3D vs. 2D Acquisition

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Session: Advanced Diffusion Acquisition

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STANFORD
SCHOOL OF MEDICINE
Radiological Sciences Laboratory
Declaration of Relevant Financial Interests or Relationships

Speaker Name: Jennifer A. McNab, Ph.D.

I have no relevant financial interest or relationship to disclose with regard to the subject matter of this presentation.
3D vs. 2D Acquisitions

3D

2D
3D vs. 2D Acquisitions

3D

2D

slice-selective RF excitation pulse
3D vs. 2D Acquisitions

3D

- Slices excited and acquired sequentially.

2D

- Slice-selective RF excitation pulse

- Slices excited and acquired sequentially.
3D vs. 2D Acquisitions

3D

- Slices excited and acquired sequentially.
- k-space encoding along 2 dimensions.

2D

slice-selective RF excitation pulse

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3D vs. 2D Acquisitions

3D
- Slices excited and acquired sequentially.
- k-space encoding along 2 dimensions.

2D
- Slice-selective RF excitation pulse
- k-space encoding along 1 dimension.
3D vs. 2D Acquisitions

3D

- Entire volume excited every TR.
- Slab-selective RF excitation pulse

2D

- Slices excited and acquired sequentially.
- Slice-selective RF excitation pulse
- k-space encoding along 2 dimensions.
3D vs. 2D Acquisitions

3D

- Entire volume excited every TR.
- k-space encoding along 3 dimensions.

2D

- Slices excited and acquired sequentially.
- k-space encoding along 2 dimensions.
3D vs. 2D Acquisitions

For entire volume:
- 3D k-space
- 3D Fourier Transform

For each slice:
- 2D k-space
- 2D Fourier Transform
3D vs. 2D Acquisitions

3D

slab-selective RF excitation pulse

2D

slice-selective RF excitation pulse
3D vs. 2D Acquisitions

3D

- slab-selective RF excitation pulse

2D

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3D FT ⇒
3D vs. 2D Acquisitions

3D

- slab-selective RF excitation pulse

2D

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3D FT ⇒
3D vs. 2D Acquisitions

3D
- slab-selective RF excitation pulse
- 3D FT ⇒

2D
- slice-selective RF excitation pulse
- 2D FT ⇒
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3D vs. 2D Acquisitions

3D

- Slab-selective RF excitation pulse

2D

- Slice-selective RF excitation pulse

3D FT ⇒

2D FT ⇒
3D vs. 2D Acquisitions

- **3D**: slab-selective RF excitation pulse
  - 3D FT ⇒
  - Images of brain sections

- **2D**: slice-selective RF excitation pulse
  - 2D FT ⇒
  - Multiple images of brain sections
3D vs. 2D Acquisitions

3D

2D
3D vs. 2D Acquisitions

3D

2D
- single-shot
- multi-shot
3D vs. 2D Acquisitions

3D: • multi-shot

2D: • single-shot
  • multi-shot
3D vs. 2D Acquisitions

3D
• multi-shot

2D
• single-shot
• multi-shot

3D navigation is tough!
3D vs. 2D Acquisitions

3D: multi-shot

“2.5D”

2D: single-shot
multi-shot
3D vs. 2D Acquisitions

3D
- multi-shot
- multi-slab

2D
- single-shot
- multi-shot

“2.5D”
3D vs. 2D Acquisitions

3D:
- multi-shot
- multi-slab

“2.5D”
- simultaneous-multi-slice

2D:
- single-shot
- multi-shot
3D vs. 2D Acquisitions

3D
- multi-shot
- multi-slab
- simultaneous-multi-slice

2D
- single-shot
- multi-shot

“2.5D”

improved SNR efficiency
3D vs. 2D Acquisitions

3D
• multi-shot

2D
• single-shot
• multi-shot

multi-slab
reduces 3D navigation burden

simultaneous-multi-slice

“2.5D”

improved SNR efficiency
Overview

For 2D, 3D and 2.5D methods, we will discuss:
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One clear win for 3D diffusion imaging......
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2D or 3D ? : Summary
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2D or 3D ? : Summary
Image Distortions and Motion Artifacts

- Multi-shot sequences reduce distortions but require navigation.
Image Distortions and Motion Artifacts

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- 3D sequences **must** be multi-shot.
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- 3D navigation more difficult than 2D navigation → time-consuming to acquire a full 3D navigator along with each k-space segment.
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- 3D multi-slab eases 3D navigation burden
Image Distortions and Motion Artifacts

- Multi-shot sequences reduce distortions but require navigation.
- 3D sequences must be multi-shot.
- 3D navigation more difficult than 2D navigation → time-consuming to acquire a full 3D navigator along with each k-space segment.

  - 3D multi-slab eases 3D navigation burden
  - DW-SSFP - highly efficient sequence
Motion is most severe along S-I.

Steady-State Diffusion MRI with TURBINE

Diffusion-Encoding Orientation

Uncorrected

Corrected

Do 3D Sequences Need a 3D Navigator?

Figure courtesy of Karla Miller.
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2D or 3D ? : Summary
For 2D single-shot, in-plane resolution is limited by the amount of data that can be acquired:

- in a read-out length that yields an acceptable level of distortion.
Spatial Resolution

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\[
d_{pe}(\mathbf{r}) = \frac{\gamma}{2\pi} \text{FOV}_{\text{phase}} \ T_{\text{esp}} \ \Delta B_0(\mathbf{r}) \ [\text{mm}]\]
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Parallel imaging can help!
Spatial Resolution

For 2D single-shot, **in-plane resolution** is limited by the amount of data that can be acquired:

- in a read-out length that yields an acceptable level of distortion.

- before the signal decays away ($T_2^*$).
Spatial Resolution

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$T_2^*$-decay
Spatial Resolution

For 2D single-shot, in-plane resolution is limited by the amount data that can be acquired:

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- before the signal decays away ($T_2^*$).
- $T_2^*$ blurring.
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Farazaneh et al. 1990.
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Spatial Resolution

2D Slice-Selection: How thin can we make the slice?
Spatial Resolution

2D Slice-Selection: How thin can we make the slice?

Depends on:
Spatial Resolution

2D Slice-Selection: How thin can we make the slice?

- RF amplifier limits

\[ f = \gamma(B_0 + G_{z1}z) \]

\[ f = \gamma(B_0 + G_{z2}z) \]
Spatial Resolution

2D Slice-Selection: How thin can we make the slice?

- RF amplifier limits
- Gradient limits
Spatial Resolution

2D Slice-Selection: How thin can we make the slice?

Depends on:
- RF amplifier limits
- gradient limits
- time constraints (pulse duration)
Spatial Resolution

2D Slice-Selection: How thin can we make the slice?

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- time constraints (pulse duration)
- tolerance for slice distortion
Spatial Resolution

2D Slice-Selection: How thin can we make the slice?

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- SAR ($\sim B_1^2B_0^2$) → efficiency of transmit coil
Spatial Resolution

**2D Slice-Selection:** How thin can we make the slice?

Depends on:
- RF amplifier limits
- gradient limits
- time constraints (pulse duration)
- tolerance for slice distortion
- SAR ($\sim B_1^2 B_0^2$) → efficiency of transmit coil
SAR vs. Slice Bending

Slide courtesy of Jon Polimeni.

30 mT/m on-res.

image slice profile

z position (mm)

1 mm
SAR vs. Slice Bending

30 mT/m on-res.

Slide courtesy of Jon Polimeni.
SAR vs. Slice Bending

30 mT/m on-res.

1 mm

Slide courtesy of Jon Polimeni.
SAR vs. Slice Bending

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SAR vs. Slice Bending

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SAR vs. Slice Bending

increase gradient strength to reduce bending,
shortens pulse, increases SAR

Slide courtesy of Jon Polimeni.
SAR vs. Slice Bending

- Increase gradient strength to reduce bending.
- Shortens pulse.
- Increases SAR.

Slide courtesy of Jon Polimeni.

**Graph details:**
- Image slice profile.
- z position (mm) scale.
- 0.1 mm (10%)
- 30 mT/m +100 Hz (0.34ppm)
- 70 mT/m +100 Hz
- 1 mm

**Equation:**
\[ B_0 + \Delta B \]
SAR vs. Slice Bending

Increase gradient strength to reduce bending, shortens pulse, increases SAR.

Slide courtesy of Jon Polimeni.
Spatial Spreading in Slice Direction

measured slice profile for 0.75 mm slice select

(Hanning-windowed sinc)

sharp transition available with alternative pulse (e.g., SLR) but these pulses are longer, have more $B_0$ vulnerability!

Slide courtesy of Jon Polimeni.
2D Slice-Selection: How thin can we make the slice?

Answer:
Spatial Resolution

2D Slice-Selection: How thin can we make the slice?

Answer:

- ~0.5 - 1 mm
Spatial Resolution

2D Slice-Selection: How thin can we make the slice?

Answer:

• ~0.5 - 1 mm

• will be system-specific
Spatial Resolution

For 3D pulse sequences, **through-plane resolution** is limited primarily due to:
Spatial Resolution

For 3D pulse sequences, through-plane resolution is limited primarily due to:

• SNR
Spatial Resolution

For 3D pulse sequences, through-plane resolution is limited primarily due to:

- SNR

\[
\text{SNR} \propto \text{voxel volume} \\
\text{SNR} \propto \sqrt{\text{scan time}}
\]
For 3D pulse sequences, through-plane resolution is limited primarily due to:

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\[
\text{SNR} \propto \sqrt{\text{scan time}} \quad \text{SNR} \propto \text{voxel volume}
\]

**Spatial Resolution**

<table>
<thead>
<tr>
<th>Isotropic Voxel Dimensions (mm)</th>
<th>Scan Time Relative to 1mm³ voxel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
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<td>1.0</td>
</tr>
</tbody>
</table>

| 10                            | 21                             |
| 20                            | 40                             |
| 30                            | 60                             |
| 40                            | 80                             |
| 50                            | 100                            |
| 60                            | 120                            |
| 70                            | 140                            |
| 80                            | 160                            |
| 90                            | 180                            |
| 100                           | 200                            |
Spatial Resolution

For 3D pulse sequences, through-plane resolution is limited primarily due to:

- SNR
- time constraints

\[
\text{SNR} \propto \text{voxel volume} \quad \text{SNR} \propto \sqrt{\text{scan time}}
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</tr>
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</tr>
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</tr>
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<td>0.8</td>
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Spatial Resolution

For 3D pulse sequences, through-plane resolution is limited primarily due to:

- **SNR**
  
  \[
  \text{SNR} \propto \text{voxel volume}
  \]
  
  \[
  \text{SNR} \propto \sqrt{\text{scan time}}
  \]

- **time constraints**

  e.g. for 1 mm isotropic acquisition
  
  \[
  \text{TR} = 0.5 \text{s} \times 120 \text{ slices} \times 3 \text{ shots per slice}
  \]
  
  \[\rightarrow 3 \text{ min. per volume}\]
Spatial Resolution

For 3D pulse sequences, through-plane resolution is limited primarily due to:

- SNR
  \[ \text{SNR} \propto \sqrt[3]{\text{voxel volume}} \]
  \[ \text{SNR} \propto \sqrt{\text{scan time}} \]

- time contraints

\[ \text{TR} = 0.5s \times 120 \text{ slices} \times 3 \text{ shots per slice} \]
\[ \rightarrow 3 \text{ min. per volume} \]

\[ 21 \text{ min. to get 6 directions } + b=0 \]
(minimum for DTI)
Spatial Resolution

For 3D pulse sequences, through-plane resolution is limited primarily due to:

- **SNR**
  
  \[ \text{SNR} \propto \frac{\text{voxel volume}}{\text{voxel volume}} \]
  
  \[ \text{SNR} \propto \sqrt{\text{scan time}} \]

- **time contraints**
  
  e.g. for 1 mm isotropic acquisition
  
  \[ \text{TR} = 0.5\text{s} \times 120 \text{ slices} \times 3 \text{ shots per slice} \]
  
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  21 min. to get 6 directions + b=0
  
  (minimum for DTI)

  HARDI not feasible.
Overview

For 2D, 3D and 2.5D methods, we will discuss:

- image distortions
- motion artifacts
- spatial resolution
- SNR efficiency

One clear win for diffusion imaging......

2D or 3D? : Summary
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2D or 3D? : Summary
Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume}) \sqrt{N_{excite} T_{\text{read-out}}} \]
Signal-to-Noise Ratio (SNR)

$$SNR \propto (\text{voxel volume}) \sqrt{N_{\text{excite}} T_{\text{read-out}}}$$

2D single-shot
Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume}) \sqrt{N_{\text{excite}} T_{\text{read-out}}} \]

2D single-shot

\[ N_{\text{excite}} = 1 \]
Signal-to-Noise Ratio (SNR)

$$SNR \propto (\text{voxel volume})\sqrt{N_{\text{excite}} T_{\text{read-out}}}$$

2D single-shot

$N_{\text{excite}} = 1$

$T_{\text{read-out}} = T_{ss}$
Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume}) \sqrt{N_{\text{excite}} T_{\text{read-out}}} \]

2D single-shot

\( N_{\text{excite}} = 1 \)

\( T_{\text{read-out}} = T_{ss} \)

\[ SNR_{2DSS} \propto \sqrt{T_{ss}} \]
Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume})\sqrt{N_{\text{excite}}T_{\text{read-out}}} \]

2D single-shot
\[ N_{\text{excite}} = 1 \]
\[ T_{\text{read-out}} = T_{ss} \]

2D segmented
\[ SNR_{2DSS} \propto \sqrt{T_{ss}} \]
Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume}) \sqrt{N_{\text{excite}} T_{\text{read-out}}} \]

2D single-shot
- \( N_{\text{excite}} = 1 \)
- \( T_{\text{read-out}} = T_{ss} \)

2D segmented
- \( N_{\text{excite}} = N_{\text{segments\_per\_slice}} \)

\[ SNR_{2DSS} \propto \sqrt{T_{ss}} \]
Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume}) \sqrt{N_{\text{excite}} T_{\text{read-out}}} \]

2D single-shot
\[
N_{\text{excite}} = 1 \\
T_{\text{read-out}} = T_{ss}
\]

2D segmented
\[
N_{\text{excite}} = N_{\text{segments\_per\_slice}} \\
T_{\text{read-out}} = T_{ss}/N_{\text{segments\_per\_slice}}
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Signal-to-Noise Ratio (SNR)

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2D single-shot

\begin{align*}
N_{\text{excite}} &= 1 \\
T_{\text{read-out}} &= T_{ss}
\end{align*}

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2D segmented

\begin{align*}
N_{\text{excite}} &= N_{\text{segments\_per\_slice}} \\
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## Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume}) \sqrt{N_{\text{excite}} T_{\text{read-out}}} \]

### 2D single-shot
- \( N_{\text{excite}} = 1 \)
- \( T_{\text{read-out}} = T_{ss} \)
- \( SNR_{2DSS} \propto \sqrt{T_{ss}} \)

### 2D segmented
- \( N_{\text{excite}} = N_{\text{segments\_per\_slice}} \)
- \( T_{\text{read-out}} = T_{ss}/N_{\text{segments\_per\_slice}} \)
- \( SNR_{2Dseg} = SNR_{2DSS} \)
Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume}) \sqrt{N_{\text{excite}} T_{\text{read-out}}} \]

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<th>3D segmented</th>
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<td>( N_{\text{excite}} = 1 )</td>
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Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume}) \sqrt{N_{\text{excite}} T_{\text{read-out}}} \]

2D single-shot

\[ N_{\text{excite}} = 1 \]
\[ T_{\text{read-out}} = T_{\text{ss}} \]

\[ SNR_{2DSS} \propto \sqrt{T_{\text{ss}}} \]

2D segmented

\[ N_{\text{excite}} = N_{\text{segments\_per\_slice}} \]
\[ T_{\text{read-out}} = T_{\text{ss}}/N_{\text{segments\_per\_slice}} \]

\[ SNR_{2Dseg} = SNR_{2DSS} \]

3D segmented

\[ N_{\text{excite}} = N_{\text{segments\_per\_slice}} \cdot N_{\text{slices}} \]
Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume}) \sqrt{N_{\text{excite}} T_{\text{read-out}}} \]

2D single-shot

\[ \begin{align*}
N_{\text{excite}} &= 1 \\
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2D segmented

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N_{\text{excite}} &= N_{\text{segments\_per\_slice}} \\
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\[ SNR_{2Dseg} = SNR_{2DSS} \]

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N_{\text{excite}} &= N_{\text{segments\_per\_slice}} \cdot N_{\text{slices}} \\
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Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume})\sqrt{N_{\text{excite}}T_{\text{read-out}}} \]

**2D single-shot**
- \( N_{\text{excite}} = 1 \)
- \( T_{\text{read-out}} = T_{ss} \)

\[ SNR_{2\text{DSS}} \propto \sqrt{T_{ss}} \]

**2D segmented**
- \( N_{\text{excite}} = N_{\text{segments\_per\_slice}} \)
- \( T_{\text{read-out}} = T_{ss}/N_{\text{segments\_per\_slice}} \)

\[ SNR_{2\text{Dseg}} = SNR_{2\text{DSS}} \]

**3D segmented**
- \( N_{\text{excite}} = N_{\text{segments\_per\_slice}} \cdot N_{\text{slices}} \)
- \( T_{\text{read-out}} = T_{ss}/N_{\text{segments\_per\_slice}} \)
Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume}) \sqrt{N_{\text{excite}} T_{\text{read–out}}} \]

### 2D single-shot
- \( N_{\text{excite}} = 1 \)
- \( T_{\text{read–out}} = T_{\text{ss}} \)
- \( SNR_{2\text{DSS}} \propto \sqrt{T_{\text{ss}}} \)

### 2D segmented
- \( N_{\text{excite}} = N_{\text{segments\_per\_slice}} \)
- \( T_{\text{read–out}} = T_{\text{ss}}/N_{\text{segments\_per\_slice}} \)
- \( SNR_{2\text{Dseg}} = SNR_{2\text{DSS}} \)

### 3D segmented
- \( N_{\text{excite}} = N_{\text{segments\_per\_slice}} \)
- \( T_{\text{read–out}} = T_{\text{ss}}/N_{\text{segments\_per\_slice}} \)
- \( N_{\text{slices}} \)
Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume}) \sqrt{N_{\text{excite}} T_{\text{read-out}}} \]

2D single-shot
\[
N_{\text{excite}} = 1 \\
T_{\text{read-out}} = T_{ss}
\]
\[ SNR_{2DSS} \propto \sqrt{T_{ss}} \]

2D segmented
\[
N_{\text{excite}} = N_{\text{segments\_per\_slice}} \\
T_{\text{read-out}} = T_{ss}/N_{\text{segments\_per\_slice}}
\]
\[ SNR_{2Dseg} = SNR_{2DSS} \]

3D segmented
\[
N_{\text{excite}} = N_{\text{segments\_per\_slice}} N_{\text{slices}} \\
T_{\text{read-out}} = T_{ss}/N_{\text{segments\_per\_slice}}
\]
\[ SNR_{3D} \propto \sqrt{N_{\text{slices}} SNR_{2DSS}} \]
Signal-to-Noise Ratio (SNR)

\[ SNR \propto (\text{voxel volume}) \sqrt{N_{\text{excite}} T_{\text{read-out}}} \]

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Therefore, 3D sequences have a higher SNR compared to 2D by a factor equal to the square root of the number of slice-encoding steps.
Signal-to-Noise Ratio (SNR)

$$SNR \propto (\text{voxel volume}) \sqrt{N_{\text{excite}} T_{\text{read-out}}}$$

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$$SNR_{2DSS} \propto \sqrt{T_{ss}}$$

$$SNR_{2Dseg} = SNR_{2DSS}$$

$$SNR_{3D} \propto \sqrt{N_{\text{slices}} SNR_{2DSS}}$$

Caveat:

3D segmented sequences typically use a shorter TR otherwise the sequence would take $N_{\text{segments}} \cdot N_{\text{slices}}$ longer to acquire the data (e.g. 4 segments * 60 slices = 240x longer!)

Shorter TR = less signal because the signal is not fully relaxed.
SNR Efficiency

SNR Efficiency = SNR per unit time

An Example: Unit of time = 15 min., 60 slices, $T_1 = 900$ ms

2D

All 60 slices acquired in a $TR=8$s.

3D

$TR=0.5s \times 60$ slices $= 30s$

30 averages in 15 min.

$M_{ss} = 1 - \exp\left(\frac{TR}{T_1}\right)$

$= 1 - \exp\left(-\frac{0.5}{0.9}\right) = 0.426$

$SNR = SNR_{2D} \times \sqrt{N_{avg}} \times \sqrt{N_{slices}} \times M_{ss}$

$= SNR_{2D} \times \sqrt{30} \times \sqrt{60} \times 0.426$

$= SNR_{2D} \times 18.1$
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112 averages in 15 min.

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\[ \text{SNR Efficiency} = \text{SNR per unit time} \]

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All 60 slices acquired in a TR=8s.

112 averages in 15 min.

$M_{ss} = 1 - \exp(\frac{TR}{T_1})$

$= 1 - \exp(-8/0.9) = 1.0$

$SNR = SNR_{2D} \times \sqrt{N_{avg}} \times M_{ss}$

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$= SNR_{2D} \times 10.6$

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An Example: Unit of time = 15 min., 60 slices, $T_1 = 900$ ms

2D

All 60 slices acquired in a TR=8s.

112 averages in 15 min.

$M_{ss} = 1 - \exp \left( \frac{TR}{T_1} \right)$

$= 1 - \exp \left( -\frac{8}{0.9} \right) = 1.0$

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SNR Efficiency = SNR per unit time

An Example: Unit of time = 15 min., 60 slices, $T_1 = 900$ ms

2D

All 60 slices acquired in a TR = 8 s.

112 averages in 15 min.

$M_{ss} = 1 - \exp\left(\frac{TR}{T_1}\right) = 1 - \exp\left(-\frac{8}{0.9}\right) = 1.0$

$SNR = SNR_{2D} \times \sqrt{N_{avg}} \times M_{ss}$

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2D

All 60 slices acquired in a TR=8s.

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$M_{ss} = 1 - \exp(TR/T_1)$

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$SNR = SNR_{2D} * \sqrt{N_{avg}} * M_{ss}$

$= SNR_{2D} * \sqrt{112} * 1.0$

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SNR Efficiency of 3D = 1.7x SNR Efficiency of 2D
SNR Efficiency

SNR Efficiency = SNR per unit time

An Example: Unit of time = 15 min., 60 slices, $T_1 = 900$ ms

Simultaneous-Multi-Slice, x3

All 60 slices acquired
SNR Efficiency

SNR Efficiency = SNR per unit time

An Example: Unit of time = 15 min., 60 slices, $T_1 = 900$ ms

Simultaneous-Multi-Slice, x3

All 60 slices acquired in a TR=2.7s.
SNR Efficiency

**SNR Efficiency** = SNR per unit time

**An Example:** Unit of time =15 min., 60 slices, $T_1 = 900$ ms

**Simultaneous-Multi-Slice, x3**

All 60 slices acquired in a TR=2.7s.

333 averages in 15 min.
SNR Efficiency

SNR Efficiency = SNR per unit time

An Example: Unit of time = 15 min., 60 slices, $T_1 = 900$ ms

**Simultaneous-Multi-Slice, x3**

All 60 slices acquired in a TR = 2.7 s.

333 averages in 15 min.

$$M_{ss} = 1 - \exp\left(\frac{TR}{T_1}\right)$$

$$= 1 - \exp\left(-\frac{2.7}{0.9}\right) = 0.95$$
SNR Efficiency

SNR Efficiency = SNR per unit time

An Example: Unit of time = 15 min., 60 slices, $T_1 = 900$ ms

Simultaneous-Multi-Slice, x3

All 60 slices acquired in a TR=2.7s.

333 averages in 15 min.

$M_{ss} = 1 - \exp\left(\frac{TR}{T_1}\right)$

$= 1 - \exp\left(-\frac{2.7}{0.9}\right) = 0.95$

$SNR = SNR_{2D} \times \sqrt{N_{avg}} \times M_{ss} \times \frac{1}{g}$
SNR Efficiency

SNR Efficiency = SNR per unit time

An Example: Unit of time = 15 min., 60 slices, T \(_1\) = 900 ms

Simultaneous-Multi-Slice, x3

All 60 slices acquired in a TR = 2.7s.

333 averages in 15 min.

\[ M_{ss} = 1 - \exp(\frac{TR}{T_1}) \]
\[ = 1 - \exp(-\frac{2.7}{0.9}) = 0.95 \]

SNR = \( SNR_{2D} \times \sqrt{N_{avg}} \times M_{ss} \times \frac{1}{g} \)
\[ = SNR_{2D} \times \sqrt{333} \times 0.95 \times 0.95 \]
SNR Efficiency

SNR Efficiency = SNR per unit time

An Example: Unit of time = 15 min., 60 slices, $T_1 = 900$ ms

Simultaneous-Multi-Slice, x3

All 60 slices acquired in a $TR = 2.7$ s.

333 averages in 15 min.

$M_{ss} = 1 - \exp(TR/T_1)$

$= 1 - \exp(-2.7/0.9) = 0.95$

$SNR = SNR_{2D} \cdot \sqrt{N_{avg}} \cdot M_{ss} \cdot 1/g$

$= SNR_{2D} \cdot \sqrt{333} \cdot 0.95 \cdot 0.95$

$= SNR_{2D} \cdot 16.5$
SNR Efficiency

SNR Efficiency = SNR per unit time

An Example: Unit of time = 15 min., 60 slices, $T_1 = 900$ ms

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All 60 slices acquired in a TR = 2.7 s.

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**SNR Efficiency**

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**An Example:** Unit of time = 15 min., 60 slices, $T_1 = 900$ ms
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Additional Considerations:

1) **Flexibility**: e.g. For DTI, the ability to acquire 112 or 333 diffusion-encoding directions compared to 30 in a 15 min. scan time might make a meaningful difference.
SNR Efficiency

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An Example: Unit of time = 15 min., 60 slices, $T_1 = 900$ ms

**Additional Considerations:**

1) **Flexibility**: e.g. For DTI, the ability to acquire 112 or 333 diffusion-encoding directions compared to 30 in a 15 min. scan time might make a meaningful difference.

2) **Multi-Shot Motion Artifacts**: Can decrease SNR or require additional time to correct for.
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3) **Slice Cross-Talk** and **Intra-Voxel Dephasing** decrease 2D SNR.
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An Example: Unit of time = 15 min., 60 slices, \( T_1 = 900 \text{ ms} \)

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3) **Slice Cross-Talk** and **Intra-Voxel Dephasing** decrease 2D SNR.

4) **Multi-Slab**: interleaving slabs improves efficiency, overlapping slabs reduces efficiency → Engstrom et. al. 2014.
Overview

For 2D, 3D and 2.5D methods, we will discuss:

- image distortions
- motion artifacts
- spatial resolution
- SNR efficiency

One clear win for 3D diffusion imaging......

2D or 3D? : Summary
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Post-mortem Diffusion Imaging

3D DW-SE with segmented EPI

Post-mortem Diffusion Imaging

No motion.

3D DW-SE with segmented EPI

0.7 mm iso

Post-mortem Diffusion Imaging

No motion.
No hurry.

3D DW-SE with segmented EPI

0.7 mm iso

Post-mortem Diffusion Imaging

No motion.
No hurry.
Sub-millimeter resolution.

3D DW-SE with segmented EPI

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2D or 3D? : Summary
Image Encoding Considerations for Diffusion MRI

- image distortions
- motion artifacts
- spatial resolution
- SNR efficiency
- acquisition speed
3D vs. 2D Acquisitions

3D
- multi-shot
- multi-slab
- simultaneous-multi-slice

2D
- single-shot
- multi-shot

“2.5D”
3D vs. 2D Acquisitions

3D
- multi-shot
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“2.5D”
2D or not 2D........
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