Diffusion MRI Acquisition

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Diffusion Imaging

- How is diffusion weighting achieved?
- How is the image acquired?
- What are the limitations, tradeoffs, complications?
Precession

\[ \omega_0 = \gamma (B_0 + \Delta B) \]

main field \hspace{1cm} offset (gradients!)
Dephasing

Range of frequencies within voxel leads to ‘dephasing’ and rapid signal loss
Refocusing (180°) pulses

\[ B_0 \]

Excite \( 180^\circ \) acquire
Refocusing (180°) pulses
Spin Echo

signal

RF

excite

180°

acquire

time
Diffusion-weighted spin echo

Additional gradients not used for image formation
Instead, they create sensitivity to diffusion:

diffusion gradients!
Case 1: no diffusion

1. Excite
2. Position encode
3. 180°
4. Position decode
5. Acquire

Signal: High field
Low field
Case 2: diffusion
Diffusion contrast and b-value

Gradients induce signal drop for diffusing magnetization

Faster Diffusion = Less Signal

NB: above depicts negligible $T_2$ decay, not true in practice!
Diffusion contrast and b-value

\[ S = S_0 e^{-bD} \]

Image contrast = signal loss due to diffusion
Simple relationship between signal and D
Signal sensitivity to diffusion is given by “b-value”
Diffusion contrast and b-value

b-value = sensitivity to diffusion

What affects b-value?

- Gradient strength (G)
- Gradient duration (τ)

* Note: b also affected by gap between gradients
What about diffusion orientation?

Direction 1

Direction 2

Signal loss will be minimal along direction 1, maximal along direction 2
Diffusion contrast

If diffusion is present, gradients cause a drop in signal.

Faster Diffusion = Less Signal
Diffusion-weighted imaging

Acquire multiple diffusion directions, plus an unweighted (b=0) image, and fit model of interest in each voxel.
Diffusion Imaging

✓ How is diffusion weighting achieved?
  • How is the image acquired?
  • What are the limitations, tradeoffs, complications?
Acquiring the image

Theoretically, any acquisition can be used

• single-line readout (2DFT)
• rapid scan (EPI)
• etc...

Motion sensitivity dictates what is possible
Motion in diffusion MRI

Diffusion gradients encode tiny displacement
Any subject motion will also be encoded
Image artefacts if we try to combine data from multiple excitations (different motion)

multi-shot diffusion-weighted image [Butts 1996]
Can motion be avoided?

Subject restraints can reduce bulk motion, but...

...in the brain, there is significant non-rigid motion from cardiac pulsatility

cardiac gating helps, but brain is never very still!
Echo-planar imaging
Single-shot EPI

- tissue contrast
- EPI acquisition
- EPI image

Single-shot imaging freezes motion

Most common method is echo-planar imaging (EPI)

Images have serious distortion and limited resolution
Scan times in diffusion

Total scan time: \( n_{\text{directions}} \times TR \)

- Large number of directions \( (n_{\text{directions}}) \) desirable
- Reducing TR is an important goal

TR is dictated by time per slice and number of slices
Accelerating diffusion imaging

1 2 3 4 5 6 7 8 9

TR

EPI EPI EPI EPI EPI EPI EPI EPI EPI

Brain scan with EPI sequences highlighted.
Simultaneous multi-slice

TR
Simultaneous multi-slice

45 → 15 minutes


Accelerations of 3-6 currently achievable
## Typical* Diffusion Imaging Parameters

* Typical, *not* fixed!!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Relevant points</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_E$ (echo time)</td>
<td>50-100 ms</td>
<td>Limited by b-value, gradient strength</td>
</tr>
<tr>
<td>Resolution</td>
<td>1.5-2 mm</td>
<td>Limited by distortion, SNR</td>
</tr>
<tr>
<td>Number of directions</td>
<td>20-100</td>
<td>Lower limit: tensor model Upper limit: scan time</td>
</tr>
<tr>
<td>b-value</td>
<td>1000-3000 s/mm²</td>
<td>Larger b = more contrast Smaller b = more signal</td>
</tr>
</tbody>
</table>
Diffusion Imaging

✓ How is diffusion weighting achieved?
✓ How is the image acquired?

• What are the limitations, tradeoffs, complications?
EPI gradients: Approximation

Simplify gradient sequence to understand source of image distortions...
EPI gradients: Approximation

Readout (‘fast’)

Phase encode (‘slow’)

Simplify gradient sequence to understand source of image distortions...
EPI gradients: Approximation

Simplify gradient sequence to understand source of image distortions...
“Fast” direction (frequency encode)

Total field similar to fast gradient = negligible errors
“Slow” direction (phase encode)

Total field differs from slow gradient = misplaced signal
Parallel imaging (GRAPPA, SENSE, etc)

Receive coils impart some spatial information
Skip parts of k-space, fill in based on coil information
Allows “acceleration” of k-space acquisition
EPI gradients: Approximation

If nothing else changes, acceleration increases strength of slow gradient! What effect will this have on the image?
Image distortion depends on gradient along ‘slow’ (PE) direction

\[ \text{field “error”} + \text{expected field} = \text{actual field} \Rightarrow \% \text{ error} \]

NB: Distortion corrections refer to “echo spacing”, which is related to low gradient strength
Parallel imaging

Above: images acquired with reversed distortions (bottom-up vs top-down k-space traversal)

Parallel imaging reduces distortion (above: 2x less)

More later: correction based on reversed distortions
Important: Distortion vs Dropout

Distortion & dropout are both caused by field inhomogeneity, but they are independent artifacts

- Distortion is an EPI artifact, scales with echo spacing
- Dropout is a GRE artifact, scales with echo time

Diffusion can avoid dropout through spin echo (but does suffer from distortion)
Tradeoff: b-value vs TE

b-value depends on gradient strength (G) and duration (T)
With limited G, high b ⇒ long T ⇒ long echo time!
How to reduce TE?

One way:
Partial k-space
How to reduce TE?

Another way: Parallel imaging

signal (S)

echo time, TE (ms)

Diffusion weighting
Eddy Currents

Changing gradients induces ‘eddy currents’ in metal surfaces of scanner

Creates magnetic fields that counteract gradients

Gradients can’t change as quickly as we’d like!
Eddy Currents

Diffusion-weighting is gradient intensive

Eddy currents create decaying gradients that generally persist into the EPI imaging window

These ‘field inhomogeneities’ distort the images
Eddy Currents

Classically: re-align images using linear registration
Low SNR, variable contrast: difficult to correct!
Next term: a more sophisticated approach (eddy)...

Other artefacts: Motion sensitivity

Here: table vibration induces signal loss when diffusion weighting along R/L

Consistent artefact appears as directional structure

Tractography “finds” tracts that don’t exist!!!

Gallichan et al, HBM 2010
Scratching the surface...

Only most common methods covered today!

Diffusion acquisition

• Alternatives to spin-echo diffusion weighting
• Alternatives to single-shot, echo-planar imaging