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

\[ q(t) = -\int_0^t \Delta \omega(\tau) d\tau \]
\[ = -\int_0^t \gamma \Delta B(\tau) d\tau \]
\[ = -\int_0^t \gamma \vec{G}(\tau) \cdot \vec{v}(\tau) d\tau \]
\[ = -\gamma \int_0^t \left( G_x(\tau) x(\tau) + G_y(\tau) y(\tau) + G_z(\tau) z(\tau) \right) d\tau \]
Phase of Moving Spin

Consider motion along the x-axis
\[ x(t) = x_0 + vt + \frac{1}{2} at^2 \]

\[ q(t) = -\gamma \int_0^t G_s(\tau) x(\tau) d\tau \]
\[ = -\gamma \int_0^t G_s(\tau) \left[ x_0 + vt + \frac{1}{2} a\tau^2 \right] d\tau \]
\[ = -\gamma \left[ x_0 \int_0^t G_s(\tau) d\tau + v \int_0^t G_s(\tau) \tau d\tau + \frac{a}{2} \int_0^t G_s(\tau) \tau^2 d\tau \right] \]
\[ = -\gamma \left[ x_0 M_0 + vM_1 + \frac{a}{2} M_2 \right] \]

Flow Moment Example

\[ M_0 = \int_0^T G_s(\tau) d\tau = 0 \]
\[ M_1 = \int_0^T G_s(\tau) \tau d\tau \]
\[ = -\int_0^T G_0 d\tau + \int_0^T G_0 T d\tau \]
\[ = G_0 \left[ \frac{\tau^2}{2} + \frac{T^2}{2} \right] \]
\[ = G_0 \left[ \frac{T^2}{2} + \frac{4T^2}{2} - \frac{T^2}{2} \right] = G_0 T^2 \]

Phase Contrast Angiography (PCA)

\[ \varphi_1 = -\gamma v M_1 = \gamma v G_0 T^2 \]
\[ \varphi_2 = -\gamma v M_1 = -\gamma v G_0 T^2 \]
\[ \Delta \varphi = \varphi_1 - \varphi_2 = 2\gamma v G_0 T^2 \]
\[ v_s = \frac{\Delta \varphi}{2G_0 T^2} \]
Aliasing in PCA

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

\[ VENC = \frac{\pi}{\gamma G_0 T} \]

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 \( \pi \) radians.

\[
\begin{align*}
\phi_1 &= 2 \frac{v}{VENC_1} \\
\phi_2 &= 2 \frac{v}{VENC_2} \\
\phi_1 - \phi_2 &= 2v \left( \frac{1}{VENC_1} - \frac{1}{VENC_2} \right)
\end{align*}
\]

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**

- Readout Gradient
- Echo Time TE

![](image)

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

**Inflow Effect**

- Prior to imaging
- Time of Flight Angiography

![](image)

- Relaxed spins flowing in
- Saturated spins

**Time of Flight Angiography**

![](image)
Cerebral Blood Flow (CBF)

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

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

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

Arterial spin labeling (ASL)

1: Tag by Magnetic Inversion
2: Acquire image

Control - Tag = \( \Delta M \propto \text{CBF} \)

Bereczki et al 1992
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.

Multislice CASL and PICORE

CASL

PICORE

QUIPSS II

ASL Pulse Sequences

PASL / VSASL

TR

Tag

Acquire Control Acquire

TI = Inversion Time

CASL

Tag

Acquire Control Acquire

Labeling Time

Post Labeling Delay

ASL Time Series

Wait

Image 1

Image 2

Image 3

Image 4

Perfusion Images
**Diffusion**

\[ <\Delta x^2> = N d^2 = 2DT \]

\[ D = \text{diffusivity} \]

In brain:
\[ D \approx 0.001 \text{ mm}^2/\text{s} \]

For \( T = 100 \text{ msec} \),
\[ \Delta x \approx 15 \mu \]

Credit: Larry Frank

**Diffusing Spins**

\[ \Delta B_z(x) \]

**Diffusion Weighting**

\[ G_0 \]

\[ -G_0 \]

\[ \delta \]

\[ T \]

Signal
\[ S \propto e^{-\gamma G_0^2 \delta^2 DT} = e^{-bD} \]

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.

Credit: Larry Frank

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 anatomy.

Functional MRI (fMRI) studies brain function.

Functional MRI

Large-amplitude, spatially correlated fluctuations in BOLD (fMRI) signals during extended rest and early sleep stages.

Functional MRI

Acute effects of alcohol on neural correlates of episodic memory encoding.

Marketing actions can modulate neural representations of experienced pleasantness.

Distinguishing specific sexual and general emotional effects in fMRI—Subcortical and cortical arousal during erotic picture viewing.

Hippocampal Activation for Antithetical Memories over the Entire Lifespan in Healthy Aged Subjects: An fMRI Study.

fMRI Setup

High spatial resolution

MP-RAGE

Voxel volume: 1 mm³

Imaging time: 6 min

fMRI Acquisition

High temporal resolution

EPI

Voxel volume: 45 mm³

Imaging time: 60 msec

Thomas Liu, BE280A, UCSD, Fall 2008

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

Buxton 2002
History of Functional MRI

Finger Tapping Task

Hemoglobin and Field Inhomogeneities

Signal Decay

Oxygen binds to the iron atoms to form oxyhemoglobin $\text{HbO}_2$

Release of $\text{O}_2$ to tissue results in deoxyhemoglobin $\text{dHbO}_2$

Field Maps

More $\text{dHb}$

Less $\text{dHb}$

Some $\text{dHb}$, Some dephasing

More $\text{dHb}$, More dephasing, Decrease in MR signal
Blood Flow and Oxygen Metabolism

Cerebral Blood Flow (CBF) measures delivery of blood to brain tissue (units of ml/(g-min))

Cerebral Metabolic Rate of (CMRO₂) is the rate of oxygen consumption (units of µmol/(g-min))

CBF [O₂]_{arterial} → Oxygen extraction fraction (E) → CMRO₂

CMRO₂ = E CBF [O₂]_{arterial}

Deoxyhemoglobin

\[ [dHB]_{venous} = \frac{E [O₂]_{arterial}}{4} = \frac{CMRO₂}{4CBF} \]

CBF → [dHB]_{venous}

EPI Scans

Initial dip → Positive BOLD → Post-stimulus Response

CBF, CMRO₂, CBV → BOLD

Phase Encode
Field Inhomogeneities

EPI Distortions and Signal Dropouts

Credit: R. Buxton

Faster

Slower

Precesses slower because of local field inhomogeneity
Slower trajectory -> more displacement

Nyquist Ghosts

Field Map Correction

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
$B_x, B_y, B_z$ components

current

low noise coils

gradiometers

sample

dBx/dx

dBy/dy

$B_0$ (precessing polarization)

$B_1$ (excitation field)

J. Clarke, UC Berkeley

Seeley et al, JMR 2004

80 mm

$80 = 132 \mu T$

G = 100 $\mu T/m$

48 projections

1.5 min. acquisition

J. Clarke, UC Berkeley

Seeley et al, JMR 2004
Compressed Sensing

- Randomly throw away 83% of samples

- Minimum - norm conventional linear reconstruction
- Min. Total Variation (TV) A convex non-linear reconstruction

Slide Credit: http://www.stanford.edu/~mlustig/