Basics of DWI and PWI

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Current Concepts
Monterey
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Proton Motions and DWI

DWI measures proton motion:
5-20 µm/image.

Samples µenvironment.
Measured as ADC.

Diffusion sensitive to:

Water content-

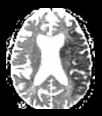
ADC increases with PD.

Water compartments-

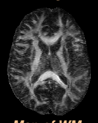
Intracellular water slower.

Water hindrances-

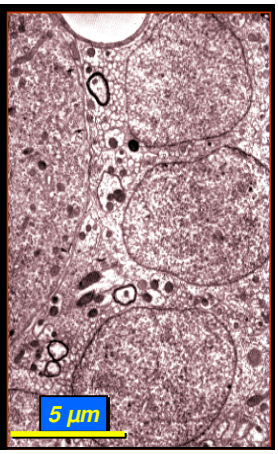
Ordered in WM.



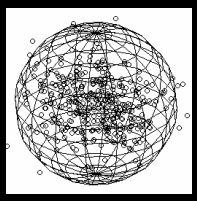
Map of Diffusion ADC



Map of WM



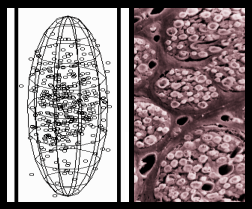
Diffusion in an isotropic medium (GM)



similar molecular displacements in all directions

The Apparent Diffusion is quantitated as the "ADC"
- Measure of translation

Diffusion in an ordered environment (WM)



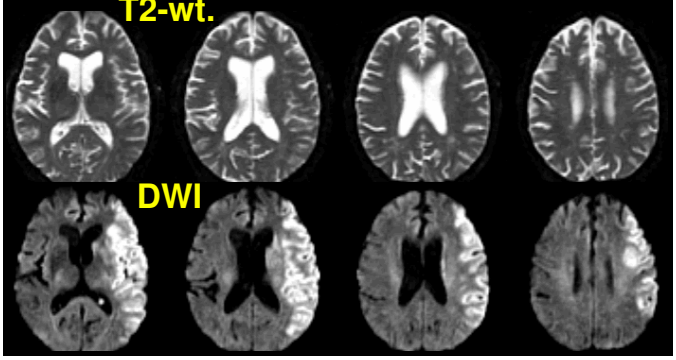
greater molecular displacement along cylinders than across

Deviation from random paths-
"Fractional Anisotropy"
-Measure of WM integrity

MRI and Acute Stroke
4 hours

T2-wt.

DWI

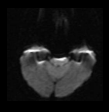


Practices of DWI: *Artifacts*
Artifacts in EPI DWI can be serious

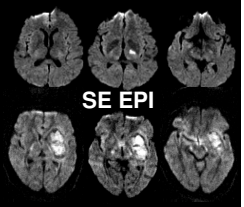
Artifacts arise from susceptibility issues
- Signal drop-outs/pile-up
- Aspect ratio distortions
- Sensitivity to shims/metal

Eddy currents effects
- Aspect ratio distortions/smearing

Use auto-shimming prior to exam
Avoid overly high resolutions (<192)
New correction algorithms
New Sequences for DWI



SE EPI



SE EPI

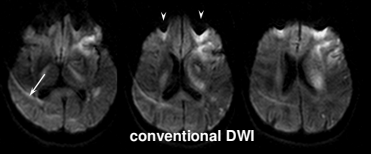
SE EPI

Can DWI Be Improved?

"Perhaps the biggest immediate improvement affecting all of MR today is the development of parallel imaging…"

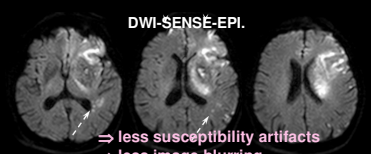
Parallel Imaging (SENSE)

Improve Temporal Resolution
Increased Volume Coverage/ Time
Reduction of Motion Artifacts
Reduce T2/T2*-Blurring
Diminish Off-resonance Artifacts
Decrease SAR Problems
Reduction of Total Acquisition Time



conventional DWI

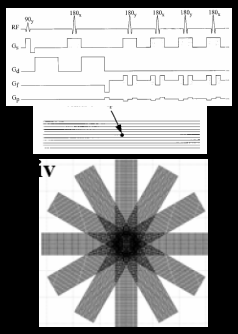
DWI-SENSE-EPI.



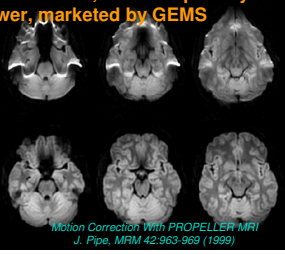
⇒ less susceptibility artifacts
⇒ less image blurring
⇒ less T2 decay (shorter TE)

The MR PROPELLER Sequence

"Periodically rotated overlapping parallel lines with enhanced reconstruction"



Multi-shot, multi-echo FSE (blades)
Each blade passes thru k-space center
Robust motion correction
No distortions, no susceptibility
Slower, marketed by GEMS



PROPELLER blades, Arfanakis, et al. ISMRM, Kyoto 2004

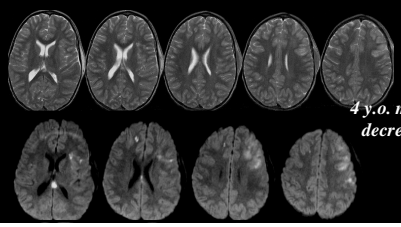
Motion Correction With PROPELLER MRI
J. Pipe, MRM 42:963-969 (1999)

DWI "Mimics" Beyond Clinical Stroke

Reduced ADC "cytoxic" vs. reduced mobility.
Screen for "non-stroke" events (headaches, TIA).
Secondary ischemia (acute trauma, venous occlusion)
ADC reduced in "cytotoxic" edema: CJD, pediatric diseases.
ADC reduced in abscess ** vs. highly cellular tumor cores.
Elevated ADC "vasogenic" (*usually seen also as elevated T2*).
MS plaques** (older), edema, inflammation, necrosis.

T2 FSE

DWI



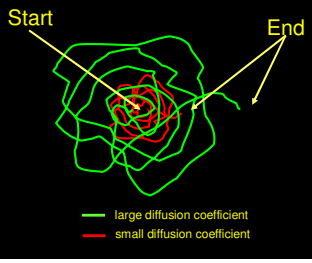
4 y.o. male, 3 days s/p MVA, decreasing mental status, UE weakness

G. Sorensen, MGH

Diffusion vs. Perfusion

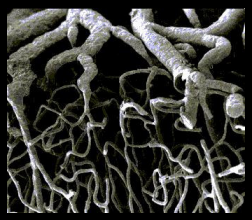
(*Self*)-Diffusion

… has zero mean, but r.m.s. displacement characterizes diffusion coefficient !



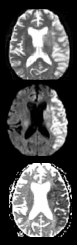
Perfusion

Capillary microcirculation in organs. Rate of nutrient supply.



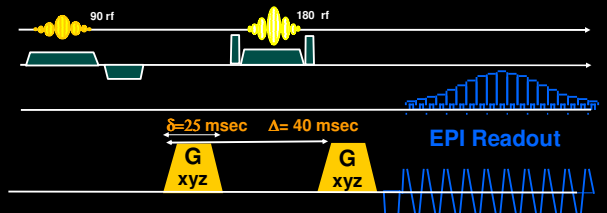
Why does ADC of water decrease in acute stroke ?

perfusion deficit
↓
energy deficit
↓
failure of Na^+/K^+ pumps
↓
intracellular accumulation of Na^+
↓
influx of water → glial and neuronal swelling → reduction in extracellular space



Eventual lysis/edema
↑
DWI hyperintensity
↑
Mobility hindered = ADC drop

Single-shot EPI is Ideal for Diffusion MR



Diffusion-Weighted images

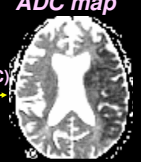
T2-wt (b=0)

DWI (b=800)

$e^{(-\gamma^2 \delta^2 G^2 [D-\delta/3] ADC)}$

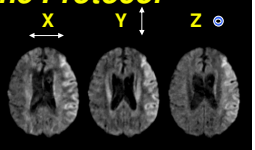
"b"

ADC map



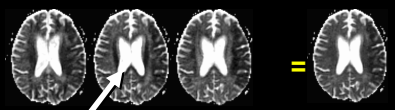
The Principles of DWI: *The Protocol*

Acquire all gradient axes.
* Don't be fooled by WM anisotropy effects.
* X, Y, and Z ("trace")
* Off-axis directions also hot ("tensor")
* Note b0, DWI, *AND* ADC!



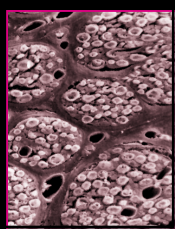
DWI

ADC



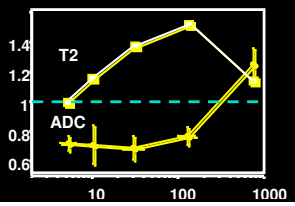
reduced ADC due to anisotropy

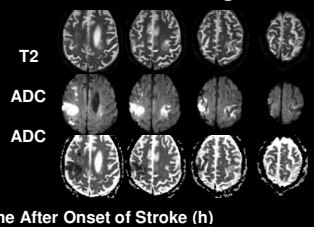
Trace ADC



ADC vs T2-wt *Shine-Thru*

	T2	DWI	ADC
• hyperacute (< 6hrs)	iso	high	low
• acute (6hrs to 4 d)	high	high	low
• subacute (4 to 10 d)	high	iso/h	iso
• chronic (>10 d)	high	iso/l	high





The Principles of DWI: *The Protocol 2004*
The impact of new MR technology

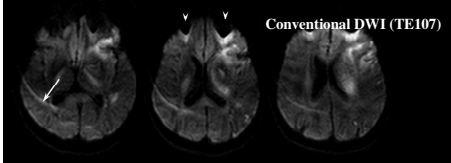
Better SE-EPI
- Image unwarping (postprocessing)
- Dual-echo (TRSE)

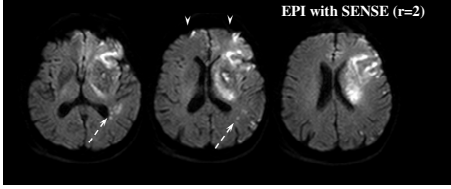
Parallel Imaging for DWI
- SENSE-DWI

FSE-based DWI
- PROPELLER (and Turbo-PROP)

Spiral-based DWI
- SNAILS

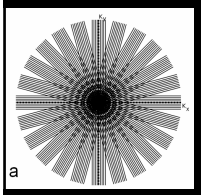
The Principles of DWI: *The Protocol 2004*
SENSE-EPI for DWI

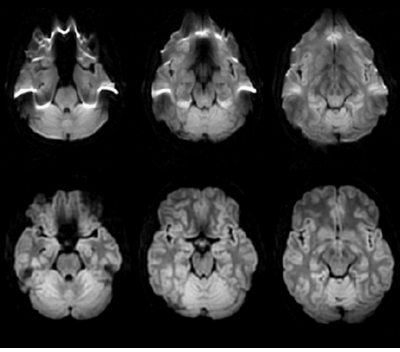




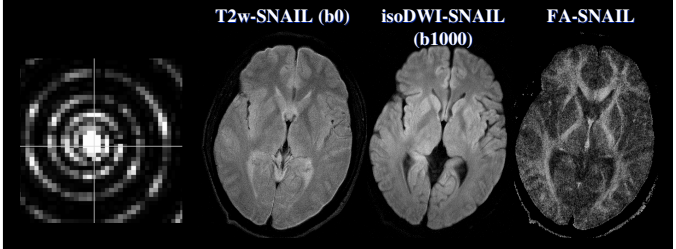
Advantages:
Image distortions
Short TE's
Less blurring
Increased conspicuity
Hi-res!

The Principles of DWI: *The Protocol 2004*
PROPELLER (and Turbo-PROP)





The Principles of DWI: *The Protocol 2004*

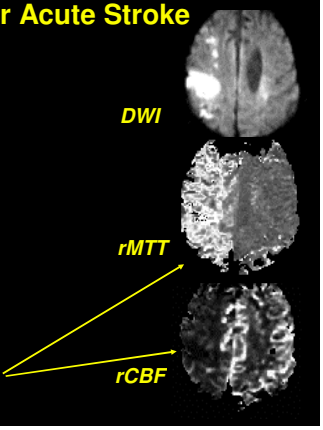


512x512, 8 averages, 64-leaf, b800, 23 minutes

Integrated MRI for Acute Stroke

What is PWI?
- Collect serial EPI images
- Inject contrast agent:
  - Perfused brain - dark
  - Ischemic brain - bright
- Hemodynamics tracked
- Time-resolved transit
- Correlate with DWI, T2

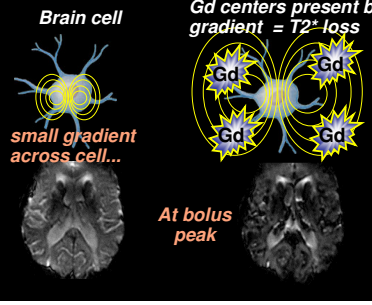
Perfusion deficit present:
(low rCBF, long rMTT)



Why Do We Call PWI "Perfusion"?

Gd shortens T1…
However…
Gd also shortens T2.*

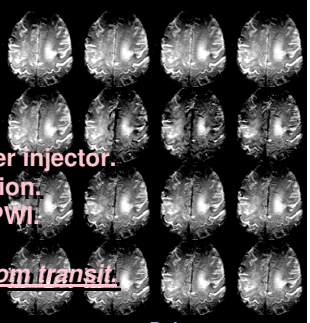
On a GRE-EPI image, a bolus of 0.1mmol/kg Gd can decrease T2 by 50%-80%*



PWI Protocol

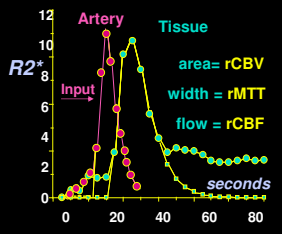
GRE-EPI images acquired during bolus injection.
- 12 slices every 2 sec.
- 40 phases over 80 sec.
- 0.1 mmol/kg Gad - Power injector.
- 1.5mm per pixel resolution.
- as for T2, FLAIR, DWI, PWI.

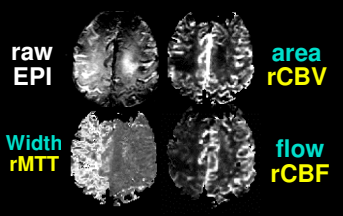
Maps of rCBV, rMTT, rCBF from transit.
Arterial input needed.



How Does PWI Map Hemodynamics?

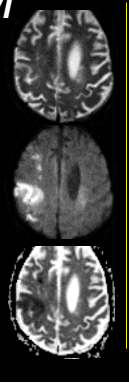
2. From the SI behavior map, model the transit dynamics by a "gamma variate" analysis. This yields parametric maps of the vascular volume, transit, and flow...



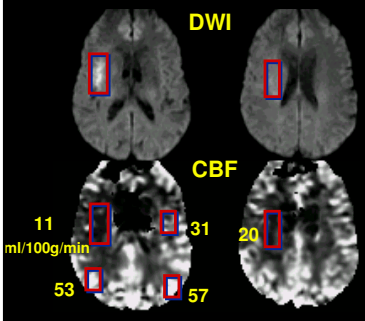


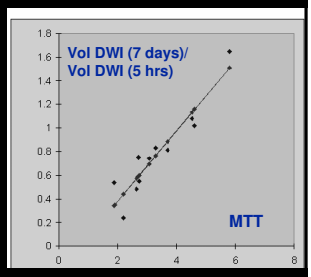
The Diffusion - Perfusion Mismatch

DWI	PWI
T2-wt Early stroke not seen	***Blood Volume*** Lesion has reduced CBV
Diffusion-wt Clear depiction of lesion	***Mean Transit*** large perfusion deficit
Apparent Diffusion Acute stroke has low ADC	***Blood Flow*** Reduced flow around lesion



Is There a Need for CBF Quantitation?





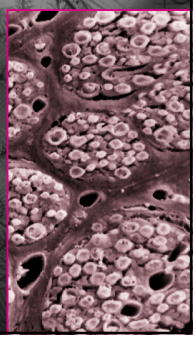
(AIC-Ostergaard, et al)
73yof - Stenosis
MRI at 6hr. - NIHSSS 13

Proton Motions are Ordered by WM

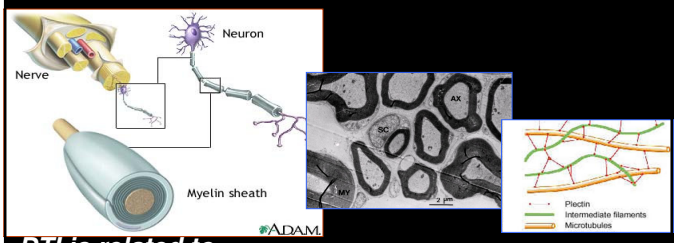
DWI White Matter "Anisotropy" is Altered with Growth, Aging, Disease…

Motion of water hindered in a restricted environment (inside neuronal fibers).
Complex motion described by a *"tensor"*.
Number, integrity, myelination of fibers alters the measured tensor.
Cognitive performance appears to be correlated with anisotropy.

How will DTI impact neuroimaging?



DTI is Not all Myelin!

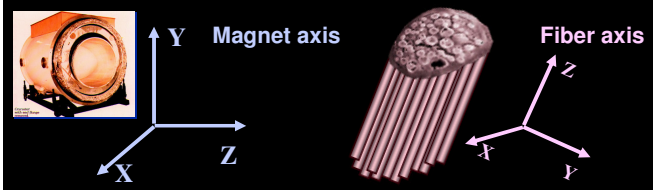


DTI is related to…

Fiber diameter and neuronal density,
Status of the myelination in neurogenesis,
Degree of (de)myelination in aging/disease,
Macrostructural features such as
intravoxel fiber-tract coherence/crossings

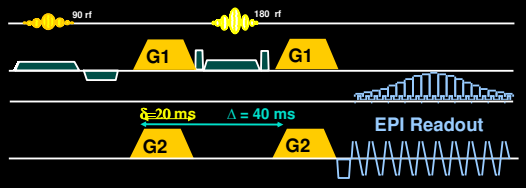
In DTI, We Measure ADC Along All Axes

ADC vs. Direction = ADC Tensor

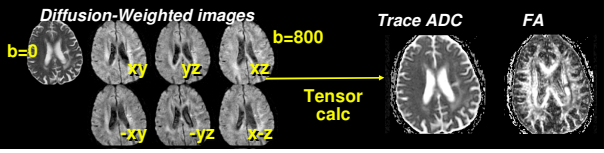


$$\underline{\underline{ADC}} = \begin{bmatrix} ADC_{xx} & ADC_{xy} & ADC_{xz} \\ ADC_{xy} & ADC_{yy} & ADC_{yz} \\ ADC_{xz} & ADC_{yz} & ADC_{zz} \end{bmatrix}$$

Diffusion Tensor Imaging DTI: *The EPI Sequence*

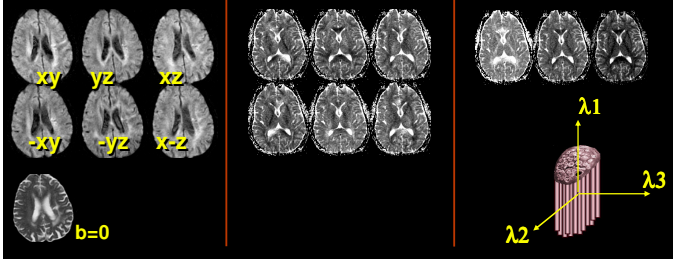


(Gx,Gy,Gz) = {(1,1,0), (0,1,1), (1,0,1), (-1,1,0), (0,-1,1), (1,0,-1)}
SE-EPI TR6000, TE107, 128x128, b0-1000, 6 axes, 3.5min/NEX



DW Images to ADC Maps to Eigenvalues

$$S(\underline{b}) = S_0 \exp\left(-\sum_{i=1}^{3}\sum_{j=1}^{3} b_{ij} ADC_{ij}\right) \quad \underline{\underline{ADC}} = \begin{bmatrix} ADC_{xx} & ADC_{xy} & ADC_{xz} \\ ADC_{xy} & ADC_{yy} & ADC_{yz} \\ ADC_{xz} & ADC_{yz} & ADC_{zz} \end{bmatrix} \quad \underline{\underline{ADC}} = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$



Eigenvalues to FA Maps

Fractional Anisotropy = FA = Created from λ1, λ2, λ3

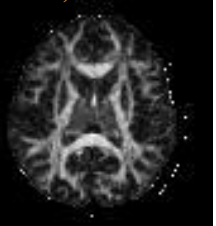
0 (sphere) < FA < 1 (cylinder)

0.05 (GM)< FA < 0.8 (splenium)

$$FA = \frac{3\sqrt{D:D}}{2\sqrt{D:D}}$$

$$D:D = (\lambda_1 - \langle D \rangle)^2 + (\lambda_2 - \langle D \rangle)^2 + (\lambda_3 - \langle D \rangle)^2$$

$$D:D = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$



Isotropic, 128x128, 25FOV, 2mm slice
37 slices, 13 min, 6NEX

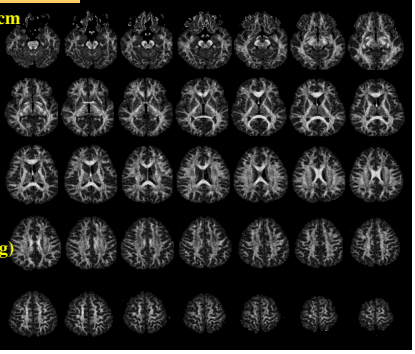
DTI Protocol

Parameters (CV-i Signa 1.5T)

δ = 20ms; Δ ≈ 34ms; G_d = 1.4G/cm
Gradients (G_x,G_y,G_z) =
{(1,1,0), (0,1,1), (1,0,1), (-1,1,0), (0,-1,1), (1,0,-1)}
TE/TR/TI = 106/6000/2100ms
FOV = 24cm; slice 2/0
matrix 128x128.

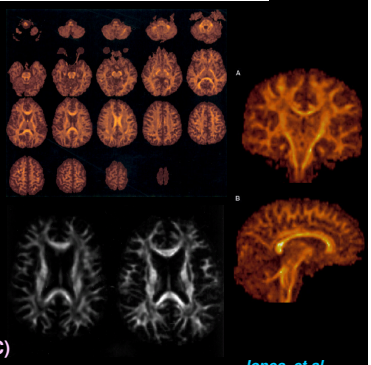
For each slice

2 images with b=0 and IR for CSF suppression (unwarping)
4-6 averages with b=800s/mm²



Clinical DTI: *Protocols and Parameters*

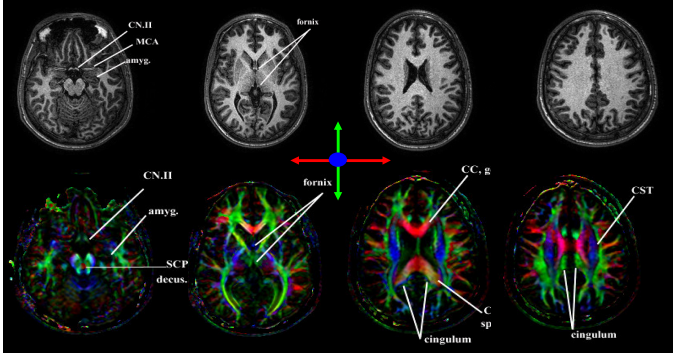
TR 10-20 RR (if gated), TR10000
TE min full (107)
FOV24, 96x96
Slice 2.5-5mm
δ (duration) 18ms
Δ (separation) 49ms
G (grad amp) 40 mT/m
b max 1300 sec/mm2
NEX (b0) 2-4
NEX (b1300) 64 (64x1)
Slices 39
Scan time 14-17minutes



"b" = $e^{(-\gamma^2 \delta^2 G^2 [\Delta - \delta/3] ADC)}$

Jones, et al.
Neuroimage 17, 2002

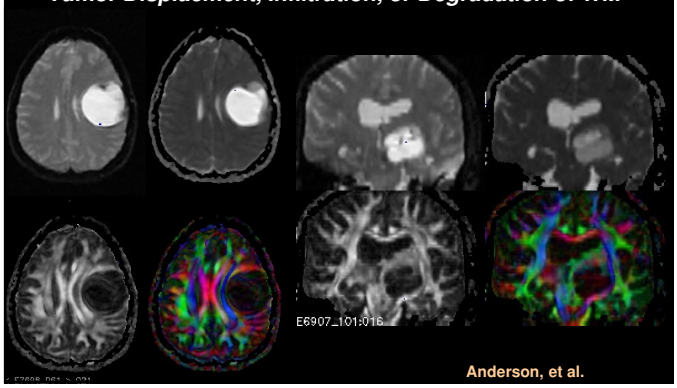
FA "Atlas" of the Brain



S. Mori, JHU

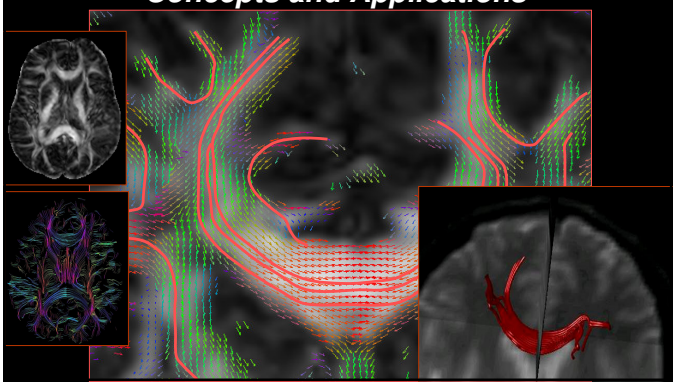
FA Mapping Applications

Tumor Displacment, Infiltration, or Degradation of WM



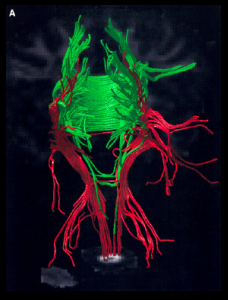
Anderson, et al.

FA Maps, Vectors and Fiber Tracking: *Concepts and Applications*



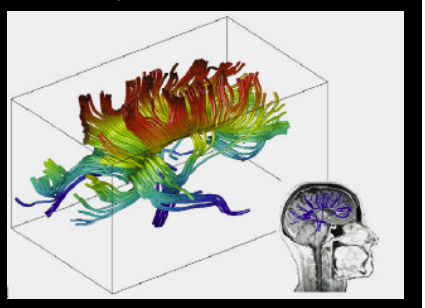
Clinical DTI: *Visualization*

Streamtubes overlaid onto FA



Jones, et al.
Neuroimage 17, 2002

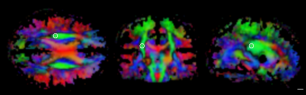
Stochastic trajectories



Tench, et al.
MRM 48, 2002

DTI and Reading

Torkel Klingberg, Maj Hedehus*, Russ Poldrack,
Mike Moseley*, John Gabrieli, Gayle Deutsch,
Bob Dougherty, WT Siok, Roland Bammer*, Brian Wandell.

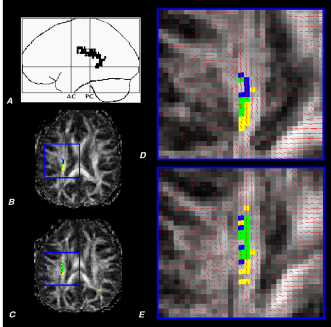


**Center for Advanced MR Technology at Stanford*
http://www-radiology.stanford.edu/research/RR.html

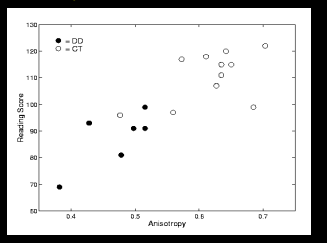
Stanford University School of Medicine

DTI and Reading, 2000

"Significant differences were found between adult dyslexics and age-matched controls in the temporo-parietal region…"



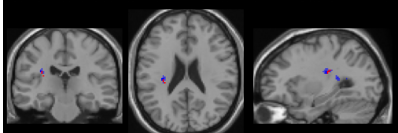
Reading Score *vs.* FA
Dyslexics (DD) – Controls (CT)



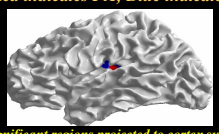
Klingberg *et al.* (2000) Neuron 25:493

DTI and Reading, 2003

"The results support the hypothesis that the microstructural integrity of left temporo-parietal neural pathways is a significant component of the neural system needed to develop fluent reading."

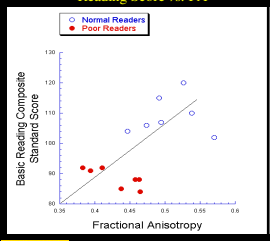


Red indicates FA; Blue indicates CI



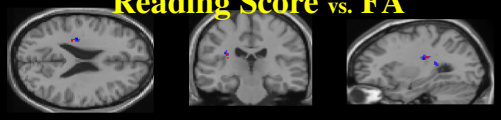
Significant regions projected to cortex surface

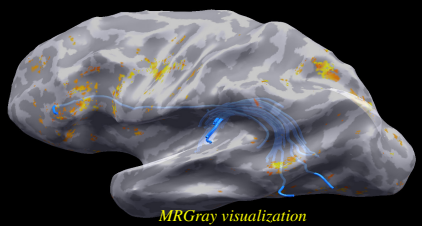
Reading Score *vs.* FA



Deutsch et al., Cortex, in press.

High Resolution DTI and fMRI @ 1.5T: Reading Score vs. FA





MRGray visualization courtesy B. Dougherty

Summary

DWI ideal for all neuro screening.

DTI is a subset of DWI - opens new doors.

FA sensitive to WM development /status.
- Does WM FA reflect status of regional GM metabolism - "Use it or lose it"?
- Would learning increase local FA?

Why does DTI correlate with performance?
- "Integrity" ala FA means what?
- Effective neural density?
- Structural defects or potholes?