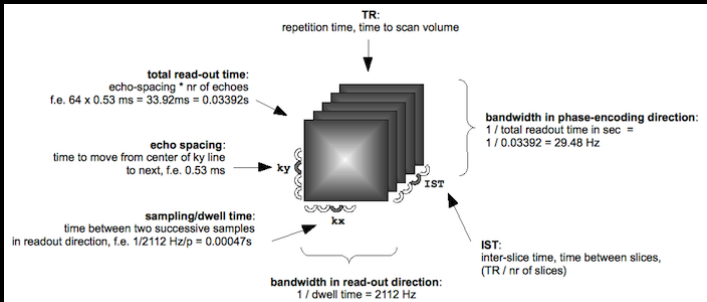
Timo Roine, PhD Defense 2017
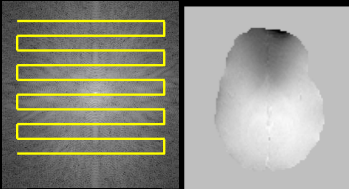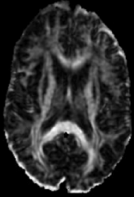
7

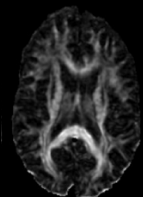## EPI Sampling Definitions

Brainvoyager.com

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EPI Distortion

Magnetic Field
ΔBo

B0 inhomogeneities:
- magnetic susceptibility
- off-resonance (fat)
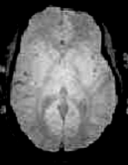
Distorted FA map

Ideal FA map

Parallel imaging (R) reduces EPI distortion!

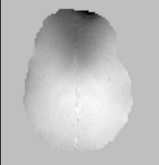Diffusion-imaging.com

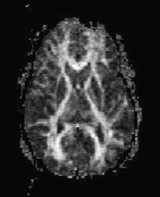$\Delta y = \Delta B_o$ esp FOV / R

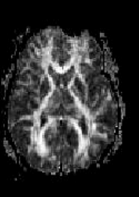DT-MRI Alexander

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Field Map Distortion Correction

Anatomy

Field Map
($\Delta\phi$: 2 GRE w/ diff TE's)
(Jezzard & Balaban; MRM, 1996)
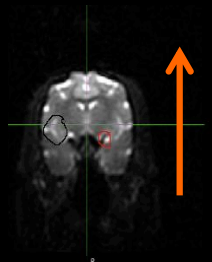
Original FA map

Corrected FA map

$\Delta y = \Delta B_o$ esp FOV / R

FSL: PRELUDE & FUGUE

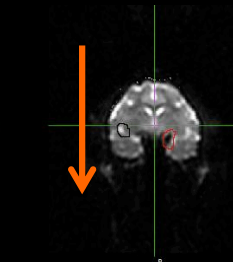DT-MRI Alexander

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Distortion Correction: Reversed Phase Encoding

Pepolar = 0   Recon   Pepolar = 1
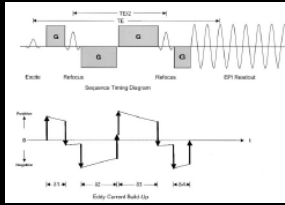
Corrected
FSL: topup

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**Eddy Currents & Head Motion Mitigation & Correction**

- Dual Echo w/ Bipolar Diffusion Gradients

- Parallel Imaging (reduce by 2-3x)

- Post-processing – image co-registration (head motion) – AFFINE transform
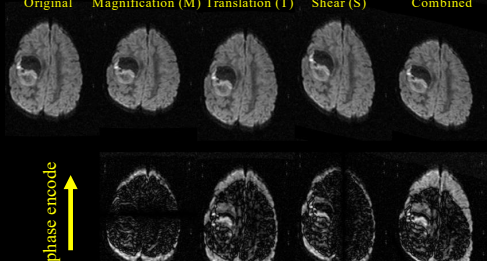
Reese MRM 2003

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Slide 13 — Eddy Currents

- Currents induced in scanner metal components – linear field distortions
- Linear Distortions in Phase Encoding Direction

Original Magnification (M) Translation (T) Shear (S) Combined
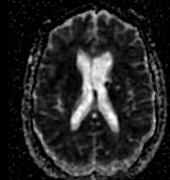
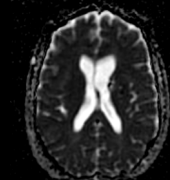phase encode

$$Y' = (1+M)Y + SX + T$$

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Slide 14 — Eddy Current Distortion - EPI

before correction
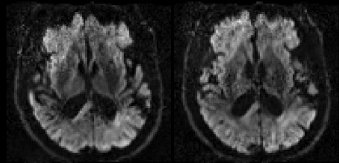
after correction (registration)
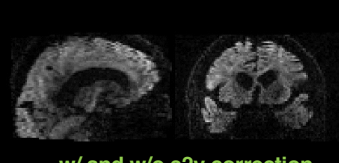**Affine transformation**

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Slide 15 — FSL eddy

- Corrects for distortion from eddy currents and head motion
- --repol option: detects and replaces outlier data – better data
- --mporder option: slice-to-volume motion correction eddy_cuda
  - computationally demanding, requires NVIDIA GPU and CUDA GPU Programming language

w/ and w/o outlier correction

w/ and w/o s2v correction

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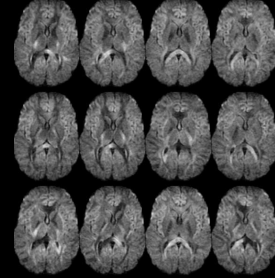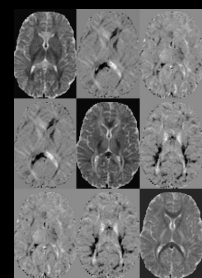Slide 16 — Diffusion Tensor Estimation

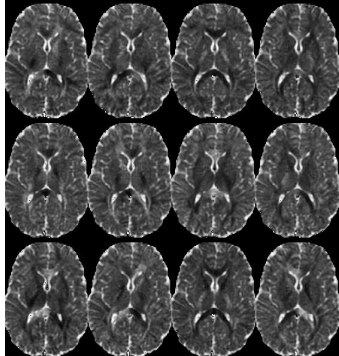DW images

Linear Least Squares (FSL)
Nonlinear Least Squares
RESTORE – Robust Estimator

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Slide 17 — Apparent Diffusivities

$$D_i = \frac{\ln S_o - \ln S_i}{b}$$

12 encoding directions

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Slide 18 — Diffusion Tensor Decoding / Linear Least Squares

diffusivities

diffusion tensor vector

$$\mathbf{Y} = \begin{pmatrix} D_1 \\ D_2 \\ \vdots \\ D_N \end{pmatrix} = \mathbf{H} \begin{pmatrix} D_{xx} \\ D_{yy} \\ D_{zz} \\ D_{xy} \\ D_{xz} \\ D_{yz} \end{pmatrix} = \mathbf{Hd}$$

$$\mathbf{d} = \begin{pmatrix} D_{xx} \\ D_{yy} \\ D_{zz} \\ D_{xy} \\ D_{xz} \\ D_{yz} \end{pmatrix} = (\mathbf{H}'\mathbf{H})^{-1}\mathbf{H}'\mathbf{Y}$$

gradient encoding vector

encoding matrix

$$\mathbf{h}_i = \begin{pmatrix} g_{xi}^2 \\ g_{yi}^2 \\ g_{zi}^2 \\ 2g_{xi}g_{yi} \\ 2g_{xi}g_{zi} \\ 2g_{yi}g_{zi} \end{pmatrix}$$

$$\mathbf{H} = \begin{pmatrix} \mathbf{h}_1 \\ \mathbf{h}_2 \\ \vdots \\ \mathbf{h}_N \end{pmatrix}$$

$N \geq 6$

$= (\mathbf{H}'\mathbf{H})^{-1}\mathbf{H}'$

$\mathbf{d}$

Hasan et al. JMRI 2001

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Slide 19 — DTI Estimators

- Linear Least Squares
- Weighted Linear Least Squares
- Nonlinear Least Squares
- Constrained Nonlinear Least Squares (Koay 2006)
- Robust Estimators (RESTORE)
  - Reduce effects of outlier measurements
  - Single b-value ($\sim$1000s/mm^2)

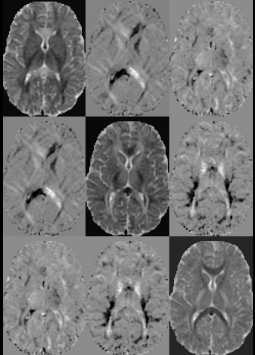**Software:**
FSL, Camino, DiPy, many others

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Slide 20 — The Diffusion Tensor

$$\mathbf{D} = \begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{pmatrix} =$$

Not Rotationally Invariant!

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