Echo Planar Imaging

BioE 594 – Advanced Topics in MRI

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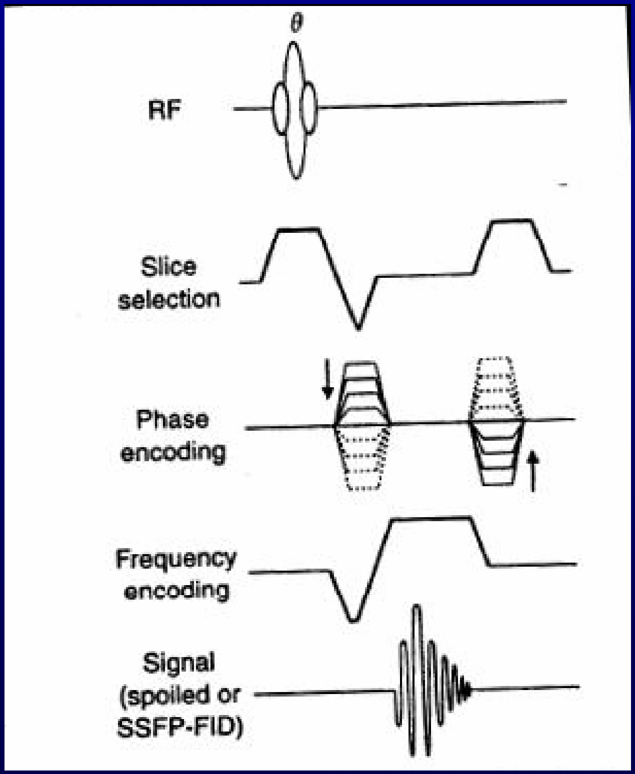
Review

- Gradient Recalled Echo (GRE) Pulse Sequence
  - 90° RF excitation → *dephasing gradient* → echo
  - The dephasing frequency encoding gradient is applied at the same time as the phase encoding gradient, causing the spins to be in phase at the center of the acquisition period
  - This leads to a gradient-induced echo when the frequency encoding gradient is turned back on for signal acquisition
  - Main parameters: TR, TE, flip angle

Review

- GRE Pulse Sequence



Review

- GRE vs Spin Echo (SE) Pulse Sequence

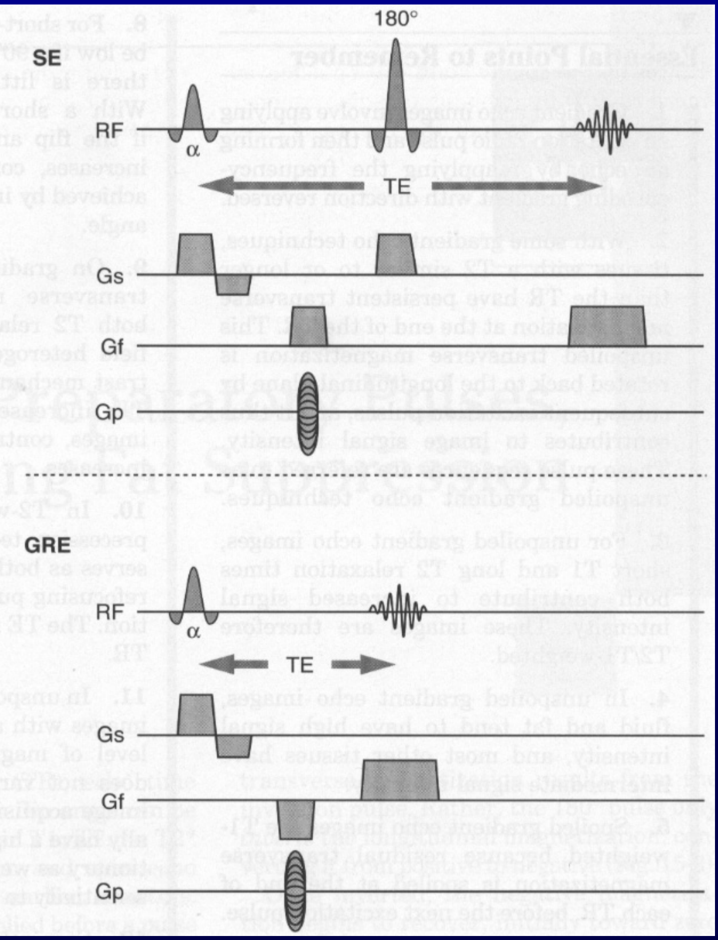


Figure 14-13
Comparison between spin echo (SE) (*top*) and gradient echo (GRE) (*bottom*) pulse sequences. The GRE pulse sequence does not include a 180° refocusing pulse or its accompanying slice-select gradient, so the TE can be shorter than for SE sequences.

Review

- Advantages of GRE
  - Faster imaging (compared to SE)
  - Less RF energy deposition (decreased SAR)

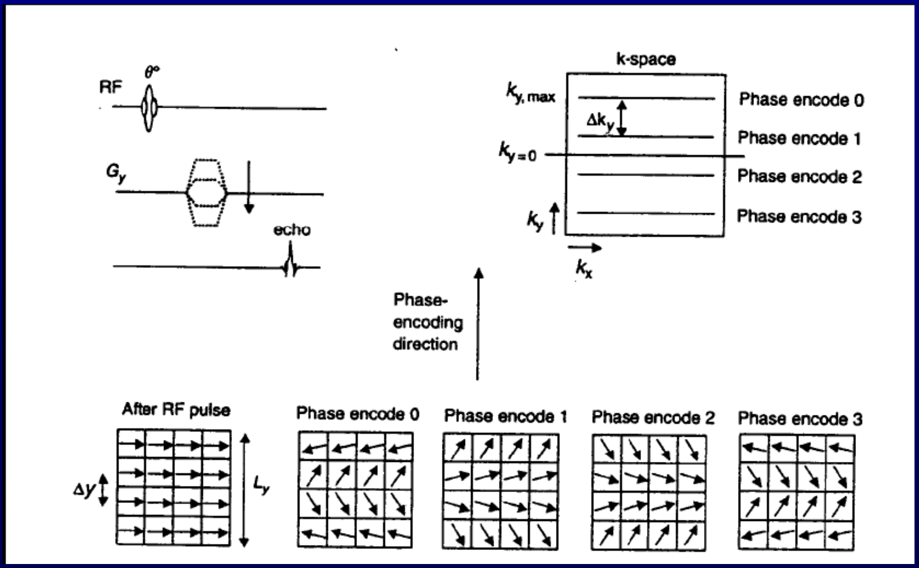
$$S = \frac{k\rho\left(1 - e^{-TR/T_1}\right)\sin\theta \cdot e^{-TE/T_2^*}}{1 - \cos\theta \cdot e^{-TR/T_1}}$$

Review

- Disadvantages of GRE
  - Poor T_2-weighted image quality (highly susceptible to T_2* effects)
  - Potentially large signal loss due to magnetic field inhomogeneities and other off-resonance effects

Moving Beyond GRE

- Although GRE is considerably faster than SE imaging techniques, *k*-space is still filled in an inefficient manner



- *Can k-space be filled faster without losing substantial image resolution?*

Echo Planar Imaging

- Pulse sequence for GRE-based echo planar imaging (EPI)

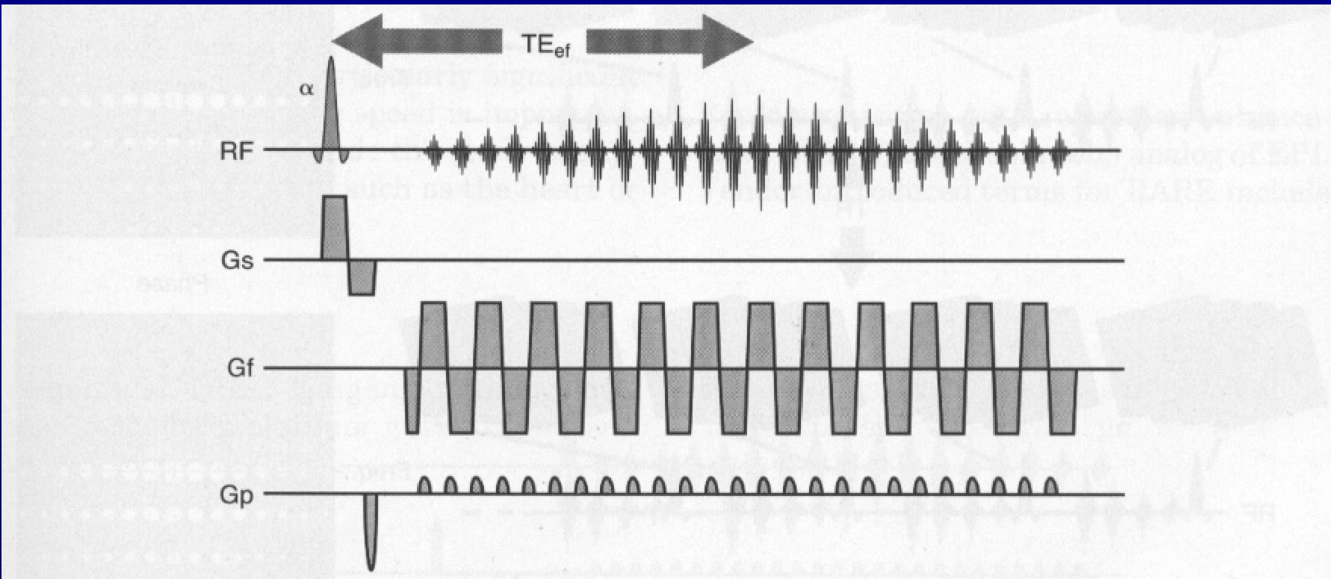


Figure 16-7
Echo planar pulse sequence, showing multiple signals created following a single excitation pulse (α). After an initial strong negative phase-encoding gradient pulse, successive weak phase-encoding gradient pulses (blips) gradually move the phase encoding toward zero, corresponding to the TE$_{ef}$. Further phase encoding blips incrementally increase the phase encoding.

Echo Planar Imaging

- Can form a complete imaging from a single shot
- Multiple echoes are created by oscillating the frequency encoding gradient
- Each echo is individually phase encoded so that multiple *k*-space lines can be read in a single excitation

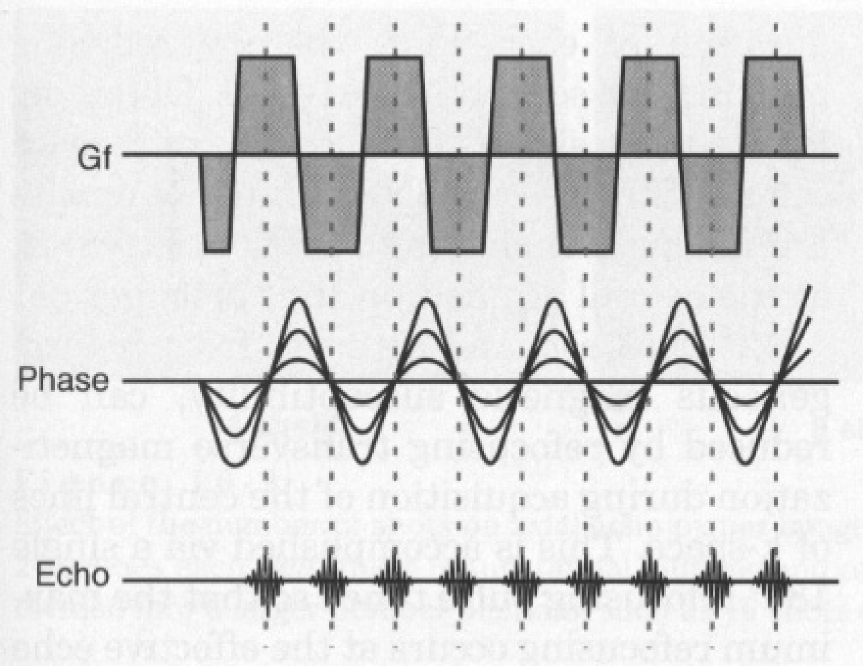


Figure 16-6
Multiple echoes can be created using the echo planar technique by oscillating the Gf. The transverse magnetization is refocused at the center of each lobe of this gradient, producing the echo.

Echo Planar Imaging

- Difference between GRE and EPI

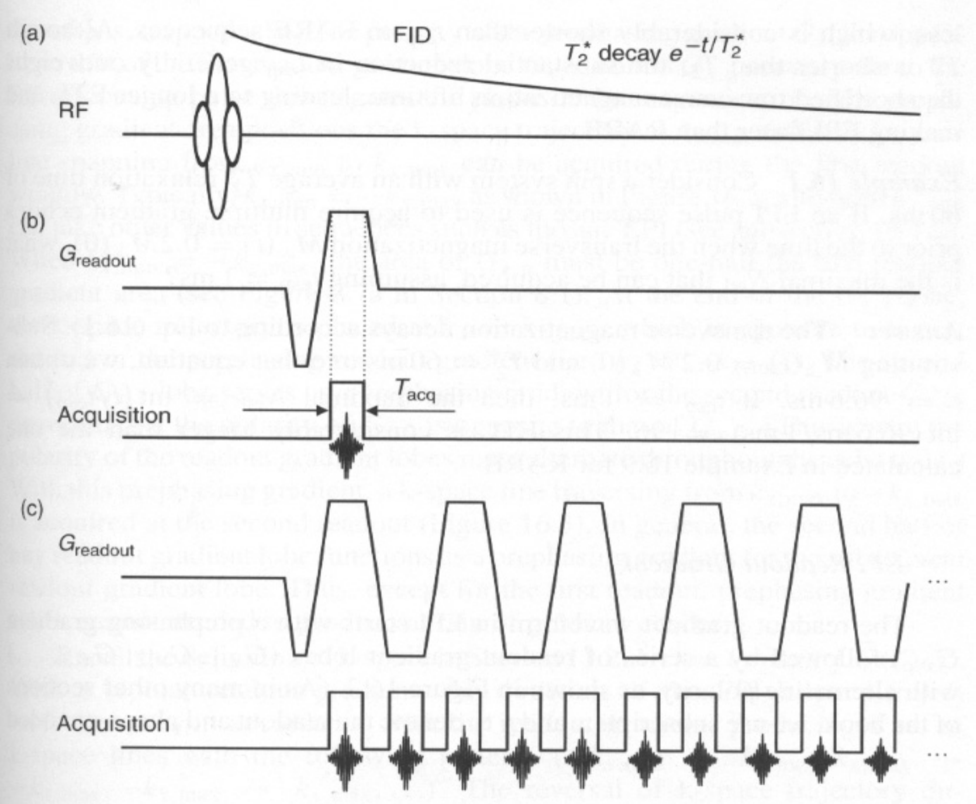


FIGURE 16.2 (a) An RF excitation pulse and comparison between (b) conventional gradient-echo acquisition and (c) EPI acquisition.

Echo Planar Imaging

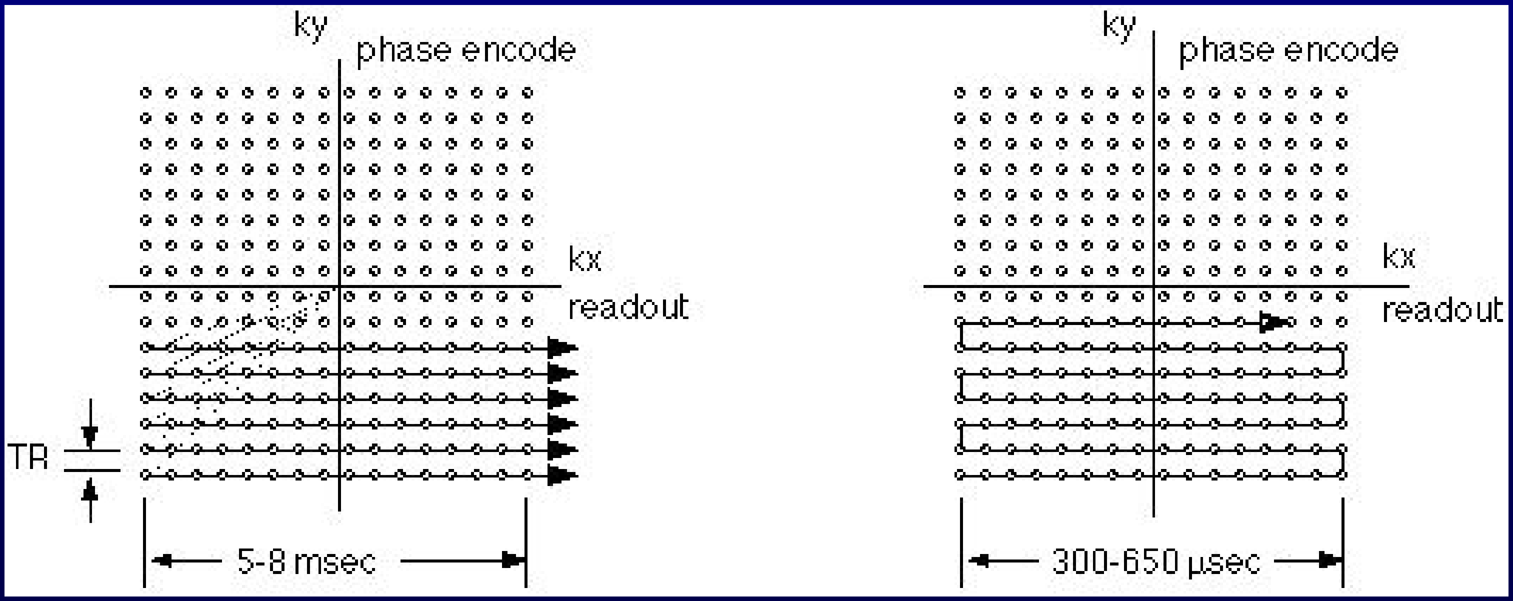
- The amplitude of an EPI gradient echo signal decays according to:

$$S(n) = S_0 e^{-TE(n) / T_2^*}$$

  - where *n* is the echo index in the train and S_0 is the signal at time zero.

EPI – Filling *k*-space

- In conventional imaging, each line of *k*-space is acquired separately after an excitation pulse
- In EPI, *k*-space lines are acquired continuously as shown:



Conventional **EPI**

EPI – Filling *k*-space

- Filling *k*-space in this manner results in drastically reduced acquisition times
- Variation of filling trajectories depends on the phase encoding gradient pattern used
- Image contrast is dependant on the RF sequence and ***not*** on the spatial encoding technique

EPI – Basic Parameters

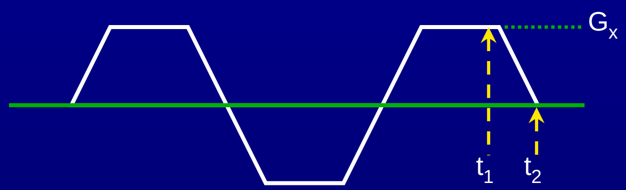
- As in Fast Spin Echo (FSE), the following parameters are used to define an EPI pulse sequence (where the 'echoes' are gradient echoes instead of spin echoes):
  - Echo Train Length (ETL)
  - Echo Spacing (ESP)
  - Effective Echo Time and Repetition Time (TE_{ef} and TR)
- ETL directly determines the amount of scan time reduction
- Contrast is largely determined by TE_{ef}

Readout Gradient Parameters

- The oscillation of the frequency encoding gradient enables the rapid acquisition of lines in *k*-space as well as generating multiple gradient echoes
- Three different types of frequency encoding gradient waveforms are used in EPI:
  - Trapezoidal
  - Sinusoidal
  - Catch-and-hold (hybrid of trapezoid and sinusoid)

Readout Gradient Parameters

- Trapezoidal Readout Gradient Lobes
  - Area and amplitude described using standard trapezoidal lobe expressions



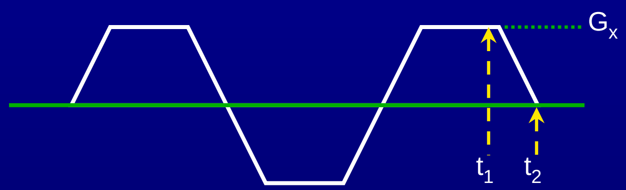
  - The acquisition time T_{acq} for a single echo is given by:

$$T_{acq} = \frac{n_x}{2\Delta V} = \frac{2\pi n_x}{\gamma L_x G_x}$$

  - where $2\Delta V$ is the full receiver bandwidth, n_x is the number of complex *k*-space data points in the readout (frequency) direction, G_x is the gradient amplitude, and L_x is the readout FOV

Readout Gradient Parameters

- Trapezoidal Readout Gradient Lobes
  - The readout *k*-space trajectory is described as:



$$k_x(t) = \begin{cases} S_R(t+t_2) & t \in [-t_2, -t_1) \\ G_x & t \in [-t_1, t_1) \\ S_R(t_2 - t) & t \in [t_1, t_2) \end{cases}$$

  - where S_R is the slew rate, t_1 and t_2 describe the beginning and ending points of the trapezoid ramps respectively, and G_x is the gradient amplitude

Readout Gradient Parameters

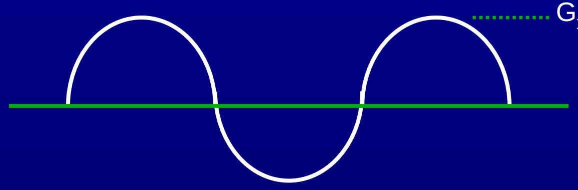
- Trapezoidal Readout Gradient Lobes
  - A minimal value for ESP is desired for an EPI sequence because long ESP can compromise acquisition efficiency and exacerbate image artifacts
  - When using trapezoidal lobes, the minimal ESP is given by:

$$ESP_{\min} = T_{acq} + 2(t_2 - t_1) = \frac{2\pi n_x}{\gamma L_x G_x} + \frac{2G_x}{S_R}$$

  - where t_1 and t_2 describe the beginning and ending points of the trapezoid ramps respectively, S_R is the slew rate, and T_{acq} is the acquisition time (this assumes a gradient echo EPI sequence in which ESP is determined solely by the readout gradient waveform)

Readout Gradient Parameters

- Sinusoidal Readout Gradient Lobes
  - Area and amplitude described using standard sinusoidal lobe expressions



  - T_{acq} is described by the same expression used for trapezoidal lobes
  - The readout *k*-space trajectory is described as:

$$k_x(t) = \frac{\gamma G_x T_{acq}}{2\pi^2} \sin\left(\frac{\pi t}{T_{acq}}\right)$$

Ramp Sampling

- Both trapezoidal and sinusoidal lobes contain ramping periods
- In order to further minimize ESP, *k*-space data can be acquired during these ramps (known as “ramp sampling”)
  - Helps minimize image artifacts (blurring, etc.)
  - Maintains acquisition efficiency without increasing gradient slew rate

Phase Encoding Gradient Parameters

- Each echo is individually phase encoded to facilitate rapid movement thought *k*-space
- Phase rewinding is not necessary because EPI pulse sequences are not subject to the CPMG conditions of FSE
- Incidentally, the bandwidth along the phase encoding axis is relatively low due to the continuous *k*-space filling scheme

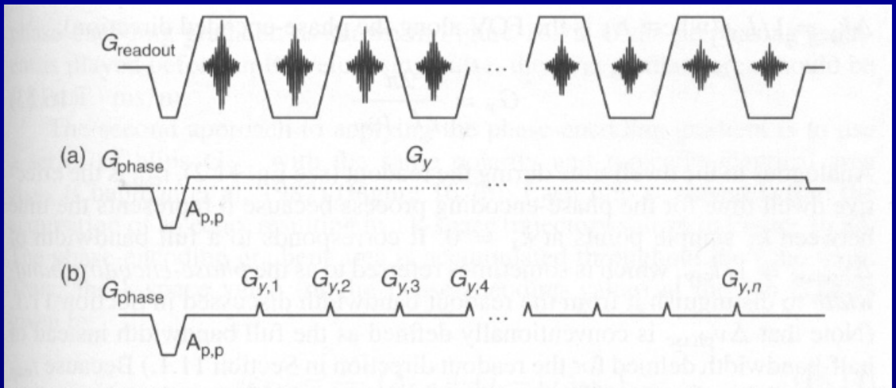


FIGURE 16.7 Two EPI phase-encoding waveforms: (a) constant gradient G_y, and (b) blip gradients $G_{y,1}, G_{y,2}, G_{y,3}, \ldots, G_{y,n}$. Both waveforms generally use a prephasing gradient with an area of $A_{p,p}$. To illustrate the relationship with readout gradient, a trapezoidal readout gradient waveform is also shown.

FIGURE 16.8 k-space trajectories (a) and (b) corresponding to the phase-encoding gradient waveforms (a) and (b) in Figure 16.7. The dotted diagonal lines show the trajectory of the prephasing gradients.

Clinical Use

- Pulse Sequence Types
  - Both GRE and SE RF sequences can be used (depending on desired contrast mechanism)

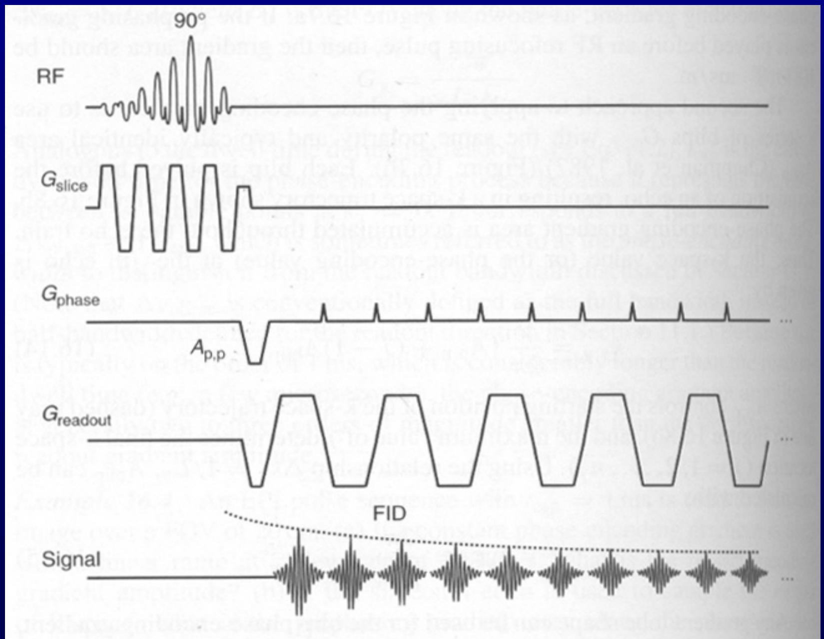


FIGURE 16.9 An example of a gradient-echo EPI pulse sequence. The spatial-spectral excitation pulse can be replaced by a slice-selection pulse preceded by a spectrally selective pulse to suppress lipid signals. For simplicity the optional spoiler gradient at the end of the sequence is not shown.

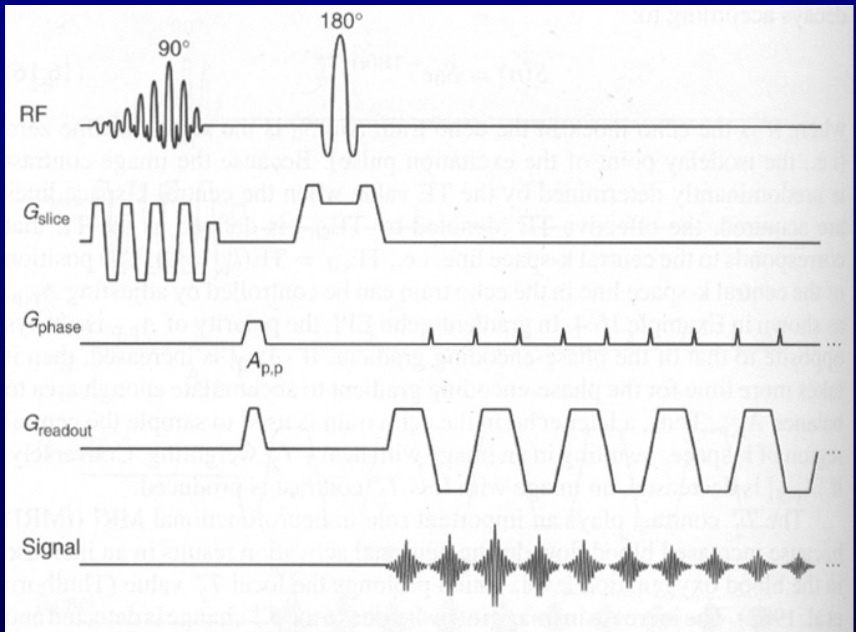


FIGURE 16.10 An example of a spin-echo EPI pulse sequence. The spatial-spectral excitation pulse can be replaced by a slice-selection pulse preceded by a spectrally selective pulse to suppress lipid signals. For simplicity the optional spoiler gradient at the end of the sequence is not shown.

Clinical Use

- Single-Shot EPI
  - Entire 2D *k*-space data needed for image reconstruction obtained using an echo train generated by a single excitation pulse

- Multi-Shot EPI
  - A fraction of the *k*-space needed to reconstruct the image is obtained with each echo train

Clinical Use

- Single-Shot EPI
  - The total scan time (assuming no averaging) is given by:

$$T_{scan} = N_{slice}\left(C + ETL \cdot ESP\right)$$

  - where *C* is the interval between the start of the sequence and the beginning of data acquisition
- Multi-Shot EPI
  - The total scan time is given by:

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

Clinical Use

- Single-Shot EPI
  - Excellent temporal resolution
  - SNR and spatial resolution are usually lower
  - More stringent hardware requirements
- Multi-Shot EPI
  - Improved spatial quality and SNR
  - Longer acquisition time

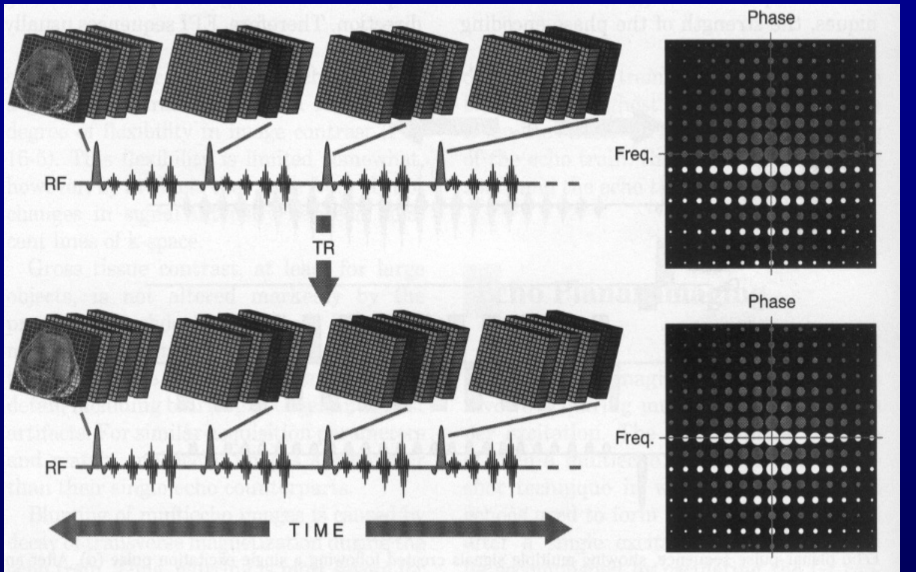


Figure 16-8
Filling of k-space in multislice, multishot echo planar techniques. In this example, four echoes follow each excitation pulse, filling four lines of k-space for a given slice. After each slice has been excited once, filling four lines of k-space for each, the slices are excited for a second time, at the TR, filling four additional lines of k-space.

Homework Problem #1

- When determining the scan time for a single-shot EPI sequence in which signal averaging is not used, why isn't TR a factor? How would the formula for calculating the scan time change if signal averaging were used?
  - *Hint*: What is the definition of TR and what effect does it have in single-shot EPI?

Signal-to-Noise Ratio

- EPI has considerably lower SNR when compared to SE or FSE due to:
  - Higher susceptibility to off-resonance effects
  - Extremely wide receiver bandwidths needed for fast data acquisition
- In theory the SNR is about one-third that of conventional imaging due to bandwidth differences alone
- In practice the SNR is comparable to conventional imaging sequences because of:
  - Imaging techniques such as increased N_{acq}, signal averaging, careful selection of TR, ETL, etc.
  - Inherent reduced motion artifact
  - Reduced imager instability

Hardware Requirements

- EPI is a demanding pulse sequence that requires:
  - High performance gradients with rapid rise times (slew rates of ~100 T/m/sec or higher for some systems)
  - High peak amplitudes (~25 mT/m or higher for some systems)
  - High receiver bandwidth (up to 300 kHz is typical)
  - Large amounts of power (2000 volts at 350 amps, or 750 kW, on a conventional system, for example)
  - Low eddy currents and field imhomogeneities
  - Fast analog-to-digital converters (up to 2 MHz)

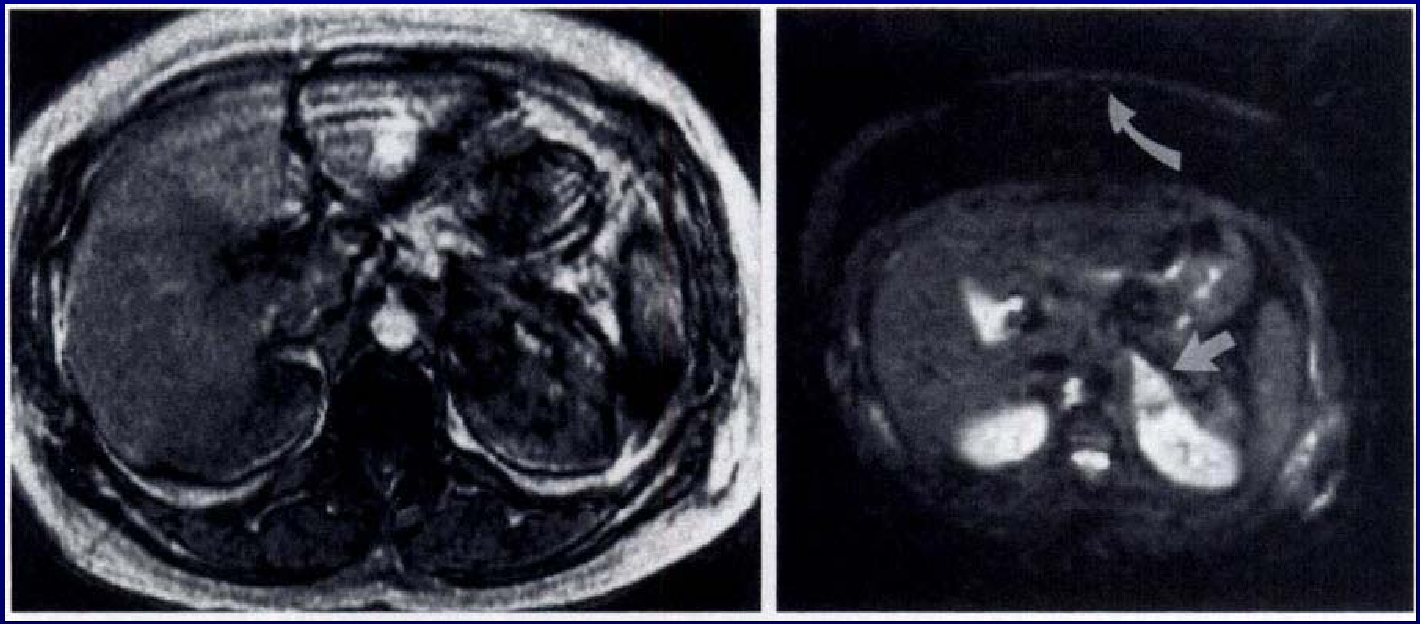
Patient Safety Considerations

- Rapidly switched magnetic field gradients can result in current induction in the patient
  - Induced current is proportional to the cross-sectional area of the body exposed as well as the magnetic field
  - Shorter and smaller gradient coils are used to localize the area of imaging
- High slew rates can cause pain, peripheral neurostimulation, induced respiration, and other problems
  - Frequency encoding gradient waveforms must be designed with this factor in mind

Advantages of EPI

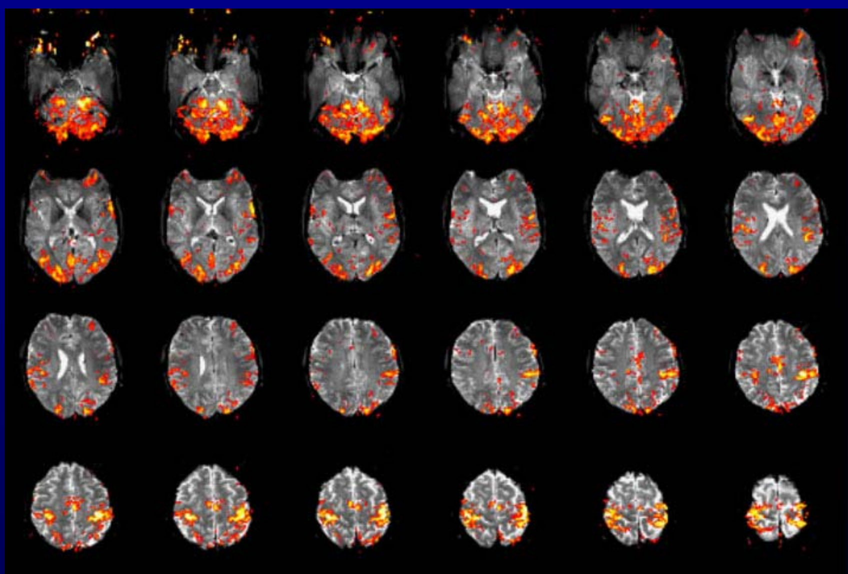
- Extremely fast image acquisition times
  - Compare a canonical T_2-weighted image scan time of about 384 seconds (128 samples with a TR of 3 sec) to a similar EPI scan at 40 to 150 milliseconds (~10,000-fold speed gain)
- Reduced motion artifacts
- Reduced SAR from RF compared to SE sequences
- Potential for functional imaging techniques
  - GRE EPI can produce frame rates of up to 16 fps, suitable for cardiac imaging
  - Ability to produce contrast from T_2* behavior allows for blood oxygen-level dependent (BOLD) imaging and other functional techniques

Advantages of EPI

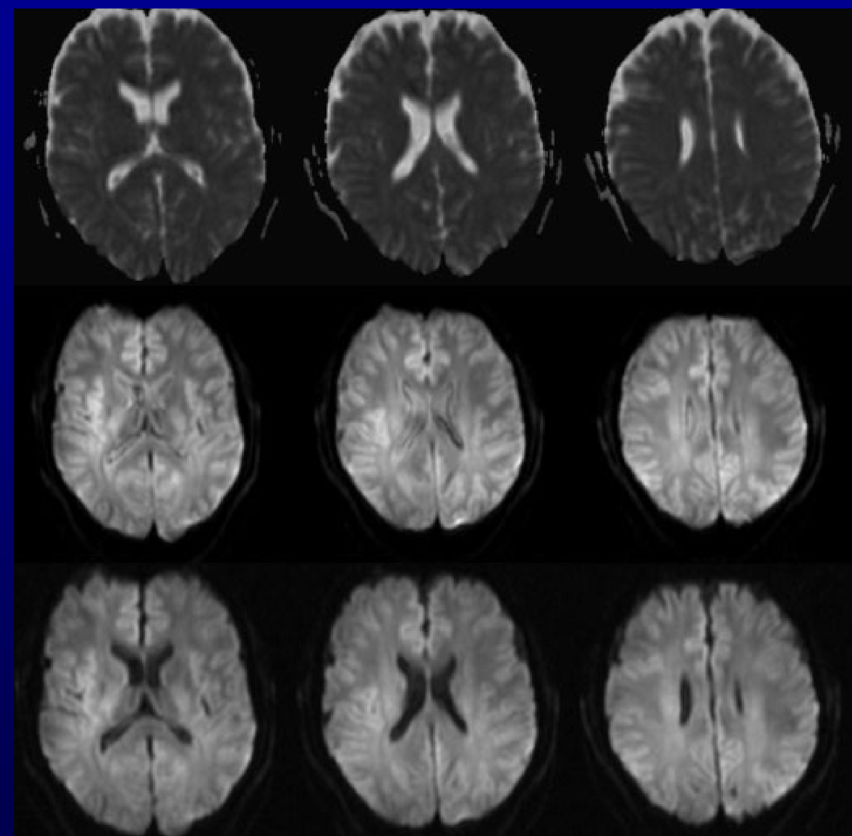


The image on the left was generated using a GRE sequence and contains artifacts from respiratory motion. The image on the right was generated using an EPI sequence and is free of motion artifact.

Advantages of EPI



GRE EPI BOLD sequence



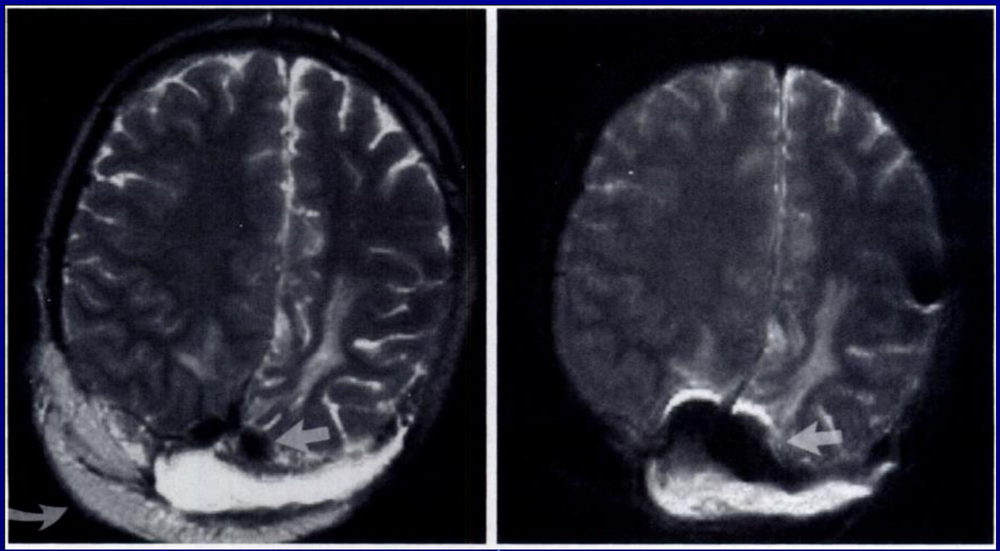
Diffusion EPI BOLD sequence

Images from Bruker BioSpin, GmbH (http://www.bruker-biospin.de/MRI/applications/)

Disadvantages of EPI

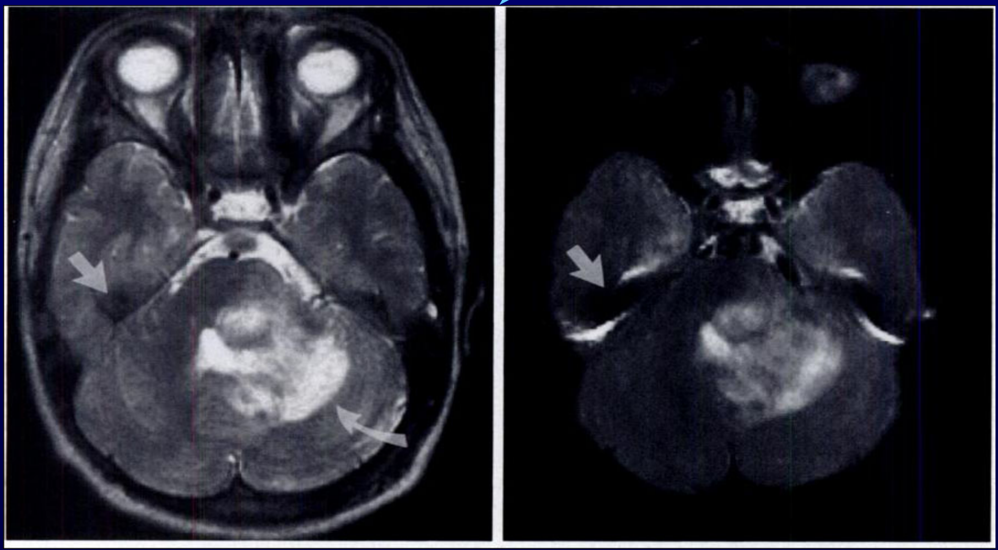
- Highly susceptible to image artifacts
  - **Nyquist ghosting**: gradient-induced eddy currents cause time-dependent frequency shifts, which in turn create phase differences from line to line in *k*-space because of the back and forth acquisition trajectories (this is exacerbated when row-flipping must be used to fill the *k*-space)
  - **Chemical shift artifacts**: the low bandwidth along the phase-encoding direction (***not*** the frequency-encoding direction) can cause substantial chemical shifting
  - **Image and shape distortion**: field inhomogeneities and other off-resonance effects can cause considerable distortion along the phase-encoding direction due to low bandwidth
  - **T_2* blurring**: each line in *k*-space carries a different T_2* weighting because they are acquired at different times

Disadvantages of EPI



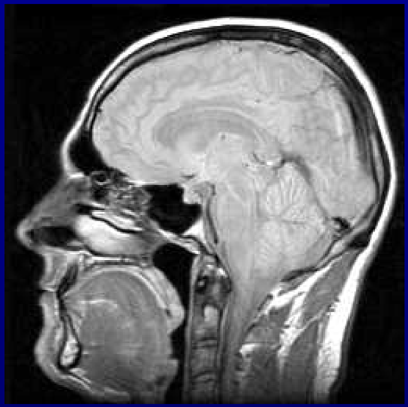
The image on the left was generated using an FSE sequence. The image on the right was generated using an EPI sequence. Magnetization transfer is more prominent in the EPI image (arrows).

The image on the left was generated using an FSE sequence. The image on the right was generated using an EPI sequence. Ferromagnetic artifacts from surgical clips are more prominent in the EPI image (arrows).



Disadvantages of EPI

- Examples of "ghosting" artifact



Uncorrupted image

Phantom with ghosting

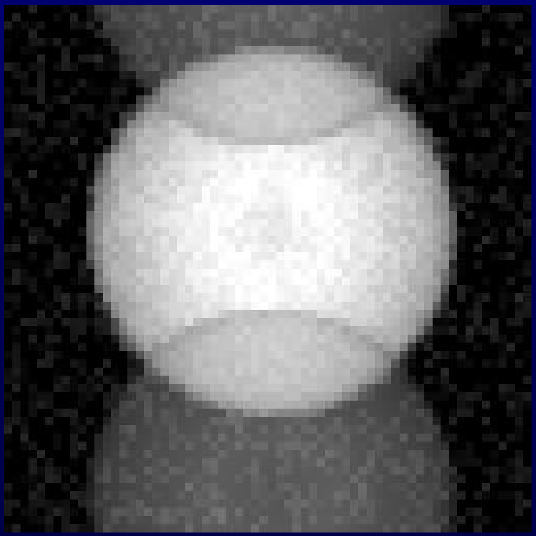


Image with ghosting

Head MRI images from www.cgl.uwaterloo.ca/~mmwasile/ presentations/epighost.ppt

Disadvantages of EPI

- Many of these artifacts can be corrected or compensated:
  - Use of gradient coils designed to minimize eddy current induction
  - Use of reference images without phase encoding as a basis for determining where time-dependent phase shifts have occurred (reduces ghosting)
  - Fat suppression techniques (reduces chemical shift)
  - T_2* mapping and multi-shot techniques can reduce blurring
  - Decreasing the ESP or ETL, and active shimming (reduces image and shape distortion)

Homework Problem #2

- An EPI scan using a trapezoidal readout gradient waveform is performed using the following parameters:
  – Receiver bandwidth (ΔV) = ±62.5 kHz
  – n_x = 128 points
  – Readout FOV = 22 cm
  – Slew rate = 120 T/m/sec
- Assume no ramp sampling was used. What is ESP_{min}? If the bandwidth is increased to ±125 kHz, what is ESP_{min}?
- Recalculate ESP_{min} for both receiver bandwidths (±62.5 kHz and ±125 kHz) using a reduced slew rate of 20 T/m/sec. Does increasing the bandwidth in this instance increase or decrease ESP_{min}? Why?
  – *Hint*: Think about the time necessary for ramping at this lower slew rate.

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