Bioengineering 280A
Principles of Biomedical Imaging

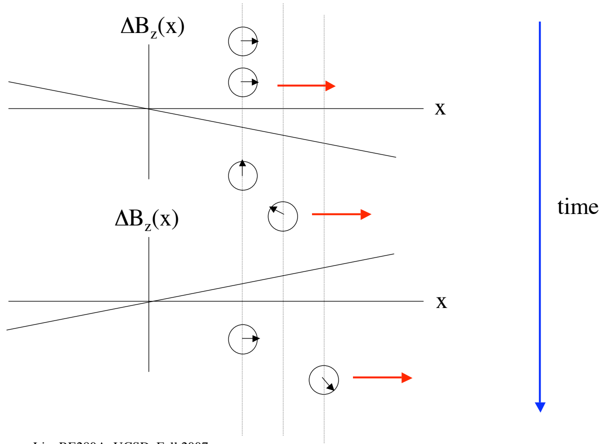
Fall Quarter 2007
MRI Lecture 6

Moving Spins

So far we have assumed that the spins are not moving (aside from thermal motion giving rise to relaxation), and contrast has been based upon T_1, T_2, and proton density. We were able to achieve different contrasts by adjusting the appropriate pulse sequence parameters.

Biological samples are filled with moving spins, and we can also use MRI to image the movement. Examples: blood flow, diffusion of water in the white matter tracts. In addition, we can also sometimes induce motion into the object to image its mechanical properties, e.g. imaging of stress and strain with MR elastography.

Phase of Moving Spin



Phase of a Moving Spin

$$
\begin{aligned}
\varphi(t) &= -\int_0^t \Delta\omega(\tau)\,d\tau \\
&= -\int_0^t \gamma \Delta B(\tau)\,d\tau \\
&= -\int_0^t \gamma \vec{G}(\tau)\cdot\vec{r}(\tau)\,d\tau \\
&= -\gamma\int_0^t \left[G_x(\tau)x(\tau) + G_y(\tau)y(\tau) + G_z(\tau)z(\tau)\right]d\tau
\end{aligned}
$$

Phase of Moving Spin

Consider motion along the x-axis

$$x(t) = x_0 + vt + \frac{1}{2}at^2$$

$$\begin{aligned}
\varphi(t) &= -\gamma \int_0^t G_x(\tau)x(\tau)d\tau \\
&= -\gamma \int_0^t G_x(\tau)\left[x_0 + v\tau + \frac{1}{2}a\tau^2\right]d\tau \\
&= -\gamma\left[x_0 \int_0^t G_x(\tau)d\tau + v\int_0^t G_x(\tau)\tau d\tau + \frac{a}{2}\int_0^t G_x(\tau)\tau^2 d\tau\right] \\
&= -\gamma\left[x_0 M_0 + vM_1 + \frac{a}{2}M_2\right]
\end{aligned}$$

Phase of Moving Spin

$$\varphi(t) = -\gamma\left[x_0 M_0 + vM_1 + \frac{a}{2}M_2\right]$$

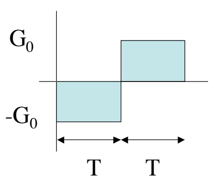
$M_0 = \int_0^t G_x(\tau)d\tau$ Zeroth order moment

$M_1 = \int_0^t G_x(\tau)\tau d\tau$ First order moment

$M_2 = \int_0^t G_x(\tau)\tau^2 d\tau$ Second order moment

Thomas Liu, BE280A, UCSD, Fall 2007

Flow Moment Example



$$\begin{aligned}
M_0 &= \int_0^t G_x(\tau)d\tau = 0 \\
M_1 &= \int_0^t G_x(\tau)\tau d\tau \\
&= -\int_0^T G_0 \tau d\tau + \int_T^{2T} G_0 \tau d\tau \\
&= G_0\left[-\frac{\tau^2}{2}\Big|_0^T + \frac{\tau^2}{2}\Big|_T^{2T}\right] \\
&= G_0\left[-\frac{T^2}{2} + \frac{4T^2}{2} - \frac{T^2}{2}\right] = G_0 T^2
\end{aligned}$$

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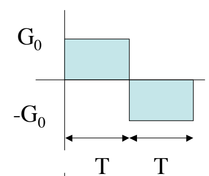
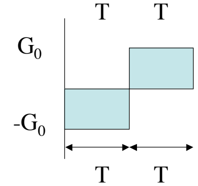
Phase Contrast Angiography (PCA)



$$\varphi_1 = -\gamma v_x M_1 = \gamma v_x G_0 T^2$$



$$\varphi_2 = -\gamma v_x M_1 = -\gamma v_x G_0 T^2$$

$$\Delta\varphi = \varphi_1 - \varphi_2 = 2\gamma v_x G_0 T^2$$

$$v_x = \frac{\Delta\varphi}{2G_0 T^2}$$

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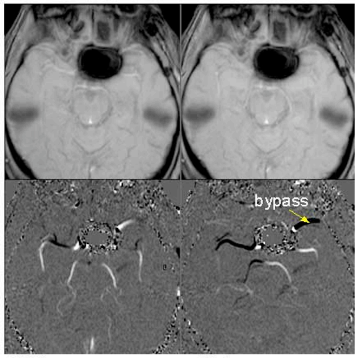
PCA example

-G_0



White = Flow direction AP (↓)

White = Flow direction RL (→)

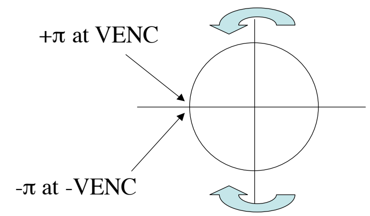
http://www.medical.philips.com/main/products/mri/assets/images/case_of_week/cotw_51_s5.jpg

Aliasing in PCA

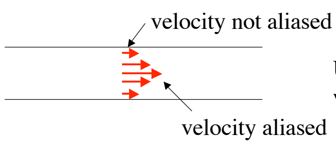
Define VENC as the velocity at at which the phase is 180 degrees.

$$VENC \equiv \frac{\pi}{\gamma G_0 T^2}$$

Because of phase wrapping the velocity of spins flowing faster than VENC is ambiguous.



Aliasing Solutions



Use data from regions with slower flow

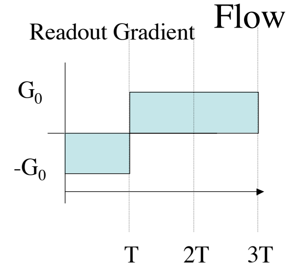
Use multiple VENC values so that the phase differences are smaller than π radians.

$$\varphi_1 = \pi \frac{v_x}{VENC_1}$$

$$\varphi_2 = \pi \frac{v_x}{VENC_2}$$

$$\varphi_1 - \varphi_2 = \pi v_x \left(\frac{1}{VENC_1} - \frac{1}{VENC_2} \right)$$

Flow Artifacts

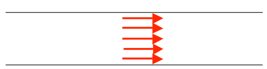


During readout moving spins within the object will accumulate phase that is in addition to the phase used for imaging. This leads to

1) Net phase at echo time TE = 2T.
2) An apparent shift in position of the object.
3) Blurring of the object due to a quadratic phase term.

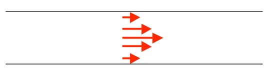
Flow Artifacts

Plug Flow



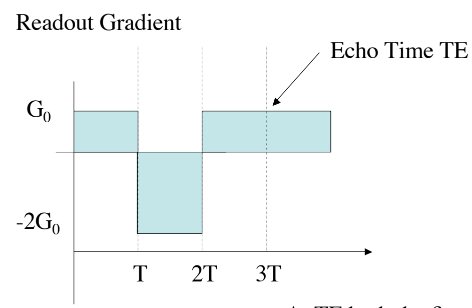
All moving spins in the voxel experience the same phase shift at echo time.

Laminar Flow



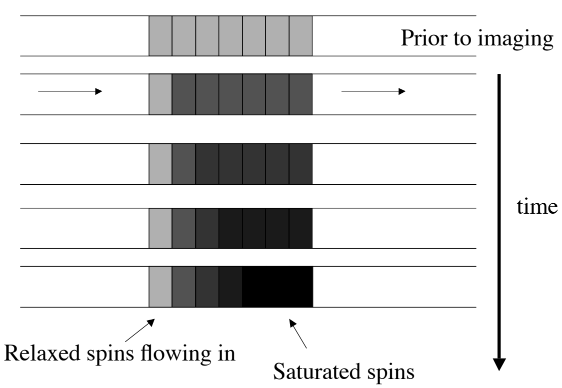
Spins have different phase shifts at echo time. The dephasing causes the cancelation and signal dropout.

Flow Compensation

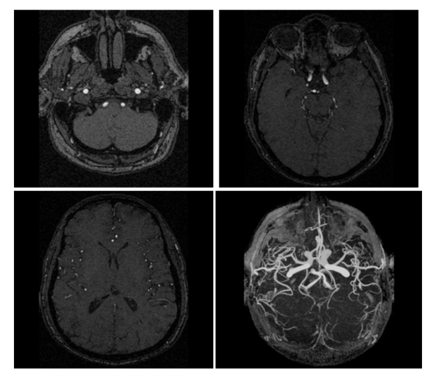


At TE both the first and second order moments are zero, so both stationary and moving spins have zero net phase.

Inflow Effect



Time of Flight Angiography

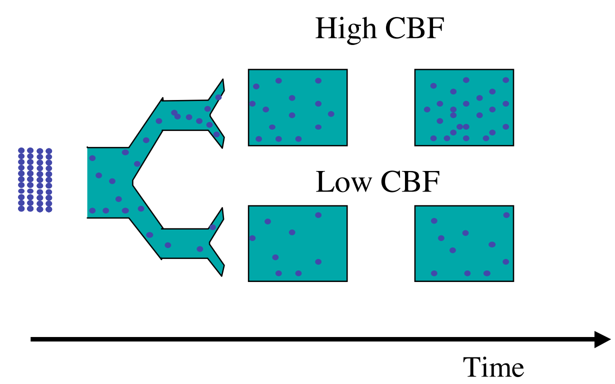


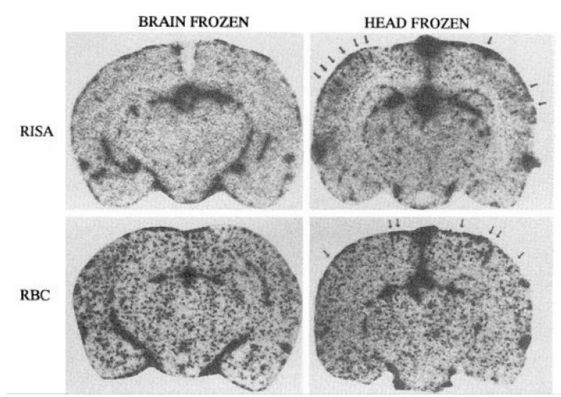
Cerebral Blood Flow (CBF)

CBF = Perfusion
= Rate of delivery of arterial blood to a capillary bed in tissue.

Units: $\frac{\text{(ml of Blood)}}{\text{(100 grams of tissue)(minute)}}$

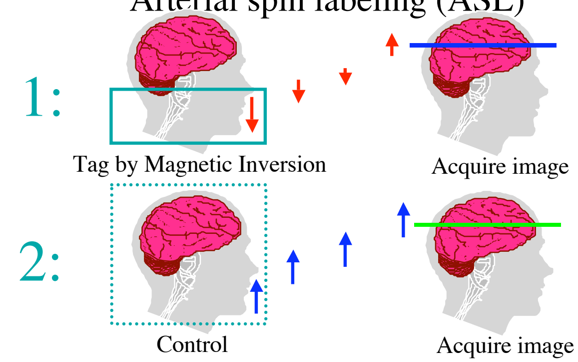
Typical value is 60 ml/(100g-min) or 60 ml/(100 ml-min) = 0.01 s^{-1}, assuming average density of brain equals 1 gm/ml





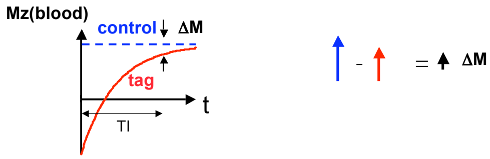
Bereczki et al 1992

Arterial spin labeling (ASL)



Control - Tag = $\Delta M \propto$ CBF

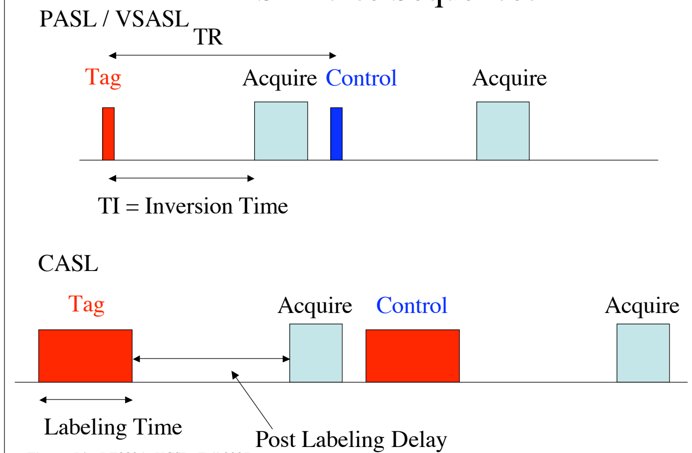
ASL Signal Equation



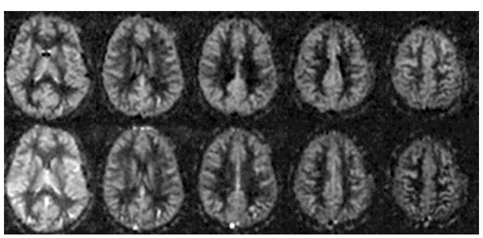
$$\Delta M = CBF \cdot A_{eff}$$

A_{eff} is the effective area of the arterial bolus. It depends on both physiology and pulse sequence parameters.

ASL Pulse Sequences

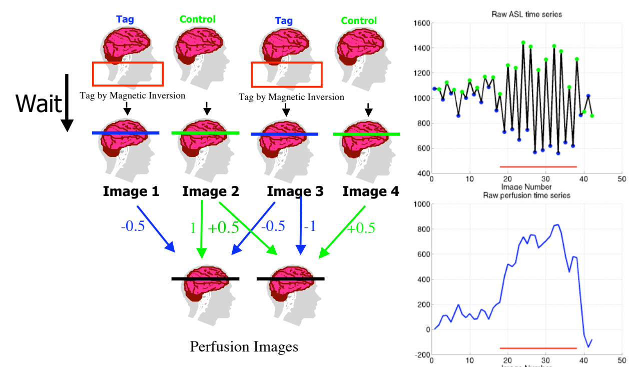


Multislice CASL and PICORE

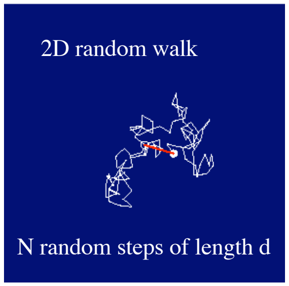


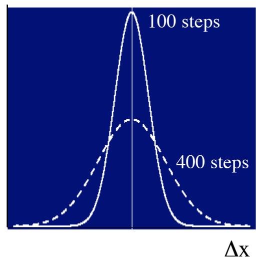
Credit: E. Wong

ASL Time Series



Diffusion





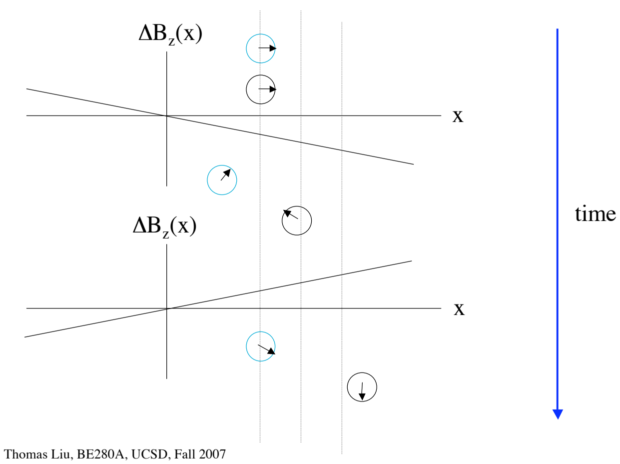
$<\Delta x^2> = Nd^2 = 2DT$

D = diffusivity

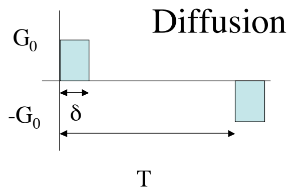
In brain:
$D \cong 0.001\ mm^2/s$
For T=100 msec,
$\Delta x \cong 15\ \mu$

Credit: Larry Frank

Diffusing Spins



Diffusion Weighting



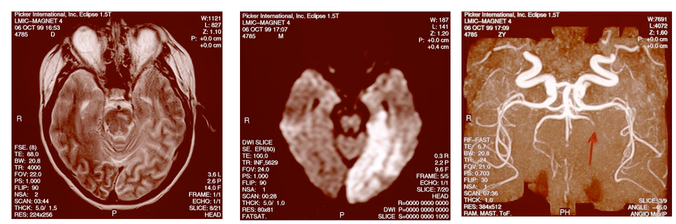
Signal

$$S \propto e^{-\gamma^2 G_0^2 \delta^2 DT} = e^{-bD} \quad \text{where } b = \gamma^2 G_0^2 \delta^2 (T - \delta/3)$$

Diffusivity

Diffusion Weighted Images

T2 weighted | Diffusion Weighted | Angiogram

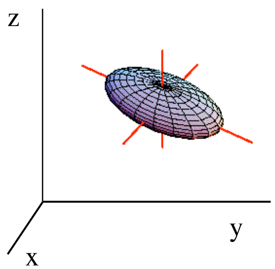


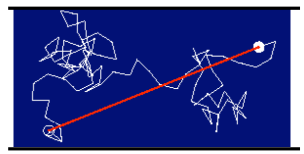
After a stroke, normal water movement is restricted in the region of damage. Diffusivity decreases, so the signal intensity increases.

http://lehighmri.com/cases/dwi/patient-b.html

Restricted Diffusion

D depends on direction

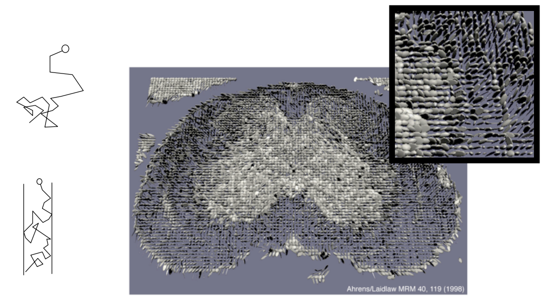




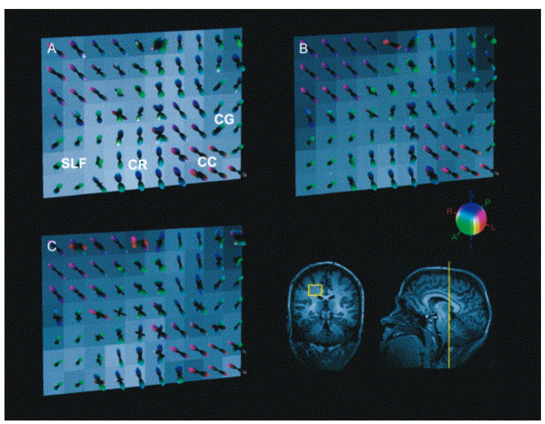
Diffusion tensor:
3 values of D
3 angles

Credit: Larry Frank

Diffusion Imaging Example

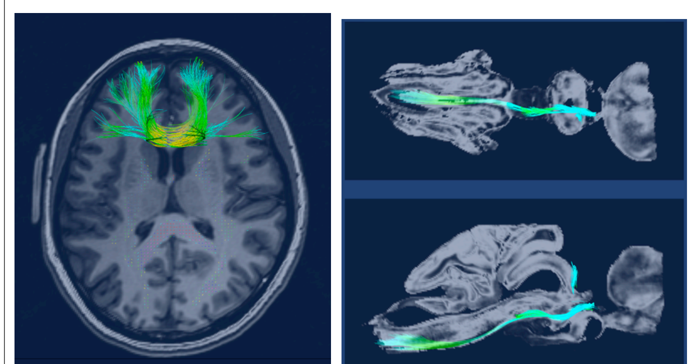


Q-ball imaging



Tuch et al, Neuron 2003

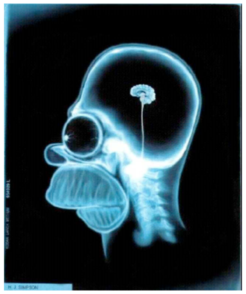
Fiber tract mapping of neural connectivity



Courtesy of L. Frank

fMRI

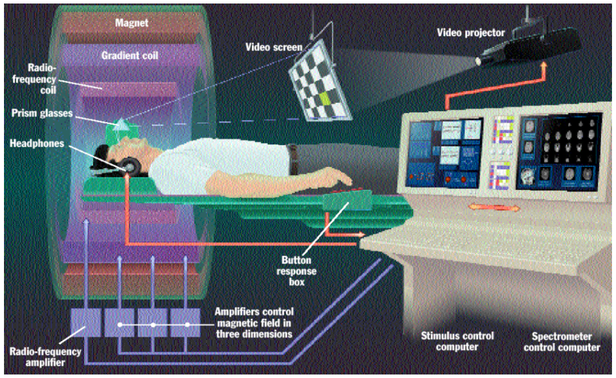
MRI studies brain <u>anatomy</u>.



<u>Functional</u> MRI (fMRI) studies brain <u>function</u>.

http://defiant.ssc.uwo.ca/Jody_web/fmri4dummies.htm

fMRI Setup

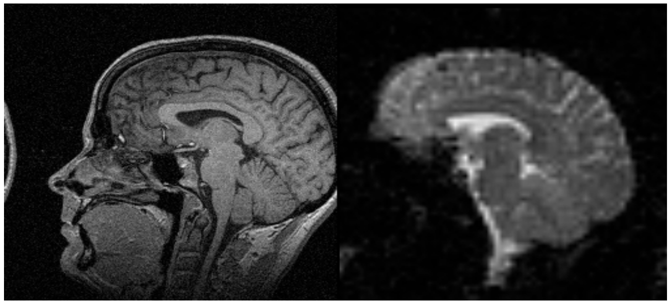


http://defiant.ssc.uwo.ca/Jody_web/fmri4dummies.htm

fMRI Acquisition

High spatial resolution

High temporal resolution

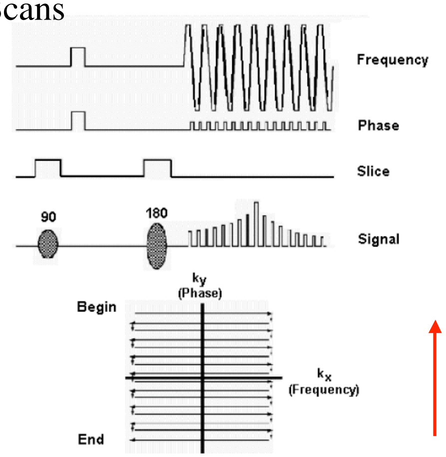


MP-RAGE
Voxel volume: 1 mm^3
Imaging time: 6 min

EPI
Voxel volume: 45 mm^3
Imaging time: 60 msec

Buxton 2002

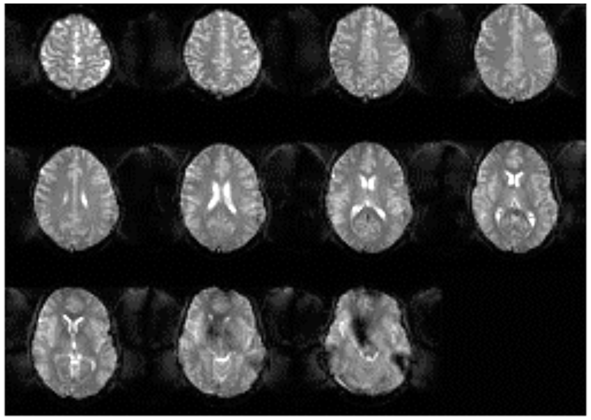
EPI Scans



Phase Encode

GE Medical Systems 2003

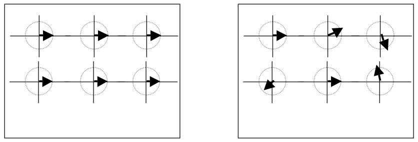
EPI Distortions and Signal Dropouts



Credit: R. Buxton

Signal Dropouts

Field inhomogeneities also cause the spins to dephase with time and thus for the signal to decrease more rapidly. To first order this can be modeled as an additional decay term.



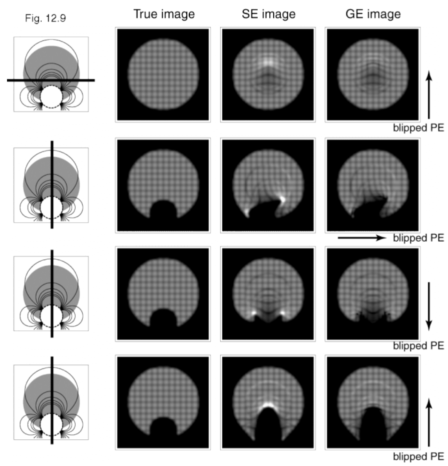
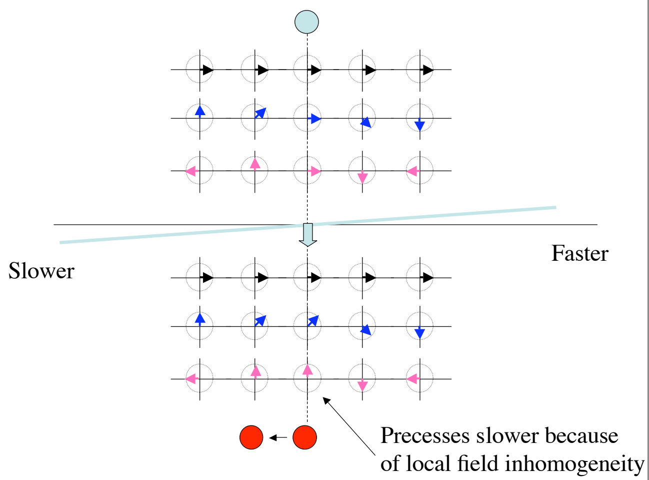
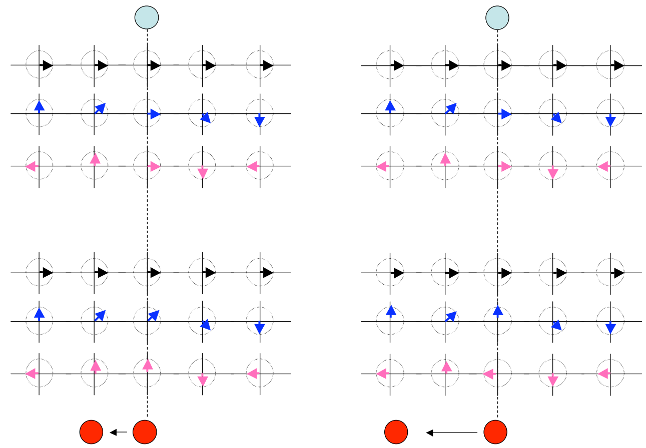


Fig. 12.9

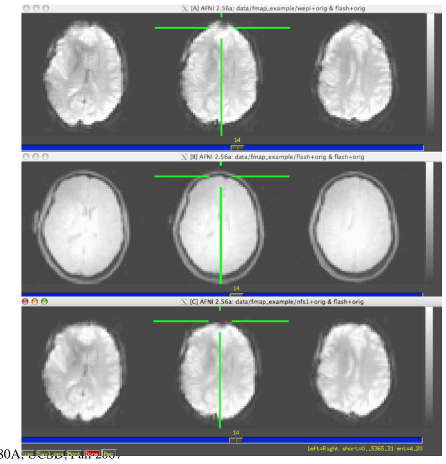
Credit: R. Buxton



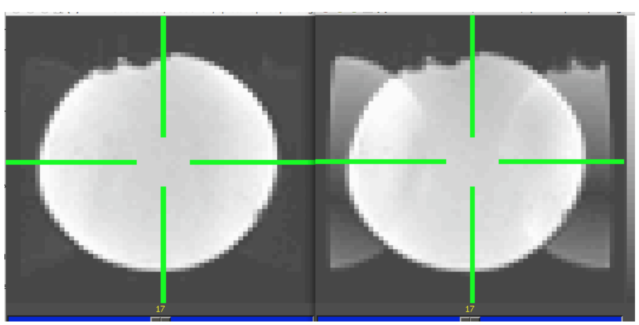


Slower trajectory->more displacement

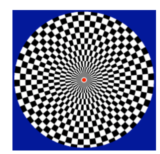
Field Map Correction



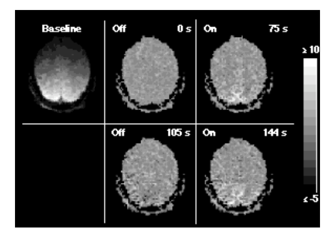
Nyquist Ghosts



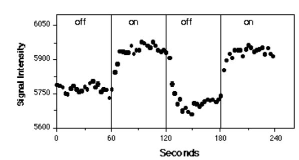
Visual Activation



Flickering Checkerboard
OFF (60 s) - ON (60 s) -OFF (60 s) - ON (60 s) - OFF (60 s)



Brain Activity

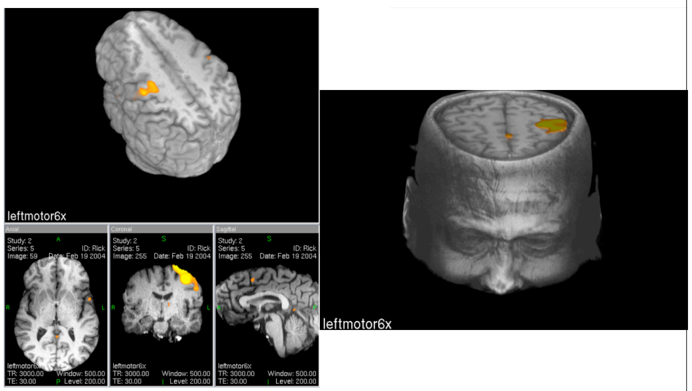


Time ⇨

Source: Kwong et al., 1992

http://defiant.ssc.uwo.ca/Jody_web/fmri4dummies.htm

Finger Tapping Task



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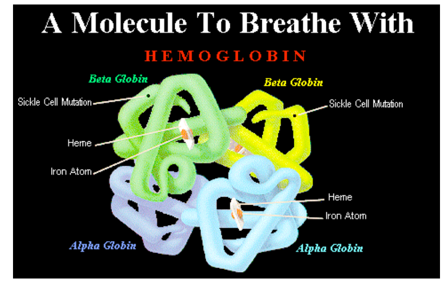
Hemoglobin



Oxygen binds to the iron atoms to form oxyhemoglobin HbO_2

Release of O_2 to tissue results in deoxyhemoglobin $dHBO_2$

Thomas Liu, BE280A, UCSD, Fall 2007 http://www.people.virginia.edu/~rjh9u/hemoglob.html

Effect of $dHBO_2$

$dHBO_2$ is paramagnetic due to the iron atoms. As it becomes oxygenated, it becomes less paramagnetic.

$dHBO_2$ perturbs the local magnetic fields. As blood becomes more deoxygenated, the amount of perturbation increases and there is more dephasing of the spins. Thus as $dHBO_2$ increases we find that T_2^* decreases and the amplitude $\exp(-TE/T_2^*)$ image of a T_2^* weighted image will decrease. Conversely as $dHBO_2$ decreases, T_2^* increases and we expect the signal amplitude to go up.

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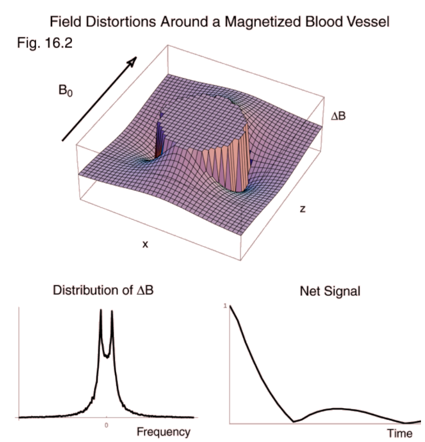

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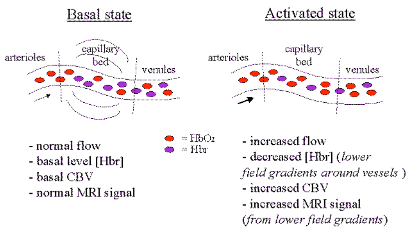
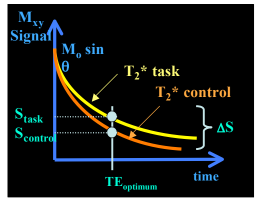
BOLD Effect

Blood Oxygen Level Dependent signal

↑neural activity ➔ ↑ blood flow ➔ ↑ oxyhemoglobin ➔ ↑ T2* ➔ ↑ MR signal

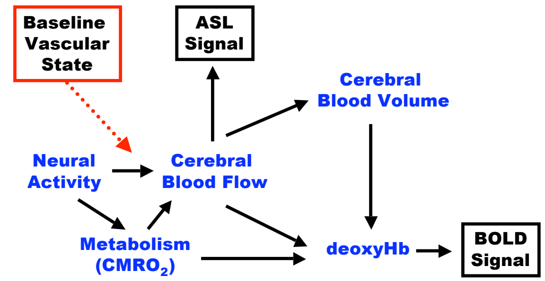




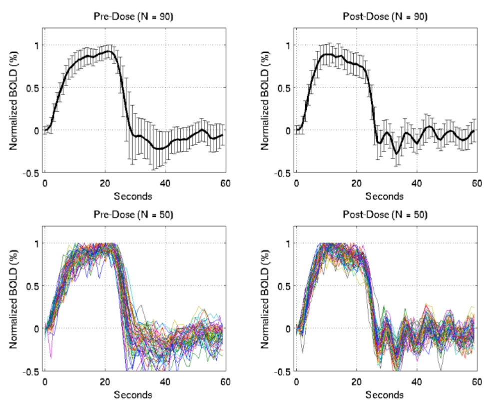
Source: fMRIB Brief Introduction to fMRI

Source: Jorge Jovicich

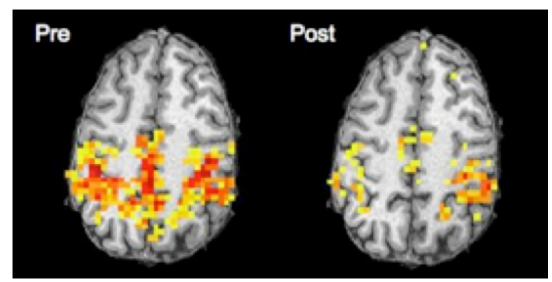
http://defiant.ssc.uwo.ca/Jody_web/fmri4dummies.htm



BOLD and Vascular Dynamics



Effect of Caffeine on Functional Connectivity

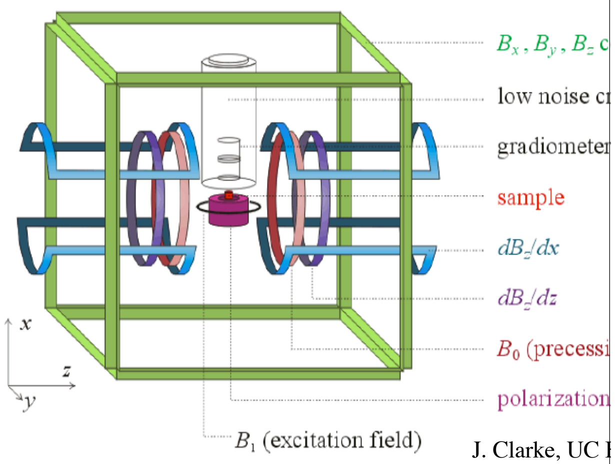


Timeline

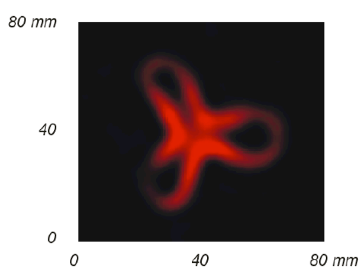
Michael Crichton, 1999

"Most people", Gordon said, "don't realize that the ordinary hospital MRI works by changing the quantum state of atoms in your body ... But the ordinary MRI does this with a very powerful magnetic field - say 1.5 tesla, about twenty-five thousand times as strong as the earth's magnetic field. We don't need that. We use Superconducting QUantum Interference Devices, or SQUIDs, that are so sensitive they can measure resonance just from the earth's magnetic field. We don't have any magnets in there".

J. Clarke, UC Berkeley

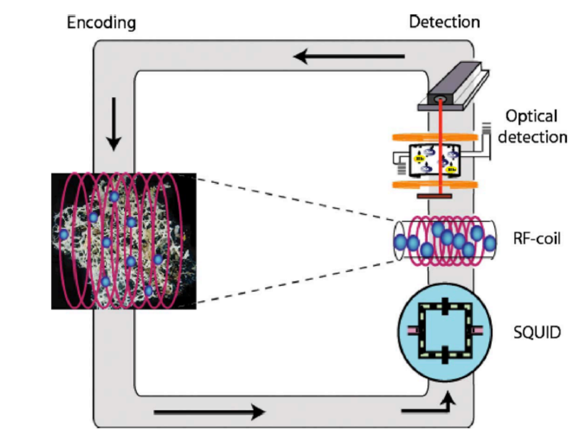


J. Clarke, UC

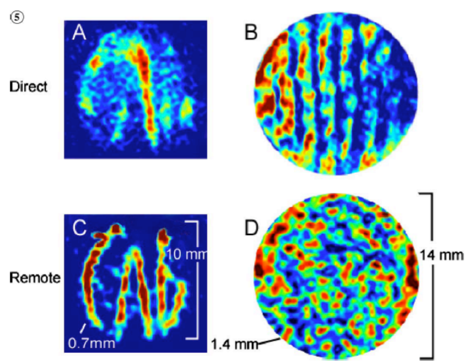


B0 = 132μT
G = 100μT/m
48 projections
1.5 min. acquisition

J. Clarke, UC Berkeley



Seeley et al, JMR 2004



Seeley et al, JMR 2004