Fast Imaging

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UCLA Radiology

Class Business

- **Tuesday (3/7) from 6-9pm**
  - **6:00-7:30pm Groups**
    - **Avanto**
      - **Sara Said, Yara Azar, April Pan**
    - **Skyra**
      - **Timothy Marcum, Diana Lopez, Zhaohuan Zhang**
    - **Prisma**
      - **Daisong Zhang, Jingwen Yao, Fang-Chu Lin, Andy Vuong**
  - **7:30-9:00pm Groups**
    - **Avanto**
      - **Binru Chen, Junjie Chen, Yuhua Chen**
    - **Skyra**
      - **Jie Fu, Qihui Lyu, Cass Wong**
    - **Prisma**
      - **Nyasha Maforo, Fadil Ali, Vahid Ghodrati**

Class Business

- **HW #1**
  - 13.3±3.2 [15.75,6.5]
- **HW #2**
  - 11.7±2.6 [15, 6]
- **HW #3**
  - 13.7±1.4 [15, 9.5]
- **Class Average**
  - 38.7±6.5 [46, 22.4]

Lecture #14 - Learning Objectives

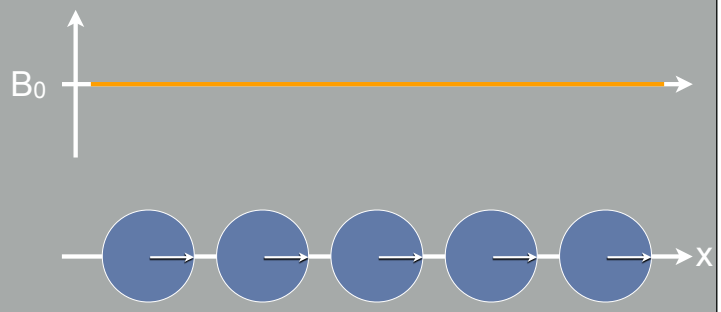
- Describe the origin and correction for several artifacts.
- Understand the impact of spatial resolution and scan time on signal-to-noise ratio.
- Explain the importance of readout bandwidth and the +/- of high (or low) readout bandwidth.
- Define the origin, artifact, and possible correction for chemical shift artifacts.
- Appreciate why motion causes image artifacts in MRI
- Be able to identify several artifacts in an MR image.

Lecture #15 - Learning Objectives

- Distinguish Type-1 and Type-2 chemical shift artifacts, their origin, and mitigation.
- Describe advantages and disadvantages of two partial fourier acquisition methods.
- Explain the advantages and disadvantages of multi-slice imaging.
- Explain the advantages and disadvantages of multi-echo imaging.
- Identify ways to improve imaging protocols.

Gradient Echoes & Fat

GRE & Fat/Water Frequency



Water Spins in a Uniform Field

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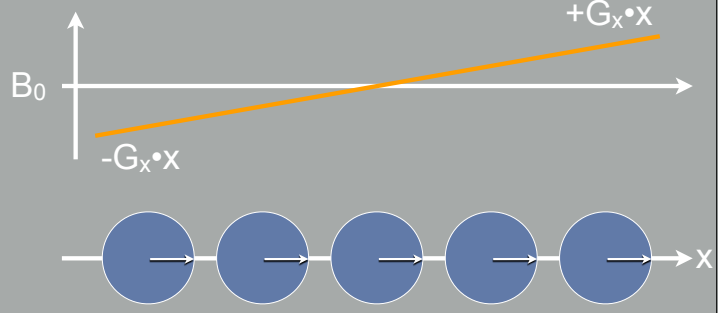
GRE & Fat/Water Frequency



Water Spins in a Gradient Field

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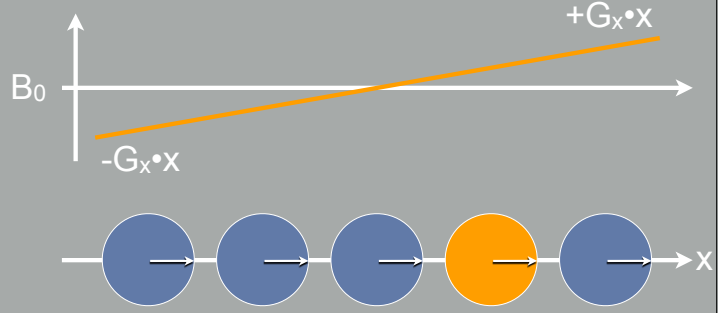
GRE & Fat/Water Frequency



Water & Fat Spins in a Gradient Field

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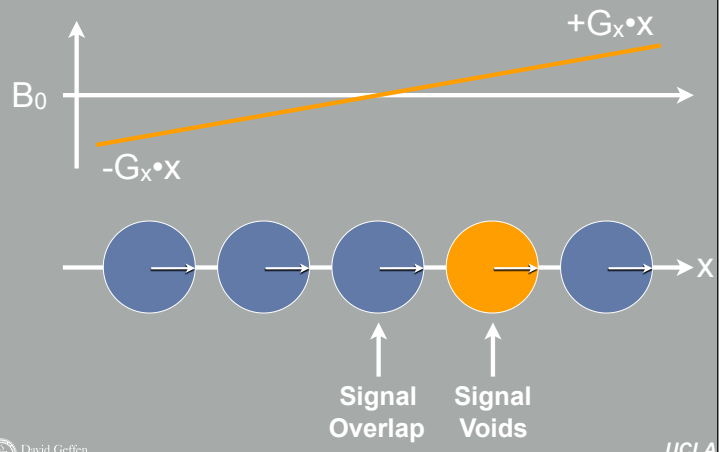
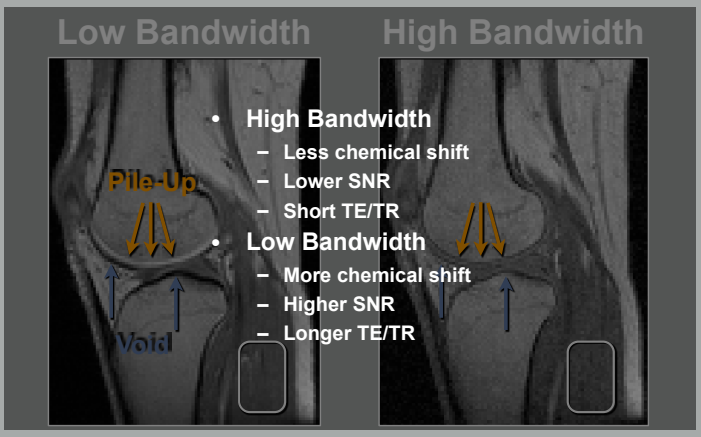
GRE & Fat/Water Frequency



GRE & Fat/Water Frequency

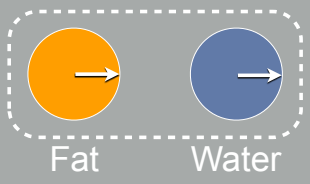


- **High Bandwidth**
  - Less chemical shift
  - Lower SNR
  - Short TE/TR
- **Low Bandwidth**
  - More chemical shift
  - Higher SNR
  - Longer TE/TR

Type-1 Chemical Shift Artifact (spatial mis-registration)

GRE and Fat/Water Phase

- Pixels are frequently a mixture of fat and water
- Pixel intensity is the vector sum of fat and water



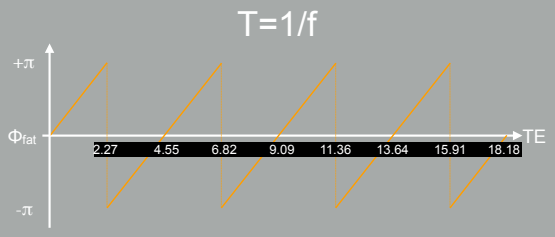
In-Phase → + → >0

Opposed-Phase ← + → =0

The TE controls the phase between fat and water.

GRE and Fat/Water Phase

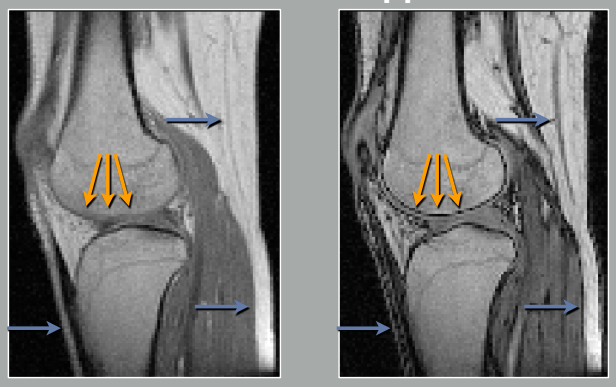
- Pixels are frequently a mixture of fat and water
- Pixel intensity is the vector sum of fat and water



The TE controls the phase between fat and water.

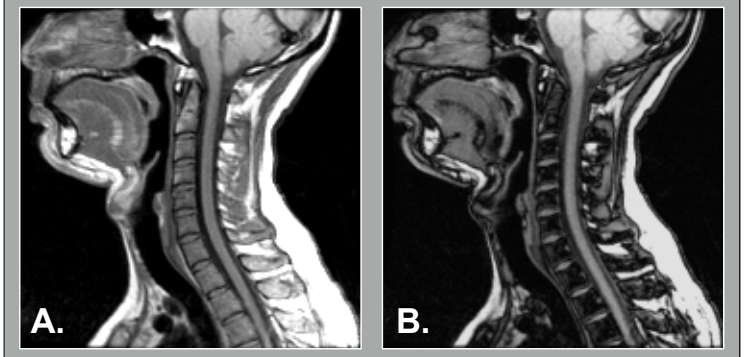
GRE and Fat/Water Phase

In-Phase **Opposed-Phase**



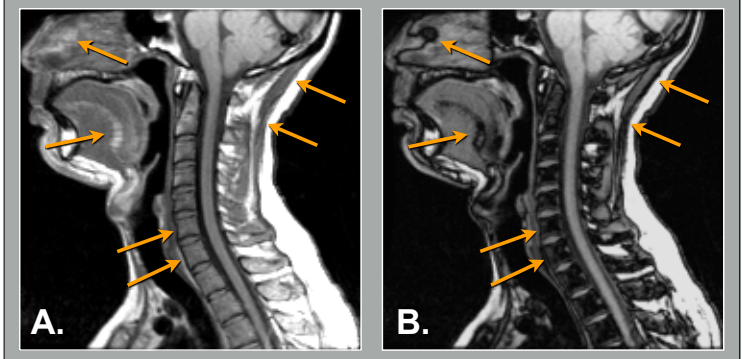
Type-2 Chemical Shift Artifact (aka India Ink artifact).

Which image is the in-phase image?



Images Courtesy of Scott Reeder

Which image is the in-phase image?



In-Phase **Opposed-Phase**

Images Courtesy of Scott Reeder

Gradient Echoes & Fat Suppression

- **Why is fat suppression/separation important?**
  - Fat is bright on most pulse sequences.
  - But so are many other things...
    - CSF & edema
    - Flowing blood
    - Contrast enhanced tissues
- **Fat obscures underlying pathology**
  - Edema, neoplasm, inflammation
- **How can fat be eliminated in GRE images?**
  - Fat saturation pulses
  - Multi-echo acquisitions
    - Dixon/IDEAL

Fat Suppression

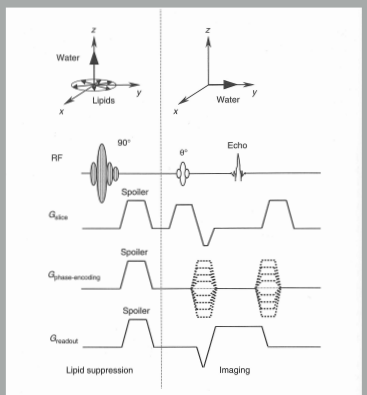
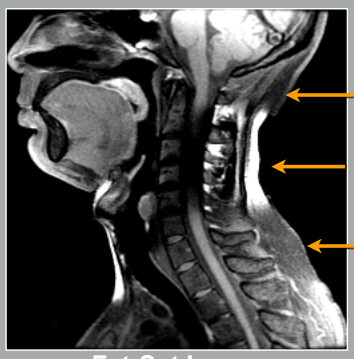


FIGURE 4.15 An example of using a spectrally selective pulse to suppress lipid signals in an imaging sequence. The 90° spectrally selective pulse (shaded area to denote the frequency offset), usually with maximal phase dispersion, is applied ~217 Hz off-resonance with respect to the water resonant frequency to excite lipids at 1.5 T. The lipid signals are dephased by one or more spoiler gradients. After lipid suppression (portion to the left of the dotted vertical line), an imaging sequence is executed to excite water signals and form a water image (portion to the right of the dotted vertical line).

Fat Suppression



Fat-Sat Can Be Spatially Non-Uniform

Fat-Sat Image

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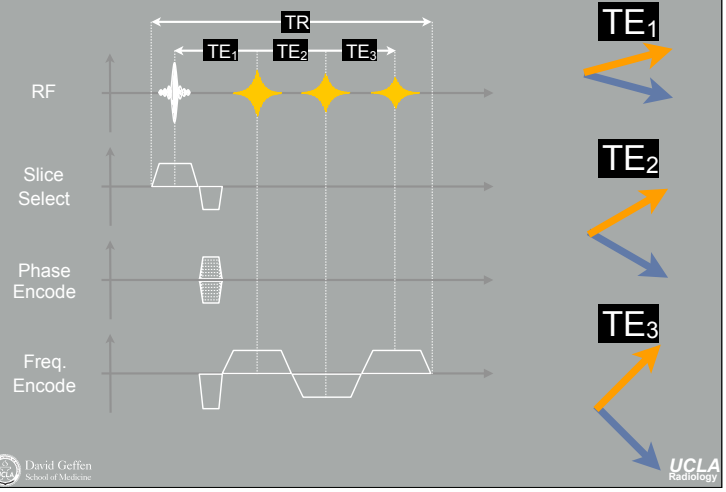
GRE & Fat/Water Separation - How?



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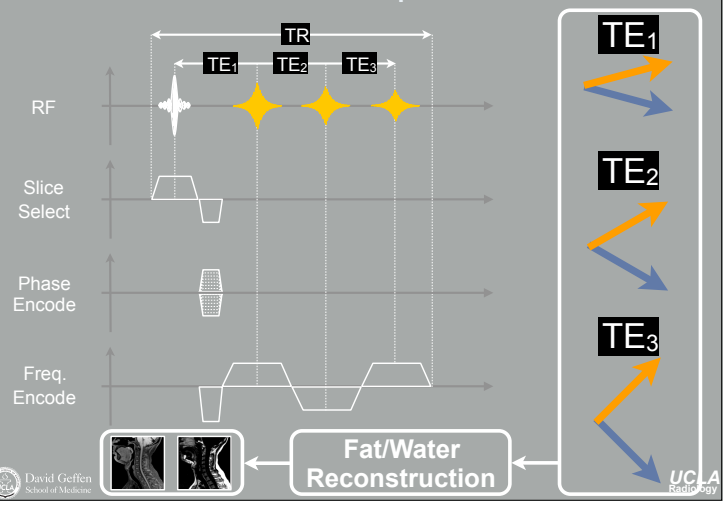
GRE & Fat/Water Separation - How?



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Gradient Echoes & Fat/Water Separation

Water Image

Fat Image

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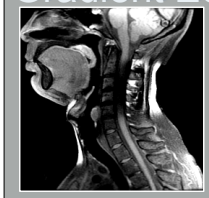
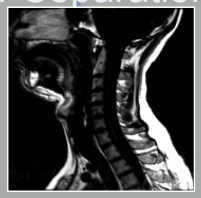
Gradient Echoes & Fat/Water Separation



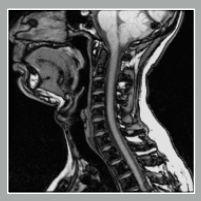
Imperfect Fat Sat

Water Image



Fat Image

In-Phase



Opposed-Phase

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Images Courtesy of Dr. Scott Reeder

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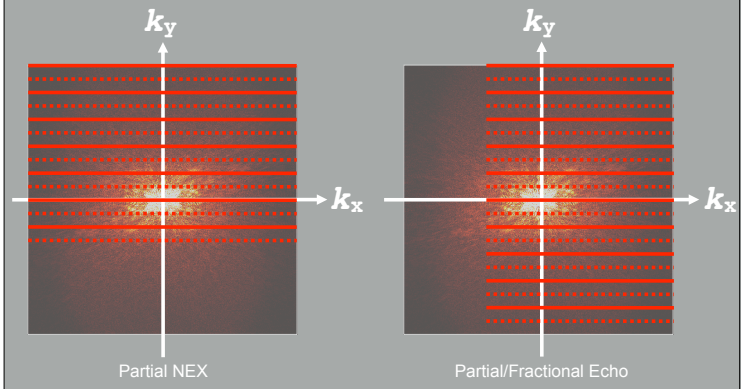
Partial Fourier Imaging

Partial Fourier Imaging



Partial NEX

Partial/Fractional Echo

How do you acquire each dataset?
What is an advantage/disadvantage to each approach?

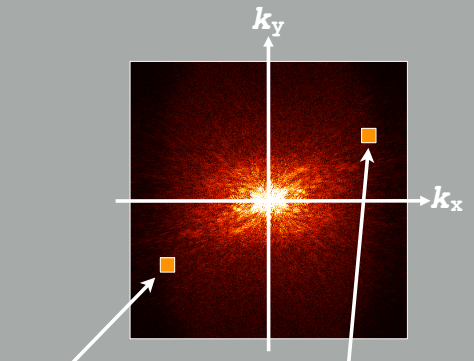
Hermitian Symmetry

- If I(x) is ***real*** valued, then its frequency representation S(k) is redundant.
- If S(k) is known for k≥0, then S(k) for k<0 can be generated according to:

$$S(-k) = S^*(k)$$

- k-space is Hermitian (conjugate) symmetric.

Hermitian Symmetry



$$S(-k_x, -k_y, -k_z) = S^*(k_x, k_y, k_z)$$

Hermitian Symmetry

$$S(k_x, k_y, k_z) = Ae^{i\phi}$$

- Every point in *k*-space has a magnitude and a phase
- The phase of the *signal* at (k_x,k_y,k_z), however, may not be the same as the phase of the signal acquired at (-k_x,-k_y,-k_z)
  - Noise
  - Motion
  - Resonance frequency offsets
  - Hardware group delays
  - Eddy currents
  - Coil phases (Receive B_1 inhomogeneity)

Partial Fourier Imaging - Advantages

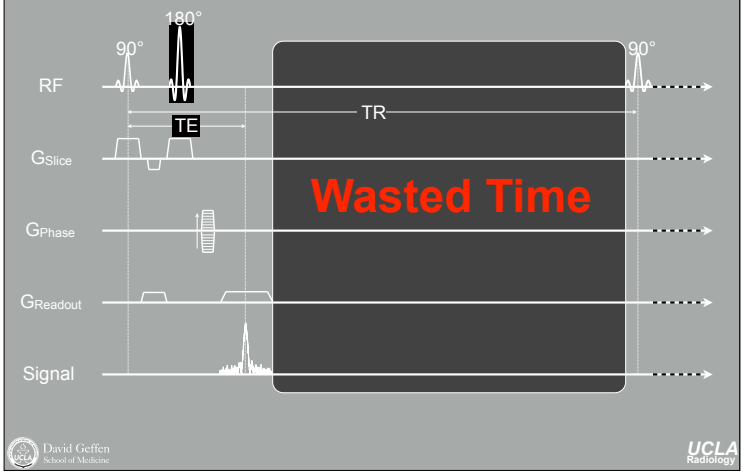
- **Readout Direction**
  - **Reduced Echo Time (TE)**
    - **Improved SNR; Less T2* decay**
  - **Reduced gradient moments**
    - **Reduced flow artifacts**
- **Phase Encode Direction**
  - **Reduced Scan Time**

Partial Fourier Imaging - Disadvantages

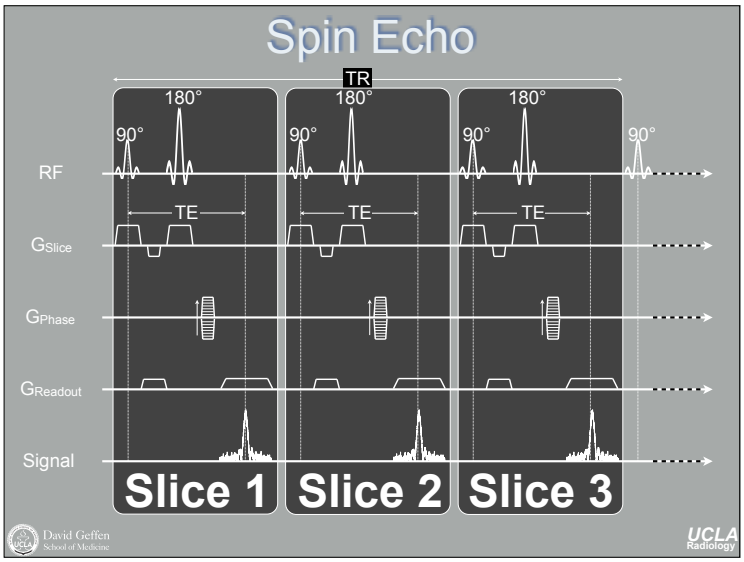
- **Lower SNR (faster scanning…)**
- **Simple reconstruction (zero-filling)**
  - **Blurring**
- **Complex reconstruction (Homodyne or POCS)**
  - **Increased recon time (trivial…)**
  - **Residual artifacts**

2D Slice Interleaving

Spin Echo

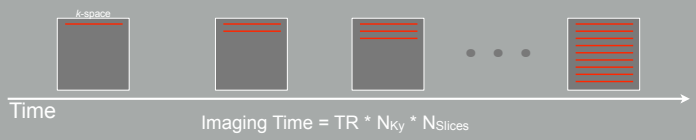


Spin Echo



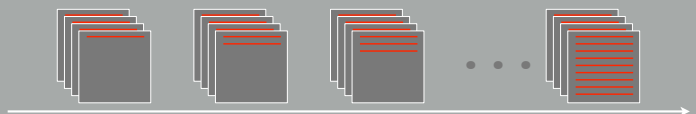
Slice Interleaving

Sequential 2D Imaging



Imaging Time = TR * N_{Ky} * N_{Slices}

Slice Interleaved 2D Imaging



Imaging Time = TR * N_{Ky} * N_{Slices} / $N_{Interleaves}$

2D Slice Interleaving

- **Advantages**
  - **Accelerate imaging by $N_{Interleaves}$**
- **Disadvantages**
  - **Acceleration limited by**
    - **$N_{Interleaves}$~TR/TE**
    - **SAR**
  - **Difficult to acquire immediately adjacent slices**
    - **Hard to get good 180° slice-profile to match 90° slice-profile for multi-slice imaging**
- **Applications**
  - **T_2 imaging**
    - **TR must be long (Why?)**
  - **DWI**
    - **TR should be long**

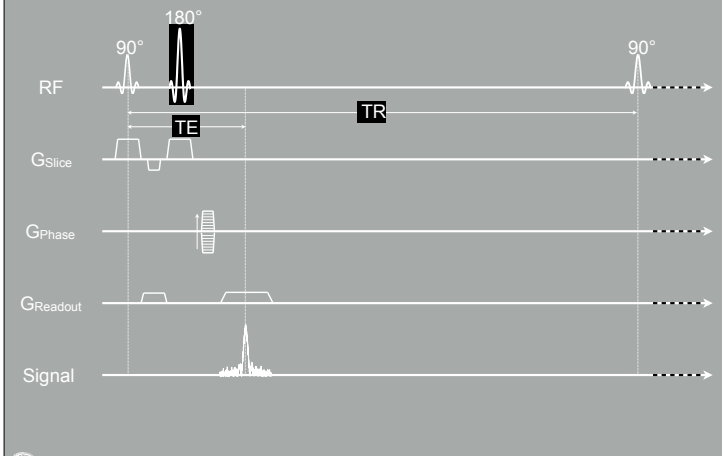
Multi-Echo Spin Echo Imaging

How do we calculate scan time?

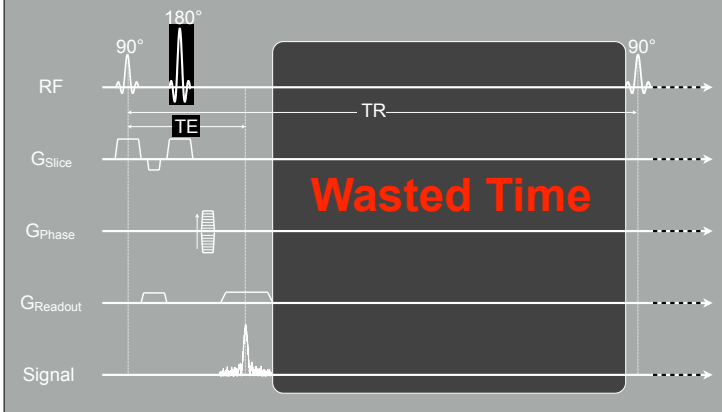
$$T_{Scan} = TR \cdot PE \cdot N_{avg}$$

- T_{Scan}=1000ms•256•1=4:16 [mm:ss]
- ***Assumes*** **one echo per TR.**

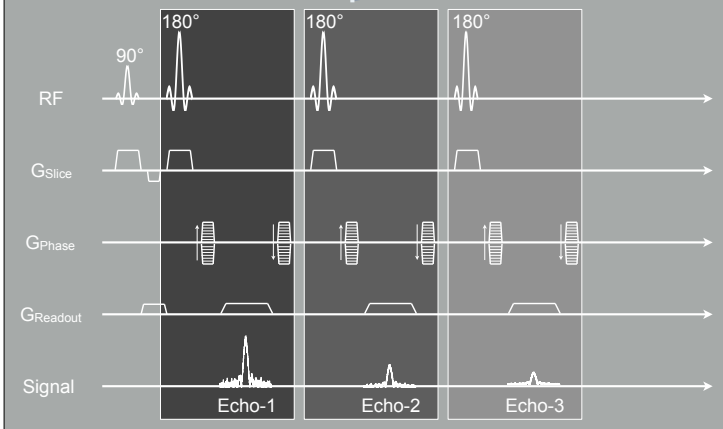
Spin Echo



Spin Echo



Fast Spin Echo



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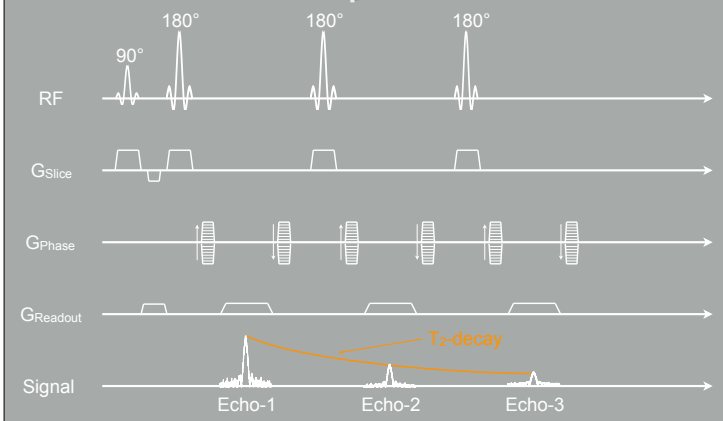
Fast Spin Echo



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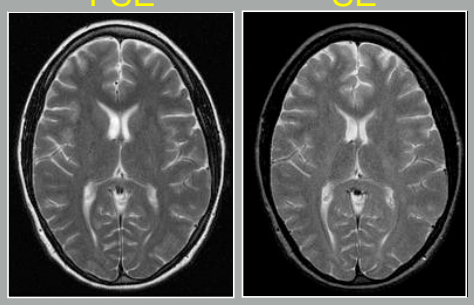
T_2 Weighting (FSE vs. SE)

FSE

SE



TR = 2500
TE = 116
ETL = 16
NEX = 2
24 slices
Time = 2:51

TR = 2500
TE = 112
ETL = N/A
NEX = 1
24 slices
Time = 22:21

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Images Courtesy of Frank Korosec

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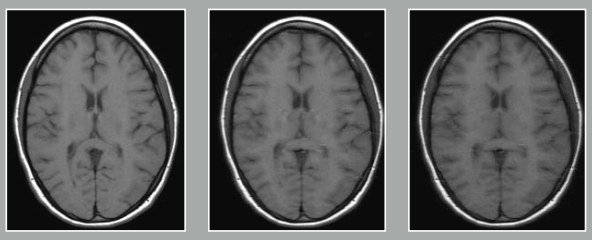
T_1 Weighting (FSE)



ETL=4 ETL=16 ETL=24

Higher ETL reduces scan time, but introduces blurring.

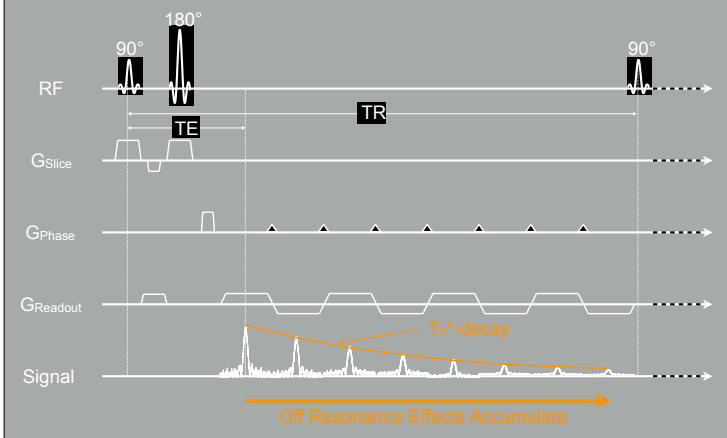
Images Courtesy of Frank Korosec

Fast Spin Echo

- **Advantages**
  - Turbo factor accelerates imaging
  - Can be used with 2D slice interleaving
  - Allows T_2 weighted imaging in a breath hold
- **Disadvantages**
  - High turbo factors (ETL>4):
    - Blur images
    - Alter image contrast
  - Fat & Water are both bright on T_2-weighted
    - Water/CSF T_2 is long (~180ms)
    - Fat T_2 is shorter (~85ms)
      - Repeated 180s reduce spin-spin interaction
      - This "lengthens" the moderate T_2 of fat
  - SAR can be high

Spin Echo EPI

Spin Echo EPI



Spin Echo EPI

- **Advantages**
  - Can acquire data in a "single shot"
  - Can be used with 2D slice interleaving
  - Allows T_2^* weighted imaging in a breath hold
- **Disadvantages**
  - Single Shot EPI
    - Ghosting
    - Blur images
    - Image distortion
    - Alter image contrast
  - Multi-shot EPI
    - Slower than single shot
      - Faster than SE
- **Applications**
  - DWI, Perfusion, fMRI

Protocol Optimization for Fast Scanning

The Infeasible Protocol

- T_1-weighted GRE (FLASH)
  - TR/TE/flip 162ms/4ms/30°
  - Matrix Size 256 (read) x 256 (phase)
  - FOV 480mm (read) x 480mm (phase)
  - Resolution 1.9mm x 1.9mm x 8mm
  - Acq. Time 43s (scanner reported)
  - rSNR 3.41
- Artifact - Breathing motion
- Advantage - Abundant SNR
- Disadvantage - Scan time too long
  - Low Resolution

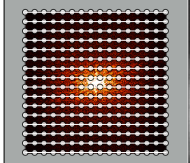
The Infeasible Protocol

Resolution: 1.9 x 1.9 x 8mm – rSNR=3.41 – Scan Time=43s

The Infeasible Protocol Cont'd

- T_1-weighted GRE (FLASH)
  - TR/TE/flip 162ms/4ms/30°
  - Matrix Size 256 (read) x 256 (phase)
  - FOV 300mm (read) x 300mm (phase)
  - Resolution 1.2mm x 1.2mm x 8mm
  - Acq. Time 43s
  - rSNR 1.33
- Artifact - Breathing motion
- Advantage - High SNR, Focused FOV
- Disadvantage - Scan time too long

The Infeasible Protocol Cont'd



$$FOV \propto \frac{1}{\Delta k}$$

Frequency Encode Direction

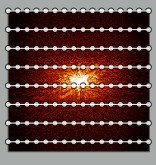
Previously...

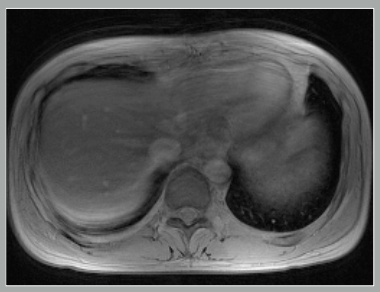
Resolution: 1.2 x 1.2 x 8mm – rSNR=1.33 – Scan Time=43s

Add Partial Phase FOV

- T_1-weighted GRE (FLASH)
  - TR/TE/flip 162ms/4ms/30°
  - Matrix Size 256 (read) x 192 (phase)
  - FOV 300mm (read) x 225mm (phase)
  - Resolution 1.2mm x 1.2mm x 8mm
  - Acq. Time 33s
  - rSNR 1.15
- Artifact - Wrap, Breathing
- Advantage - Reduced Scan Time
- Disadvantage - Reduced SNR
  - Scan time too long

Add Partial Phase FOV





Previously...

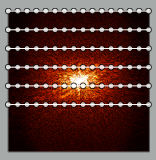
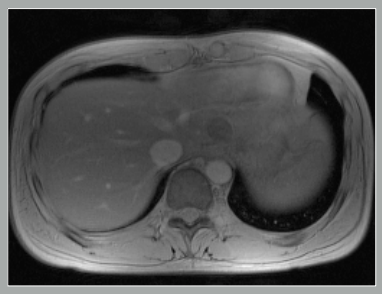
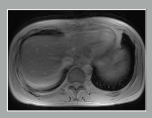
Resolution: 1.2 x 1.2 x 8mm – rSNR=1.15 – Scan Time=33s

Add 3/4 Partial Fourier

- T_1-weighted GRE (FLASH)
  - TR/TE/flip 162ms/4ms/30°
  - Matrix Size 256 (read) x 144 (phase)
  - FOV 300mm (read) x 225mm (phase)
  - Resolution 1.2mm x 1.2mm x 8mm
  - Acq. Time 23s
  - rSNR 1.00
- Artifact - Subtle blurring
- Advantage - Breath hold-able
- Disadvantage - Decreased SNR

Protocol adapted from: Herborn CU, Vogt F, Lauenstein TC, Goyen M, Debatin JF, Ruehm SG. MRI of the liver: can True FISP replace HASTE? J Magn Reson Imaging. 2003;17(2):190-196.

Add Partial Fourier

Previously...

Resolution: 1.2 x 1.2 x 8mm – rSNR=1.0 – Scan Time=23s

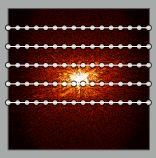
Now what? Still 23-seconds!

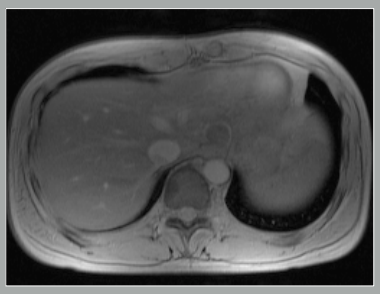
- Can't decrease FOV more.
- Can't increase partial Fourier fraction.
- Could decrease TR
  - Lower SNR
  - Altered T_1 contrast
- Could increase bandwidth
  - This shortens the TE/TR slightly
  - Decreases SNR significantly
- Could decrease spatial resolution.
  - Blurs the images

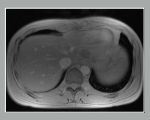
Asymmetric Voxels

- T_1-weighted GRE (FLASH)
  - TR/TE/flip 162ms/4ms/30°
  - Matrix Size 256 (read) x 108 (phase)
  - FOV 300mm (read) x 225mm (phase)
  - Resolution 1.2mm x 1.6mm x 8mm
  - Acq. Time 19s
  - rSNR 1.33
- Artifact - Partial voluming
- Advantage - Decreased scan time
- Disadvantage - Low spatial resolution

Asymmetric Voxels







Previously...

Resolution: 1.2 x 1.6 x 8mm – rSNR=1.33 – Scan Time=19s

More Asymmetric Voxels

- T_1-weighted GRE (FLASH)
  - TR/TE/flip 162ms/4ms/30°
  - Matrix Size 256 (read) x 72 (phase)
  - FOV 300mm (read) x 225mm (phase)
  - Resolution 1.2mm x 2.3mm x 8mm
  - Acq. Time 12s
  - rSNR 1.33
- Artifact - Partial voluming & blurring
- Advantage - Decrease scan time
  - Ample SNR
- Disadvantage - Very low spatial resolution

More Asymmetric Voxels

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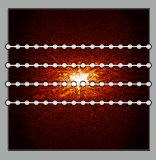

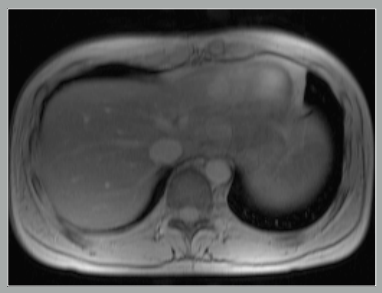

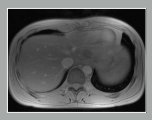

Previously...

Resolution: 1.2 x 2.3 x 8mm – rSNR=2.00 – Scan Time=12s

More Asymmetric Voxels

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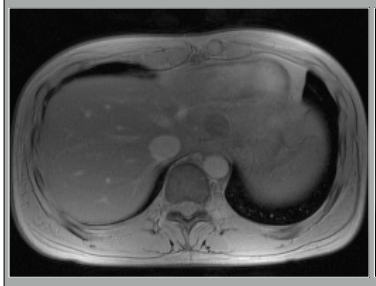
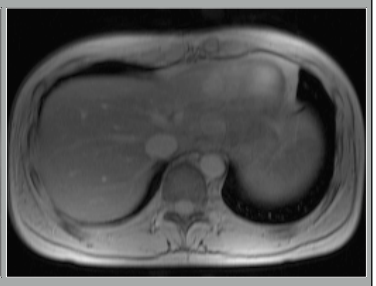
Isotropic Resolution



Resolution: 1.2 x 1.2 x 8mm
rSNR=1.0 – Scan Time=23s

Anisotropic Resolution



Resolution: 1.2 x 2.3 x 8mm
rSNR=2.00 – Scan Time=12s

Comparison

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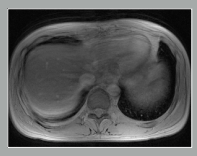
Infeasible

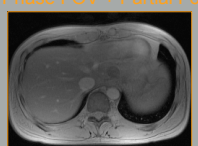
Resolution: 1.2 x 1.2 x 8mm
rSNR=3.41 ; Scan Time=43s

Partial Fourier



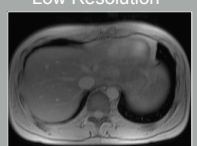
Resolution: 1.2 x 1.2 x 8mm
rSNR=1.15 ; Scan Time=33s

Partial Phase FOV + Partial Fourier



Resolution: 1.2 x 1.2 x 8mm
rSNR=1.0 ; Scan Time=23s

Low Resolution



Resolution: 1.2 x 2.3 x 8mm
rSNR=2.00 ; Scan Time=12s

Conclusion

- Minimum *k*-space acquisition only...
  - Decreases scan time from 42s to 21s
  - Decreases rSNR by 3.41x
    - BUT this is still sufficient...
  - Additional changes may compromise
    - Image contrast
    - Spatial Resolution
    - Signal-to-noise
- These approaches still benefit from multi-echo and/or multi-slice acquisitions.

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Thanks

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