Fast Spin Echo

BioE 594 – Advanced Topics in MRI

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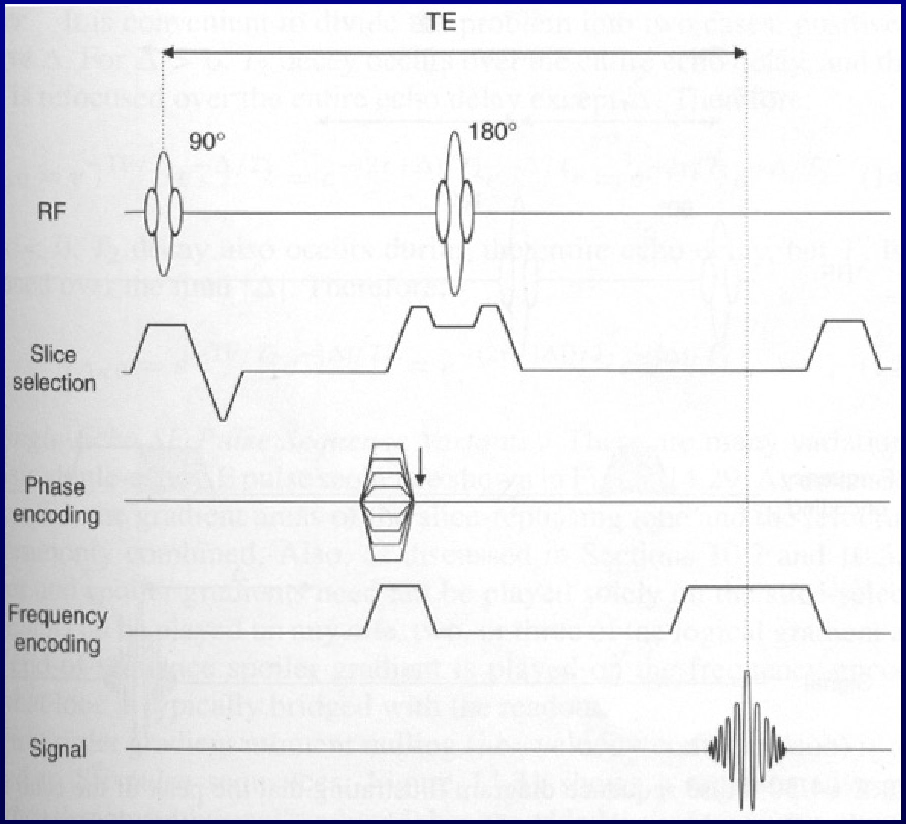
Review

- Spin Echo Pulse Sequence
  - 90° RF excitation → 180° RF refocus → echo
  - Main parameters: TR and TE
  - Can generate T_1, T_2, and proton-density images

$$S = M_0\left(1 - 2e^{-\left(TR - TE/2\right)/T_1} + e^{-TR/T_1}\right)e^{-TE/T_2}$$

Review

- Spin Echo Pulse Sequence



Review

- Advantages of SE
  - Minimal image artifacts
  - Relatively high SNR
  - 180° refocusing pulse provides:
    - Elimination of signal loss from field inhomogeneities, susceptibility effects, etc.
    - Signal decay that is only caused by T_2, not T_2^*

Review

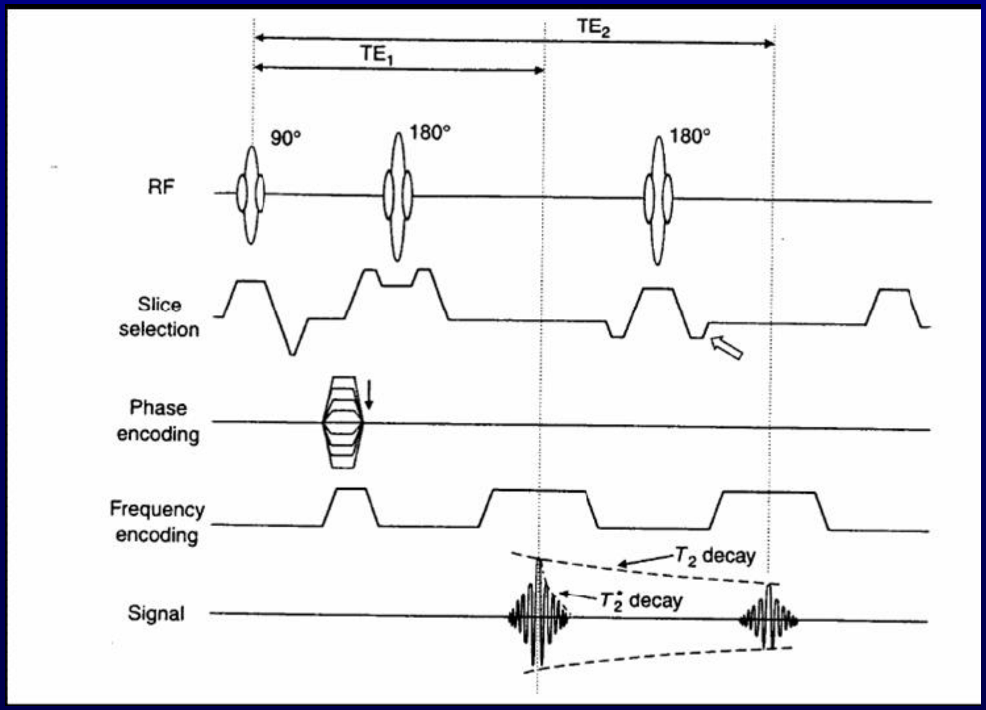
- Disadvantages of SE
  - Moderate to high SAR
  - Relatively long TRs and acquisition times

Moving Beyond Spin Echo

- In conventional spin echo, data is acquired for only a small fraction of the lifetime of the transverse magnetization created by the refocusing pulse
  - *Ex*: in a system with a readout matrix size of 256 and a receiver bandwidth of ±16 kHz, the acquisition time is $256 \times (1/(2 \times 16)) = 8$ ms per TR. The length of the actual spin echo is governed by T_2 relaxation time, which is roughly 100 ms for many tissues.
- A considerable amount of signal that could be sampled is left to decay after acquisition – ***can this signal be utilized to our advantage?***

Moving Beyond Spin Echo

- Multiecho Spin Echo
  - Obtains multiple echoes simultaneously



Moving Beyond Spin Echo

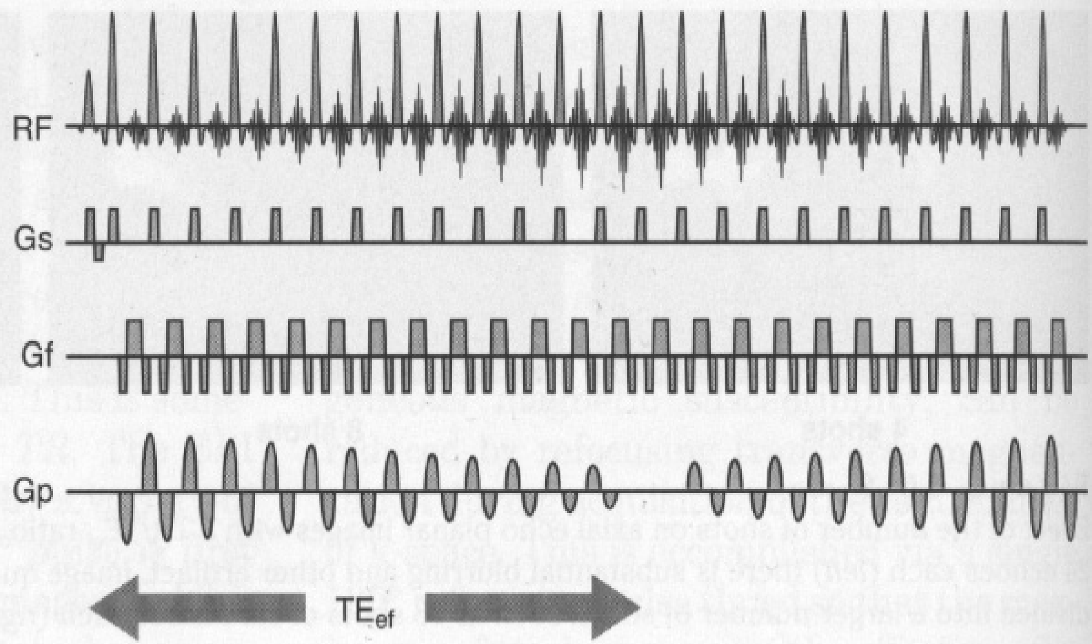
- Multiecho Spin Echo
  - Multiple echoes collected can be used to calculate T_2
  - No increase or decrease in acquisition time from single-echo SE

- ***Acquisition time***: can it be improved without loss in image quality?

Fast Spin Echo

- Rapid Acquisition with Relaxation Enhancement (RARE), also known as Fast Spin Echo (FSE)

Figure 16-11
Fast spin echo pulse sequence. Multiple echoes are created following a single excitation pulse. Each echo is a spin echo refocused by a 180° refocusing pulse. The phase-encoding gradient pulse that precedes each echo has a different value, and each echo is followed by a rewinding gradient that restores phase.

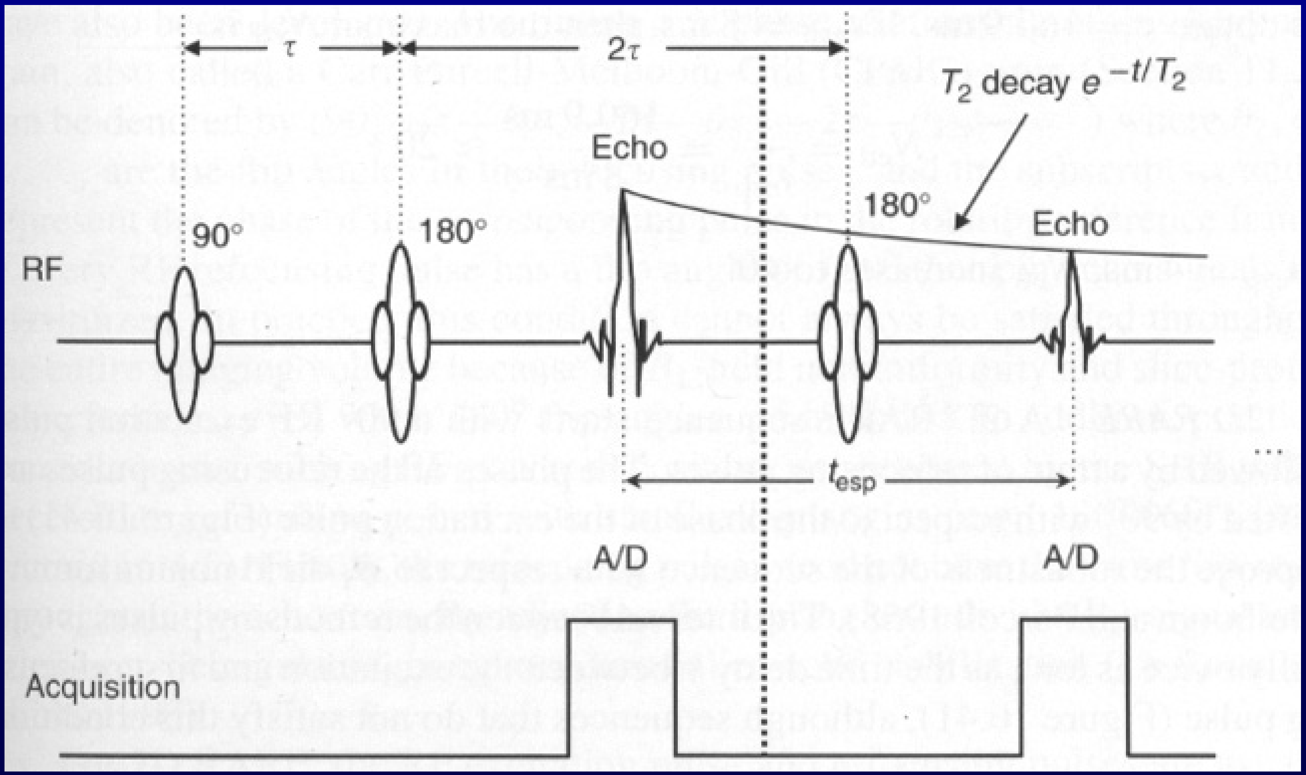


Fast Spin Echo

- A train of refocusing pulses follows the initial excitation pulse
- Multiple spin echoes are produced by the multiple refocusing pulses
- Each echo is distinctively encoded with a phase-encoding gradient
- Multiple *k*-space lines can be sampled following each excitation pulse

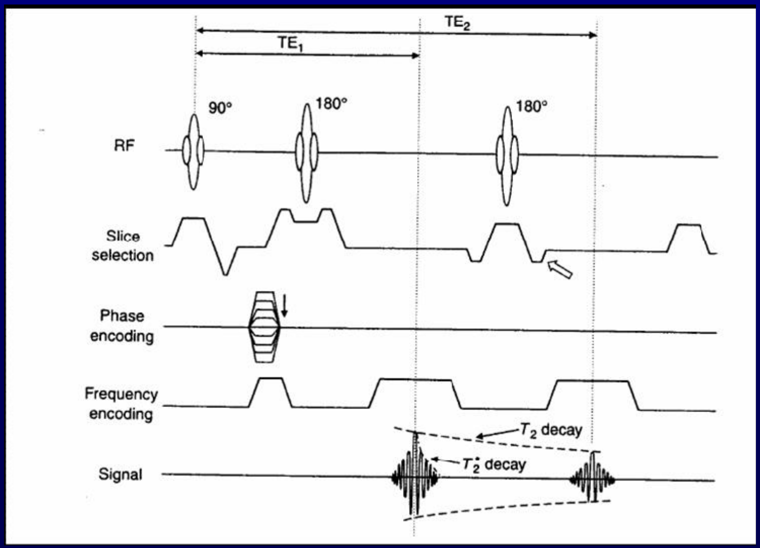
Fast Spin Echo

- **Difference between SE and FSE:**

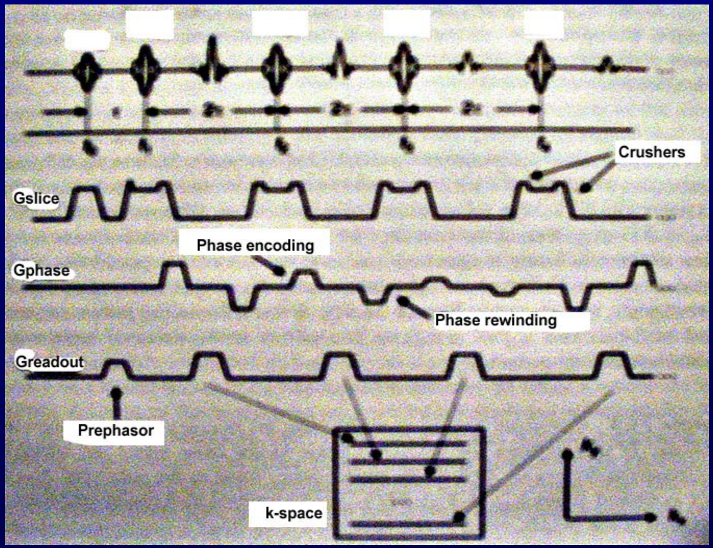


Fast Spin Echo

- **Difference between multiecho SE and FSE**
  - Multiple phase encodes per TR in FSE
  - Only one phase encode per TR in multiecho SE



Multiecho SE



FSE

Fast Spin Echo

- **Signal intensity** at the *n*th echo is determined by the conventional Bloch description as well as some additional parameters:

$$I_n \propto M_0 \left(1 - Fe^{-\frac{T_D}{T_1}}\right) e^{-\frac{TE_n}{T_2}}$$

  – where M_0 is the equilibrium magnetization, T_1 is the longitudinal relaxation time, $TE_n = 2n\tau$ is the *n*th echo time (and τ is the time interval between the excitation pulse and the first refocusing pulse), and T_2 is the transverse relaxation time
  – T_D is the time interval between the center of the last echo in the train and the end of the TR and is given by T_D = TR - $2N_\tau$, where TR is the repetition time and N_τ is the total number of refocusing pulses

Fast Spin Echo

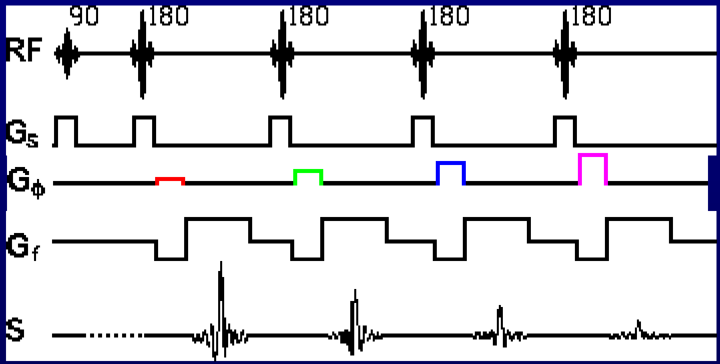
- I_n considers the intensity produced at acquisition, which is derived from transverse magnetization but is also dependent on the longitudinal magnetization that has recovered at the end of the previous TR period
- For an FSE sequence, the longitudinal magnetization M_z at the end of a TR period immediately prior to sequence repetition becomes:

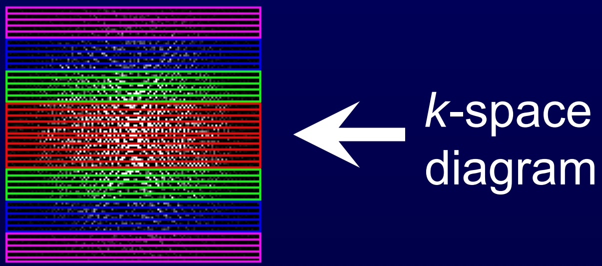
$$M_z = M_0\left(1 - Fe^{-\frac{T_D}{T_1}}\right)$$

  - where the F term is a geometric series that describes the intensity of multiple echoes separated by 2τ (in a first-order approximation where $\tau \ll T_1$, $F \approx 1$).

Fast Spin Echo

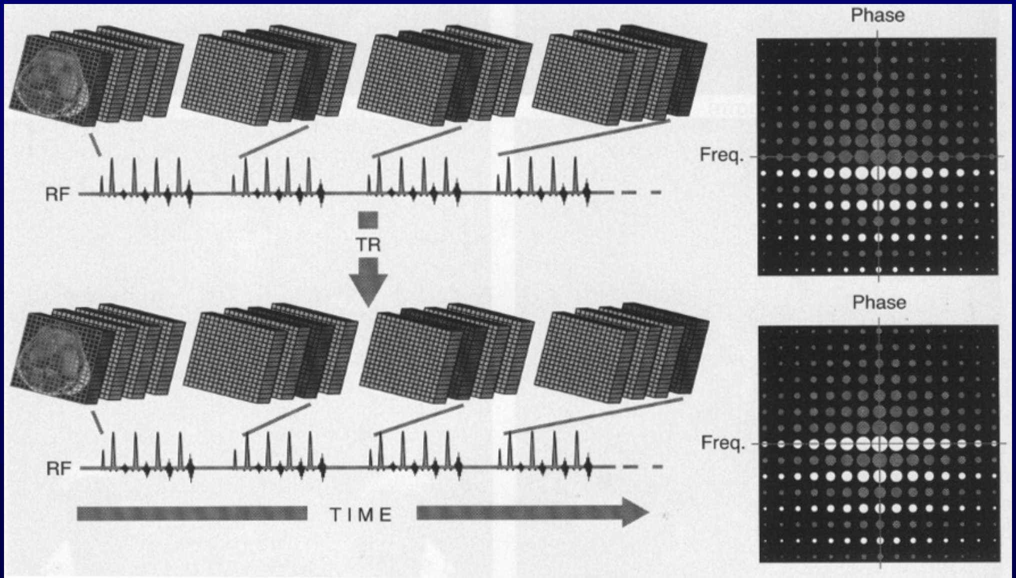
- **Reduction in image acquisition time**
  - In this example, 4 echoes are used to fill the entire *k*-space during a single TR. This takes approximately 1/4th as much time as 4 single conventional spin echoes would.





FSE – Filling *k*-space

- *k*-space is essentially divided into “sections”
- Each echo contributes to one particular section of *k*-space because it has been distinctively spatially encoded



FSE – Basic Parameters

- **Echo Train Length (ETL)**
  - The number of echoes that follows an excitation pulse ("echo train").
- **Effective TE (TE_{ef})**
  - The TE of the echo acquired with a phase encoding of zero. Represents the center line of *k*-space.
- **Number-of-Averages (NEX or NSA)**
  - Number of signal averages used.
- **Echo Spacing (ESP)**
  - The interval between the peaks of two consecutive spin echoes.
- **Number-of-Shots (N_{shot})**
  - Number of non-redundant RF excitations. In single-shot imaging, the entire *k*-space for an image is acquired using the signal acquired from an echo train that was produced using a single RF excitation pulse.

Echo Train Length

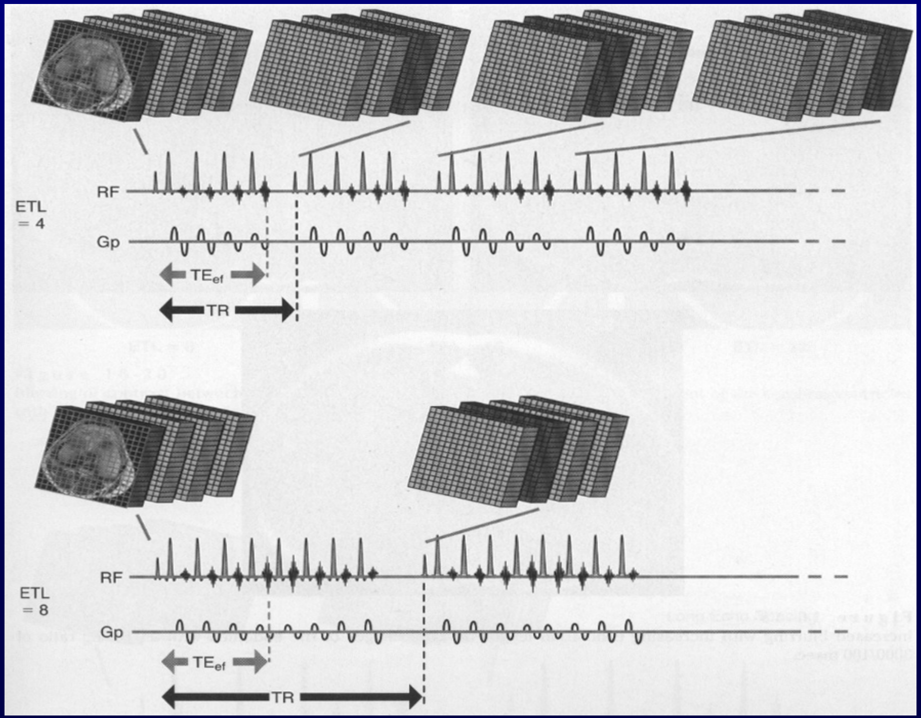
- Directly determines the amount that scan time is reduced when compared to conventional SE.
- If all echoes are distinctively phase-encoded (as with FSE) then ETL is equal to the number of *k*-space lines acquired during a single TR.
- The larger the ETL, to greater the scan time reduction: more lines of *k*-space are acquired per TR.

Echo Train Length

- The ETL has practical limitations (like T_2 relaxation times).
- A larger ETL does not always translate into a large reduction in acquisition time:

In this example, the TE_{ef} is defined by the last echo when ETL is 4.

When the ETL is 8 the TE_{ef} remains the same but only half as many images can be obtained during a single TR.



Effective TE

- Each echo has its own TE value
- The TE of an FSE sequence is defined as the TE when the central *k*-space line is acquired and is known as the TE_{ef} (effective TE).
  - Minimal TE_{ef} value: $TE_{ef} = ESP$
  - Maximal TE_{ef} value: $TE_{ef} = ETL \times ESP$

Echo Spacing

- If the ESP is minimized the ETL can be long for a given TR.
- This decreases the number of excitations that must be repeated.

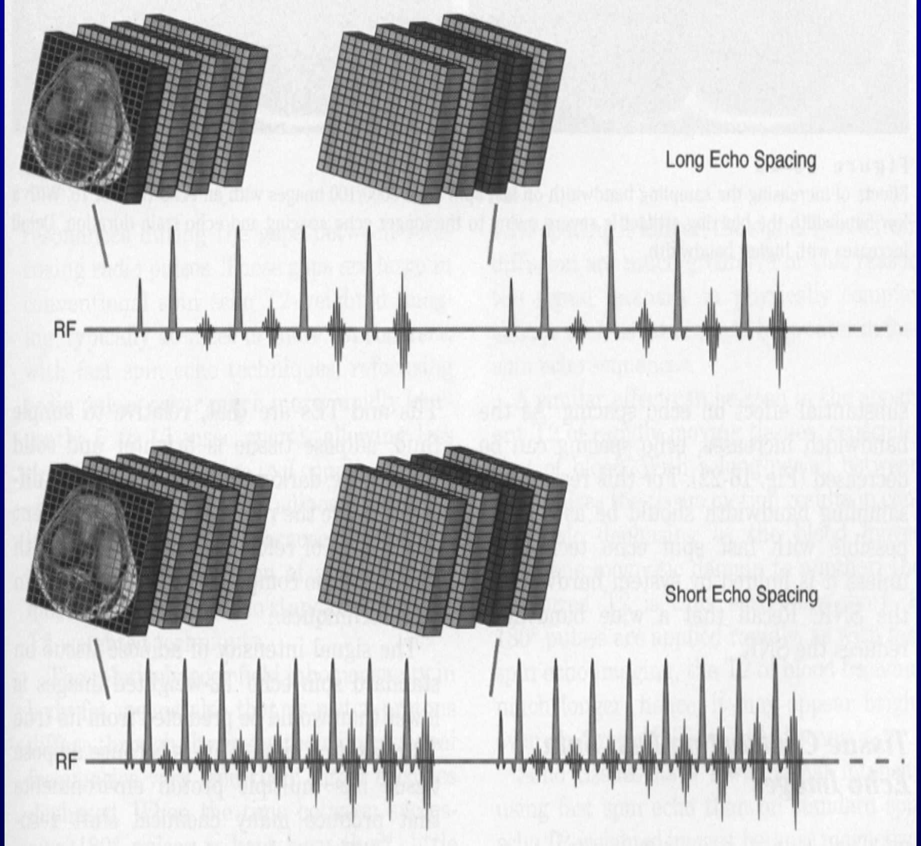


Figure 16-21
Effect of echo spacing on acquisition efficiency. With shorter echo spacing the echo train length can be increased without reducing the number of image slices obtained at a given TR.

Determining Scan Time

- The total scan time (where N_{acq} is the number of acquisitions) of an FSE sequence can be calculated by:

$$T_{scan} = TR \cdot N_{shot} \cdot NEX \cdot N_{acq}$$

- The length of a single FSE sequence can be approximated by:

$$T_{seq} \approx ETL \cdot ESP$$

Sequence Efficiency

- Multiple echoes are acquired during a given TE
- Efficiency increases by a factor equal to the number of echoes obtained by the time TE_{ef} is reached
  - *Ex*: if 6 echoes can be obtained in 90 ms, an FSE technique with an echo train of 6 and a TE_{ef} of 90 ms is six times as efficient as a single-echo technique with a TE of 90 ms.

Contrast and SNR

- Assuming 180° refocusing pulses, the peak amplitude of the echoes decays according to:

$$S(n) = S_0 e^{-n \cdot ESP / T_2}$$

  - where *n* is the echo index, *ESP* is the echo spacing, and S_0 is the peak signal value
- To produce T_1-weighted or PD-weighted images, early echoes in the train are sampled for the central *k*-space data
- To produce T_2-weighted images, later echoes are sampled for the central *k*-space data

Contrast and SNR

- FSE demonstrates higher SNR and image quality when compared to conventional SE imaging
  - SNR becomes a function of TE_{ef}, ETL, and ESP
  - Images are less sensitive to off-resonance effects

Homework Problem #1

- Consider a spin system with an average T_2 relaxation time of 100 ms. If spin echoes are acquired prior to the time when the transverse magnetization decays to 20% of its peak value, what is the maximal ETL that can be acquired when ESP = 8 ms? If ESP is shortened to 4 ms by reducing the refocusing pulse width, what is the new maximal ETL?
  - *Hint*: recall that the transverse magnetization decays according to $S = S_0 e^{-t/T_2}$ and that t = ETL × ESP.

Clinical Use

- Often used to produce T_2-weighted images
- Contrast is very similar to conventional SE
- Scan parameters usually include TR, TE, ETL

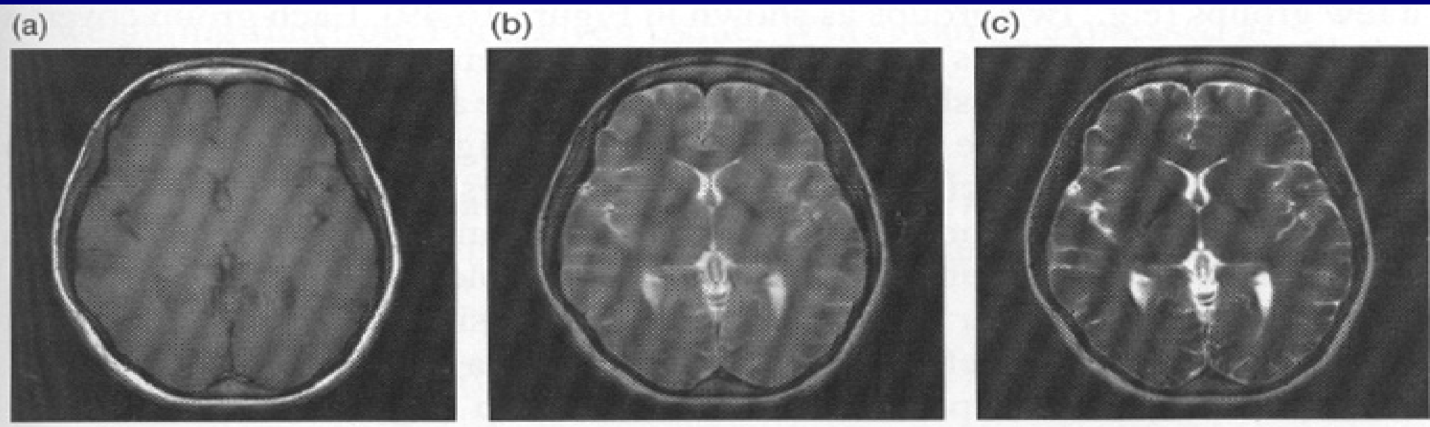


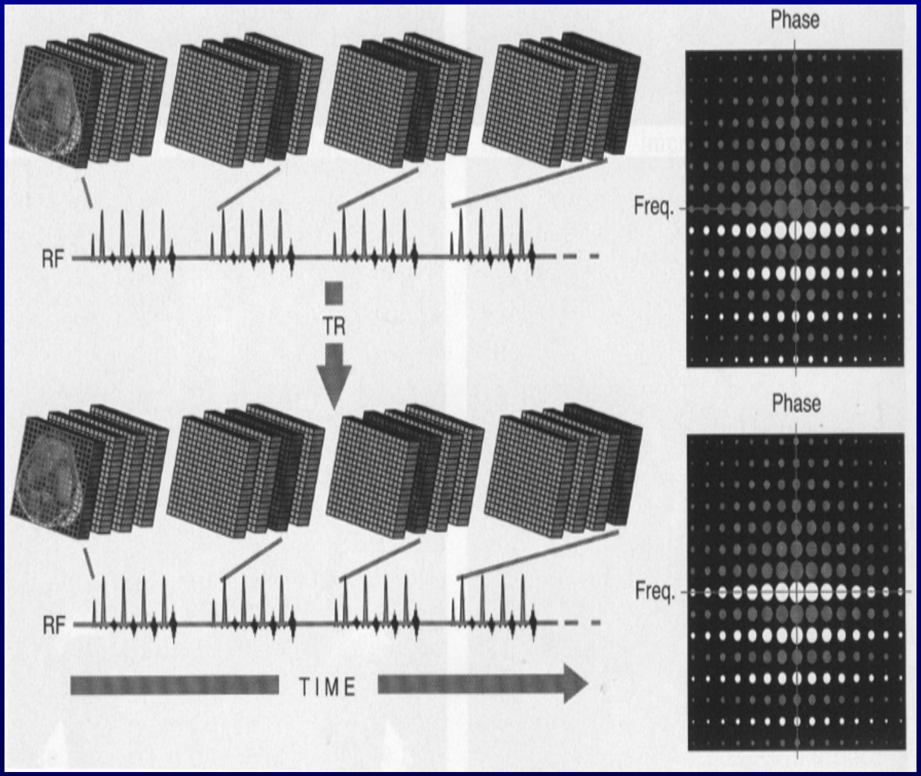
FIGURE 16.48 By using different echoes to sample the k-space center, considerably different image contrast can be obtained from a RARE sequence. (a) T_1-weighted image with TE $=$ 11 ms, TR $=$ 480 ms, and $N_{etl} = 8$. (b) Moderately T_2-weighted image with TE $=$ 77 ms, TR $=$ 4000 ms, and $N_{etl} = 16$. (c) Heavily T_2-weighted image with TE $=$ 176 ms, TR $=$ 4000 ms, and $N_{etl} = 16$.

Single-shot vs Multi-shot

- In single-shot FSE, a single echo train is used to acquire all the *k*-space data needed for the reconstruction of an image.
- Commonly used to compensate for respiratory motion or improve temporal resolution.
- ETL must be maximized to achieve acceptable spatial resolution.

Single-shot vs Multi-shot

- In multi-shot FSE, a fraction of the *k*-space data is acquired with each shot.
- Maximum ETL does not need to be used, allowing for higher spatial resolution.
- Interleaving *k*-space filling is usually used to avoid signal decay issues and phase errors.



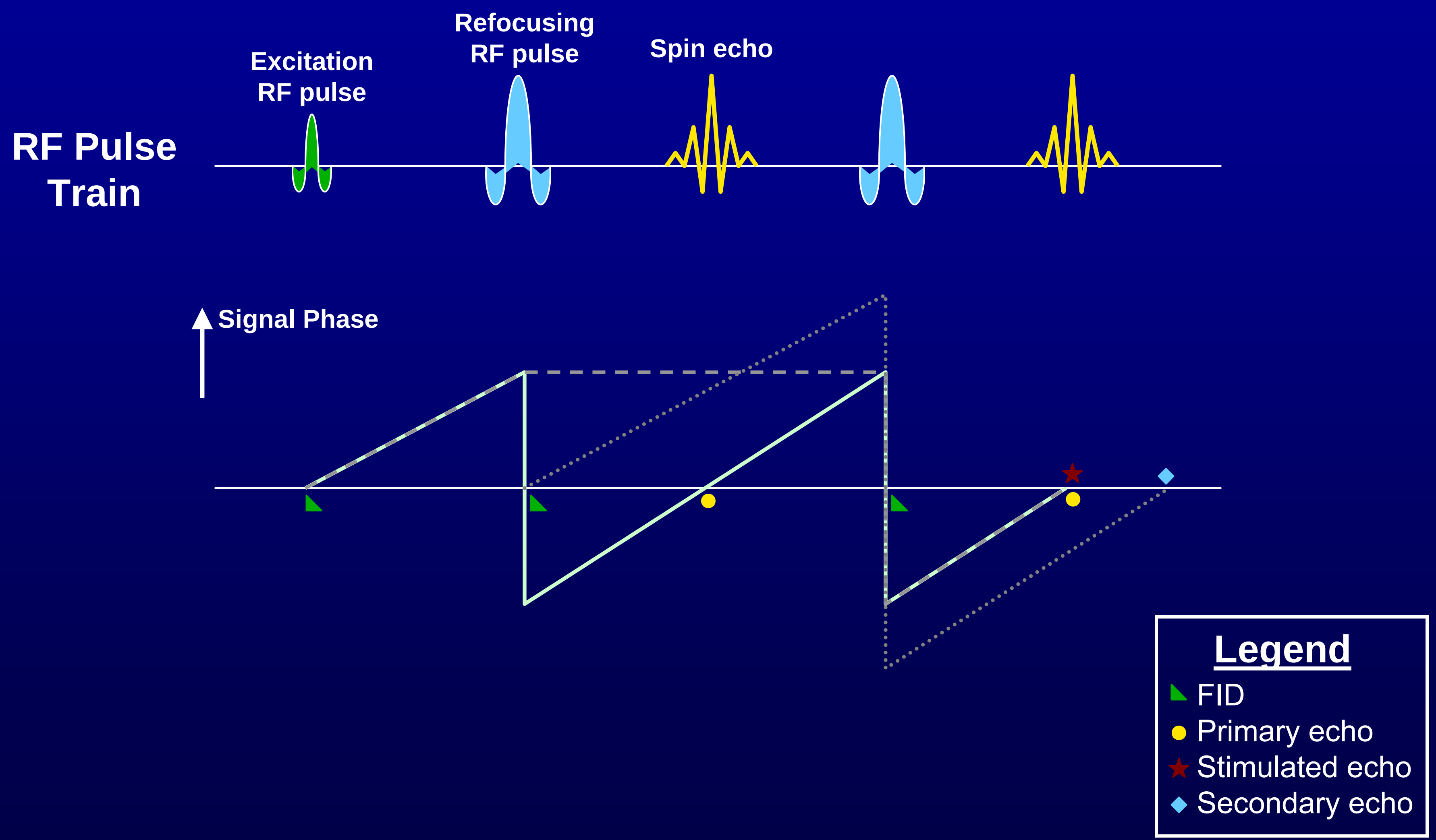
CPMG Conditions

- Refocusing pulses with flip angles of less than 180° are often used
- As a result, some transverse and longitudinal magnetization remains after refocusing (imperfect refocusing)
- Subsequent non-180° pulses further differentiate these imperfect magnetization components

CPMG Conditions

- The “interference” of these incomplete magnetizations causes the creation of primary, secondary, and stimulated spin echoes.
- Secondary and stimulated echoes are the result of excitation by imperfect refocusing pulses
- The pulses create echoes from “lingering” magnetization, which artificially increases the total number of echoes.

CPMG Conditions



CPMG Conditions

- In order to ensure that
  - Echoes only occur at the desired points in the pulse sequence
  - The signals at each temporal position have the same phase
- The **Carr-Purcell-Meiboom-Gill** (CPMG) conditions must be met for an FSE sequence
- When these conditions are met, primary and stimulated echoes occur only at the mid-point between two consecutive refocusing pulses and carry the same phase

CPMG Conditions

- **Condition 1**
  - Refocusing pulses must be 90° out-of-phase with excitation pulses
  - Refocusing pulses must be evenly positioned with equal spacing between any two consecutive pulses.
  - The spacing of the refocusing pulses must be twice the time interval τ between the excitation pulse and the first refocusing pulse

CPMG Conditions

- **Condition 2**
  - Phase accumulated by a spin isochromat between any two consecutive refocusing pulses must be equal

$$\gamma\int_{t_1}^{t_2} B(t)dt = \gamma\int_{t_3}^{t_4} B(t)dt = \cdots \gamma\int_{t_{N-1}}^{t_N} B(t)dt$$

CPMG Conditions

- **Implications of CPMG conditions in FSE**
  - All crusher gradients surrounding the refocusing pulses must have the same area (with some exceptions)
  - Each phase-encoding gradient must be accompanied by a phase-rewinding gradient after the readout window but prior to the next refocusing pulse
  - Only primary and stimulated echoes will be used; secondary echoes and the FIDs following each refocusing pulse are eliminated by crusher gradients
  - If a non-uniform space exists in the magnetization along the slice-selection direction, the CPMG conditions cannot be satisfied across the entire slice profile
  - Moving spins can violate the CPMG conditions (accumulated phase would no longer be equal)

Advantages of FSE

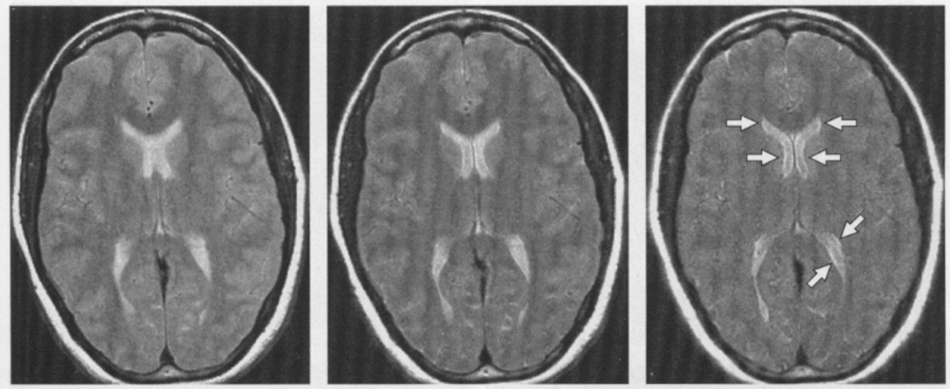
- Short acquisition time
- Image contrast similar to SE
  - Refocusing pulses eliminate signal loss from field inhomogeneities and susceptibility effects when compared to gradient echo-based techniques
- High spatial resolution and SNR
  - Can be adjusted at the expense of scan time
- Less signal loss in adipose tissue due to “J coupling” when compared to SE
  - *J coupling* is loss due to interaction between different lipid resonances during gaps between refocusing pulses

Disadvantages of FSE

- Larger power deposition/SAR
- Larger magnetization transfer (MT) effects
  - MT involves saturation of the longitudinal magnetization of macromolecular protons, which can be transferred to closely-associated water protons
- J coupling can still effect scans with long TR and TE
  - Lipids may appear brighter and obscure potential lesions

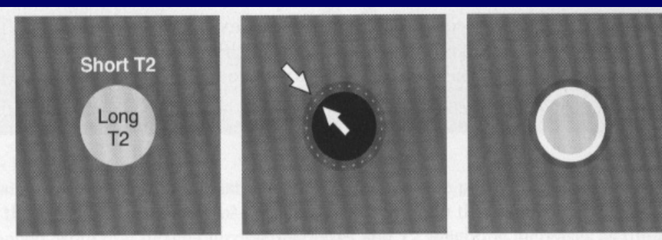
Disadvantages of FSE

- Blurring and ghosting
  - Produced by motion, T_2 effects, and phase-induced artifacts
- Edge enhancement
  - Some tissues with blurred edges are mapped to adjacent pixels, increasing apparent signal intensity (usually at fluid-tissue interfaces)



ETL = 8 ETL = 16 ETL = 32

Figure 16-20
Blurring of contrast between gray and white matter and artifactual edge enhancement of the cerebral ventricles with increasing echo train length (*arrows*).



Blurring of Short T2 Edges Long T2 + Short T2

Figure 16-19
Paradoxical edge enhancement due to blurring of short-T2 tissue (e.g., brain) on fast spin echo images with a long echo train. Blurring of brain tissue causes decreased signal intensity at its margins that extends into the area occupied by a tissue with a longer T2 (e.g., fluid). The middle image depicts brain tissue with fluid omitted. The *dotted line* represents the true margin of brain tissue, and the *arrows* indicate its blurred boundary. The image at *right* depicts brain and fluid. Note the decreased signal intensity adjacent to the fluid and increased signal intensity at the edge of the fluid, the result of the summation of signal intensities from fluid and the blurred brain edge.

Disadvantages of FSE

- Many of these disadvantages can be corrected or compensated:
  - Refocusing pulses of less than 180° for lower SAR (also reduces MT effects)
  - HASTE and SSFSE techniques to reduce blurring
  - T_2 mapping, averaging, or weighting can reduce blurring and edge enhancement
  - Phase compensation to reduce ghosting
  - Careful selection of TR, TE, ETL, and using different prepatory pulses like fat saturation for improved image quality

Homework Problem #2

- Consider an FSE sequence where N_{acq} = 2, ETL = 64, and the number of phases is 64. If the ETL is reduced to 32 what must be done to the sequence in order to acquire the same number of phase-encoded *k*-space lines? What happens to the sequence in general?
  - *Hint*: How does N_{shot} change and what happens to T_{seq}?

References and Figures from:

1. Bernstein, M.A.; King, K.F.; Zhou, X.J., *Handbook of MRI Pulse Sequences*. Elsiver/Academic Press: Burlington, MA, 2004.
2. Mitchell, G.M.; Cohen, M.S., *MRI Principles*. Elsiver/Saunders: Philadelphia, PA, 2004.
3. Hornak, J.P., *The Basics of MRI*. Online, **2005**. <http://www.cis.rit.edu/htbooks/mri/index.html>
4. Hennig, J.; Nauerth, A.; Friedburg, H., “RARE imaging: a fast imaging method for clinical MR.” *Magn Reson Med* **1986**, 3, (6), 823-833.
5. Constable, R.T.; Anderson, A.W.; Zhong, J.; Gore, J.C., “Factors influencing contrast in fast spin-echo MR imaging.” *Magn Reson Imaging* **1992**, 10, (4), 497-511.
6. Constable, R.T.; Smith, R.C.; Gore, J.C., “Signal-to-noise and contrast in fast spin echo (FSE) and inversion recovery FSE imaging.” *J Comput Assist Tomagr* **1992**, 16, (1), 41-47.
7. Meara, S.J.; Barker, G.J., “Evolution of the longitudinal magnetization for pulse sequences using a fast spin-echo readout: application to fluid-attenuated inversion-recovery and double inversion-recovery sequences.” *Magn Reson Med* **2005**, 54, (1), 241-245.