Diffusion MRI principles and its application

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The Nobel Prize in Physiology or Medicine 2003

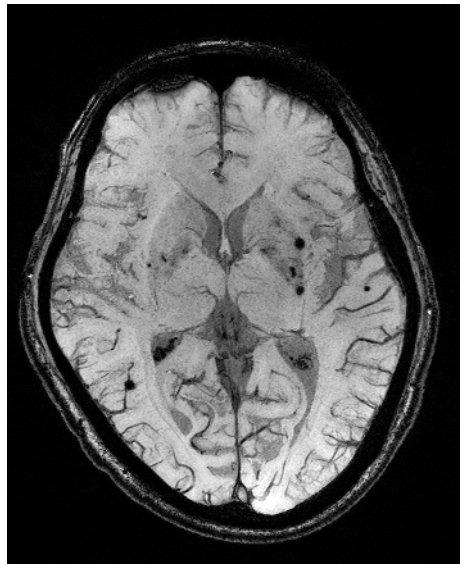
Paul C. Lauterbur
University of Illinois

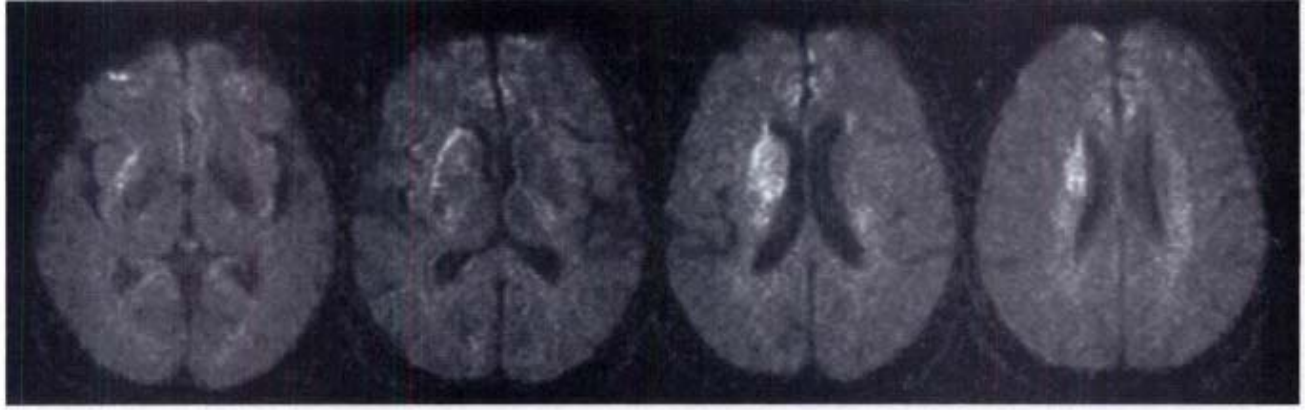
Principles of MRI

Sir Peter Mansfield
University of Nottingham,
School of Physics and Astronomy

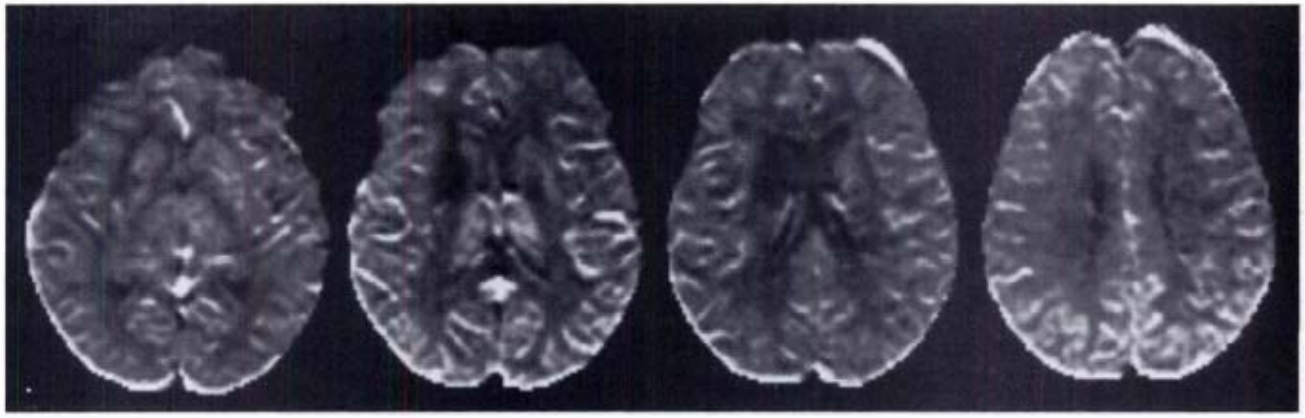
Echo Planar Imaging

T1,T2 weighted images
FLAIR
Susceptibility weighted images
Diffusion weighted images

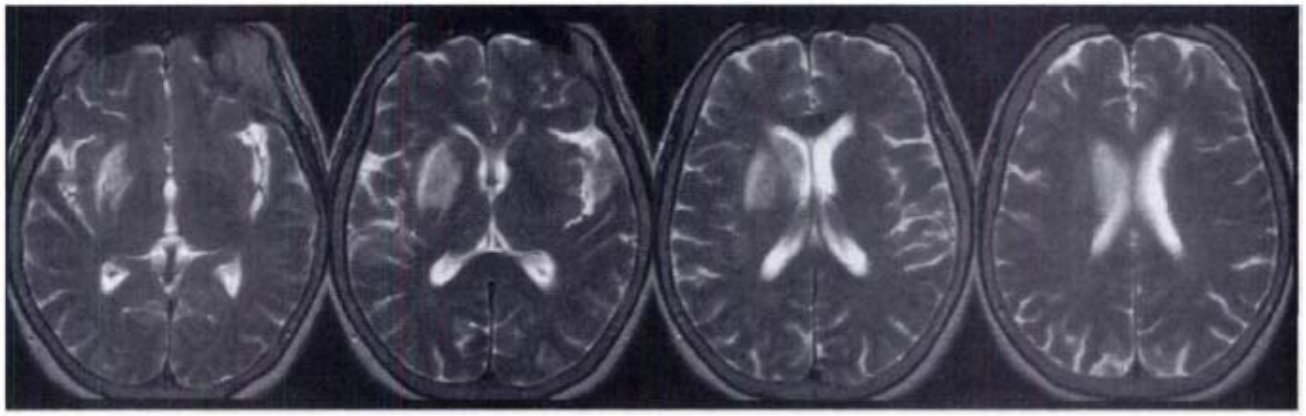




c.



d.

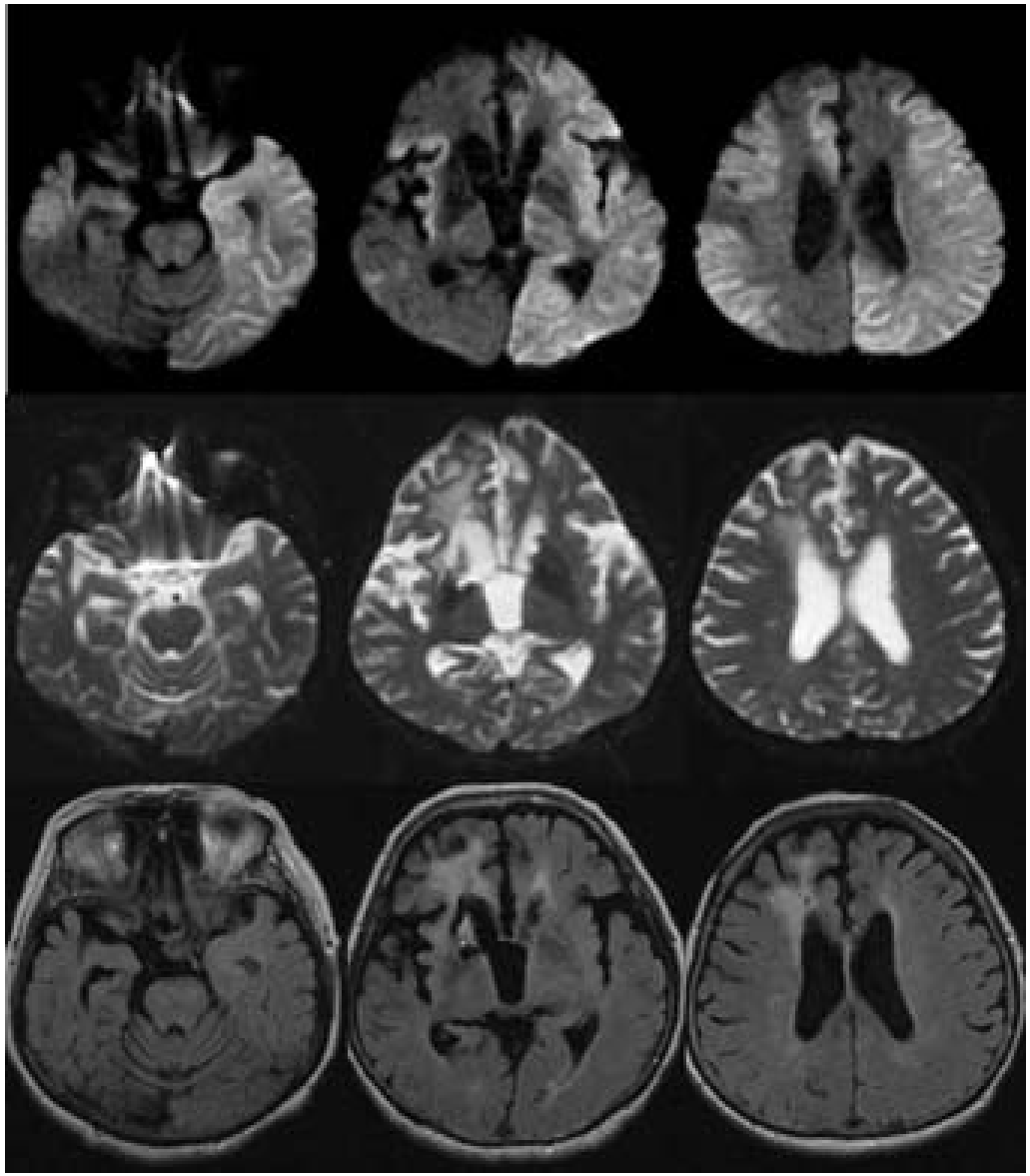


e.

Figure 2 (*continued*). **(c)** DW image and **(d)** relative CBV map demonstrate focal abnormalities in the right deep gray matter consistent with acute ischemia. **d** demonstrates normal CBV in the cortex, which indicates good collateral flow. **(e)** Follow-up MR image obtained 5 days later confirms the overall extent and location of the infarct. There is relatively little mismatch between **c** and **d**.

Sorensen GA
Radiology 199:391, 1996

Acute stroke



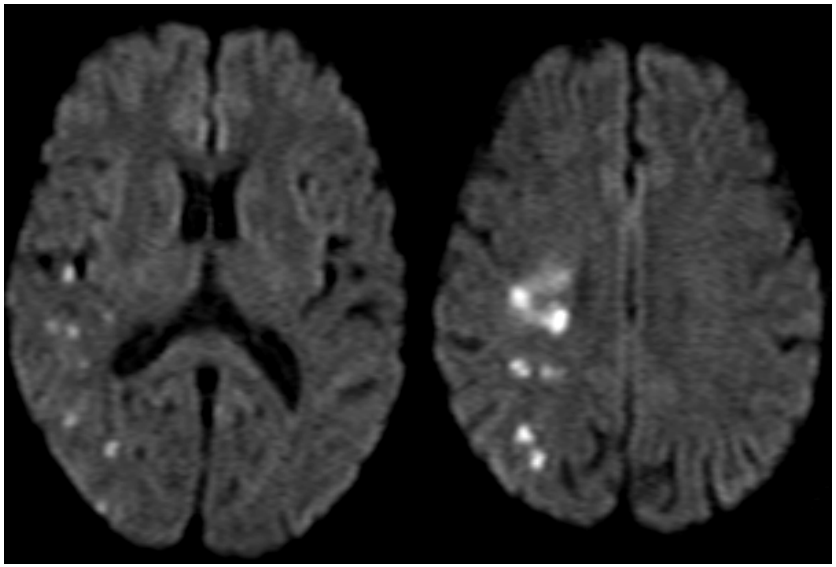
DWI

T2WI

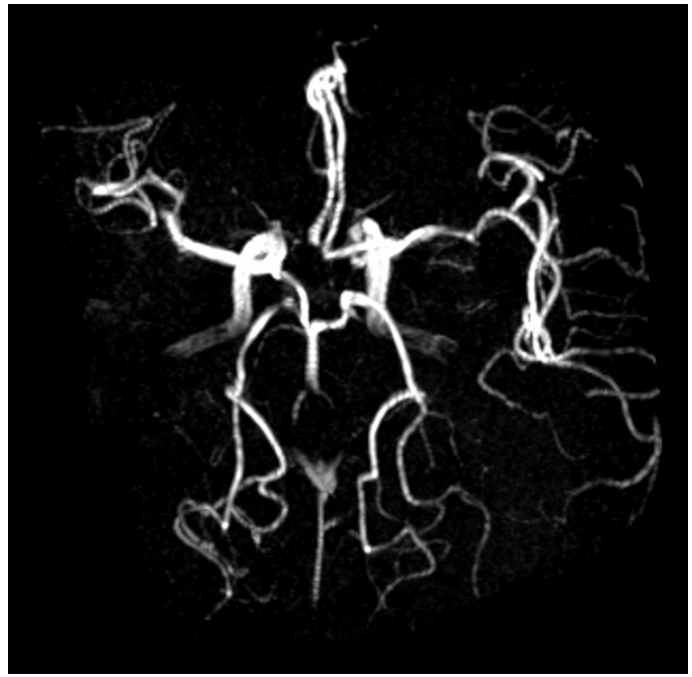
FLAIR

Ischemic penumbra

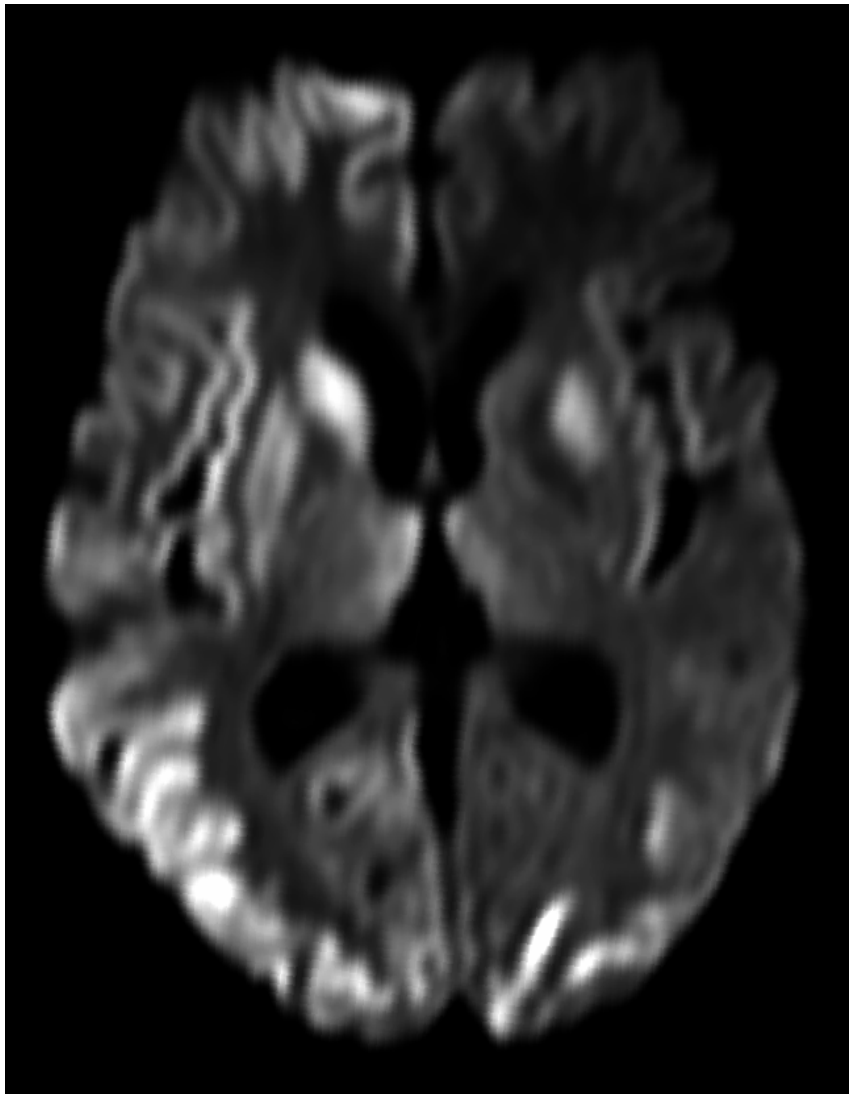
Diffusion weighted image



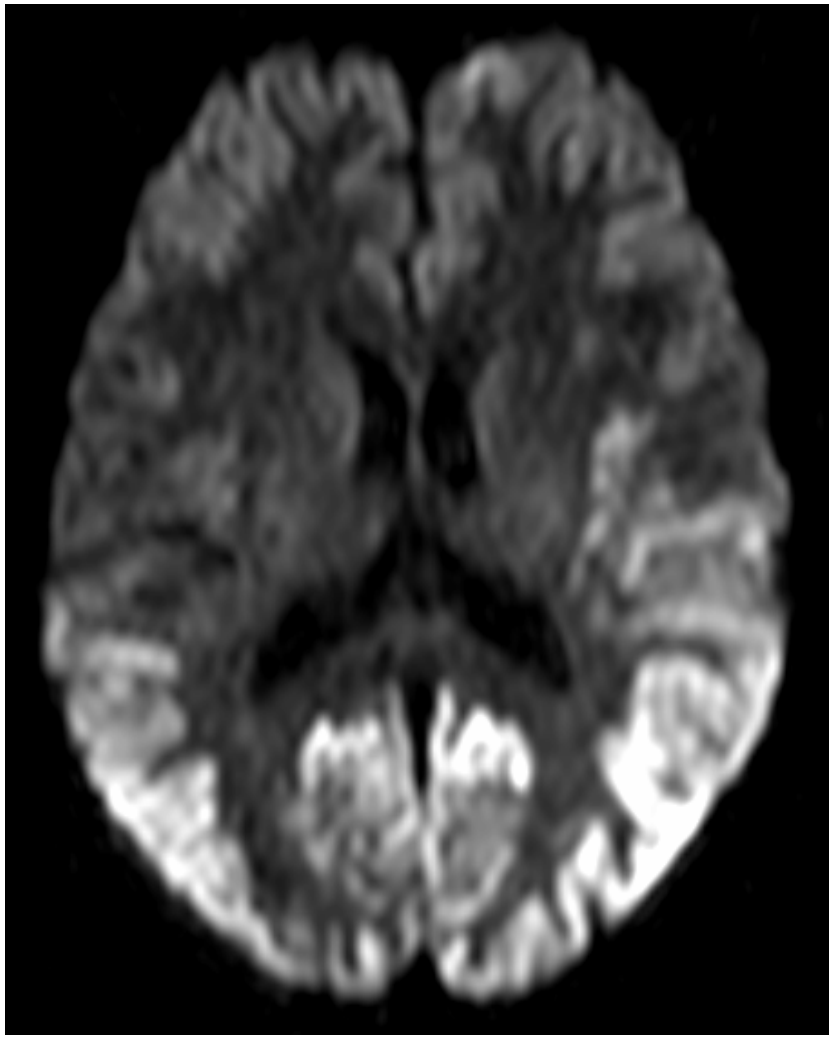
MR angiography



Creutzfeldt-Jacob Disease

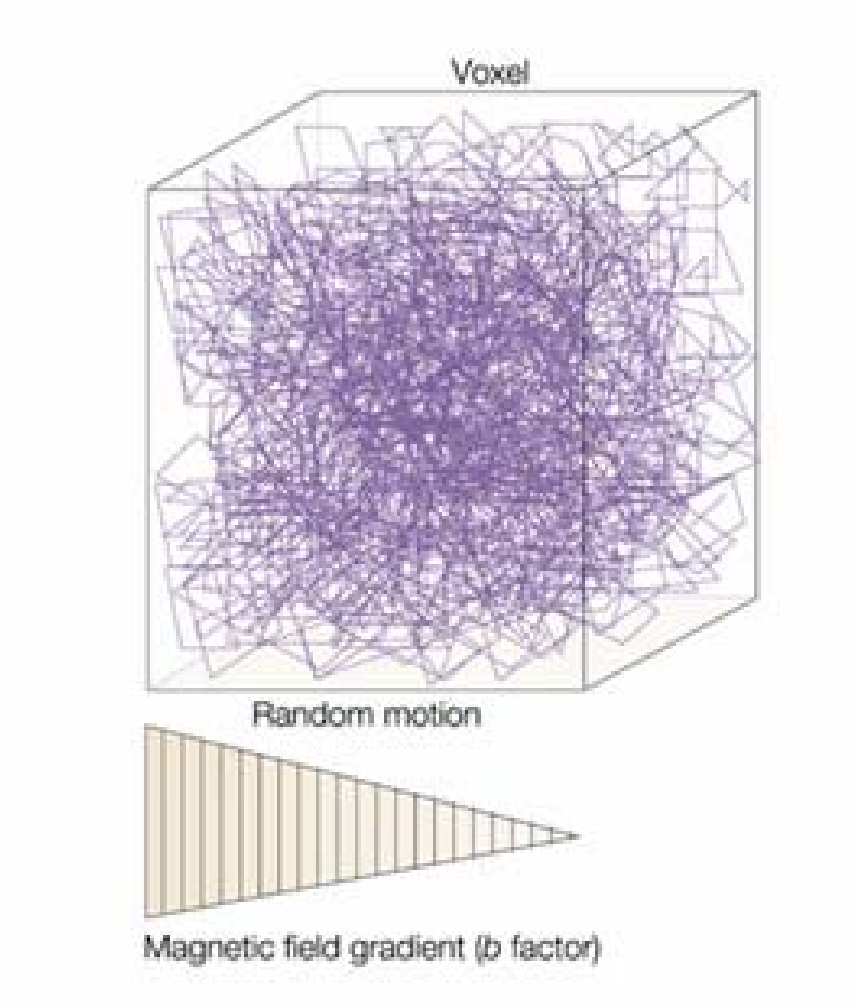


60 y.o female Sporadic CJD



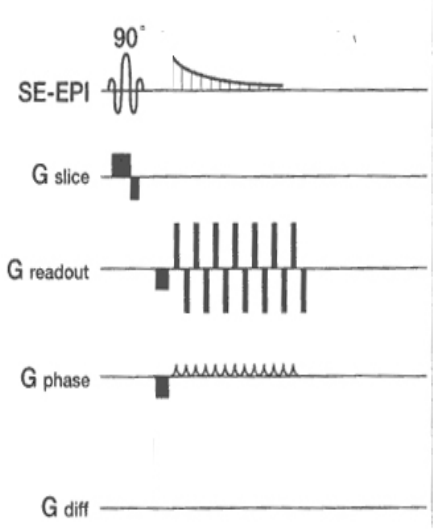
50 y.o female Heidenhain variant

Diffusion weighted image

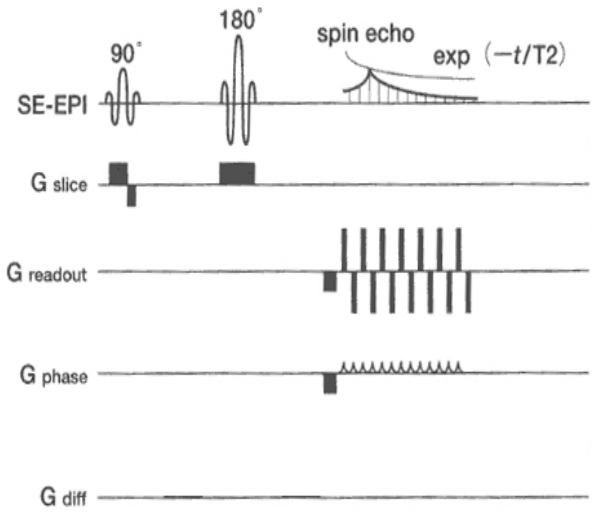


Brownian motion

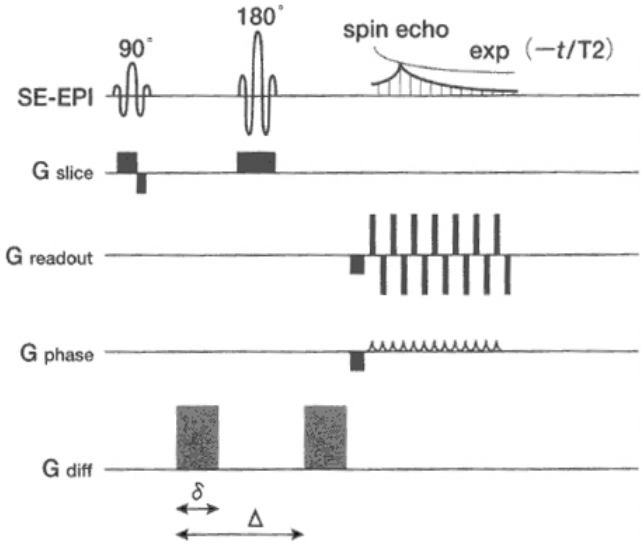
Diffusion image sequence



GRE-EPI



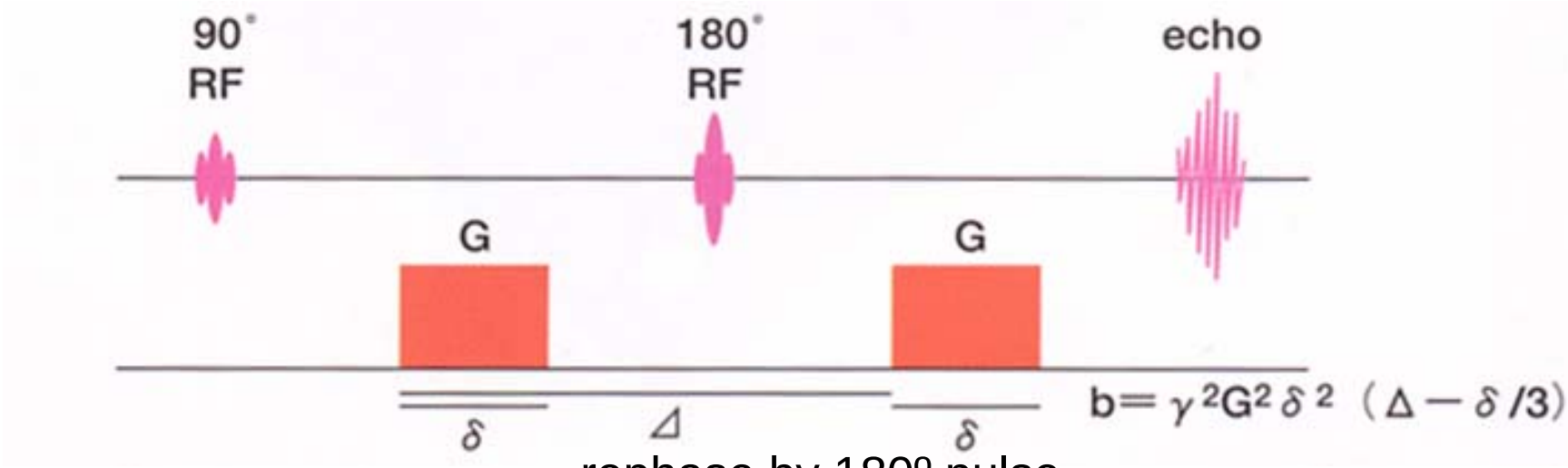
SE-EPI



DIFF-EPI

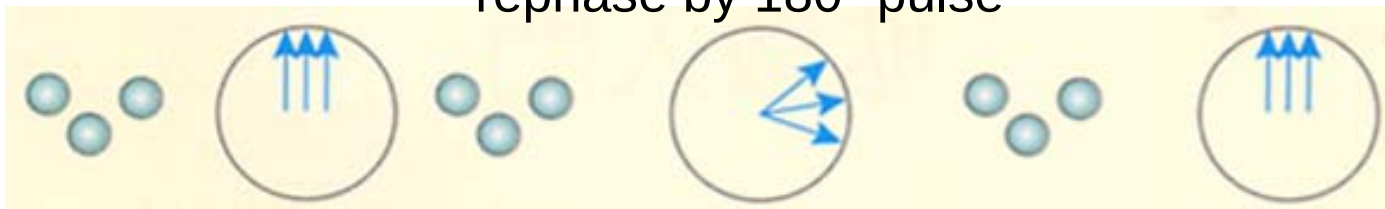
EPI : Echo Planar Imaging

MPG reduces the signal
(MPG : Motion Probing Gradient)



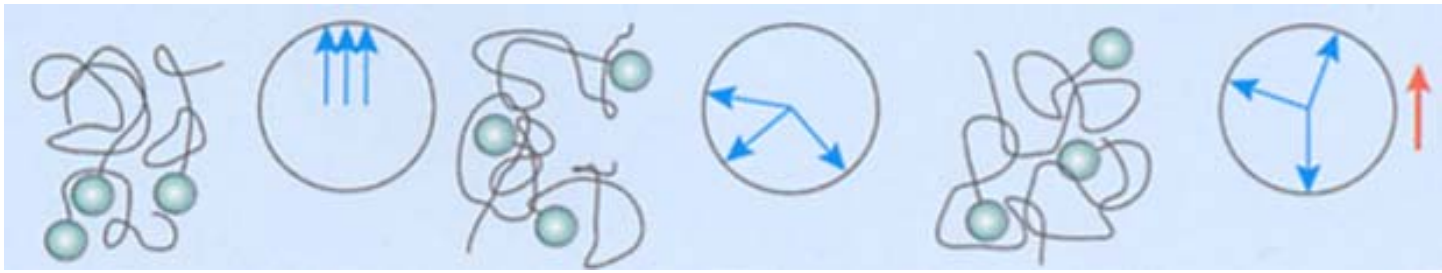
rephase by 180º pulse

resting

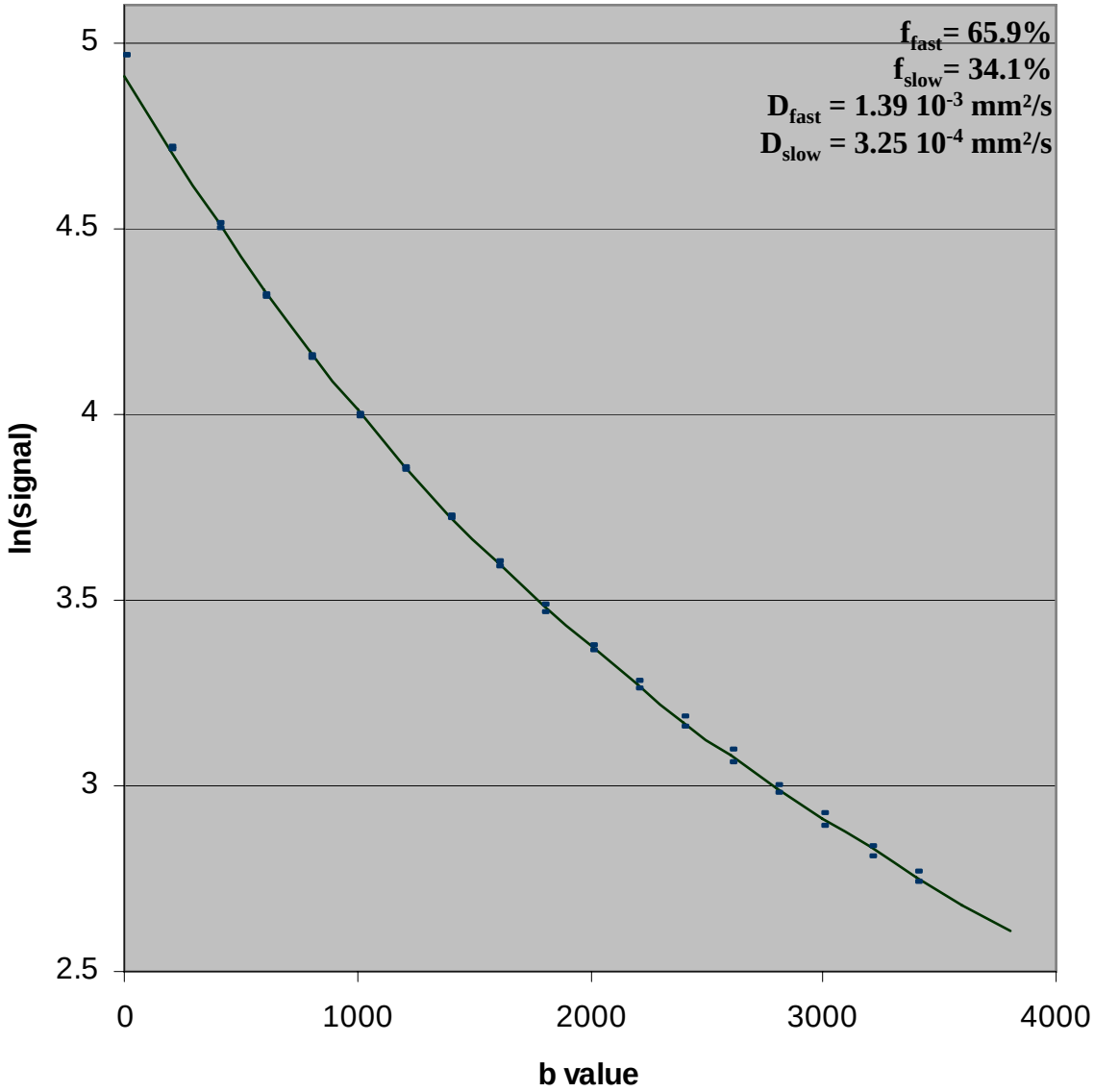


signal

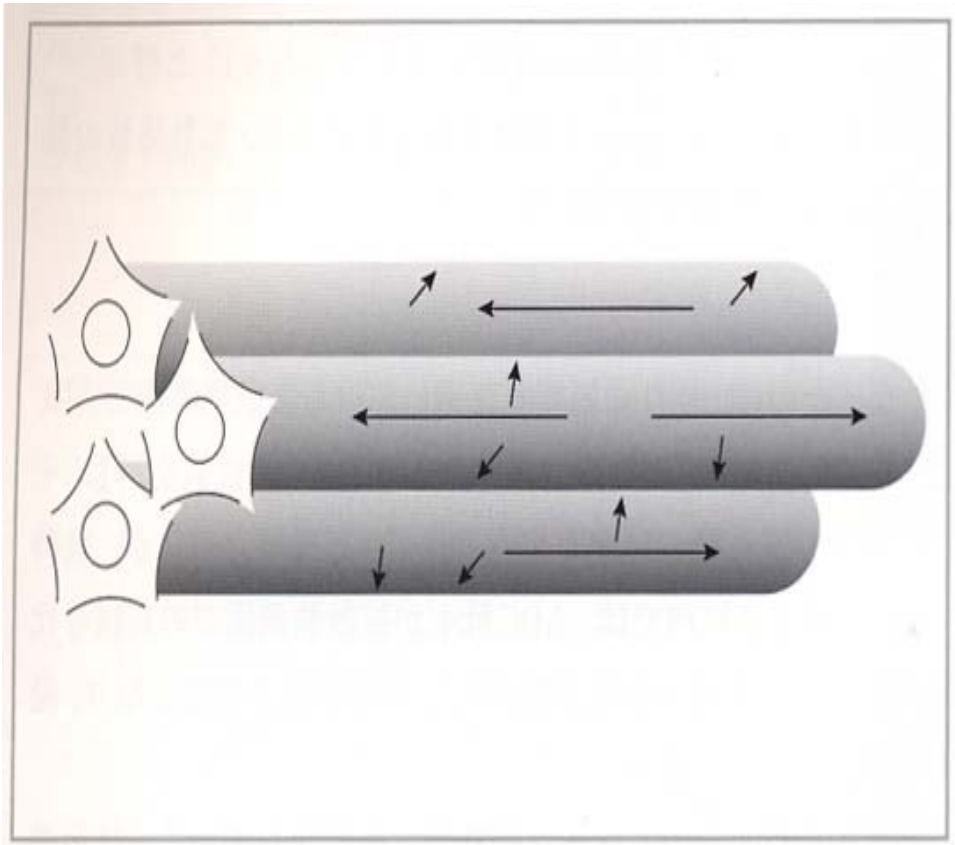
random
walk

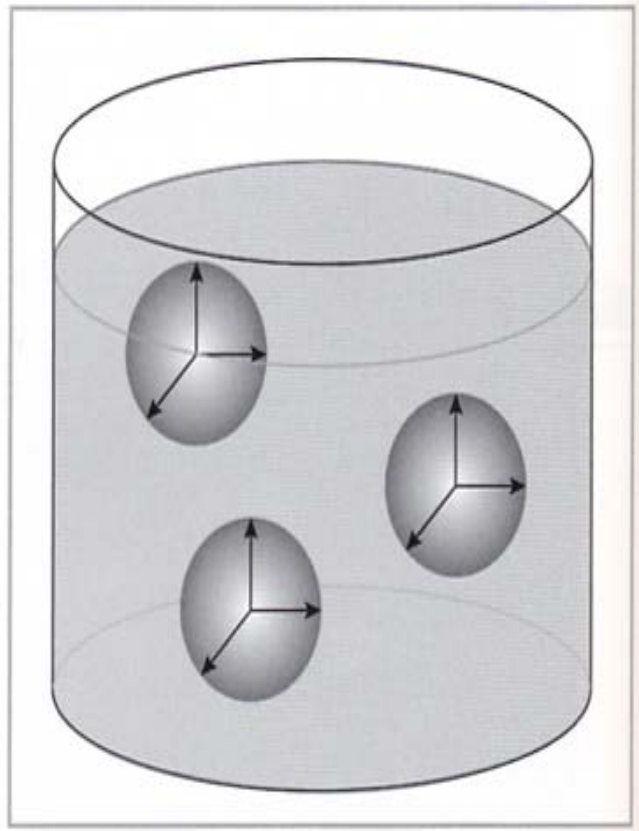


B factor and signal intensity



Anisotropy

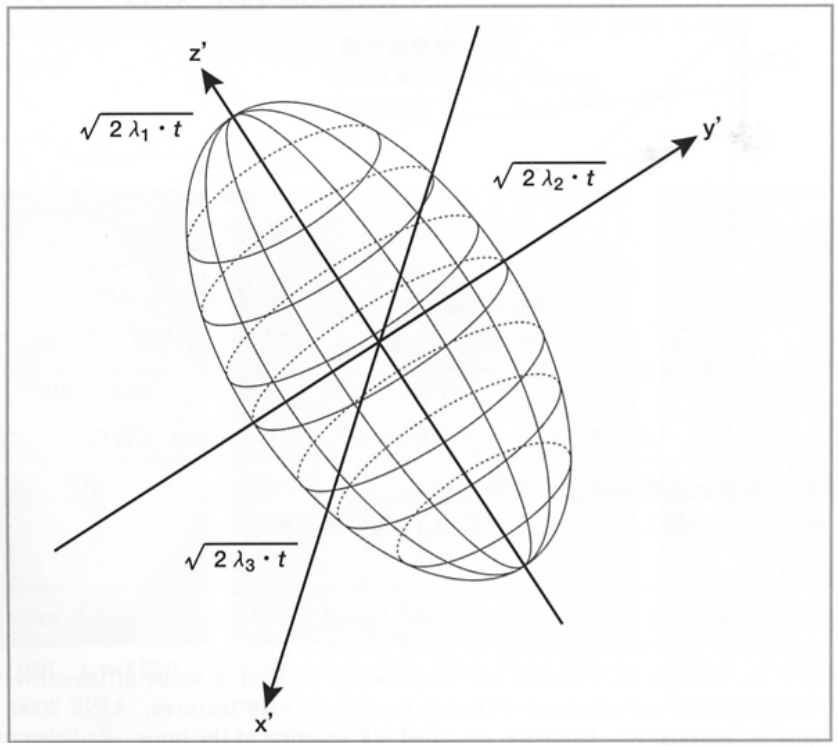




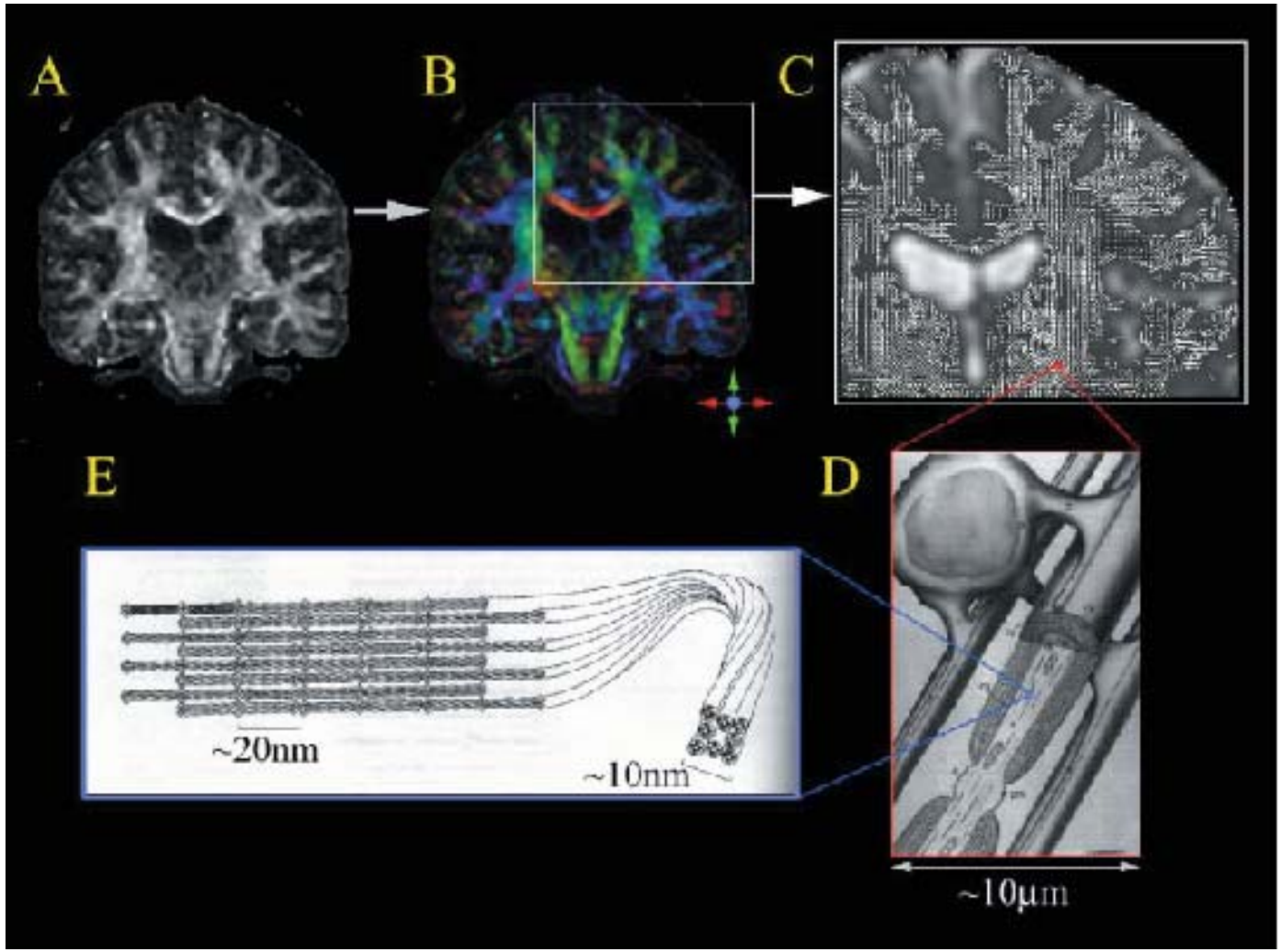
Anisotropy and Diffusion tensor imaging

$$\mu_i = S_0 \exp(-b_i \mathbf{r}_i^T \mathbf{D} \mathbf{r}_i)$$

$$\mathbf{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$$



Tractography in Diffusion MRI

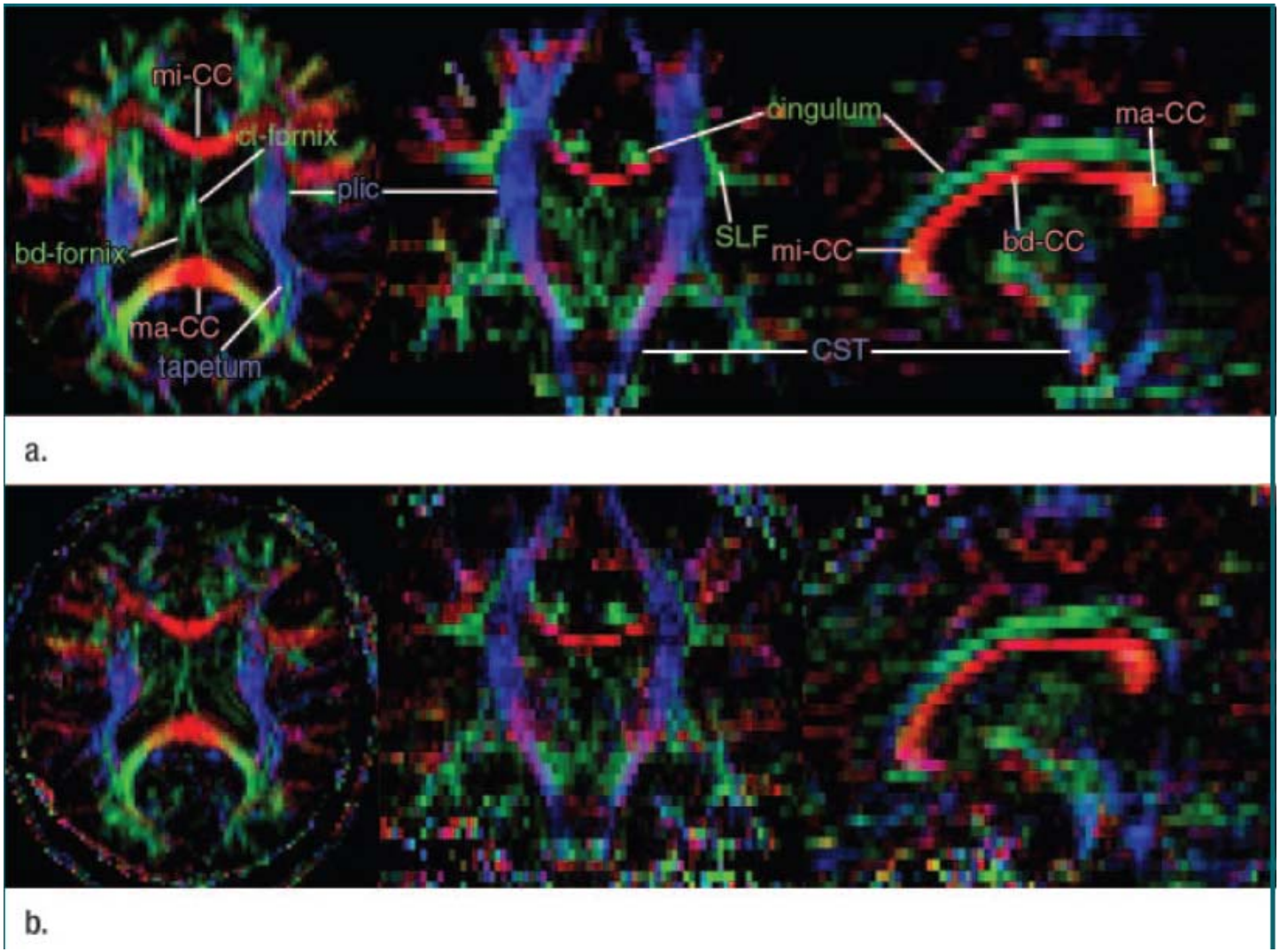


Mori et al. NMR Biomed 2002

Color-coded DTI

3T

1.5T

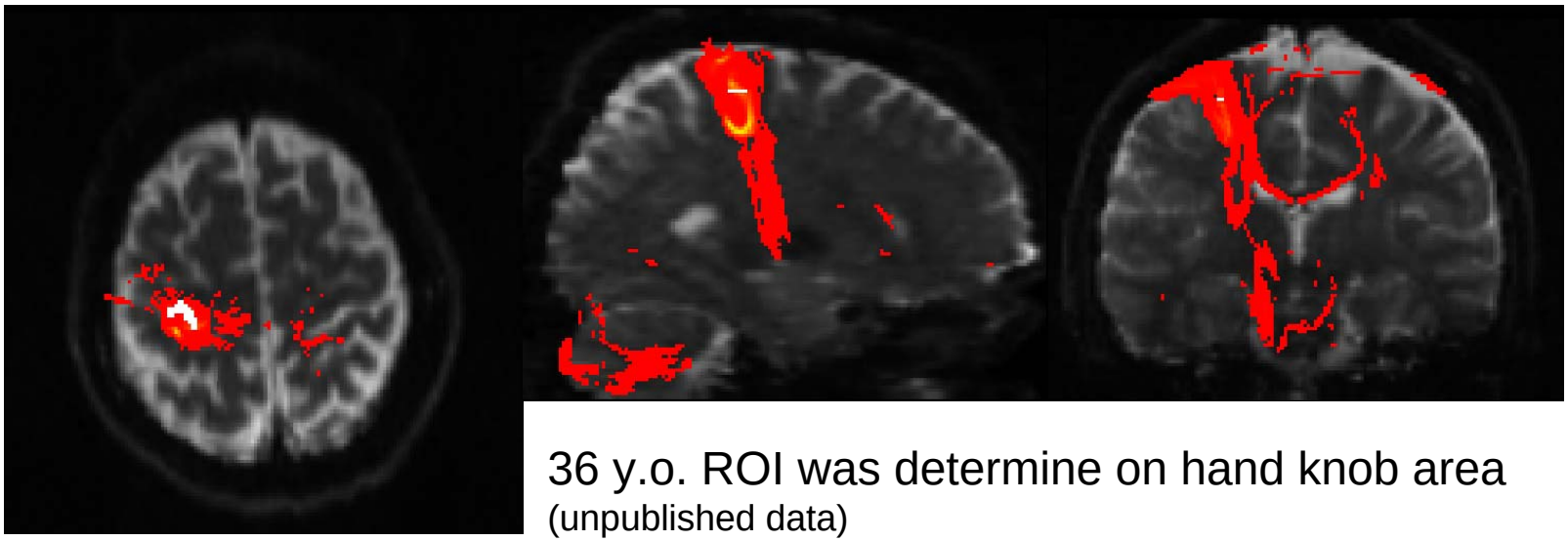


Okada, Miki, et al., *Radiology* 2006; 238:668-78

Tractography methodology in 3 Tesla

81 direction of Diffusion weighted images

- 3 tesla Siemens Trio MRI scanner
- diffusion weighted image using echo planar imaging sequence
- b = 700 s/mm^2
- Voxel size 2 x 2 x 2 mm
- FMRIB Software (http://www.fmrib.ox.ac.uk/fsl/)

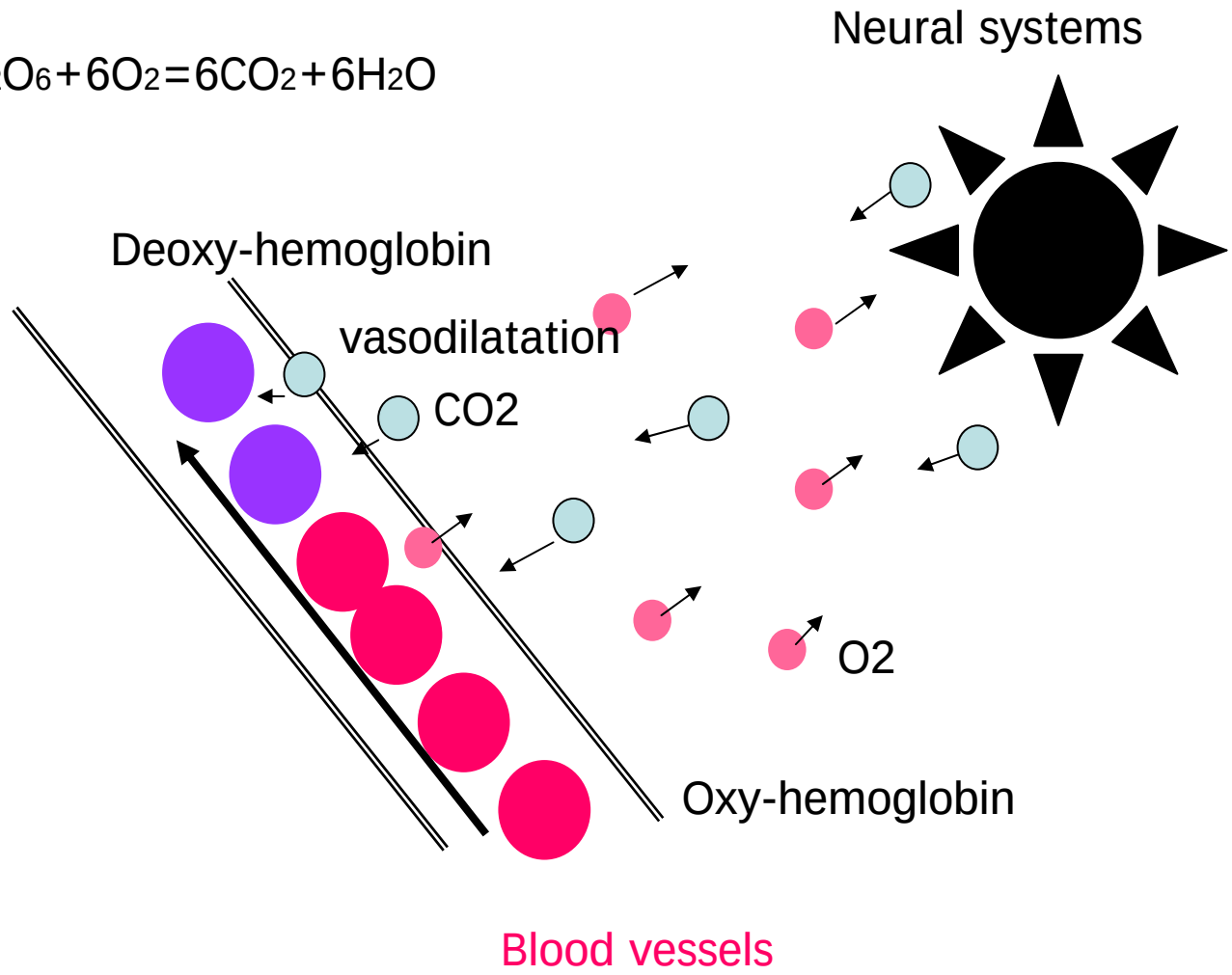


36 y.o. ROI was determine on hand knob area
(unpublished data)

Brain Activation

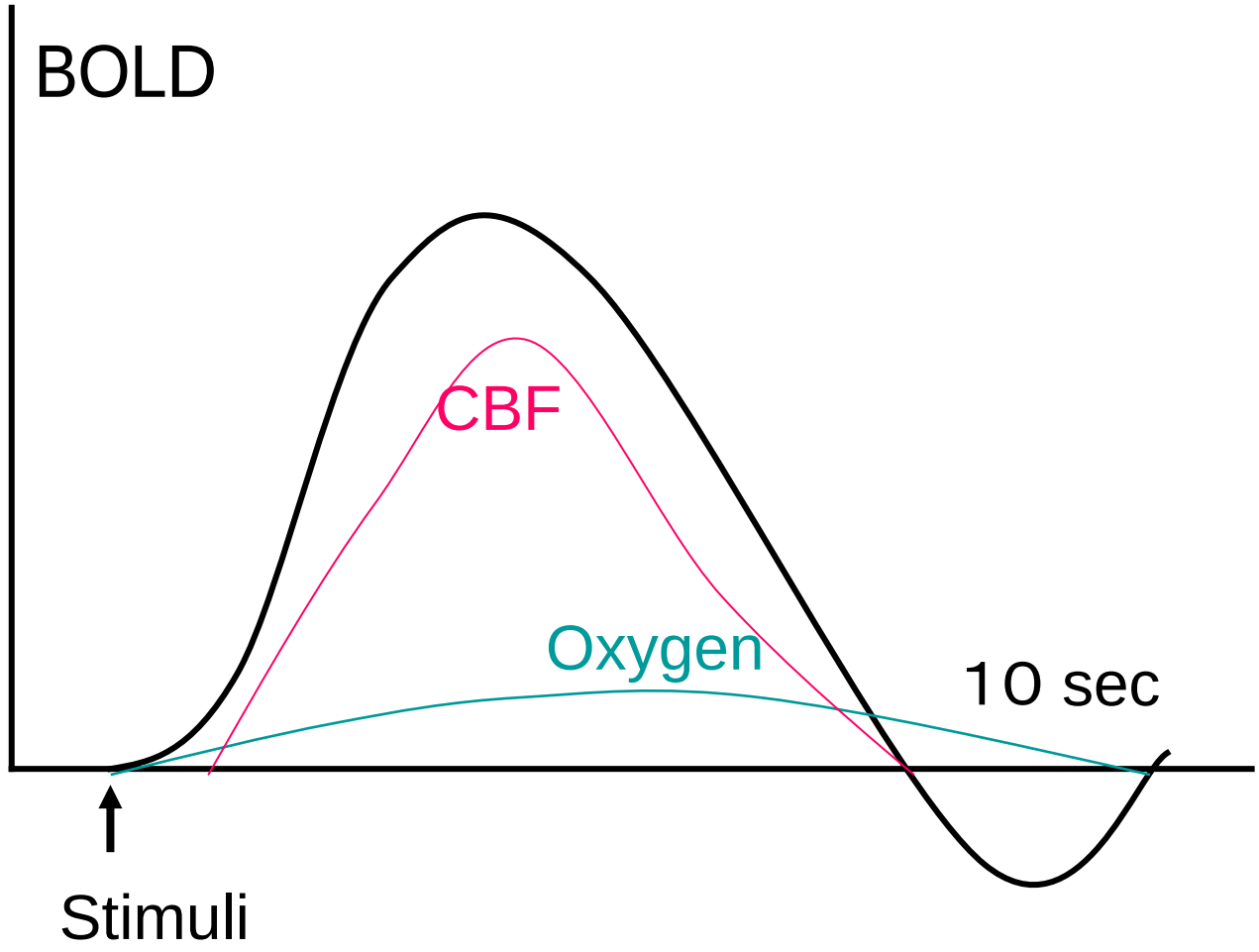
Roy & Sherrington

Glucose $C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O$

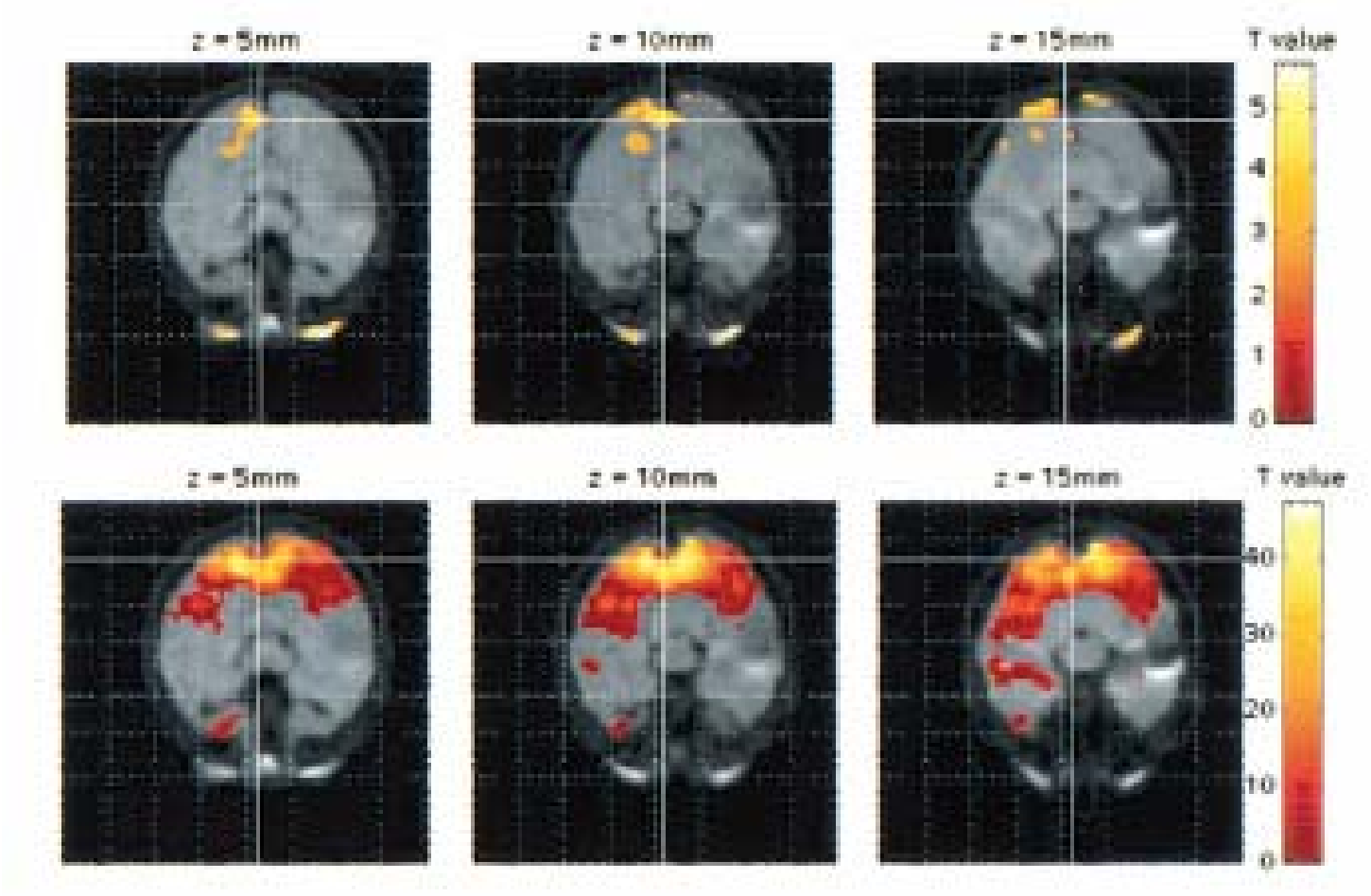


BOLD (blood oxygen level dependency)

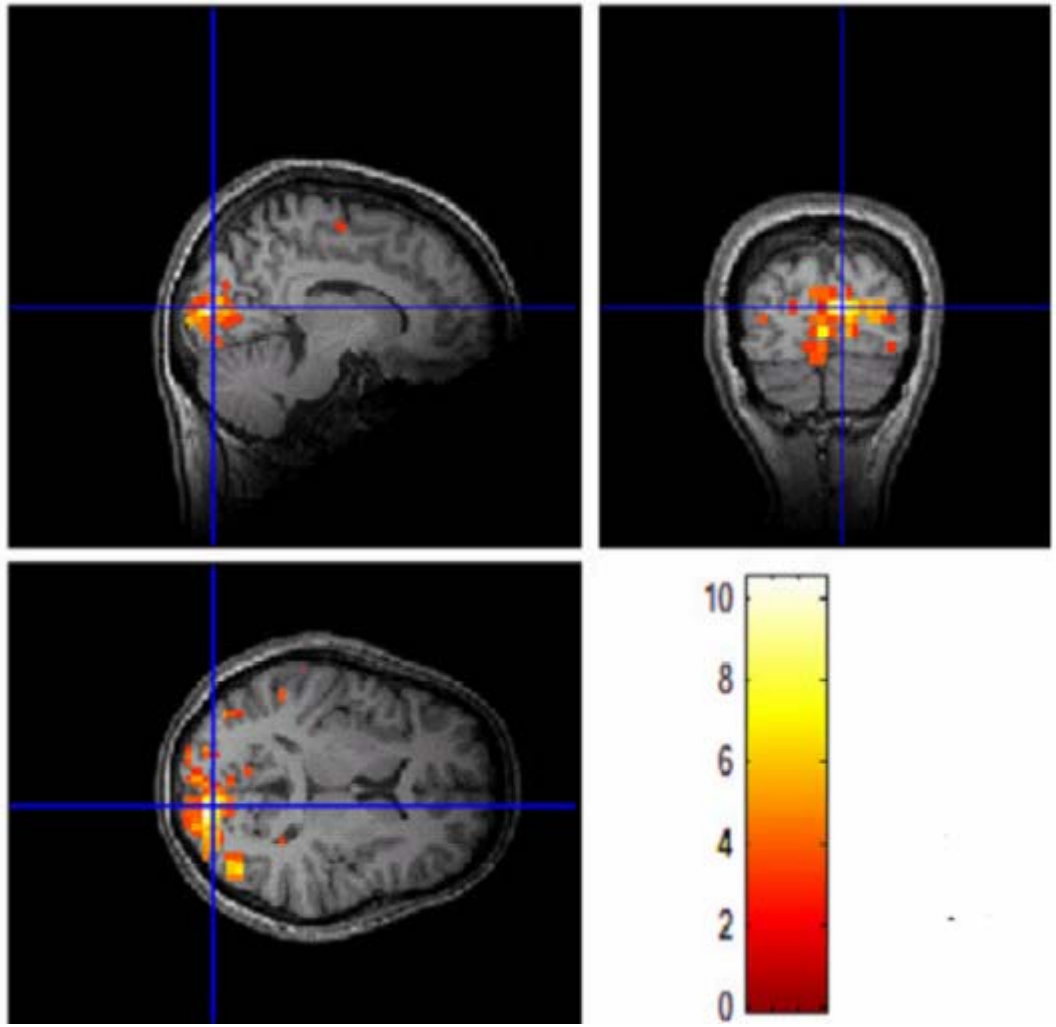
Dr. S. Ogawa



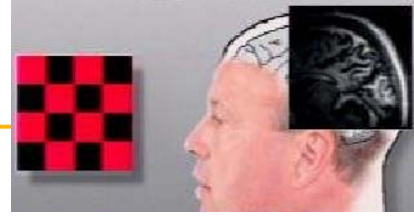
PNAS 2001; 98: 9391–9395



DfMRI **(Le Bihan et al. PNAS 102, 8263-8268, 2006)**

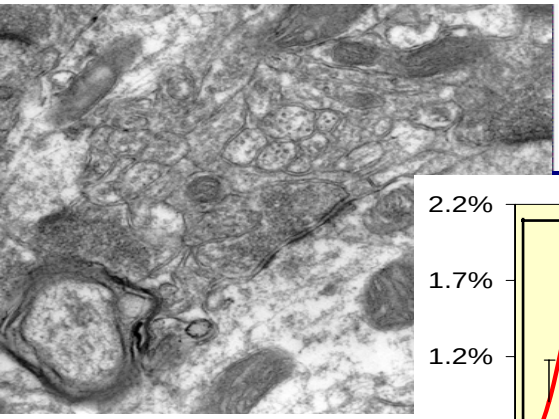


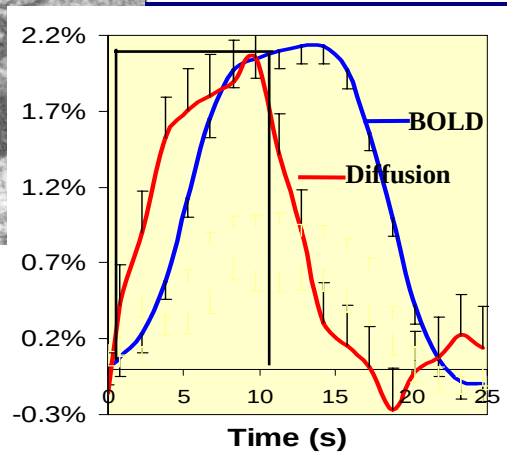
DfMRI (Le Bihan et al. PNAS 102, 8263-8268, 2006)

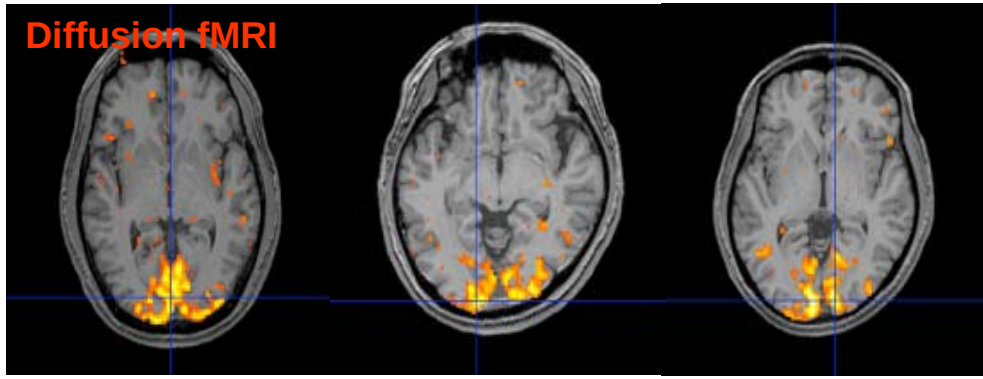


BOLD fMRI: *Hemodynamic events…*

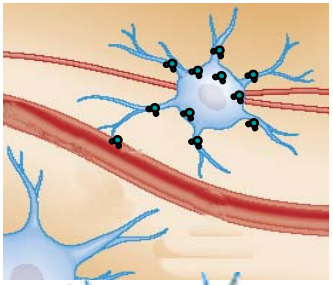
Diffusion fMRI: *Membrane events…*

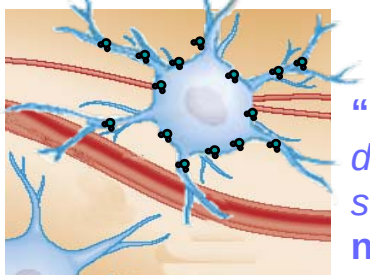






→*Other more direct mechanisms?*





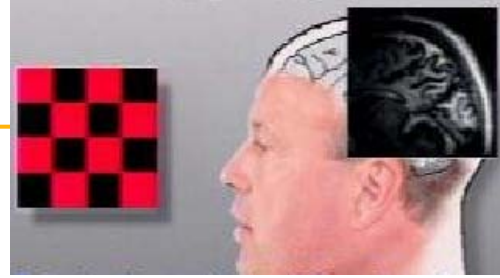
"Diffusion fMRI": *detection of cell swelling* **induced by neuronal activation?**

- **Small induced electric axonal currents (≈ EEG/MEG) ?**
  [Song et al, 8th ISMRM, 54 (2000), Bordurka et al. MRM 2002, Bonn et al. MRM 2003, this meeting!]
- **Neurotransmission: Ca^{2+} inflow as seen with MnMRI ?**
  [Lin and Korestky, MRM 1997, Pautler et al. NI 2002, MRM 2003]
- **Structural events induced in activated cortical cells**
  [Darquie et al. PNAS 2001, Le Bihan et al. ISMRM 06, PNAS 2006]

↗cell size and membrane surface
↘diffusion of water near membranes

→ *Early marker of neuronal activation ?*

DfMRI (Le Bihan et al. PNAS 102, 8263-8268, 2006)



3T MRI scanner (Siemens Trio)

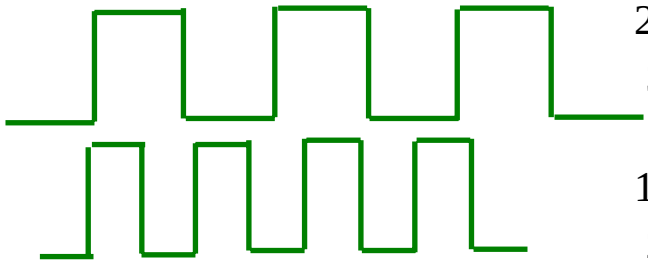
8-ch. phased array (GRAPPAx2)
40mT/m gradient coils

Materials and Methods

PROTOCOL

Acquisition

-Visual stimulation (flickering dartboard):



20s ON/ 20s OFF x 3

3.75x3.75x4mm^3, TE=87ms/TR=1s

10 ON/ 20s OFF x 4

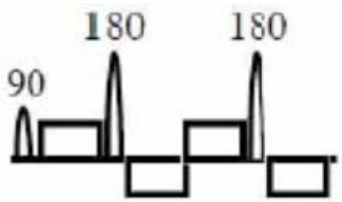
2x2x3mm^3, TE=93ms/TR=1.5s

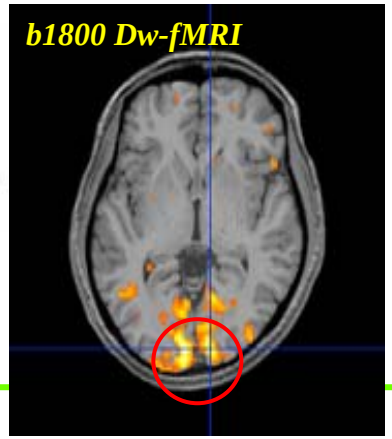
-**Diffusion**-sensitized fMRI

DfMRI: *b-values*=0, 250, 600, 1200, 1800, 2400 s/mm²

Biexp model: *b-values*=[0 to 3400 s/mm²]/200 s/mm² increment

-twice refocused spin-echo EPI
-diffusion-sensitization by an interleaved ***pair of bipolar*** gradient pulses





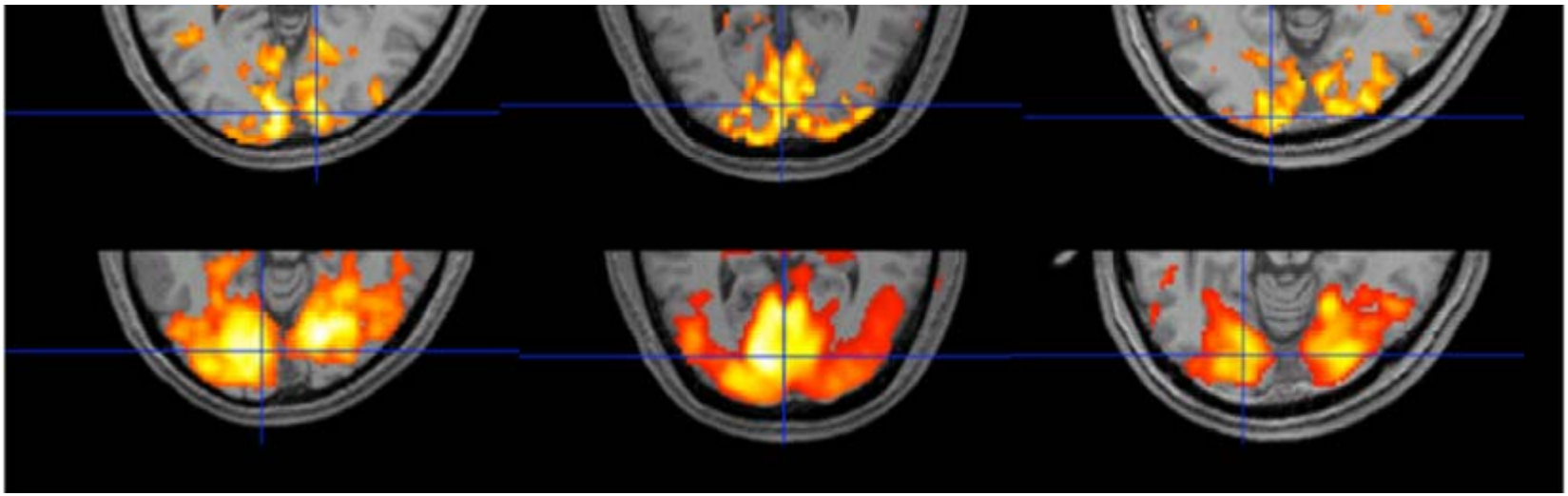
- **BOLD fMRI** (TR=1s or 1.5s)
- T1-weighted sequence (0.94x0.94x0.95 mm^3 voxels)

Processing

- preparation: *motion correction, registration, smoothing*

- SPM5 on diffusion-weighted images
→selection of ***activated visual VOI*** (p=0.001)

DfMRI **(Le Bihan et al. PNAS 102, 8263-8268, 2006)**



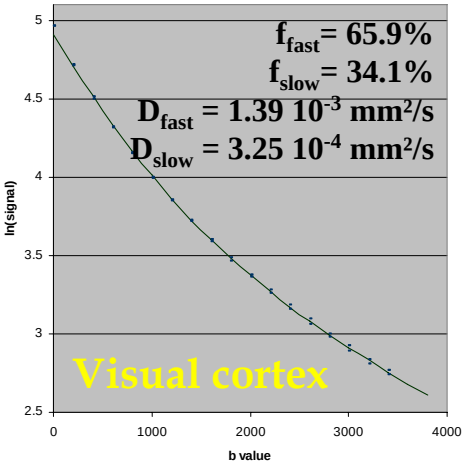
Diffusion fMRI

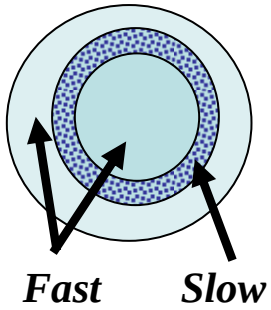
BOLD fMRI

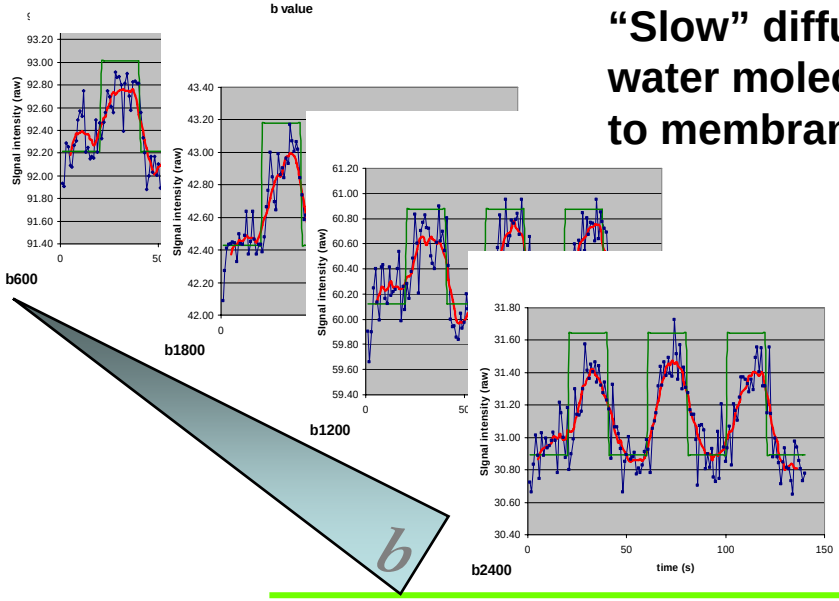
DfMRI (Le Bihan et al. PNAS 102, 8263-8268, 2006)

Bi-phasic water diffusion model:

$S = f_{slow} * \exp(-b\, D_{slow}) + f_{fast} * \exp(-b\, D_{fast})$

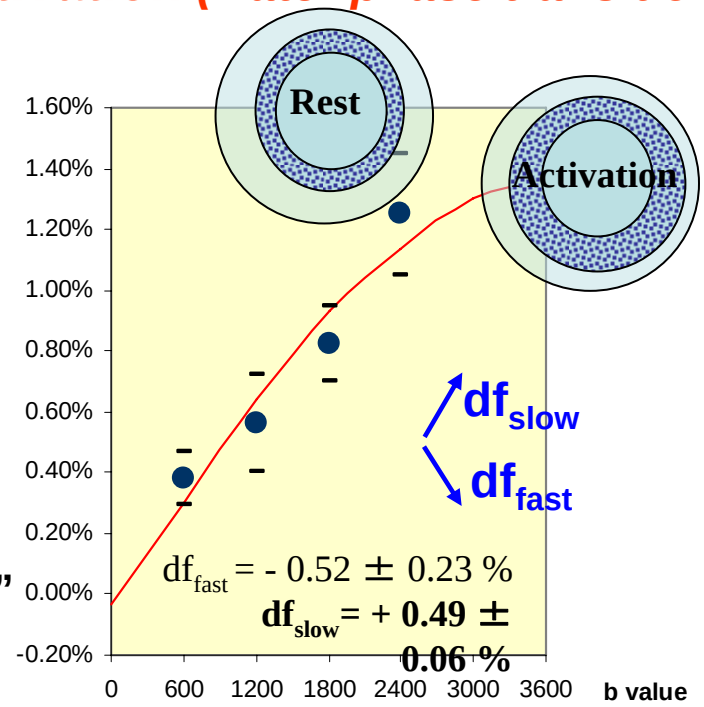






"Slow" diffusion pool: water molecules "bound" to membranes

Increased of the Slow Diffusion Phase upon activation *(water phase transition)*



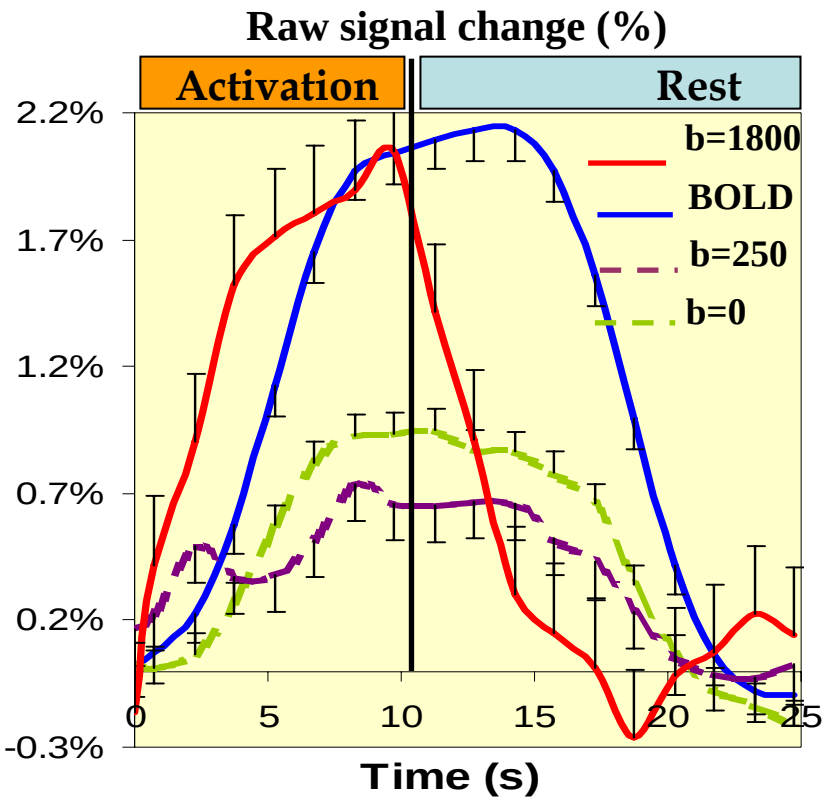
Activation response, dS/S, increases with diffusion-sensitization (*b*-value)

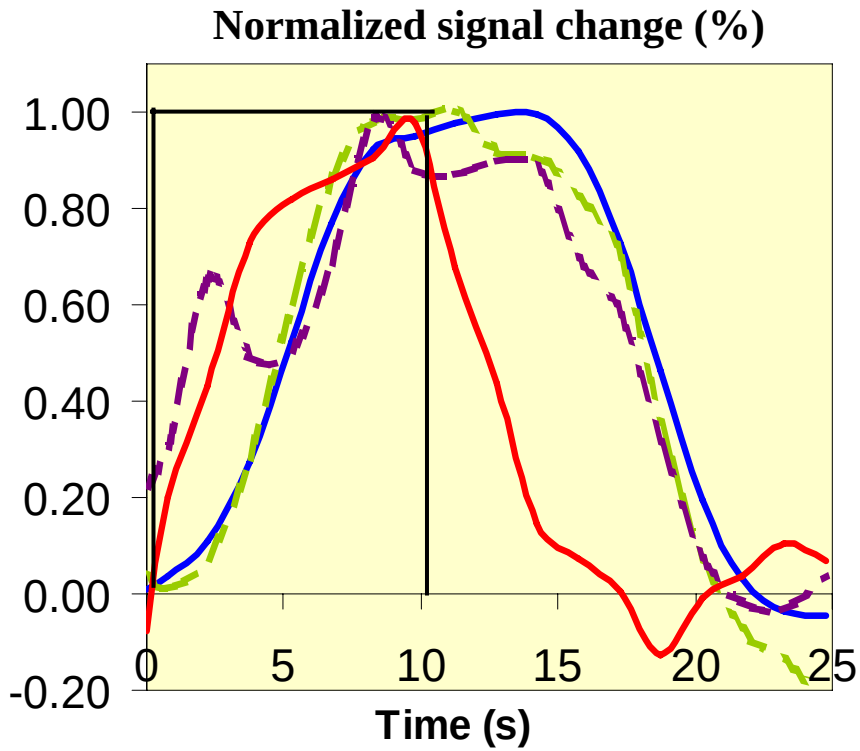
→ $dS/S = F_{slow}\, df_{slow} + F_{fast}\, df_{fast}$

$F_{i=fast,\,slow} = \exp(-bD_i) / [\, f_{slow} \exp(-bD_{slow}) + f_{fast} \exp(-bD_{fast})]$

→ *Time-course?*

DfMRI (Le Bihan et al. PNAS 102, 8263-8268, 2006)





BOLD: gradient-echo

b=0 s/mm²: BOLD spin-echo

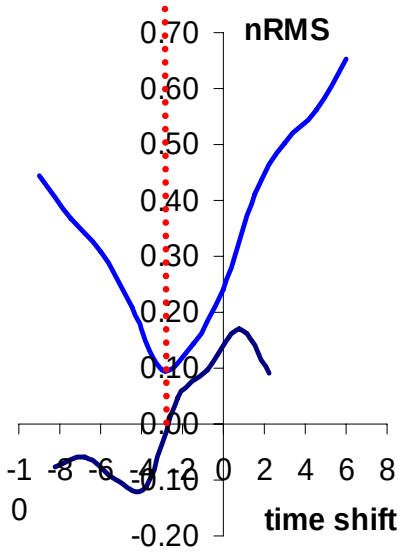
- same time-course

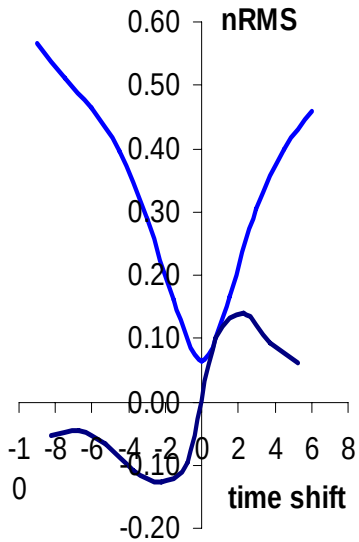
b=250 s/mm²:

- Same time-course + ***early start***

b=1800 s/mm²

- ***earlier response*** (onset & offset)





10s visual stimulation (TR=1.5s)

shifted BOLD/b=1800 s/mm²

shifted BOLD/b=0 s/mm²