Pulse Sequence Design Made Easier…

A pulse sequence is a timing diagram designed with a series of RF pulses, gradients switching, and signal readout used in MR image formation.

Pulse Sequence Design Made Easier…

Pulse sequence components

- Pulse Sequences generally have the following characteristics:
  - An RF line characterizing RF Pulse applications
  - Gradients switching to encode the volume for spatial localization
  - Signal reception used to create MR image

Pulse sequence processes

- There are four processes in pulse sequence design:
  - Excitation: RF pulse(s) is/are applied
  - Encoding: Phase encoding is performed to determine how K-space is filled
  - Refocusing: Refocusing Net Magnetization back into transverse plane
  - Readout: Signal is encoded and recorded

Pulse Sequence Guidelines

- This is a timing diagram. All lines are read left to right and top to bottom simultaneously.
  - Above line is positive direction.
  - Below line is negative direction.
  - The RF line characterizes RF pulse applications. The height and width of the pulse determines how much [watts] and how long the pulse is applied.
  - Gradients are switched on and off to spatially localize the volume or the slice for image reconstruction.
  - Gradients are switched on and off for: Slice Selection, Phase Encoding, Frequency Encoding or Readout
Pulse Sequence Guidelines

- The gradient on while the RF is applied is the Slice Select Gradient.
- The gradient on while the signal is received or recorded is the Frequency Encoding or Readout Gradient.
- The gradient that changes amplitude per TR and on prior to refocusing is the Phase Encoding Gradient.

Pulse Sequence Quiz

- Which gradient is the slice select gradient?
  - Gz

Pulse Sequence Quiz

- Which gradient is the slice select gradient?
  - Gz
- Which gradient is the phase encoding gradient?
  - Gy

Pulse Sequence Quiz

- Which gradient is the slice select gradient?
  - Gx
- Which gradient is the frequency encoding gradient?
  - Gy
Pulse Sequence Quiz

Which gradient is the slice select gradient?
- Gz

Which gradient is the phase encoding gradient?
- Gy

Which gradient is the frequency encoding gradient?
- Gx

What slice orientation will the images created from this pulse sequence have?
- AXIALS (Gz - is the slice select gradient)

More on Phase Encoding...

- Phase encoding is performed to provide spatial localization and to guide k-space filling.
- What do you notice about the phase encoding gradient?

Phase amplitude changes every TR
Each amplitude designates another line in k-space.

What do you notice about the signal as gradient changes?

• Signal gets stronger with low amplitude gradients (shallow).
• The signal gets weaker with high amplitude gradients (steeper).

Outer lines of K-space, use high amplitude gradients which yield low signal return.

Center lines of K-space use low amplitude gradients which yield high signal return.

Outer lines reconstructed yield spatial resolution.

Center lines reconstructed yield signal (S/N) and contrast.

K-Space Filling

High Spatial Resolution
High S/N and Contrast
High Spatial Resolution
There are three conventional pulse sequence designs.

- Spin Echo
- Gradient Recalled Echo
- Inversion Recovery

Spin Echo pulse sequences begin with a 90° RF pulse followed by at least one 180° RF pulse.

- Produces T1-, T2-, and PD-wt. type tissue contrast

Image parameters:
- Short TR - contrast
- Short TE - signal

Image Contrast:
- Bright Fat - short T1
- Dark CSF - long T1

SE T1-weighted

Image Parameters:
- Long TR - signal
- Short TE - signal

Image Contrast:
- Bright or Gray Fat
- Gray CSF

Contrast based on proton concentration

SE Double Echo Proton Density

Image Parameters:
- Long TR - signal
- Long TE - contrast

Image Contrast:
- Dark Fat - short T2
- Bright CSF - Long T2

SE Double Echo T2-weighted

Conventional Spin Echo Diagram
Which two processes are repeated in a Dual SE Sequence?

Refocusing and Readout

Effects of the 180° Pulse

- eliminates signal loss due to field inhomogeneities
- eliminates signal loss due to susceptibility effects
- eliminates signal loss due to water/fat dephasing
- all signal decay is caused by T2 relaxation only

Spin Echo Parameters that manipulate Tissue Characteristics

Spin Echo Parameters
- T1 is TR Dependent
- PD is TR and TE Dependent
- T2 is TE Dependent
2DFT Scan Time Formula

\[ ST = \frac{TR(\text{msec}) \times Npe \times NEX}{60,000(\text{msec})} \]

- **ST**: Scan time in minutes
- **Npe**: Number of phase steps
- **NEX**: Number of acquisitions, NAQ, NEX, NSA

**Multi Echo Spin Echo**

- Only 1 phase encode per TR

**Fast Spin Echo**

- First developed as the RARE (Rapid Acquisition with Relaxation Enhancement) method.
- A 90° pulse initiates the sequence, followed by multiple 180° pulses to generate multiple echoes.
- However separate phase encodes are used prior to each echo to fill k-space more rapidly.
**Fast Imaging Parameters**

- **ETE**
  - Effective TE
  - The TE placed in portion of k-space with greatest impact on signal.
  - Therefore determines image contrast.
- **ETL or Turbo Factor**
  - Echo Train Length
  - Number of Echoes acquired per TR
  - Determines how fast sequence is run; higher the ETL the shorter the scan time.
  - Higher ETL reduce time for slices.
- **ETS**
  - Echo Train Spacing
  - Time (msec) between echoes in Echo Train
  - Not selectable; higher spacing leads to blurriness.

**Parameter Acronyms**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Acronym</th>
<th>Terminology</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETE</td>
<td></td>
<td>Effective TE</td>
</tr>
<tr>
<td>ETL</td>
<td></td>
<td>Number of Echoes acquired per TR</td>
</tr>
<tr>
<td>ETS</td>
<td></td>
<td>Time (msec) between echoes in Echo Train</td>
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</table>

**Optimal TR is 2000 – 4000msec**

- or longer so magnetization fully recovers.
- Longer TR’s allow more signal and slices.

- Shorter TR (<2000msec) image not T2-weighted even though CSF is bright.
- Too much T1 contrast added to the image.

- ETE time is long >80msec.
  - Longer ETE’s are allowed due to longer TR (signal)

**Fast Imaging Scan Time Formula**

\[ \text{Scan Time} = \frac{\text{TR(msec)} \times \text{Npe} \times \text{NEX} (\text{Minutes})}{60,000(\text{msec})} \times \text{ETL} \]

**SE & FSE Contrast Parameter Guidelines**

<table>
<thead>
<tr>
<th>TE</th>
<th>TR</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>short</td>
<td>short</td>
<td>T1</td>
</tr>
<tr>
<td>long</td>
<td>long</td>
<td>T2</td>
</tr>
<tr>
<td>short</td>
<td>long</td>
<td>Proton density</td>
</tr>
</tbody>
</table>

**Single Shot FSE Concept**

- Single shot FSE or TSE acquires 53% of k-space and reconstructs in Half-Fourier algorithm to achieve final resolution.
- Allows T2-wt studies with reduced motion artifacts and low susceptibility.
- Adaptable for breath hold exams and uncooperative patients.
**Vendor Terminology**

- **Spin Echo**
  - All vendors use Spin Echo designation

- **Fast Imaging T2**
  - Siemens: Turbo Spin Echo
  - GE: Fast Spin Echo
  - Hitachi: Fast Spin Echo
  - Philips: Turbo Spin Echo
  - Picker: Fast Spin Echo
  - Toshiba: Fast Spin Echo

- **Single Shot SE**
  - Siemens: HASTE
  - GE: SSFSE
  - Hitachi: SSFSE
  - Philips: SSFSE
  - Picker: EXPRESS
  - Toshiba: FASE

- **FSE w/90°Flip-Back**
  - Siemens: RESTORE
  - GE: FRFSE
  - Hitachi: Driven Equilibrium
  - Philips: DRIVE
  - Toshiba: FSE T2 puls

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**Inversion Recovery Sequence**

- **TI, Time of Inversion**, is the length of time net magnetization is allowed to recover before starting the 90° RF pulse (Spin Echo).

- **STIR, Short TI or Tau Inversion Recovery**, sequences are created by shortening the TI time to 69% of T1 relaxation of fat for fat suppression.

- **FLAIR, Fluid Attenuated Inversion Recovery**, sequences are created by lengthening the TI time to 69% of T1 relaxation of water for water suppression.
The effect of inverting the magnetization vector by the 180° RF pulse allows for the tissues dynamic range to be increased.

The magnitude of magnetization $M$ is a function of time after a 180° pulse.

Magnetization starts negative ($-Z$), passes through zero at $t = 0.69 T_1$ and recovers completely by $t = 5T_1$.

Suppression occurs at the tissue’s NULL POINT.

Null point is the point at which net magnetization crosses the transverse plane.

The Null point is approximately 69% of the $T_1$ of the tissue to be suppressed.

**Inversion Recovery**

**Null Point – Suppression Point**

Desired Contrast Inversion Time (TI)

- Heavily $T_1$-wt TI is approx. ¼ TR
- STIR (Fat Suppressed) 85 – 250msec
- FLAIR (Water Suppressed) 1900 – 2500msec

**IR Parameter Guidelines**

T2 FSE and T2 STIR

- TE long 50 - 80msec
- TR long 4000 – 10,000msec
- ETL 16 – 20
- TI null point of fat

**STIR Parameter Guidelines**
STIR Imaging Guidelines

- STIR should not be used with contrast because STIR will suppress both the fat and the contrast.
- Useful in MSK imaging – normal bone is fatty marrow – bone bruises and fractures are clearly seen.

Fluid Attenuated IR

- Helps visualize stroke.
- Helps in determining Multiple Sclerosis
- Achieves suppression of CSF.

Fluid Attenuated IR Parameters

- Long TE, Long TR, Long ETL
- Ti/TAU time of 1700 - 3200msec (depending on magnetic field strength)
- Used in brain and cord imaging – see periventricular and cord lesions more clearly

FLAIR Axial Brain
In Gradient Recalled Echo, a reversed gradient technique refocuses the spin phases.
- Flip angles less than 90° are optimized to enhance T1 or T2 tissue-like contrast (T2*).
- Flip angles less than 90°, flip some component of longitudinal magnetization vector into the transverse plane, while portions remain.

Gradient Recalled Echo sequences show a wide range of variations compared to the Spin Echo and Inversion Recovery sequences.

The major benefit is the use of the gradients to refocus the net magnetization instead of an RF pulse.
- A gradient reversal in the readout direction is used to create the echo.
- Spins will either speed up or slow down pending the gradient influence.
- This is different from the 180° RF pulse which flips the spins for refocusing.

The spins are refocused by reversing the speed of the spins rather than flipping them over to the other side of the x-y plane as occurs with the spin echo sequence.

Magnetic susceptibility artifacts are more pronounced on gradient echo sequences.
Magnetic Susceptibility

- Magnetic susceptibility, caused by protons of one tissue precessing faster than the protons of an adjacent tissue, is exaggerated due to the affect the spins have on each other while under the influence of the reversed gradient.

Gradient Recalled Echo (GRE)

- The MR signal returned is due primarily to T1 longitudinal magnetization.
- The MR signal returned is also due to faster T2 relaxation rates due to field inhomogeneities.
- The information is therefore T2* information, which is T2 relaxation due to magnetic field inhomogeneities as well as tissue characteristics.

Flip Angles

- Short FA: T2*-weighted
- Medium FA: PD-weighted
- Long FA: T1-weighted

Flip Angles control GRE Contrast

<table>
<thead>
<tr>
<th>Flip Angle</th>
<th>Degree Range</th>
<th>Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>1 - 35°</td>
<td>T2*</td>
</tr>
<tr>
<td>Medium</td>
<td>36 - 59°</td>
<td>PD</td>
</tr>
<tr>
<td>Long</td>
<td>60 - 90°</td>
<td>T1</td>
</tr>
</tbody>
</table>

Refocused GRE  Coherent

- Aka FISP, GRASS, FFE, Rephased SARGE
- Uses RF or gradients to refocus accumulated transverse magnetization
- Maximizes T2 Contrast

Spoiled GRE  Incoherent

- Aka SPGR, FLASH, T1-FFE
- Uses gradients or RF to spoil or destroy accumulated transverse coherence
- Maximizes T1 contrast
A Fast GRE sequence generates gradient echoes very rapidly using similar fast imaging techniques to fill k-space.

Image contrast cannot be controlled with the flip angle, TR, and TE.

Rather, a preparation pulse (TI) creates the desired contrast.

The sequence is initiated with the 180° preparation pulse followed by a waiting period (the inversion time).

Inversion times of 200 to 1000 msec are used.

More on GRE:
- MR signal is a composite of fat and water in the imaging voxel.
- Water and fat resonate at slightly different frequencies.
- TE time will determine whether fat and water will appear in-phase or out-of-phase.
Field Strength

<table>
<thead>
<tr>
<th>Field Strength (T)</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
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</thead>
<tbody>
<tr>
<td>W-F Offset (Hz)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in</td>
<td>75</td>
<td>150</td>
<td>225</td>
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<tr>
<td>out</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>in</td>
<td>6.71</td>
<td>3.36</td>
<td>2.24</td>
</tr>
<tr>
<td>out</td>
<td>13.42</td>
<td>6.71</td>
<td>4.47</td>
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<tr>
<td>in</td>
<td>20.13</td>
<td>10.07</td>
<td>6.71</td>
</tr>
<tr>
<td>out</td>
<td>26.84</td>
<td>13.42</td>
<td>8.96</td>
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<tr>
<td>in</td>
<td>33.55</td>
<td>16.78</td>
<td>11.18</td>
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<tr>
<td>out</td>
<td>40.26</td>
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<td>46.97</td>
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<tr>
<td>out</td>
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<td>22.37</td>
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<tr>
<td>in</td>
<td>73.81</td>
<td>37.14</td>
<td>24.60</td>
</tr>
<tr>
<td>out</td>
<td>80.52</td>
<td>40.55</td>
<td>26.84</td>
</tr>
</tbody>
</table>

- Frequency difference in ppm
  - Fat frequency minus water frequency divided by the water frequency equals the frequency difference.
  - This difference is about 3.3 - 3.5 ppm.
- Frequency difference in hertz
  - Multiply 3.5ppm by the imaging system’s operating frequency.

**Quiz**

- Determine the frequency difference between fat and water at 3.0T?

**Hints:**
  - To find the operating frequency you must use the Larmor equation: \( \omega = \gamma \times B \)
  - Multiply 3.5ppm by the imaging system’s operating frequency to find the frequency difference.

**Fat/Water difference in hertz**

Answer:
1st: Larmor Equation: \( \omega = \gamma \times B \)
\( \omega = 42.58 \text{ mHz} \times 3.0 \text{T} \)
\( \omega = 127.74 \text{ mHz} \)

2nd: 3.5ppm x operating frequency
\( 3.5 \text{ppm} \times 127.74 \text{mHz} = 447 \text{ Hz} \) @3.0T
0.35T \( 14.90 \text{ mHz} \times 3.5 \text{ppm} = 52.1 \text{ Hz} \)
1.5T \( 63.86 \text{ mHz} \times 3.5 \text{ppm} = 223 \text{ Hz} \)

**Gradient Echo Vendor Acronyms**

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Siemens</th>
<th>GE</th>
<th>Philips</th>
<th>Hitachi</th>
<th>Toshiba</th>
<th>Picker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spoiled GE</td>
<td>FLASH</td>
<td>SPGR</td>
<td>T1-FFE</td>
<td>R2SSG</td>
<td>FE</td>
<td>T1 Fast</td>
</tr>
<tr>
<td>Coherent GE</td>
<td>FISP</td>
<td>GRASS</td>
<td>FFE</td>
<td>Re-SARGE</td>
<td>FE</td>
<td></td>
</tr>
<tr>
<td>SSFP</td>
<td>TrueFISP</td>
<td>FIESTA</td>
<td>T2-FFE</td>
<td>SARGE</td>
<td>True SSFP</td>
<td>CE Fast</td>
</tr>
<tr>
<td>UltraFast</td>
<td>TurboFLASH</td>
<td>FastSPGR</td>
<td>TFE</td>
<td>RGE</td>
<td>Fast GE</td>
<td>RF Fast</td>
</tr>
<tr>
<td>UltraFast</td>
<td>3D MPRAGE</td>
<td>3D FastSPGR</td>
<td>3DTFE</td>
<td>MPRAGE</td>
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</table>
Thanks for sharing your time with me!