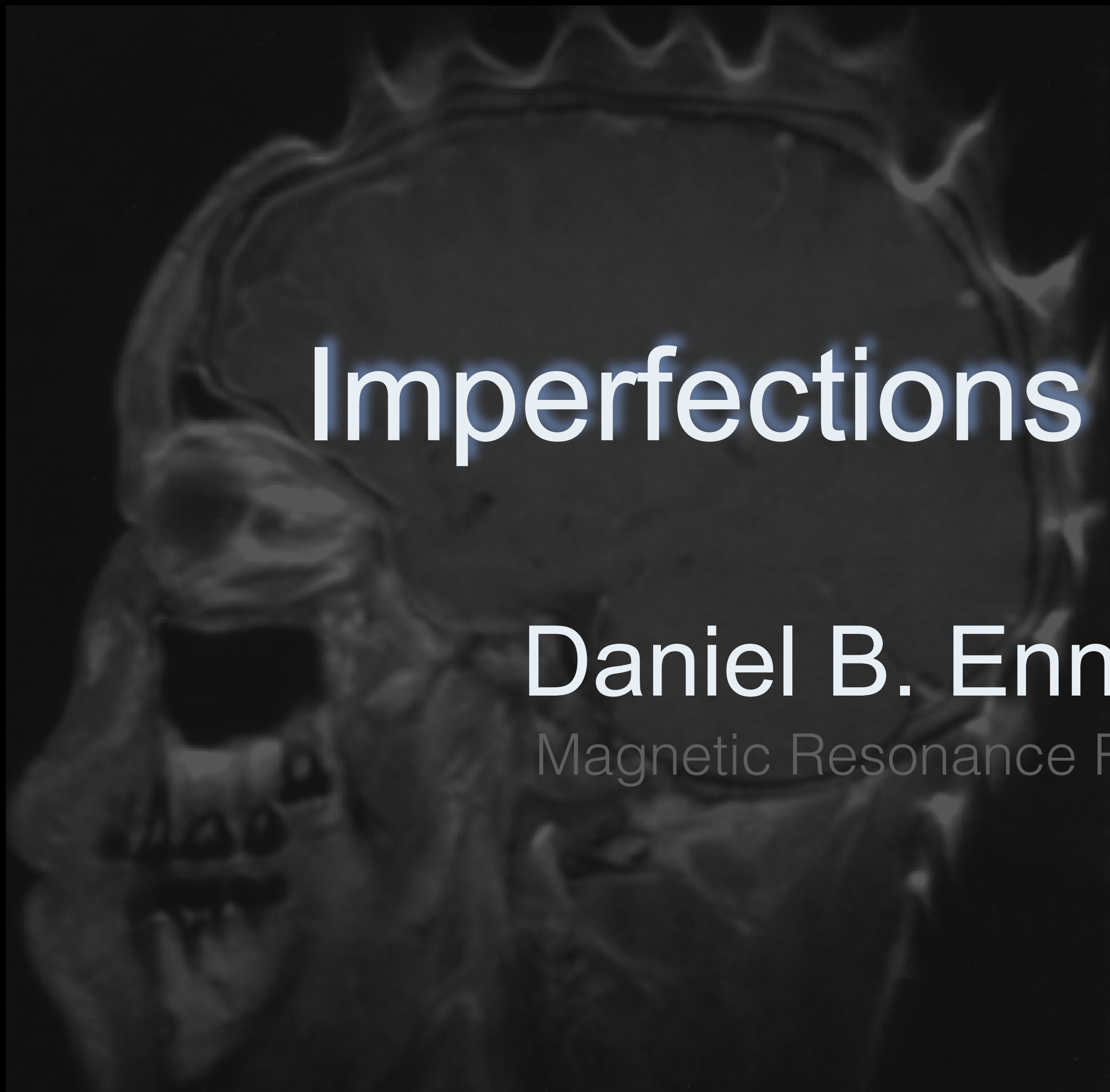


Imperfections & Artifacts

Daniel B. Ennis, Ph.D.

Magnetic Resonance Research Labs

http://www.ajronline.org/doi/pdf/10.2214/ajr.182.2.1820532

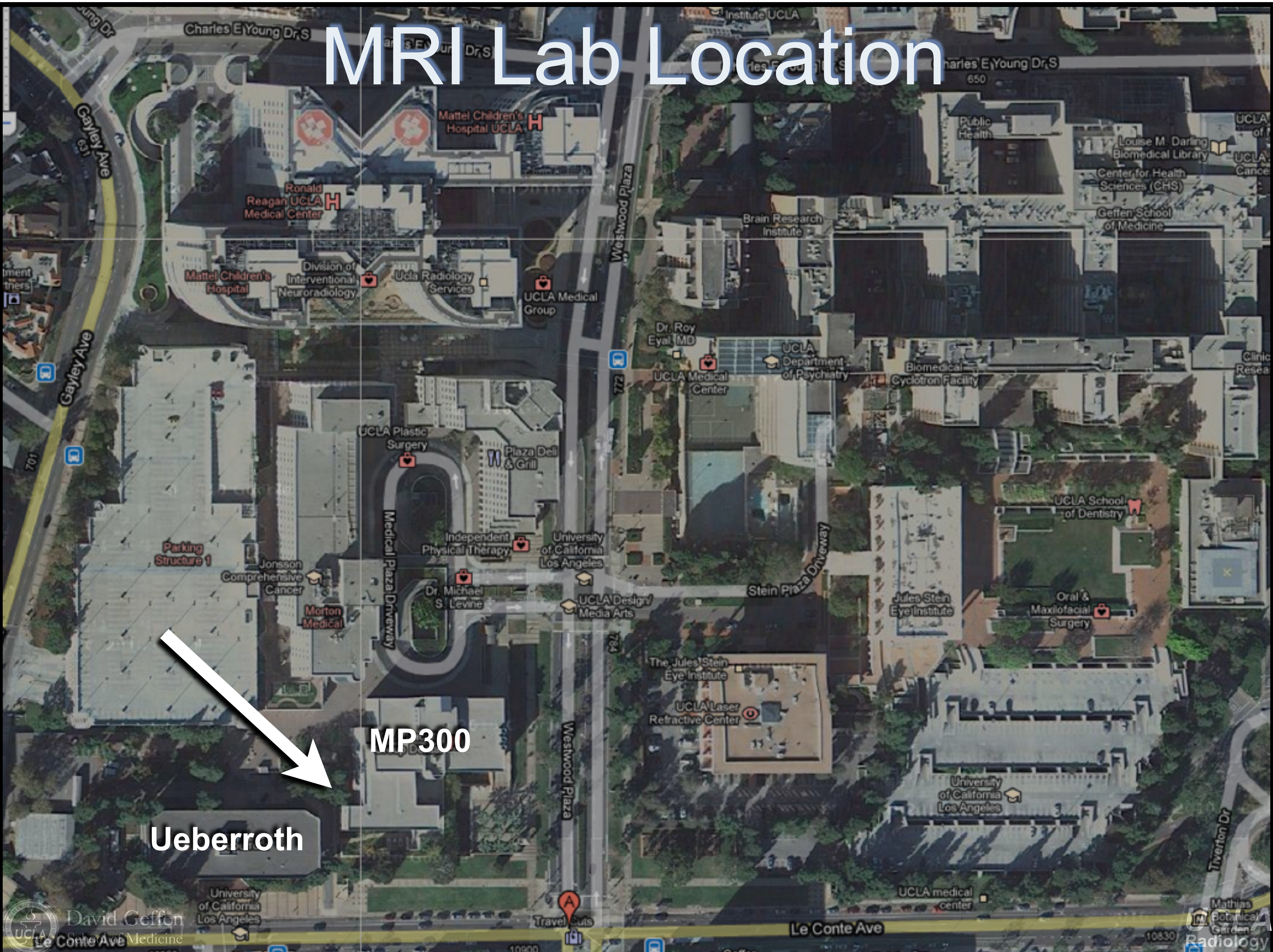
David Geffen School of Medicine

UCLA Radiology

Class Business

- Thursday (2/23) from 6-9pm
  - 6:00-7:30pm Groups
    - Avanto
      - Binru Chen, Junjie Chen, Yuhua Chen
    - Skyra
      - Jie Fu, Qihui Lyu, Cass Wong
    - Prisma
      - Nyasha Maforo, Fadil Ali, Vahid Ghodrati
  - 7:30-9:00pm 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
- **BRING THE COMPLETED SCREENING FORM**
- Re-grade opportunity.

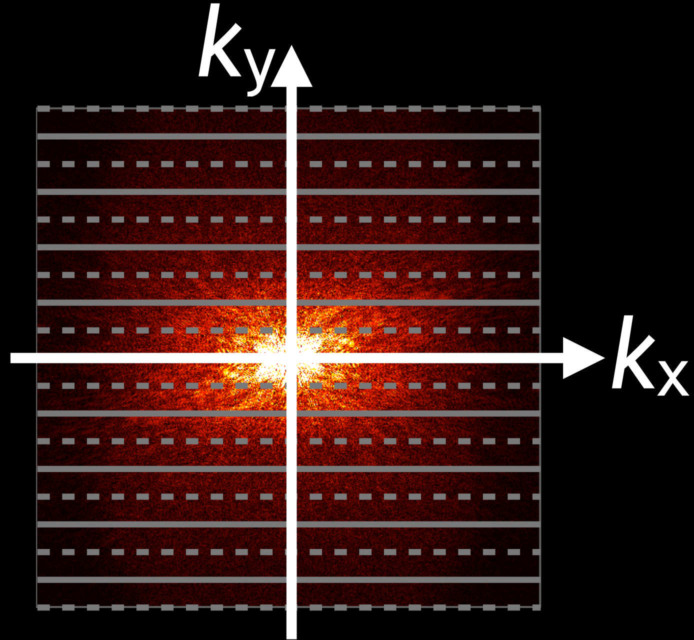
MRI Lab Location



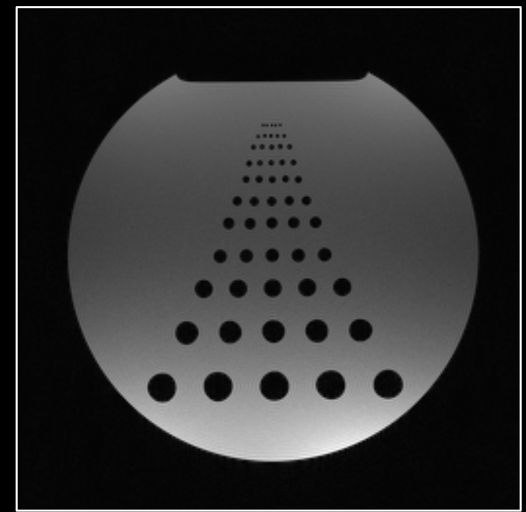
Lecture #13 - Learning Objectives

- Understand how to combine data from several receiver channels.
- Appreciate how the final image is obtained from the sum over all sampled spatial frequency (Fourier) patterns.
- Define how the field-of-view and the number of acquired data points impacts spatial resolution.
- Describe the parameters that control the field of view.
- Understand the applications of zero padding and windowed reconstructions.
- Identify sources of Gibb's ringing.

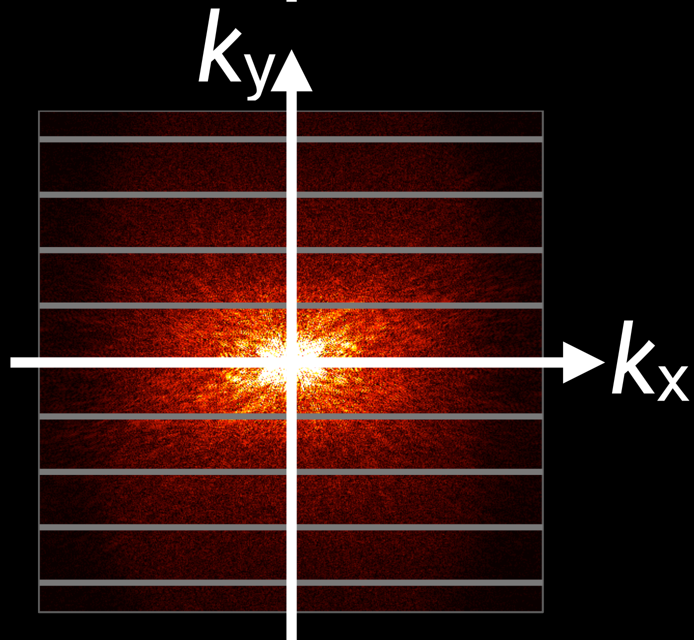
Lecture #13 Summary



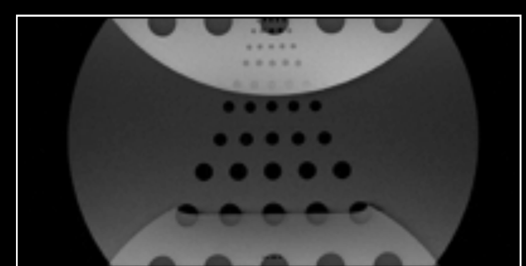
FFT



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



FFT



Uniformly skipping lines in *k*-space causes ***aliasing***.

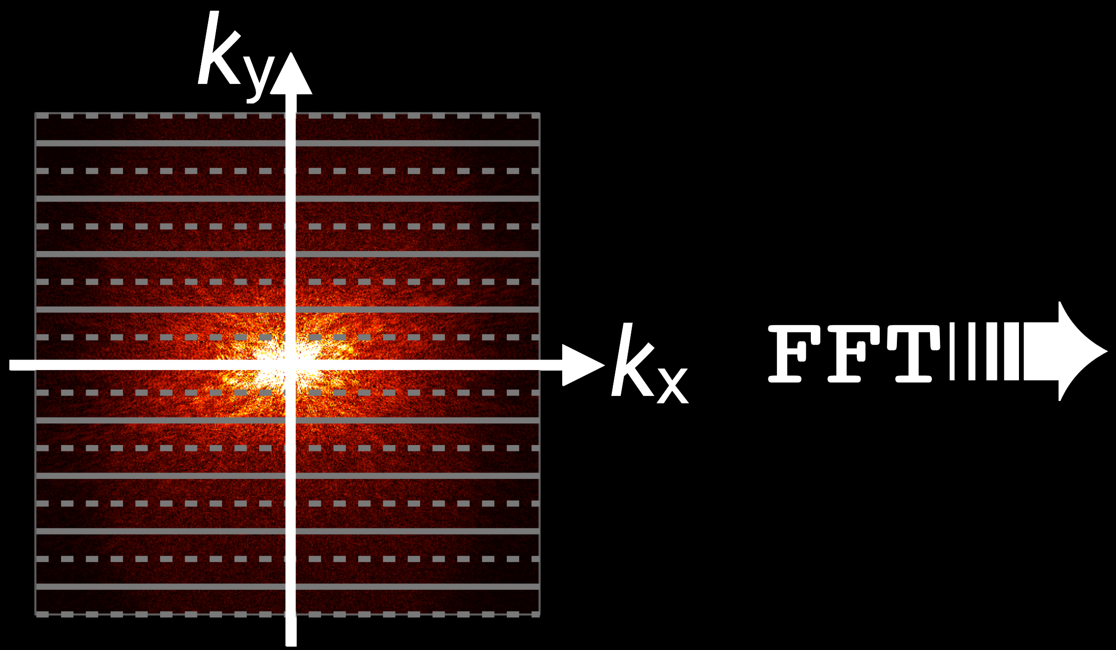
Lecture #13 Summary

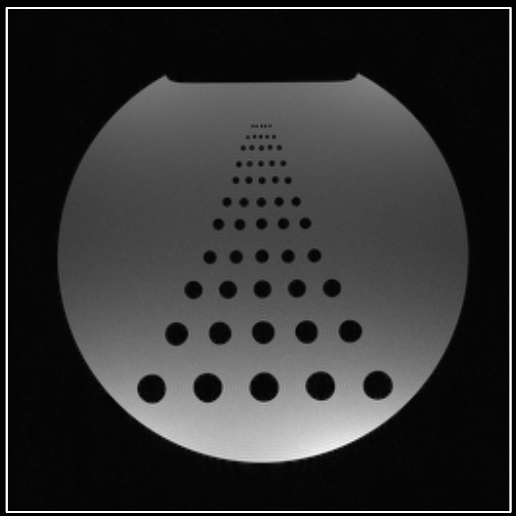
$$W_h = \frac{1}{N\Delta k} = \frac{FOV}{N}$$

Fourier Pixel Size

$$W_h \geq \frac{1}{N\Delta k}$$

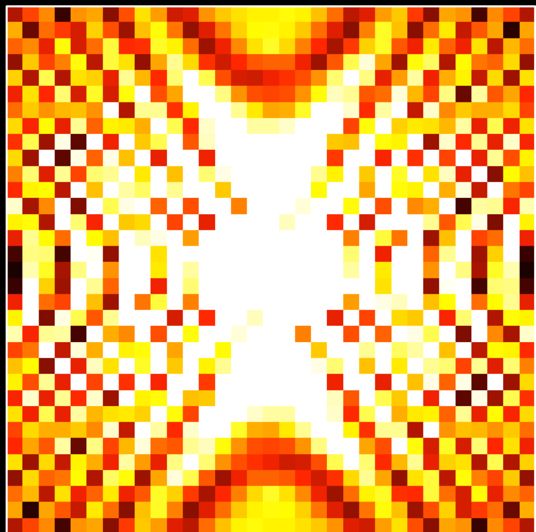
Fourier Pixel Size for Windowed Reconstructions



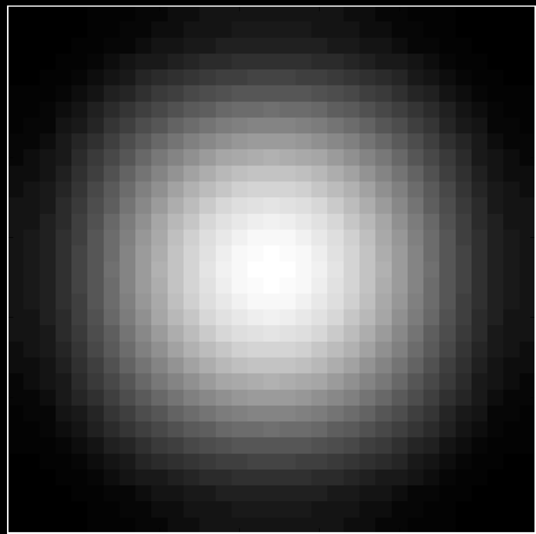


Acquiring fewer high phase encodes decreases resolution.

Lecture #13 Summary



Dot Multiply



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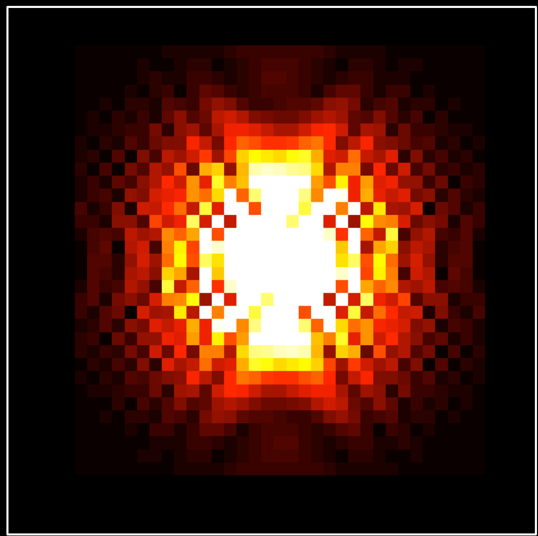


FFT

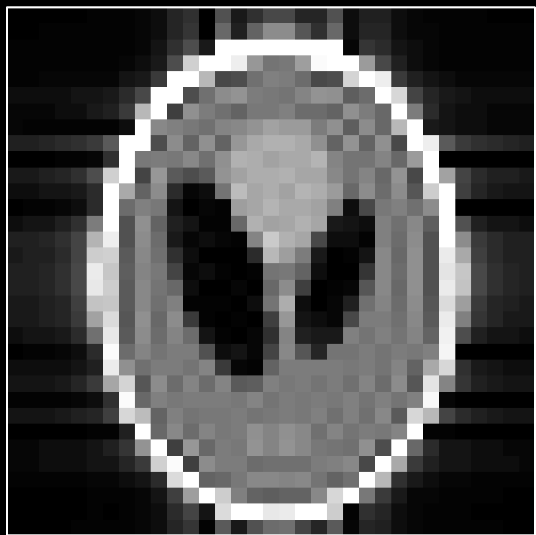
FFT

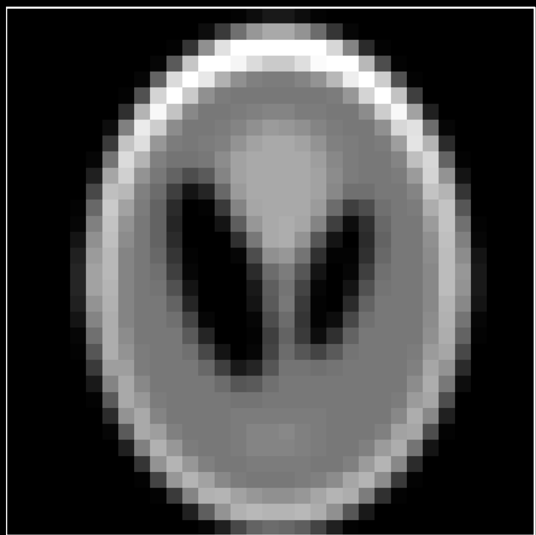
$$\hat{I}(x) = \Delta k \sum_{n=-N/2}^{N/2-1} S\left(n\Delta k\right) w_n e^{i2\pi n \Delta k x}$$

- $S(n\Delta k)$: Series Coefficient
- Δk: Fourier Step-size
- w_n: Window Weight
- $e^{i2\pi n \Delta k x}$: Spatial Frequency Encoding

On…

$$|x| < \frac{1}{\Delta k}$$





Fourier Reconstruction Formula (Eqn. 6.20)

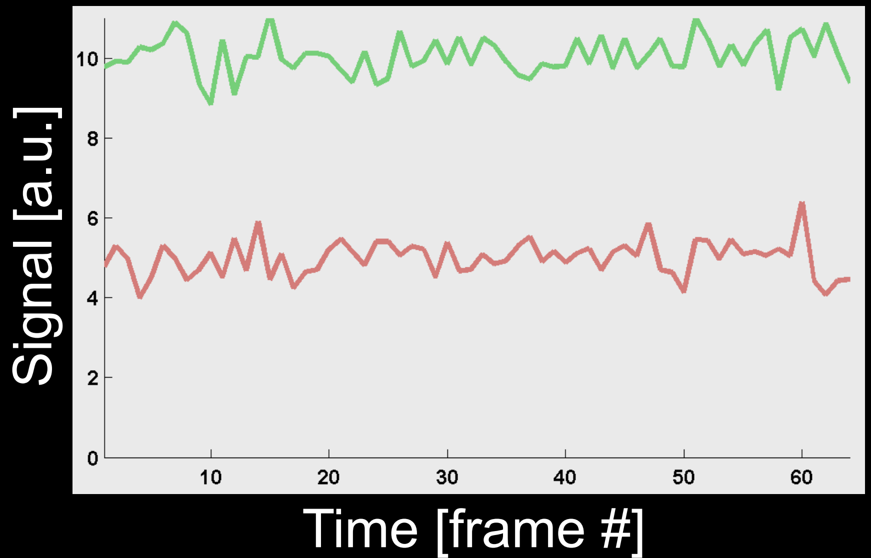
Artifacts

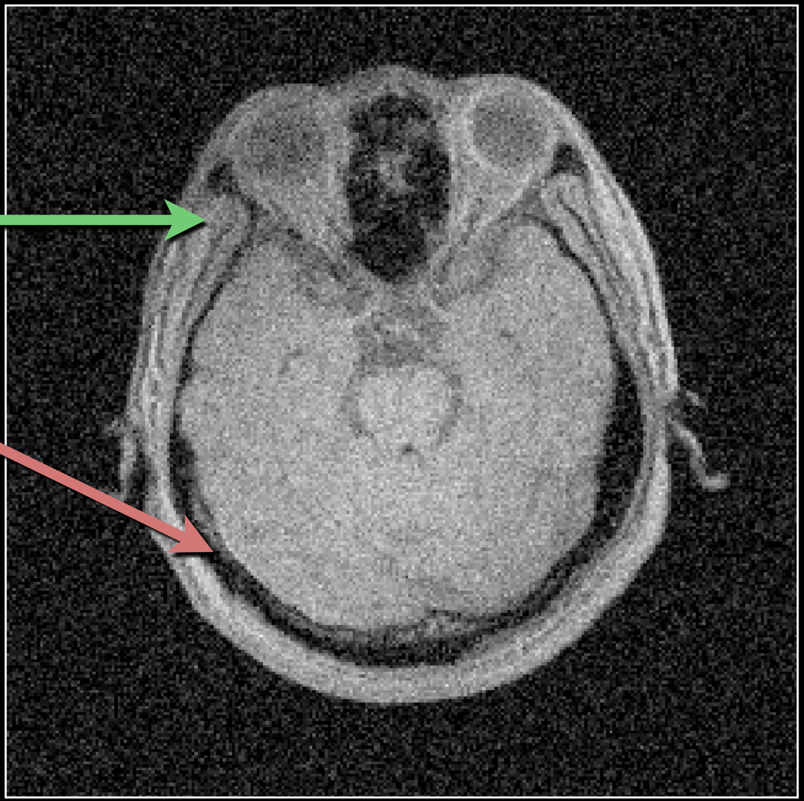
Artifacts

- Aliasing
- Gibb's Ringing
- Noisy spike artifacts
- Noise
- Chemical shift
- Motion Artifacts
- Metal artifacts
- Gradient Non-linearity
- Data clipping
- RF interference
- And more…

Noise

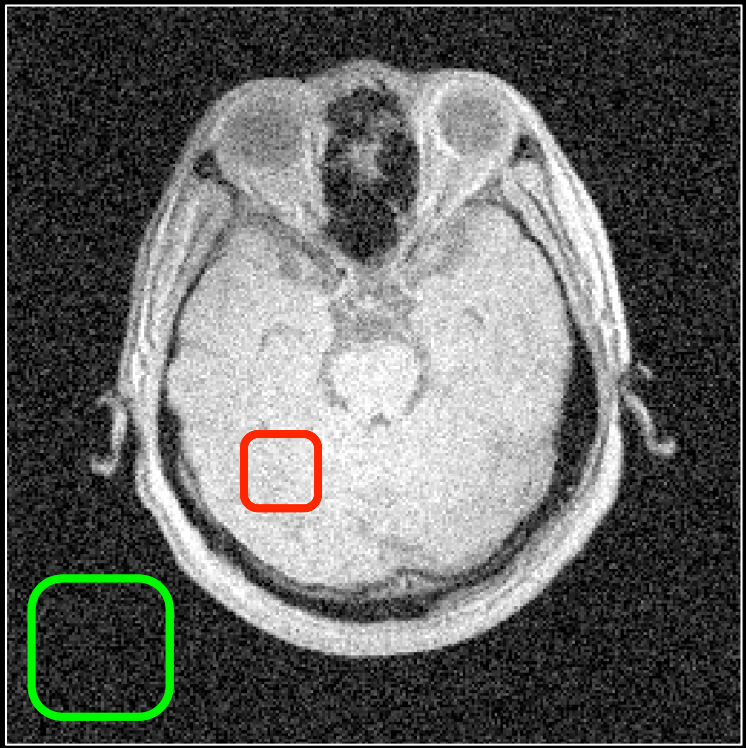
Signal-to-Noise Ratio





Signal-to-Noise Ratio

- **SNR – Signal-to-noise ratio**
  - **Signal – Mean signal intensity in ROI. Assumes:**
    - 1) Tissue homogeneity
    - 2) Noise is only source of variance
  - **Noise – SD of background ROI outside object. Assumes:**
    - 1) Noise is only source of variance



This method of measuring the SNR is widespread, but imperfect.

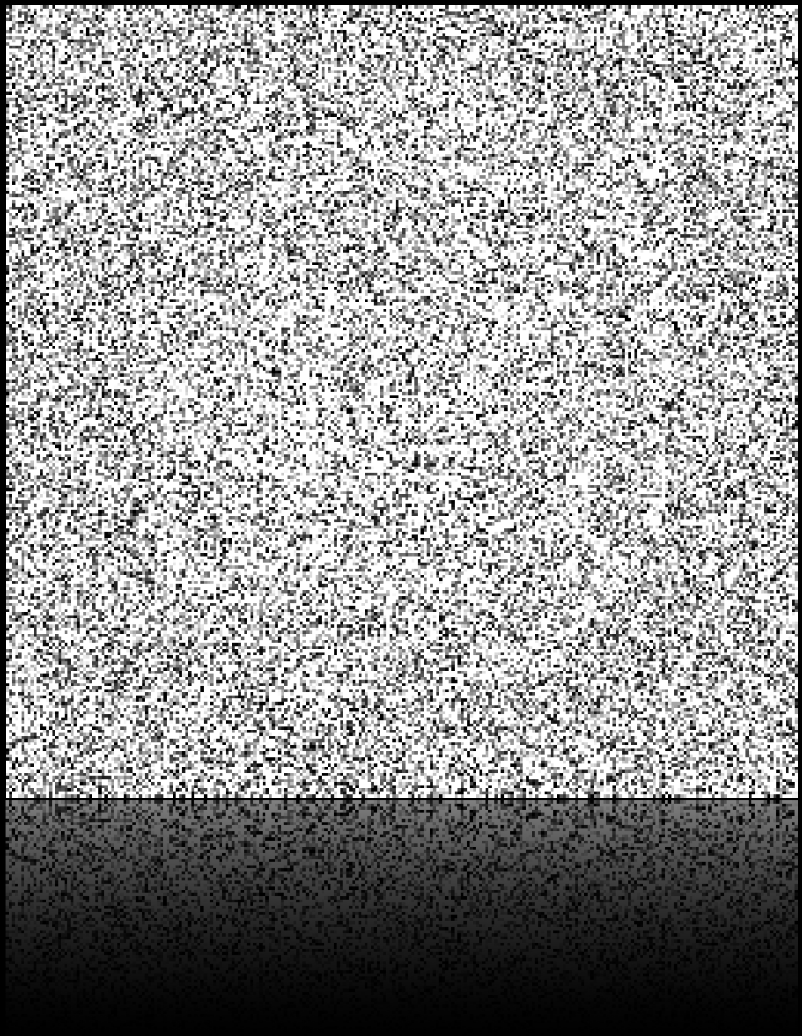
Signal-to-Noise Ratio

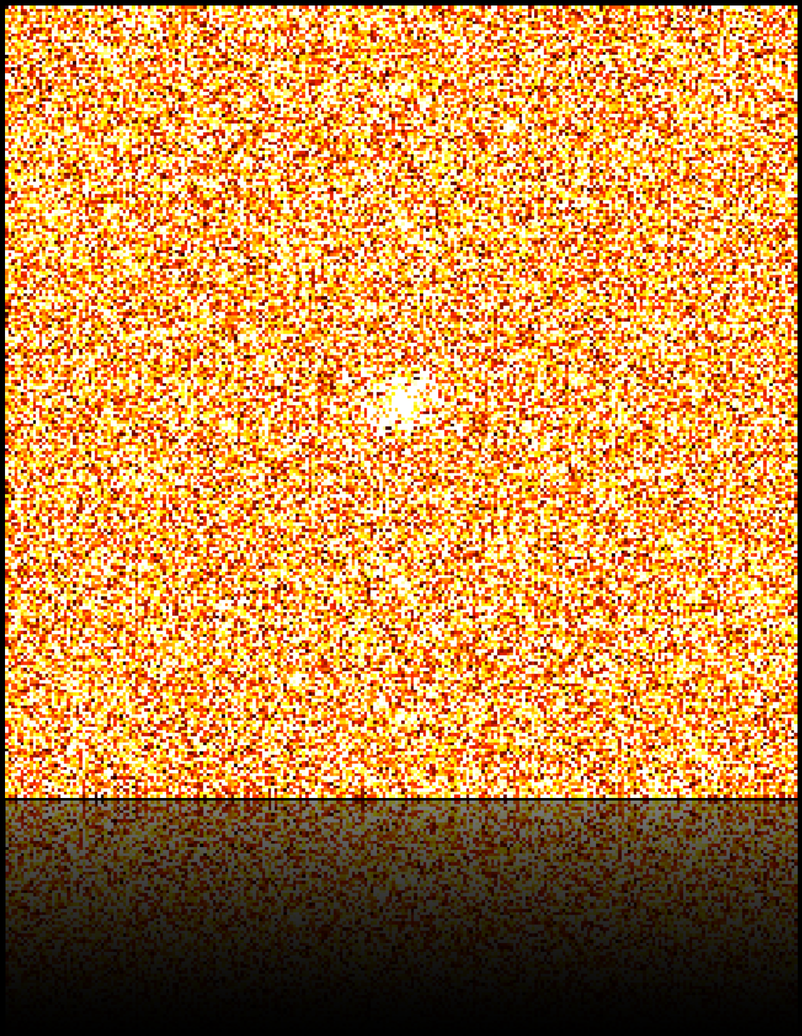
$$SNR \triangleq \frac{\text{signal amplitude}}{\text{standard deviation of noise}}$$

- **SNR – Signal-to-noise ratio**
  - **Signal – Mean signal intensity in ROI**
  - **Noise – Standard deviation of noise**
- **CNR - Contrast-to-noise ratio**
  - **Signal Difference**
    - **Difference between mean signal intensity in two ROIs**
  - **Noise - Standard deviation of noise**

$$CNR \triangleq \frac{\text{signal difference}}{\text{standard deviation of noise}}$$

What is the FT of noise? Noise.





To The Board…

Signal-to-noise Ratio

$$SNR \propto V\sqrt{t}$$

Large Voxels (Low Resolution)⇔High SNR

Long Scan Time⇔High SNR

High Resolution + Fast Imaging Severely Compromises SNR

Signal-to-noise Ratio

$$SNR \propto V\sqrt{t}$$

- **V – Voxel Volume**
  - **Slice-thickness (h) x X-res x Y-res**
    - **X-res = FOV_x/N_{kx}**
    - **Y-res = FOV_y/N_{ky}**
- **t – Data acquisition time**
  - **$(N_{kx} \times N_{ky} \times N_{averages})$/bandwidth**

$$SNR \propto \frac{FOV_x}{N_{k_x}} \frac{FOV_y}{N_{k_y}} h \sqrt{\frac{N_{k_x} N_{k_y} N_{avg}}{BW}}$$

Signal-to-noise Ratio

$$SNR \propto V\sqrt{t}$$

- **Example #1**
  - Halving slice thickness requires 4x averages to maintain SNR
- **Example #2**
  - Doubling slice thickness requires 25% time to maintain SNR
- **Example #3**
  - FOV is, in general, fixed.
  - To increase resolution we increase N_{kx} or N_{ky}.
  - This results in increased scan time, but
  - The SNR decreases.

$$SNR \propto \frac{FOV_x}{N_{k_x}} \frac{FOV_y}{N_{k_y}} h \sqrt{\frac{N_{k_x} N_{k_y} N_{avg}}{BW}}$$

Parallel Imaging and SNR

$$SNR_{P.I.} = \frac{SNR}{g\sqrt{R}}$$

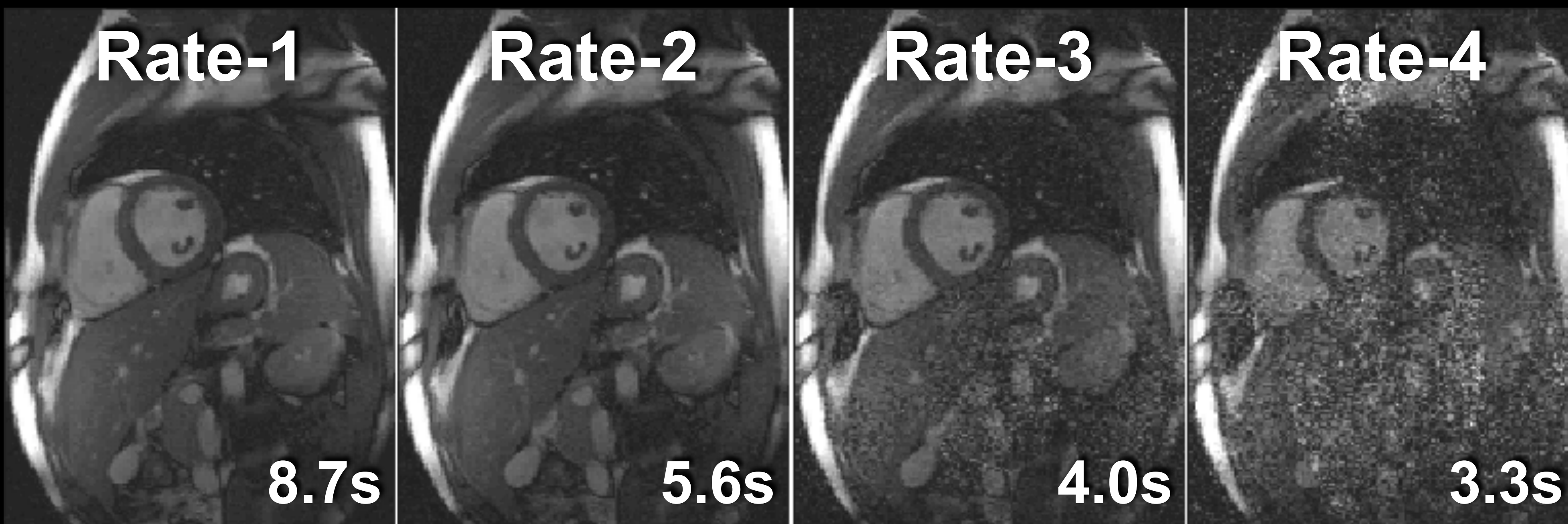
- **g - geometry factor**
  - **Loss associated with coil noise-correlation**
  - **For R=1, g=1**
  - **For R=2, g=~1.1-1.5**
- **R - reduction or acceleration factor**
  - **Loss associated with scan time reduction**
  - **Typically ~1/2 N-coils**
- **SNR for P.I. is spatially dependent**
  - **Higher in areas of aliasing**

Parallel imaging has additional SNR penalties, but decreases scan time.

Impact of Acceleration

High SNR
“Long” Acq.

Low SNR
Short Acq.



P. Kellman (NIH)

High acceleration rates lead to local noise amplification.

Readout Bandwidth

Receiver Bandwidth

- **Receiver Bandwidth (RBW, Δf)**
  - The range of frequencies across the FOV
    - ±kHz [range across FOV]
  - Alternately range of frequencies per pixel
    - Pixel bandwidth [Hz/pixel]
  - …during ***readout***.

$$\Delta f = \frac{1}{2}\frac{\gamma}{2\pi}G_x \cdot FOV_x$$

User can pick 2 of 3 (Δf, G_x, FOV_x)

Temporal Nyquist Sampling Requires: $\Delta t = \frac{1}{2\Delta f}$

k-space Nyquist Sampling Requires: $\Delta k_x = \frac{\gamma}{2\pi}G_x \Delta t$

$$\Delta k_x = \frac{1}{FOV_x}$$

$$N_x \cdot \Delta k_x = \frac{N_x}{FOV_x} = \frac{1}{\Delta x}$$

Receiver Bandwidth

- **High Receiver Bandwidth (RBW, Δf)**
  - Stronger gradients
  - Larger range of frequencies across the FOV (or pixel)
  - Less chemical shift (smaller freq. difference per pixel)
  - Lower SNR (shorter acquisition time)
  - Shorter TE (move across *k*-space faster)

$$\Delta f = \frac{1}{2}\frac{\gamma}{2\pi}G_x \cdot FOV_x$$

User can pick 2 of 3 (Δf, G_x, FOV_x)

Temporal Nyquist Sampling Requires: $\Delta t = \frac{1}{2\Delta f}$

k-space Nyquist Sampling Requires: $\Delta k_x = \frac{\gamma}{2\pi}G_x\Delta t$

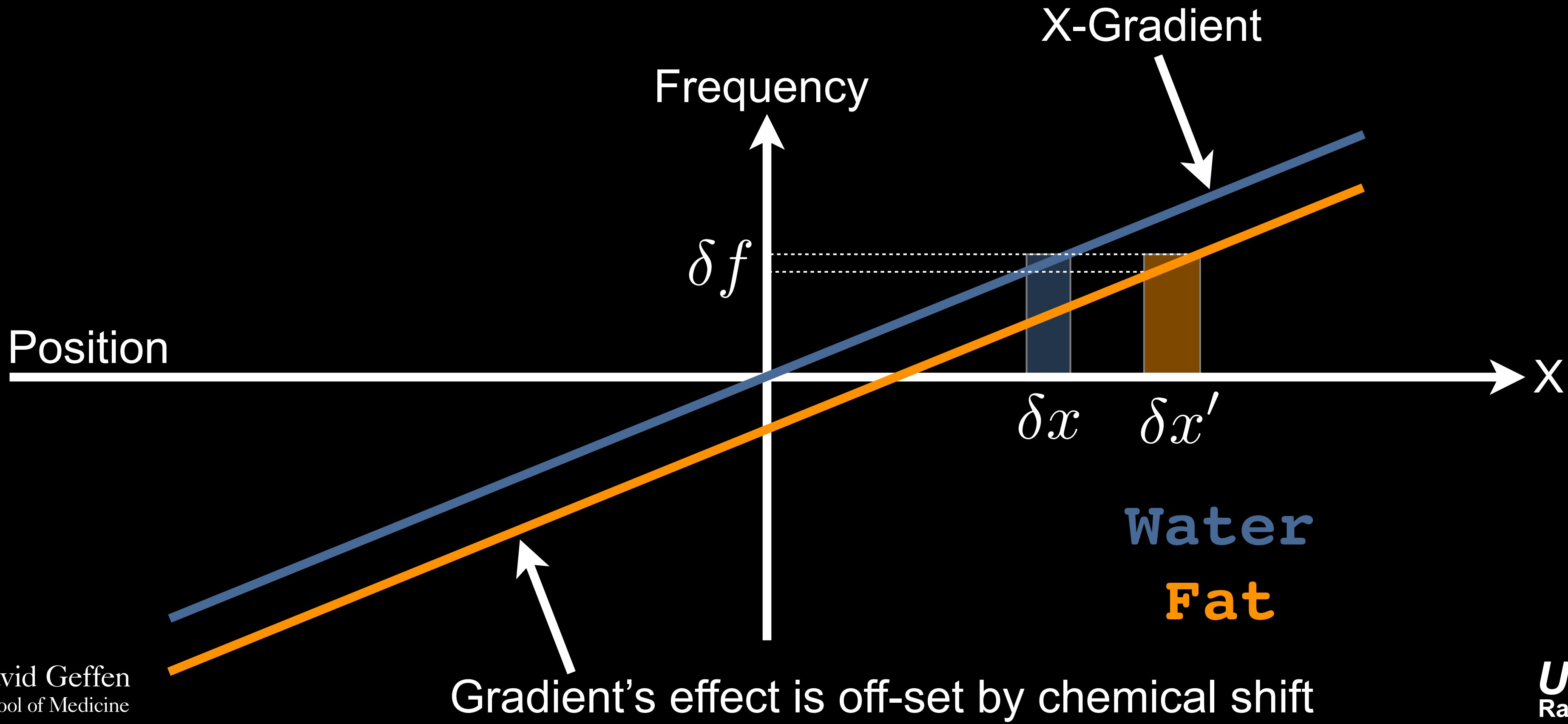
$$\Delta k_x = \frac{1}{FOV_x}$$

$$N_x \cdot \Delta k_x = \frac{N_x}{FOV_x} = \frac{1}{\Delta x}$$

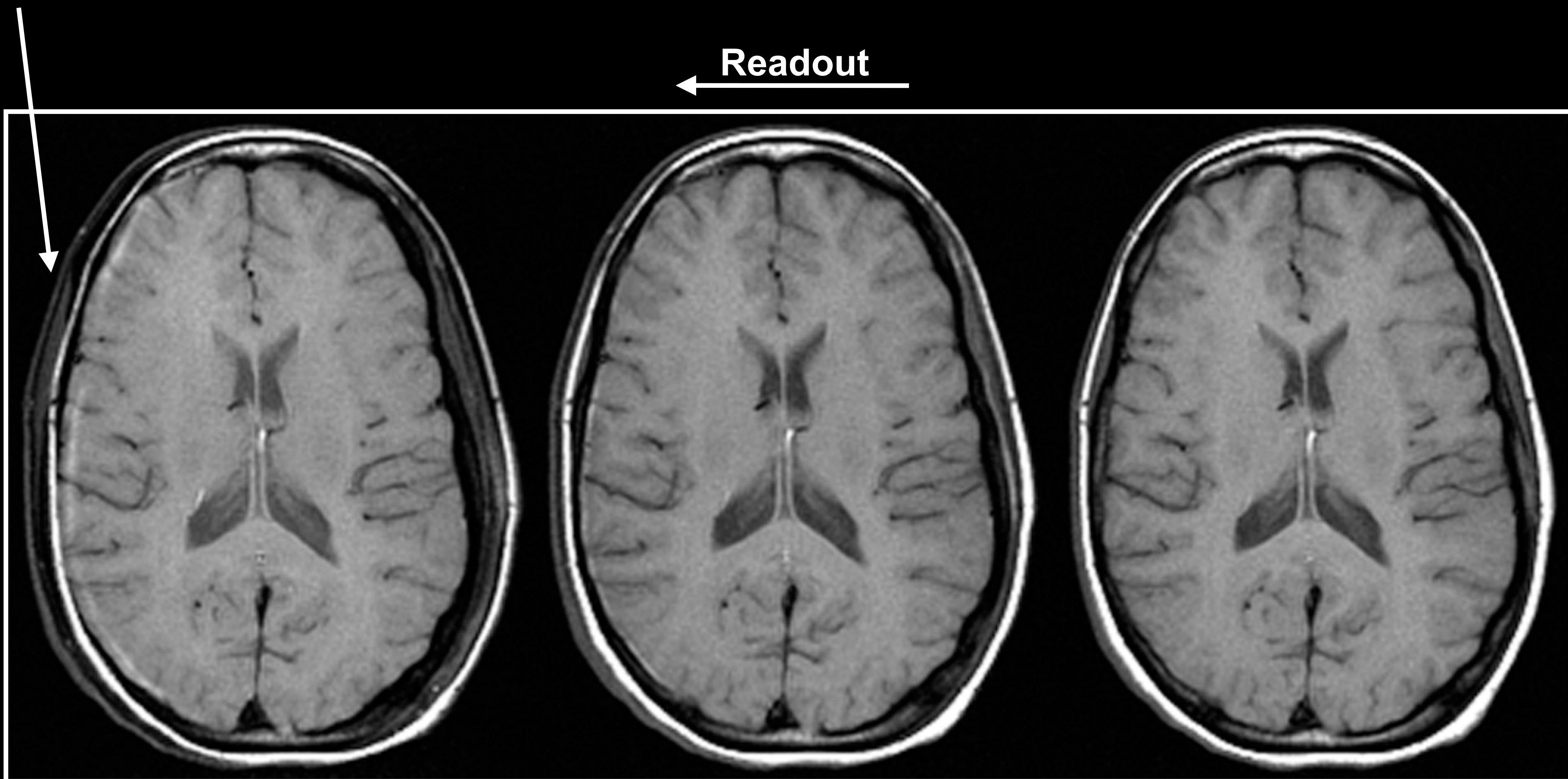
Chemical Shift

Chemical Shift Artifact

- **Gradients provide linear variation in frequency**
- **Fat has a 3.5ppm lower frequency than water**
  - **-222Hz @ 1.5T and -444Hz @ 3.0T**
- **Scanner detects frequency, then maps to position**
- **Scanner "assumes" everything is water, therefore fat (lower frequency) is interpreted as lower frequency (shifted position) water.**



Chemical Shift Artifact



BW = ± 4kHz BW = ± 8kHz BW = ± 16kHz

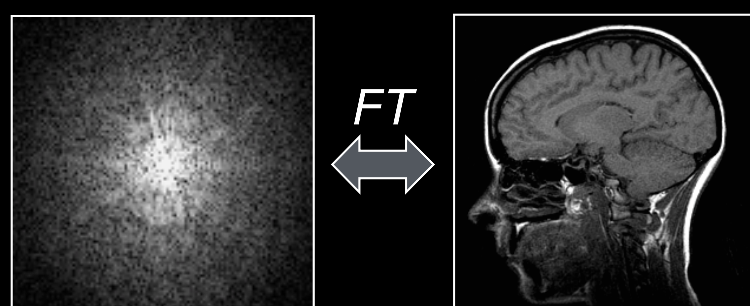
Solution

- **High bandwidth pulse sequences**
  - **Degrades SNR (reduces acquisition time)**
  - **Reduces chemical shift artifact**
- **Fat saturation pulses/techniques**

Motion Artifacts

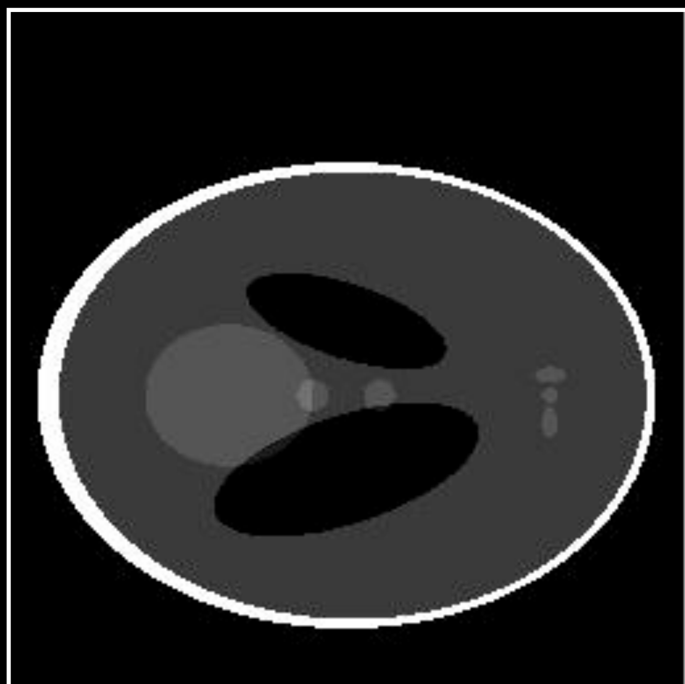
Motion in MRI

- **Motion is responsible for a corruption in spatial localization in PE direction, resulting in a blurring and/or ghosting artifacts**
- **Typical types of motion in body**
  - **Patient motion**
  - **Respiration**
  - **Cardiac motion and vascular pulsation**
  - **Peristalsis & bowel gas**
- **Recording signal in *k*-space not image domain!**



Motion Artifacts - Part I

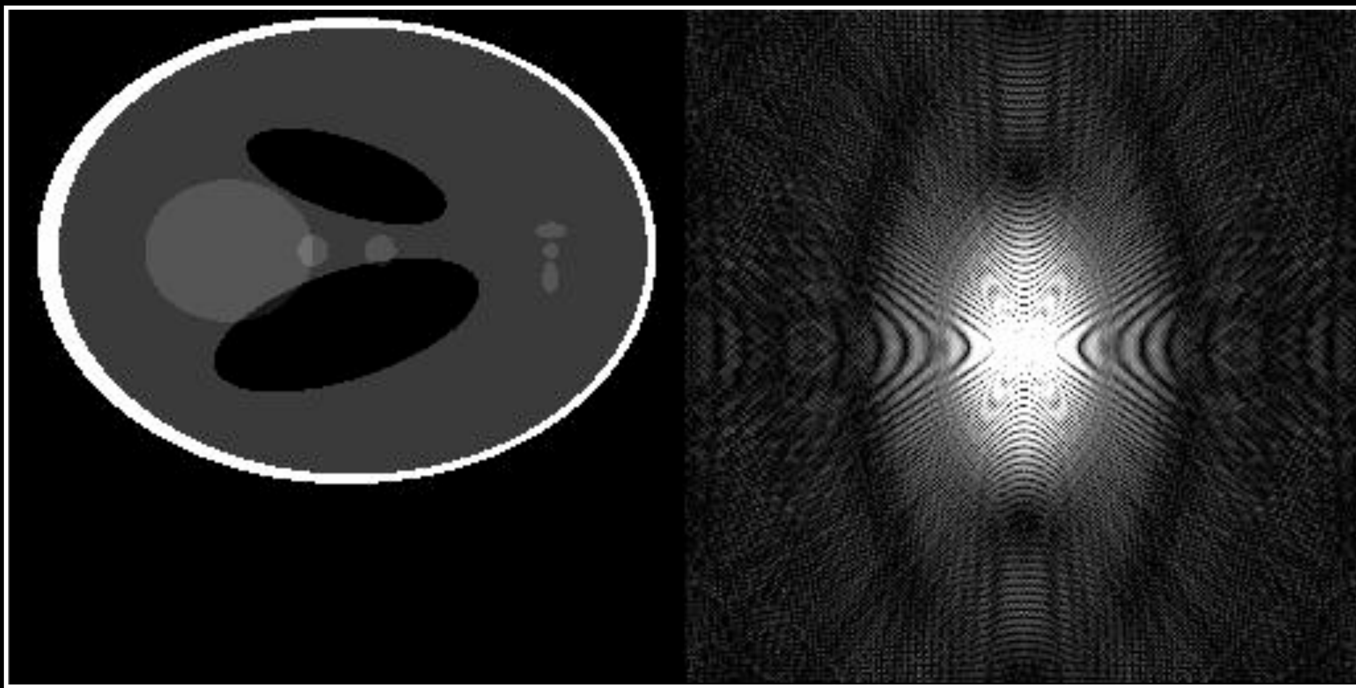
Slow/Bulk Motion



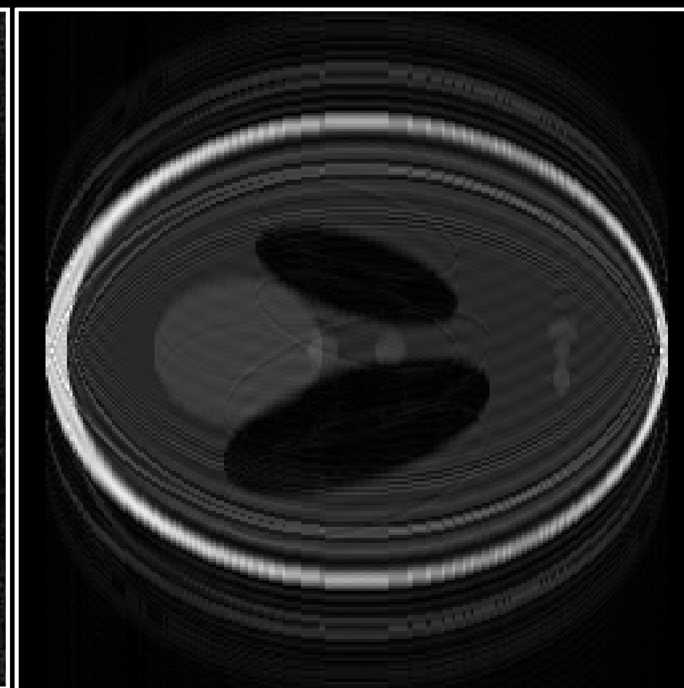
Examples:
- Respiration
- Feet motion
- Swallowing

Motion Artifacts - Part I

Slow/Bulk Motion

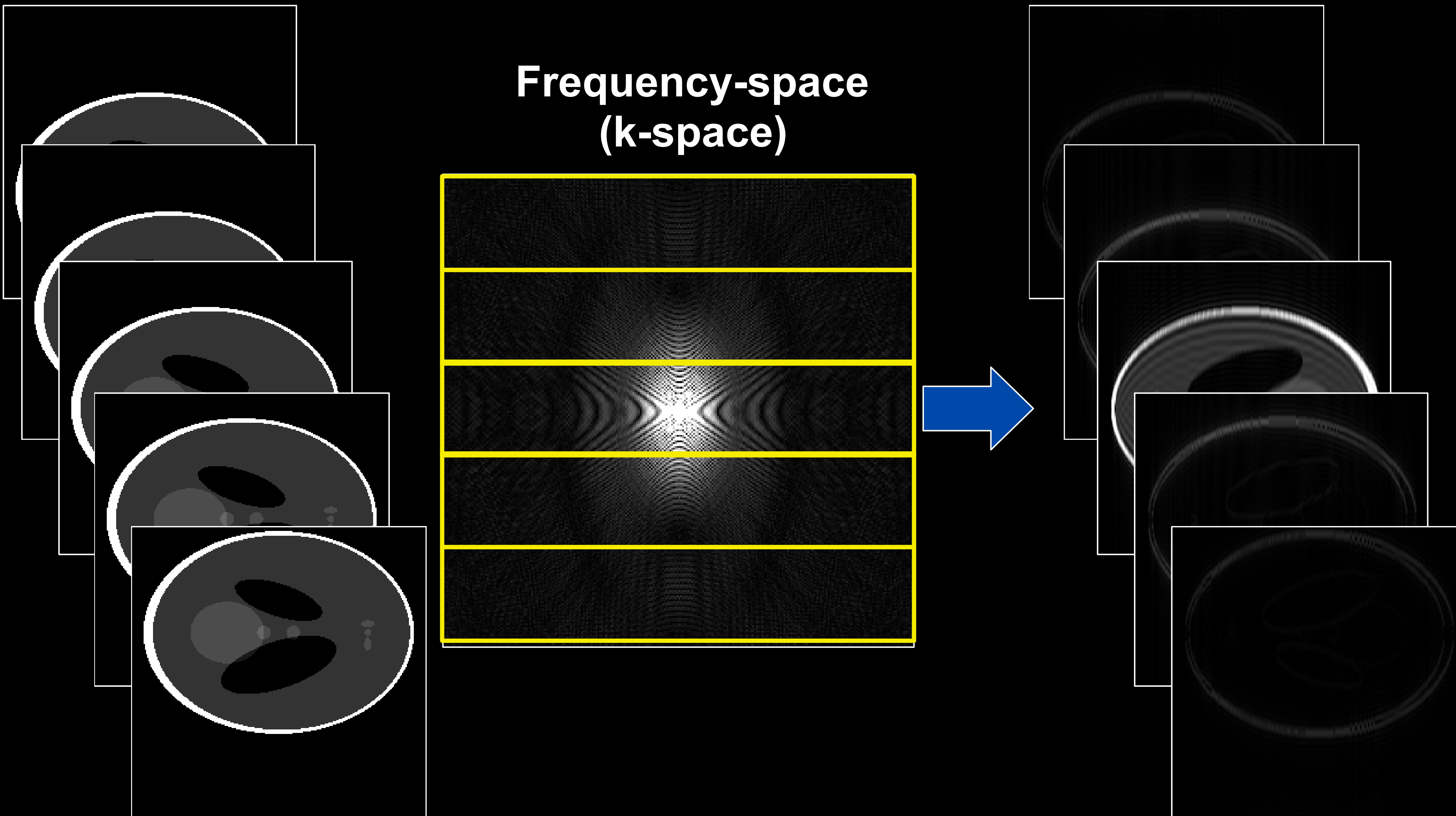


MR Image with
Motion Artifacts

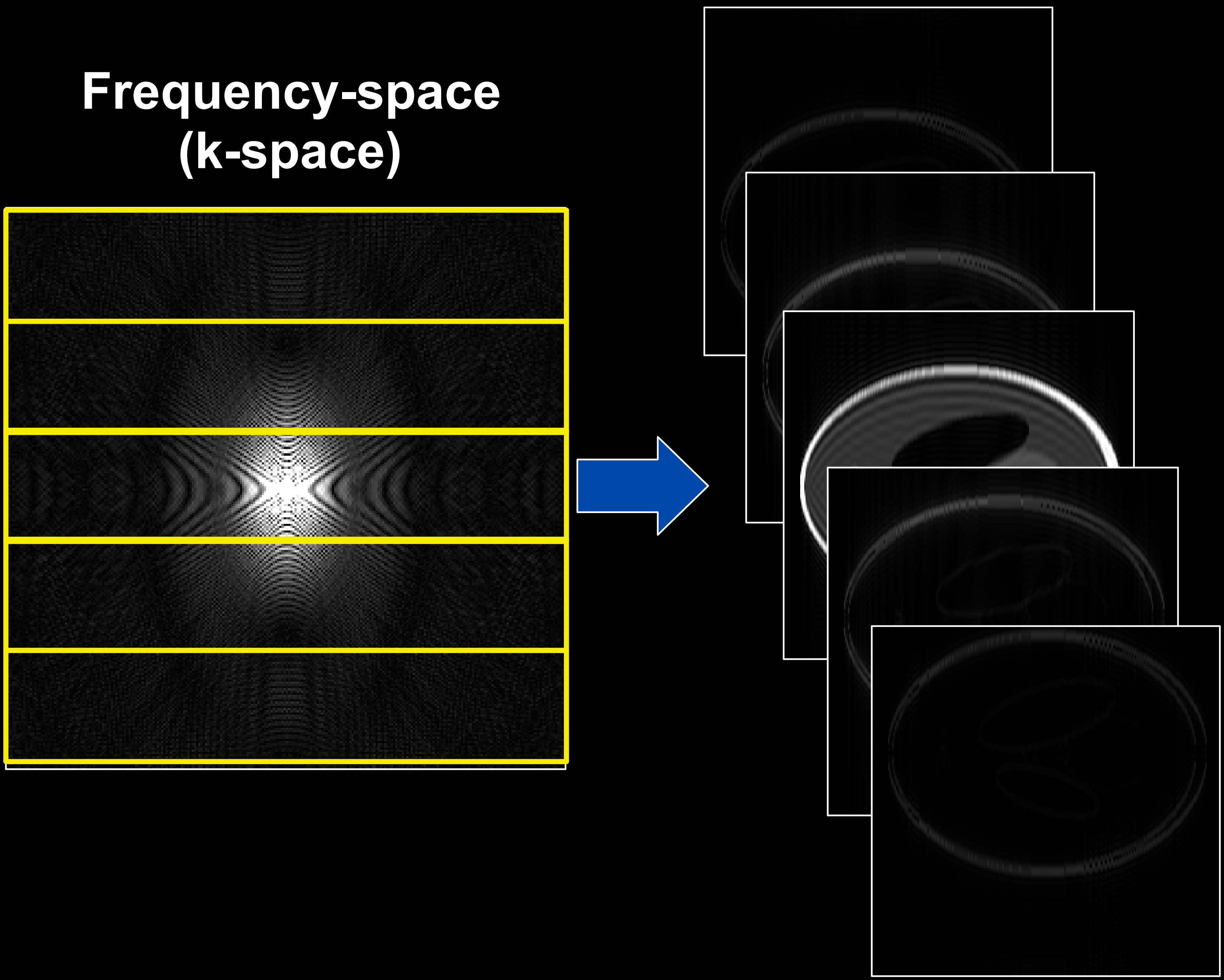


Fourier
Transform

Motion Artifacts - Part I

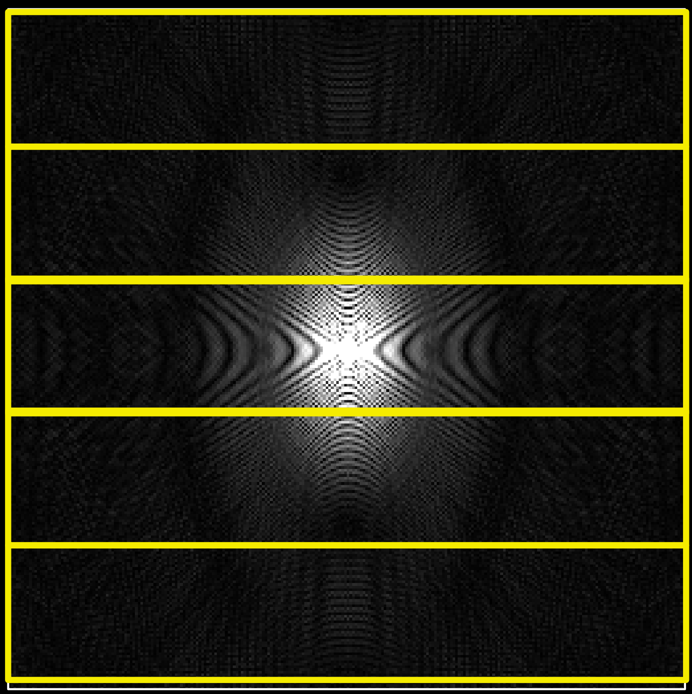


Motion Artifacts - Part I

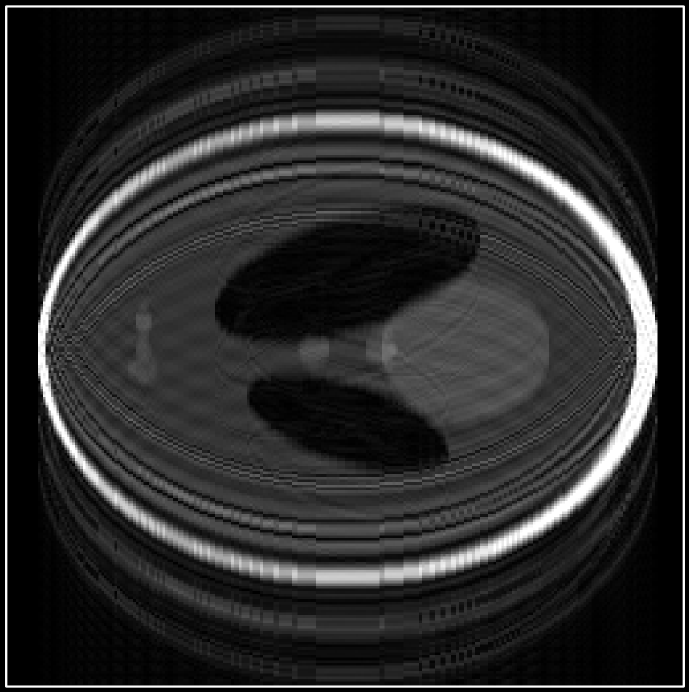


Motion Artifacts - Part I

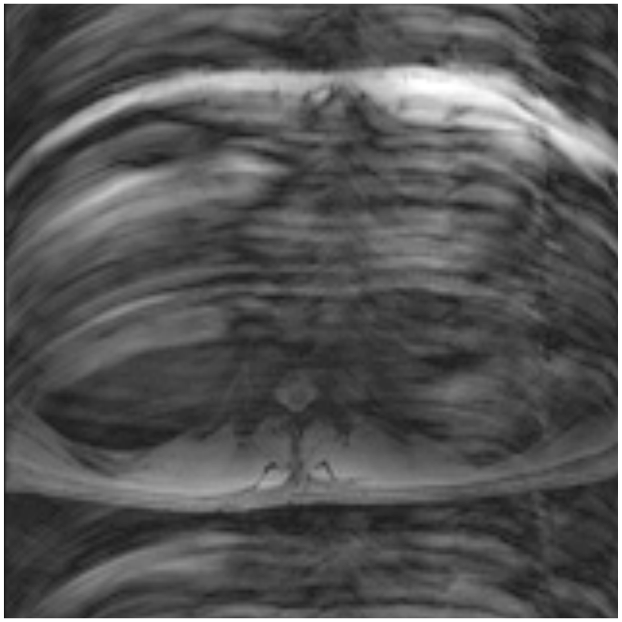
Frequency-space (k-space)



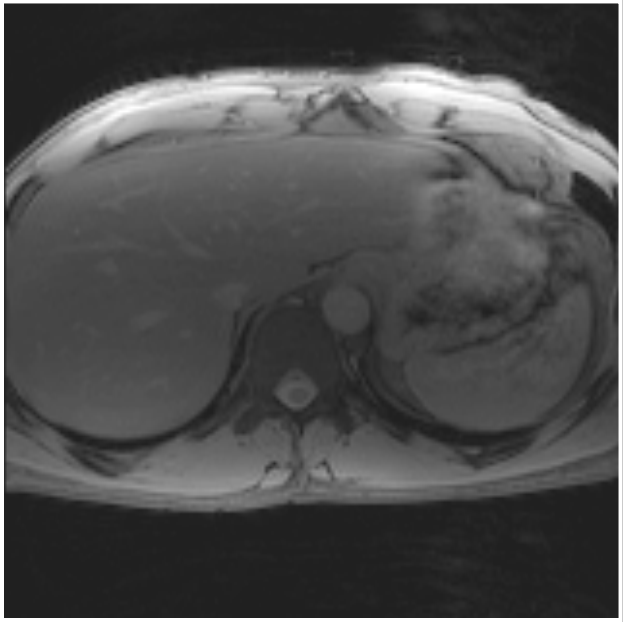
MR Image with Motion Artifacts



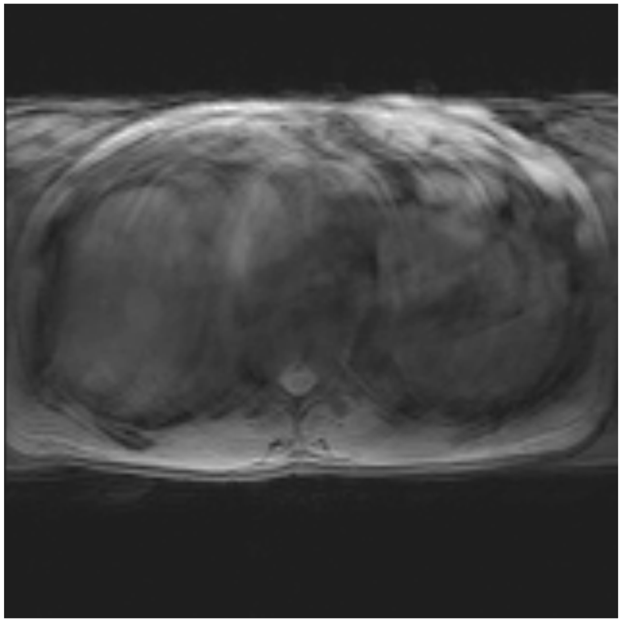
Breathing (Motion) Artifacts



Free Breathing



Breath held



Free Breathing

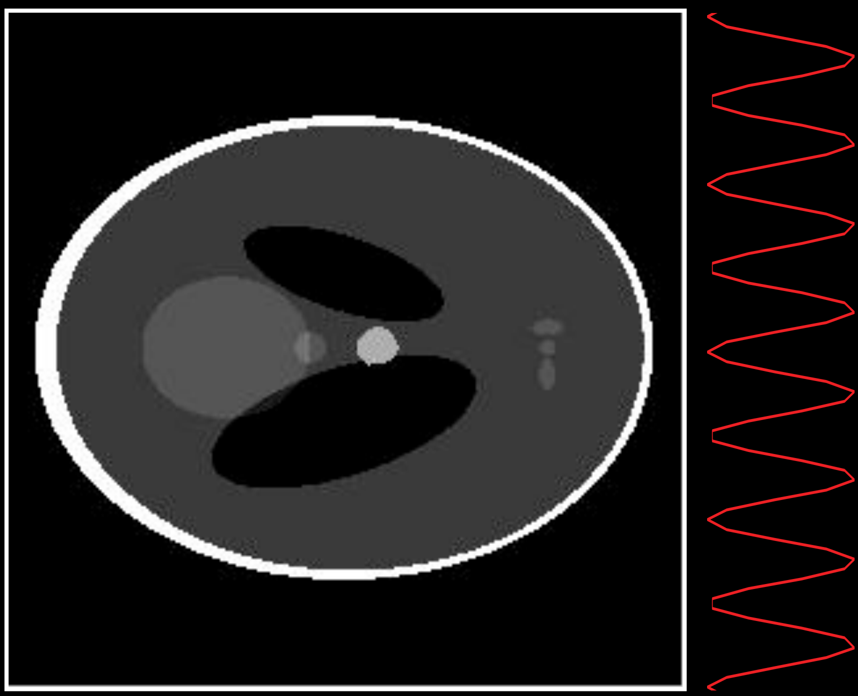
Motion artifacts appear in the phase encode direction.

Remedies (and Penalties)

- **Possible solutions?**
  - Breath-holding
  - Respiratory gating
  - Reduces body movements
    - Patient coaching, physical restraint, sedation
- **Disadvantages**
  - Requires fast sequences
  - Increases the scan time; restricts the available TRs
  - Patients acceptance and discomfort

Motion Artifacts - Part II

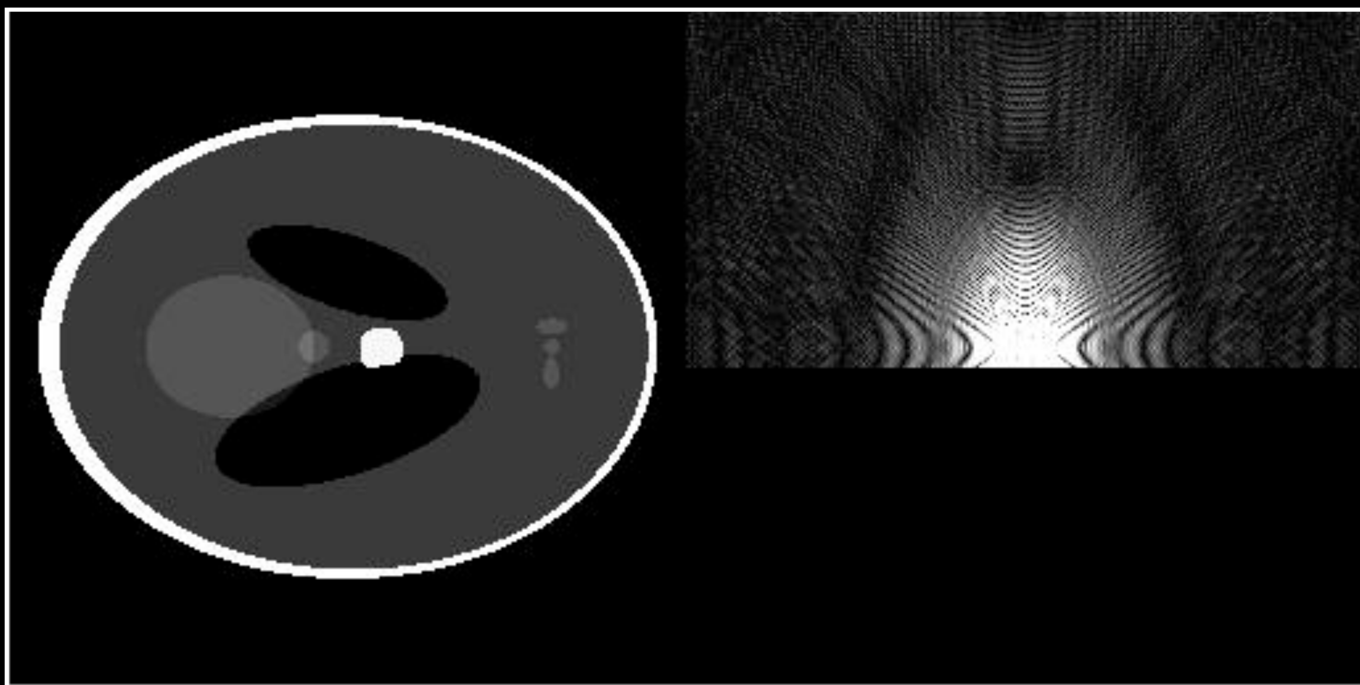
Periodic Motion



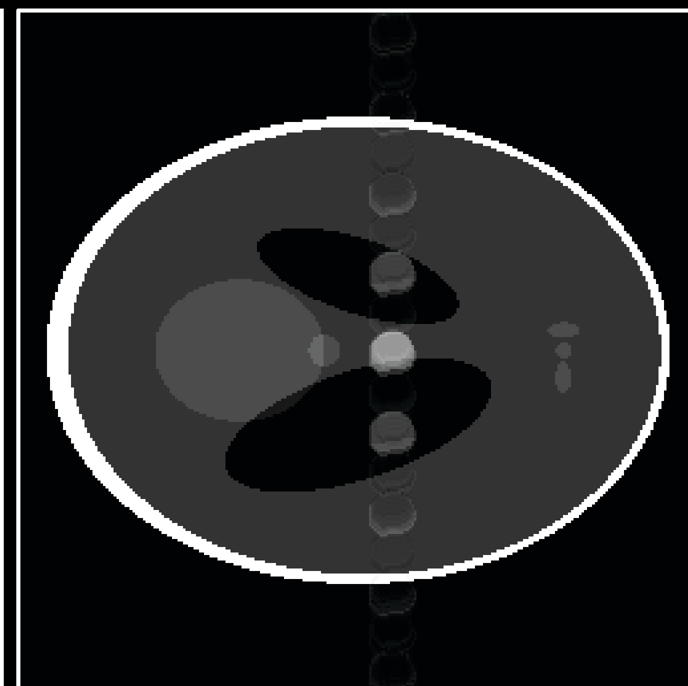
Examples:
- Aortic Pulsation
- Arterial Pulsation

Motion Artifacts - Part II

Periodic Motion



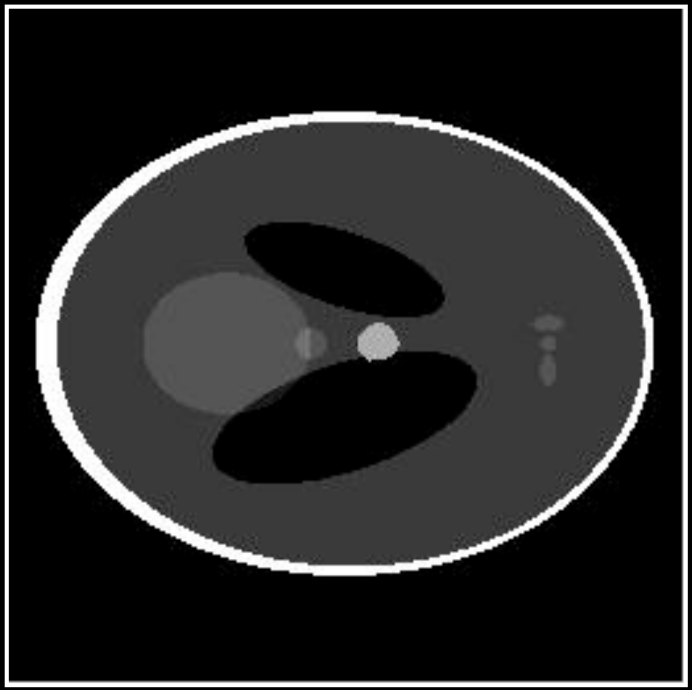
MR Image with
Motion Artifacts



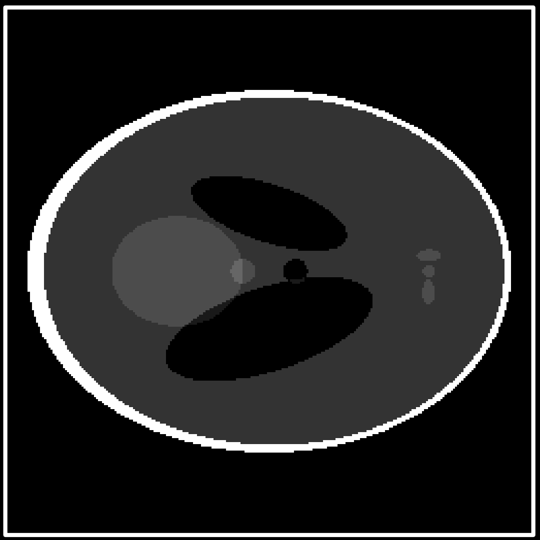
Fourier
Transform

Motion Artifacts - Part II

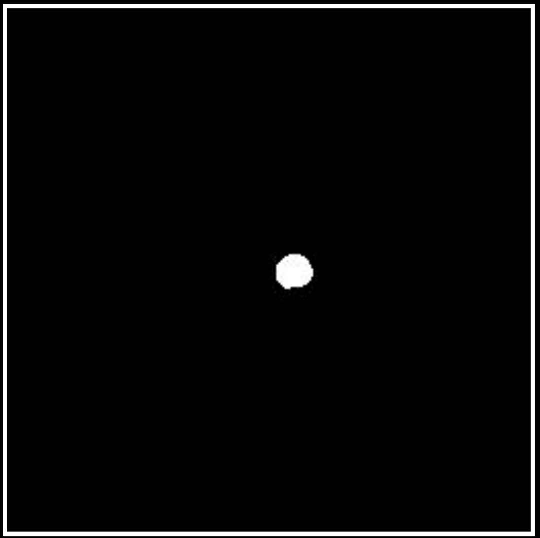
Periodic Motion



Static Part

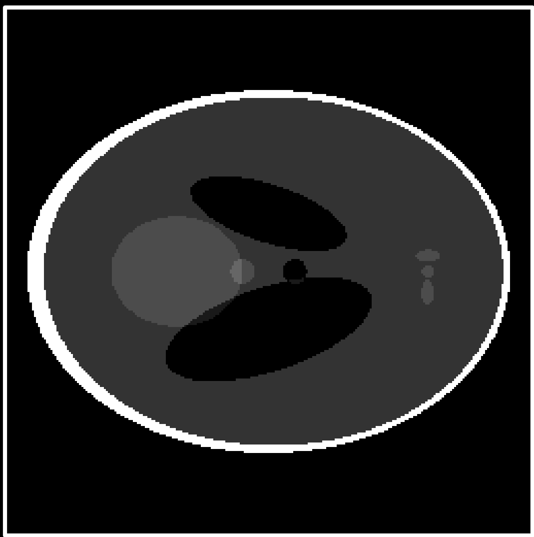


Moving Part

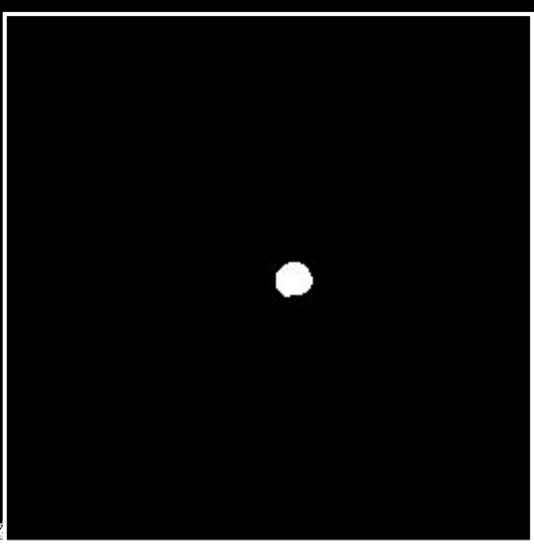


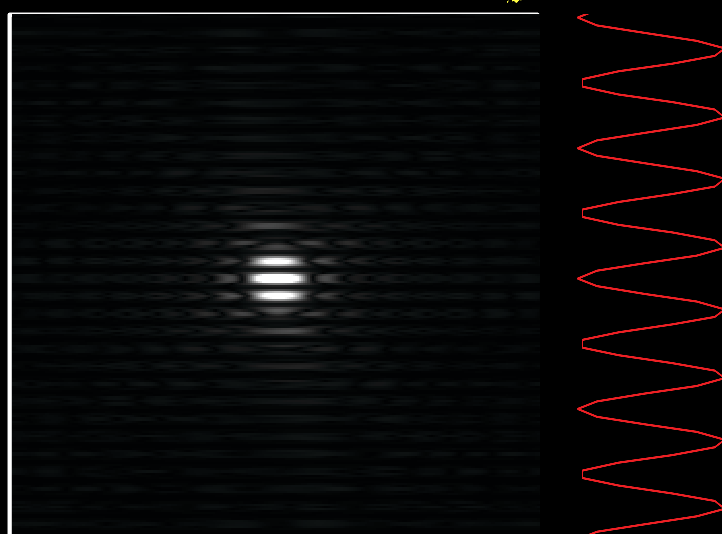
Motion Artifacts - Part II

Static Part

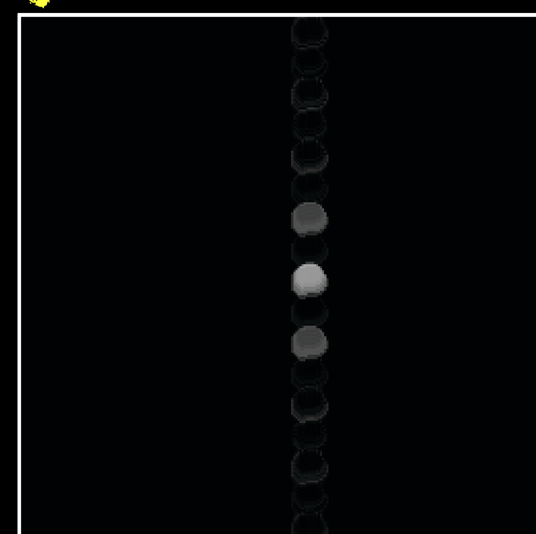


Moving Part



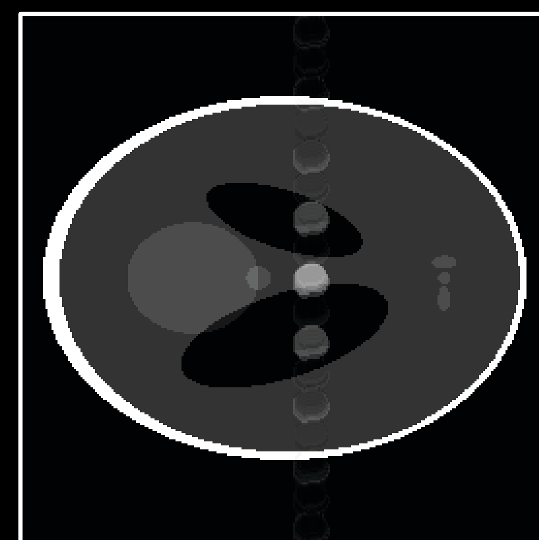


Fourier Transform

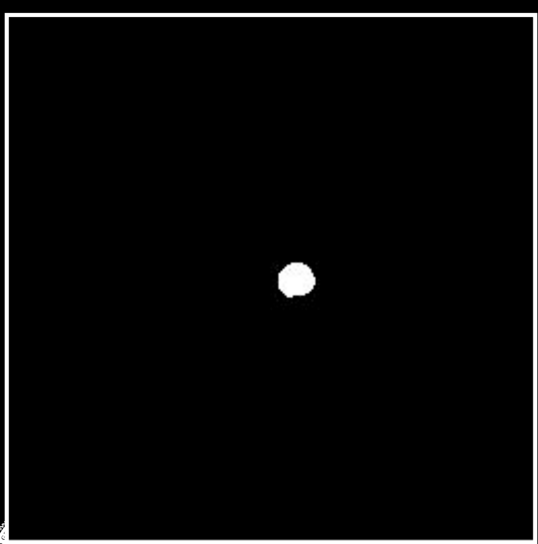


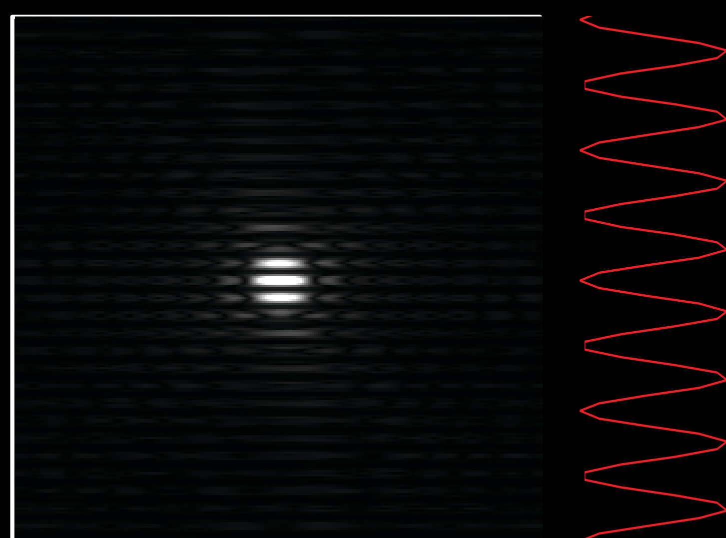
Motion Artifacts - Part II

MR Image with Ghosting Artifacts



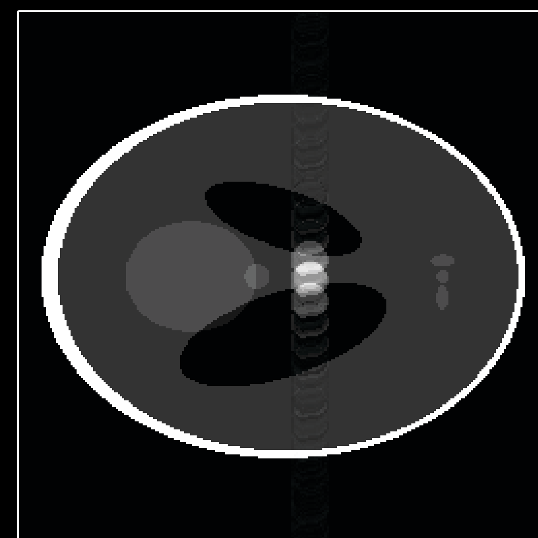
Moving Part



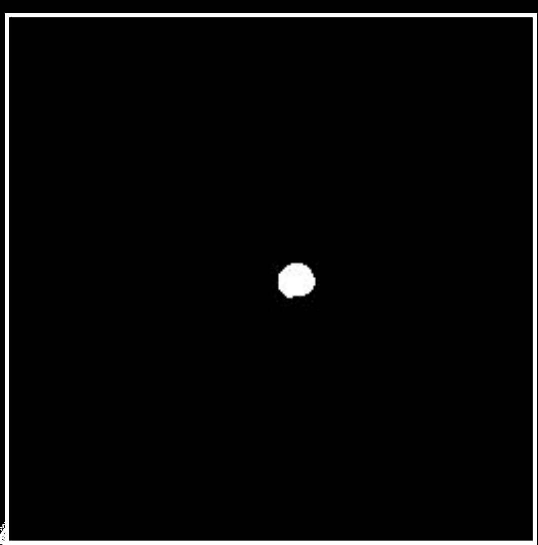


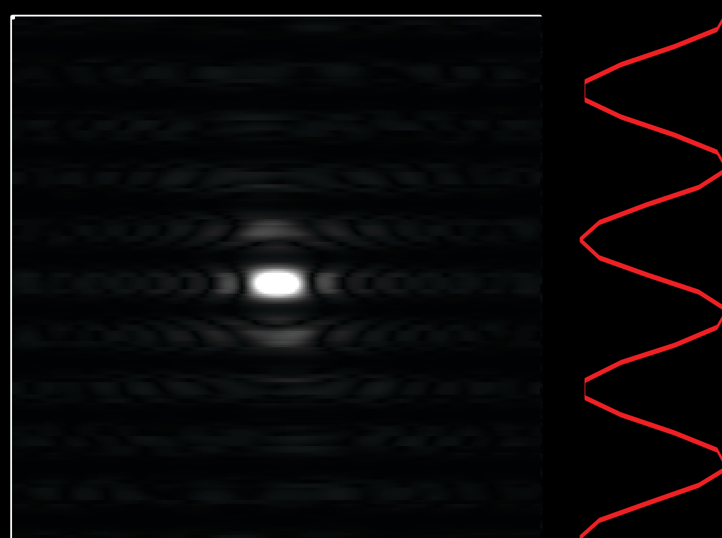
Motion Artifacts - Part II

MR Image with Ghosting Artifacts



Moving Part





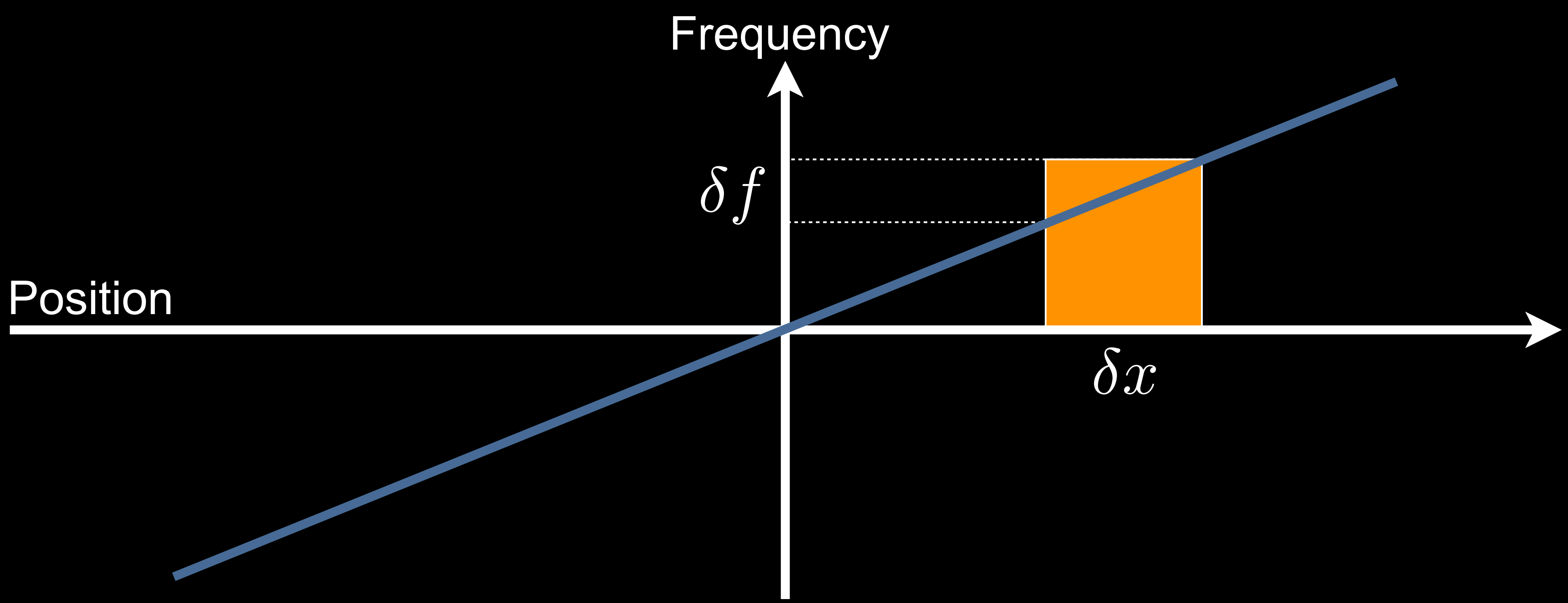
Remedies (and Penalties)

- **Possible solutions?**
  - **Cardiac gating ± segmented imaging.**
  - **Signal suppression of moving tissues.**
  - **Swapping phase-encoding and frequency encoding directions**

- **Disadvantages**
  - **Increases scan time.**
  - **Increases TR (due to preparation pulses).**
  - **Only shifts the artifacts.**

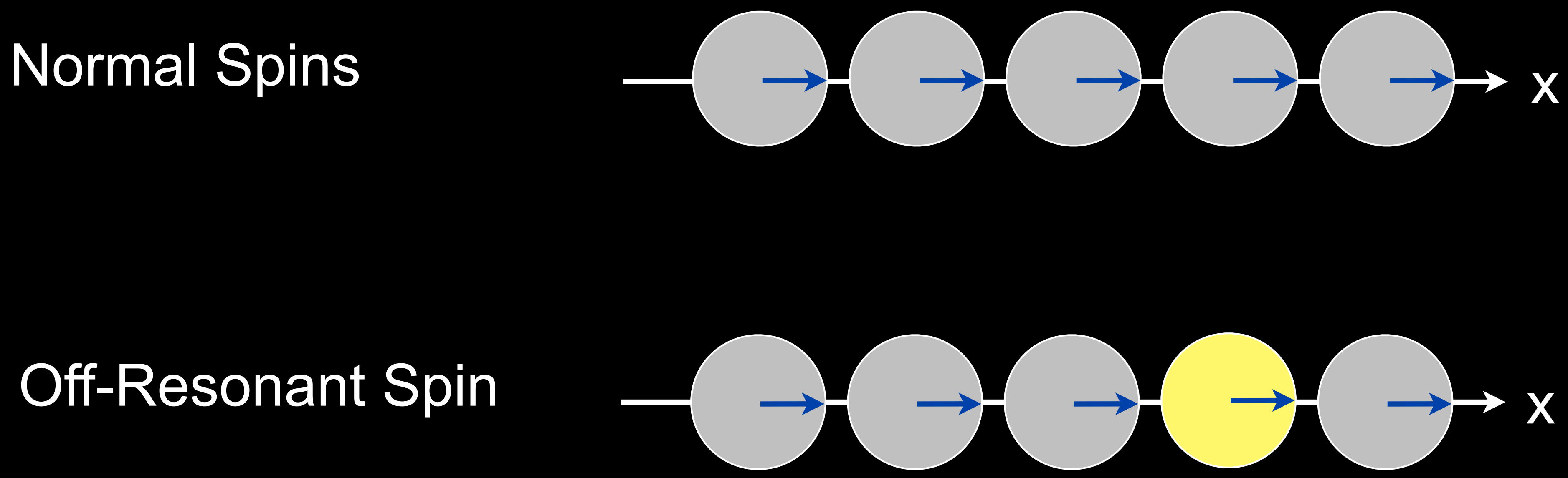
Metal Artifacts

Frequency Encoding Artifacts

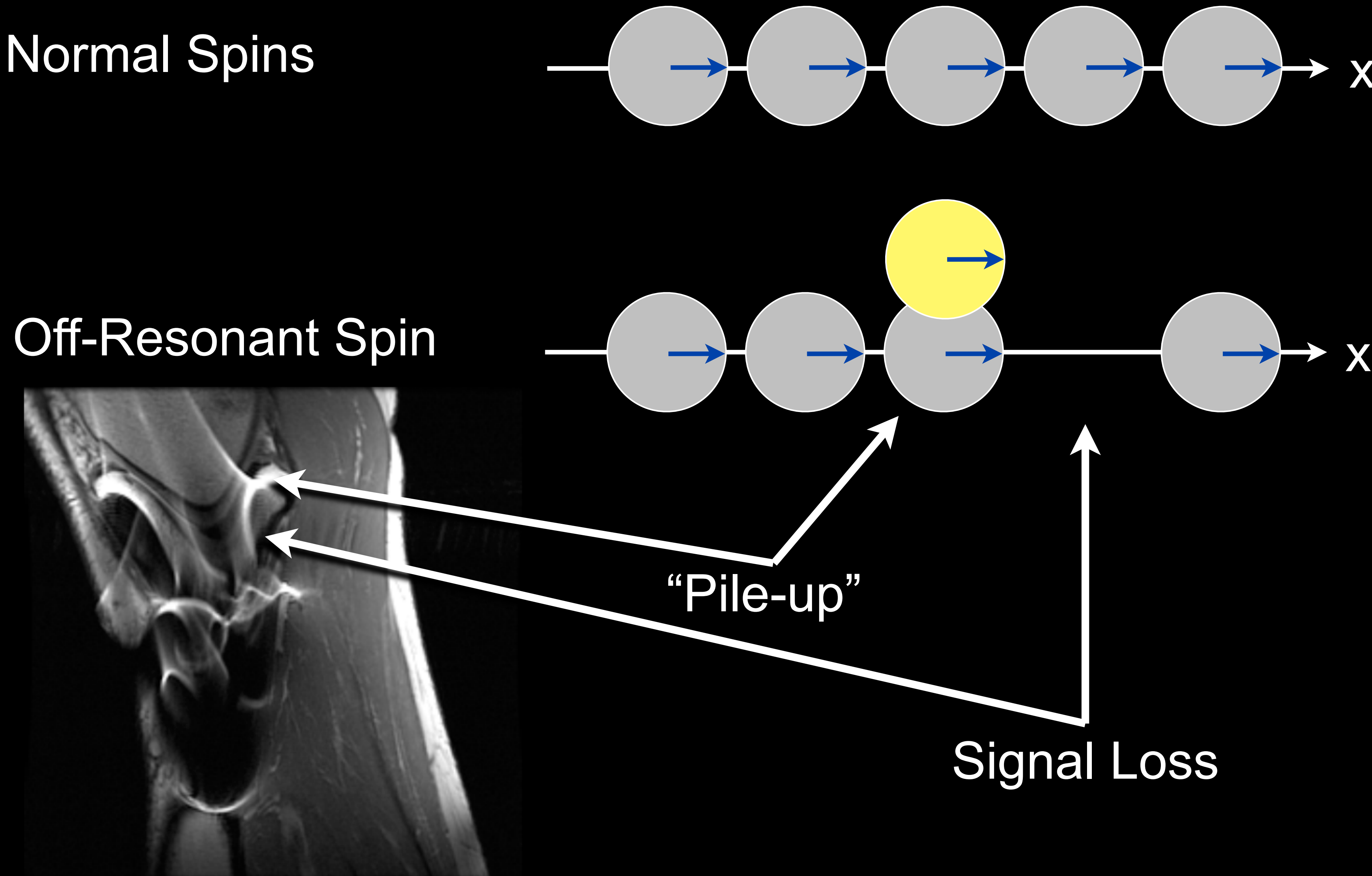


$$\delta x = \frac{2\pi \delta f}{\gamma G_x}$$

Severe Off-Resonance



Severe Off-Resonance

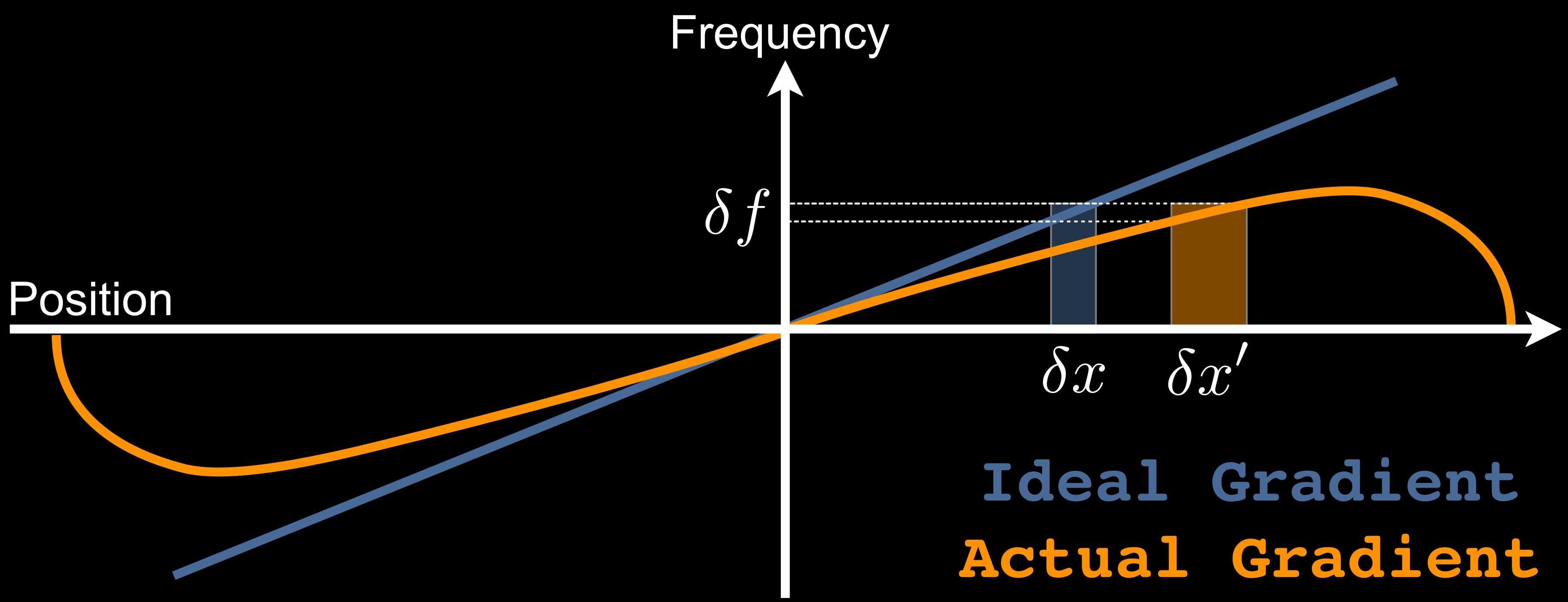


Gradient Non-linearity

Gradient Non-linearity

- Basic ***assumption*** in MRI is that the z-component of the B-field created by the gradient coils varies ***linearly*** with x, y, or z over the FOV.
- Higher gradient amplitudes and slewrates can be achieved by compromising on spatial linearity.
- Gradient non-linearity causes geometric ***and*** intensity distortions.

Gradient Non-linearity



The mapping between position (x) and frequency (f) becomes non-linear.
The mapping between Δx and Δf becomes non-linear.

Gradient Non-linearity

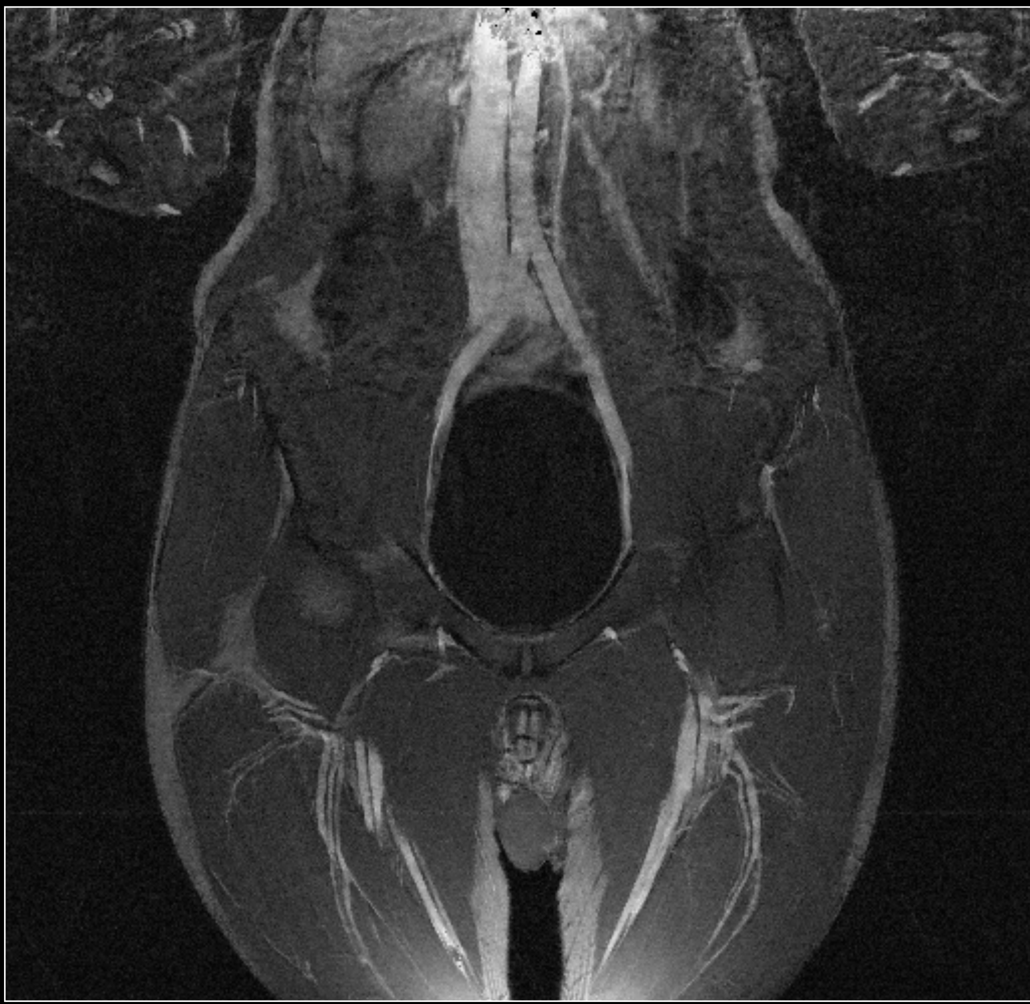
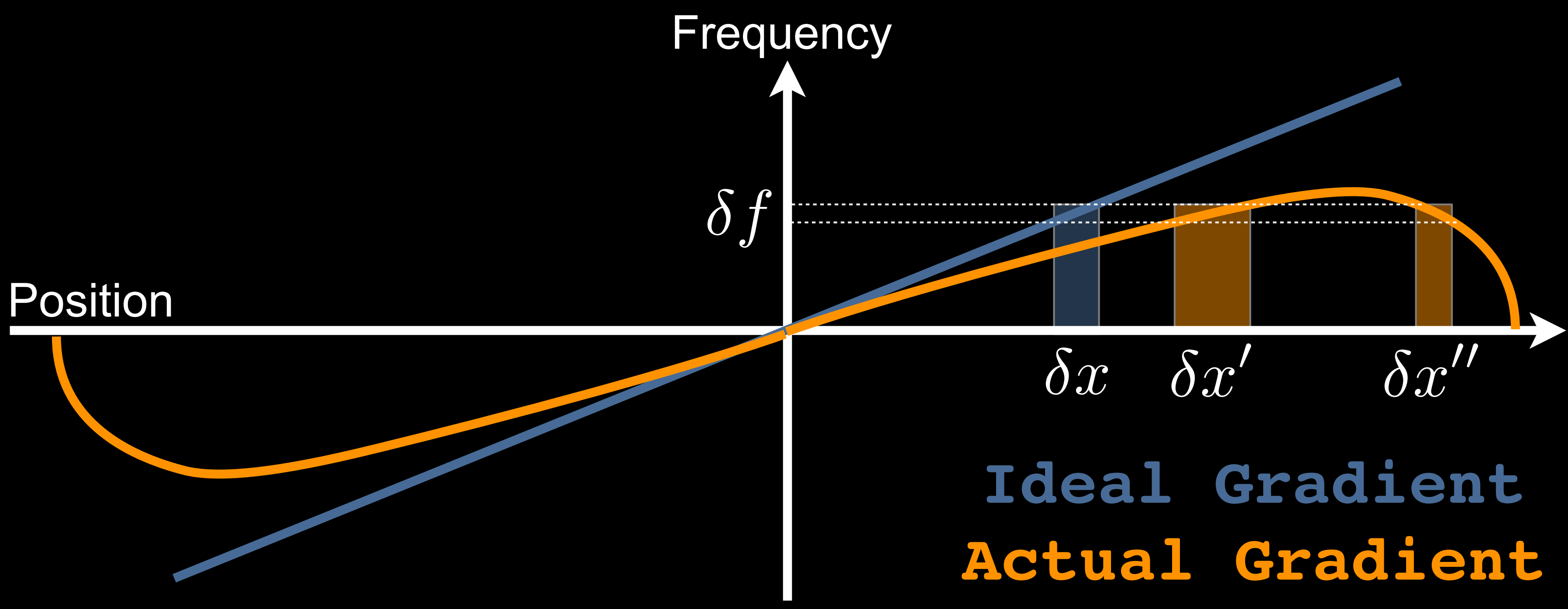


Image Courtesy of M.T. Alley & B.A. Hargeaves

Gradient Roll-off



Spins outside the desired FOV, if excited and near to the coil can become spatially mis-encoded.

Solution

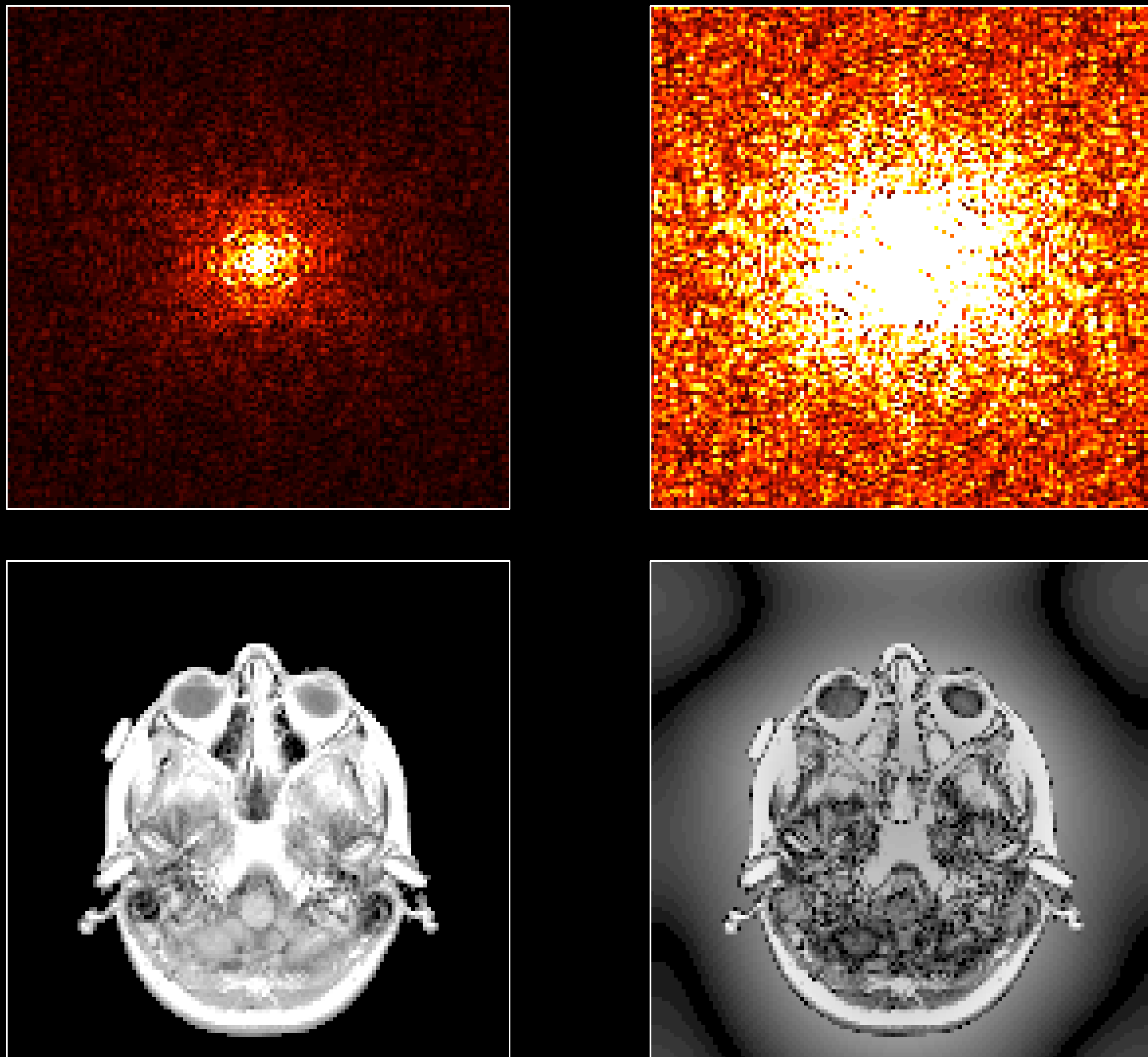
- Image warping parameters that are system specific and applied to all images.
  - Works well qualitatively.
  - Can be problematic quantitatively.
- Transmit (B_1) coils with coverage over smaller volumes.
- Receiver coil (B_r) sensitivity only over ROI.

Data Clipping

Data Clipping

- Received signal saturates the receiver.
- Peak signal usually in the middle of *k*-space, therefore lose low spatial frequency information:
  - Contrast
  - Intensity
- Pre-scan procedure usually avoids data clipping by adjusting receiver gains.

Data Clipping



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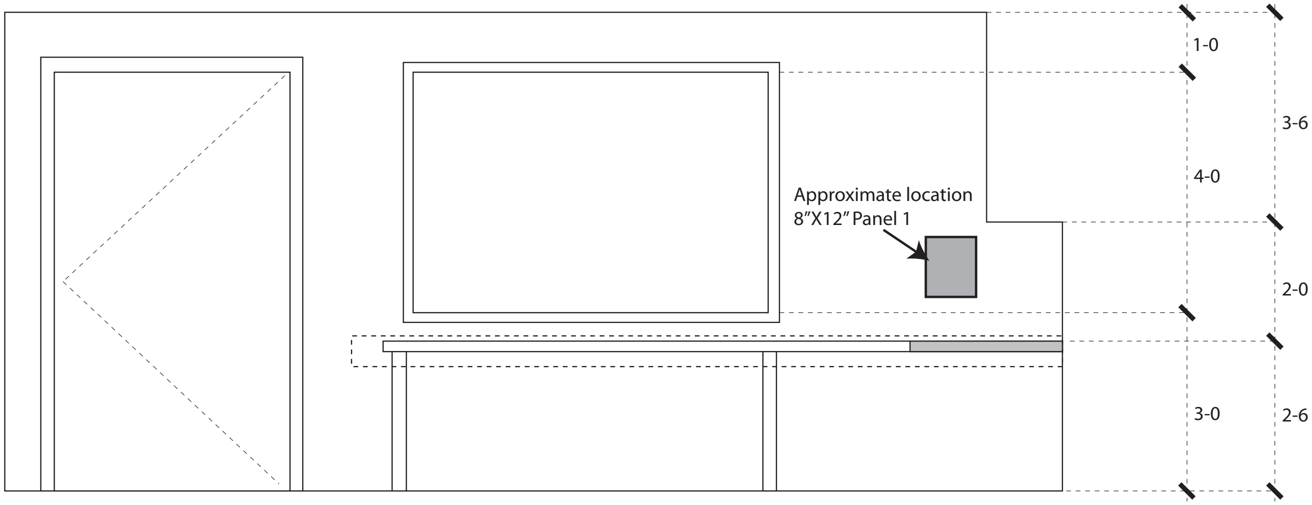
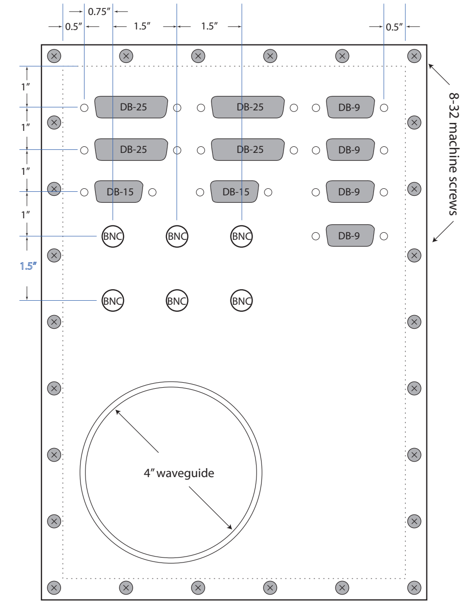
Radio Frequency Interference

RF Shielding

- **RF fields are close to FM radio**
  - **^{1}H @ 1.5T ⇒ 63.85 MHz**
  - **^{1}H @ 3.0T ⇒ 127.71 MHz**
  - **KROQ ⇒ 106.7 MHz**
- **Need to shield local sources from interfering**
- **Copper room shielding required**

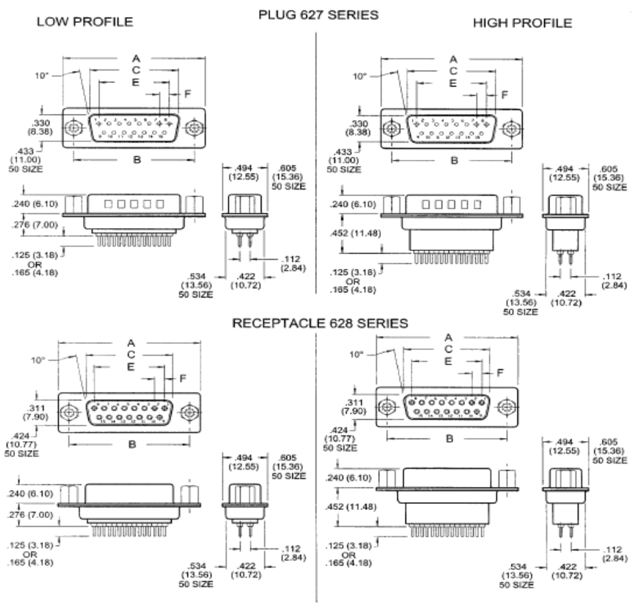
Penetration Panel





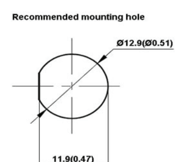
Panel 1 - between scan room and console room

8" X 12" penetration (panel size is 9" X 13")



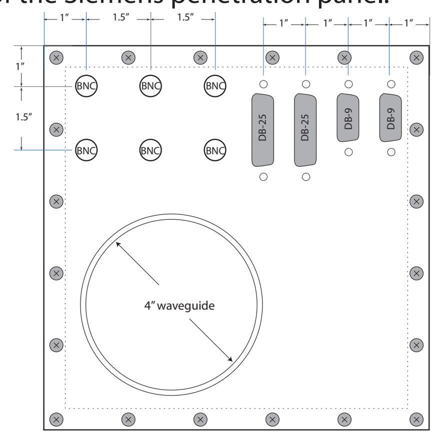
NUMBER OF CONTACTS	A Inch	A (mm)	B Inch	B (mm)	C PLUG Inch	C PLUG (mm)	C RECEPTACLE Inch	C RECEPTACLE (mm)	E Inch	E (mm)	F Inch	F (mm)
9	1.214	(30.84)	.984	(24.99)	.667	(16.92)	.640	(16.26)	.432	(10.97)	.108	(2.74)
15	1.545	(39.24)	1.312	(33.32)	.994	(25.25)	.967	(24.56)	.756	(19.20)	.108	(2.74)
25	2.088	(53.04)	1.852	(47.04)	1.534	(38.96)	1.508	(38.30)	1.304	(33.12)	.109	(2.76)
37	2.730	(69.34)	2.500	(63.50)	2.182	(53.08)	2.156	(54.76)	1.956	(49.68)	.109	(2.76)
50	2.640	(67.05)	2.406	(61.11)	2.080	(52.83)	2.054	(52.17)	1.740	(44.20)	.109	(2.76)

DB cutout dimensions



BNC Hole Dimensions

Location of Panel 2 is to be in the proximity of the Siemens penetration panel.



8" Penetration (panel size is 9")

Panel 2 - between equipment room and scan room

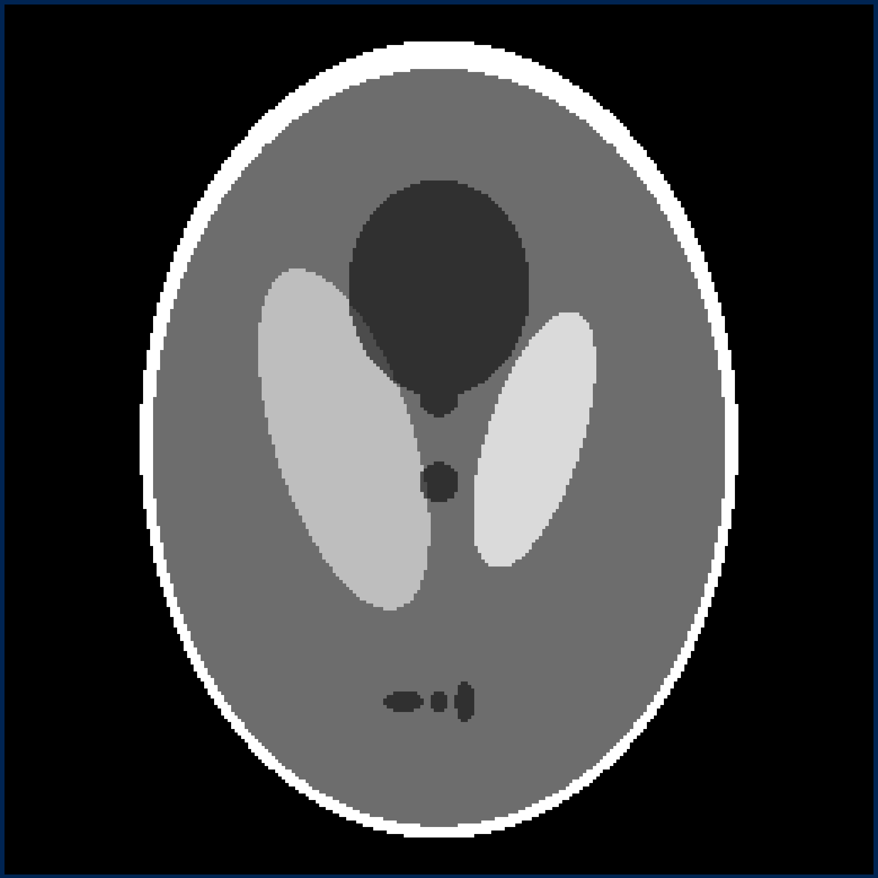
Penetration panels should be made from 16 ga. steel or aluminum

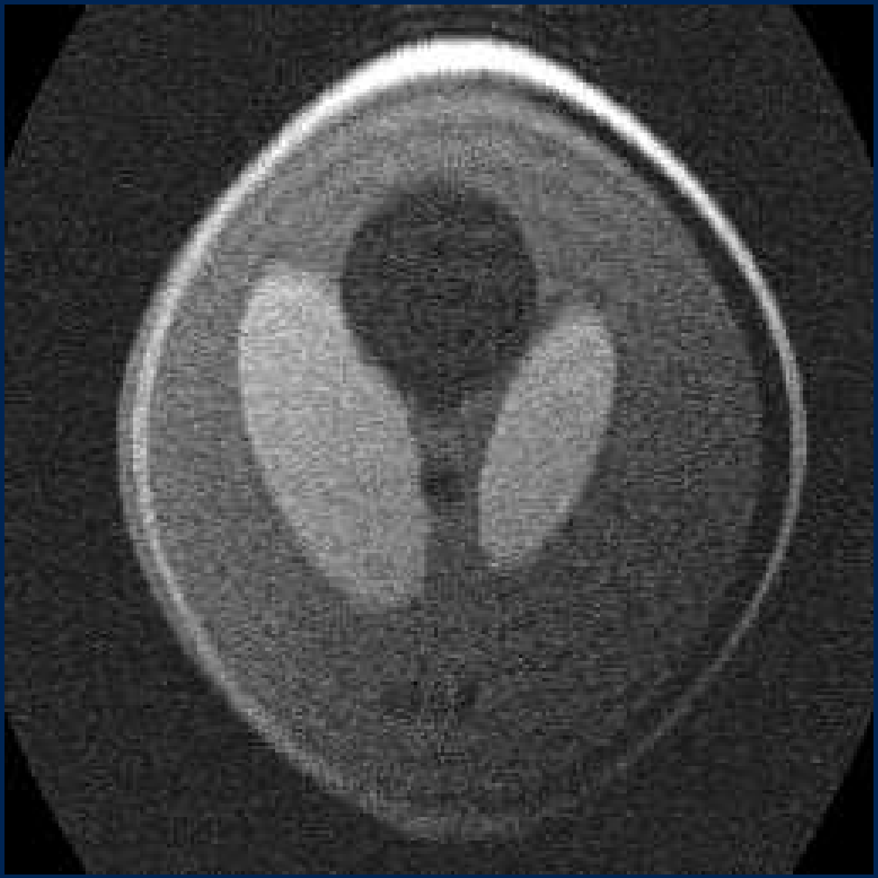
Radiofrequency Interference

- **Caused by RF leak**
  - **Scanner Door is Open**
  - **Wires running in/out of scan room**
  - **Faulty Room Shielding**

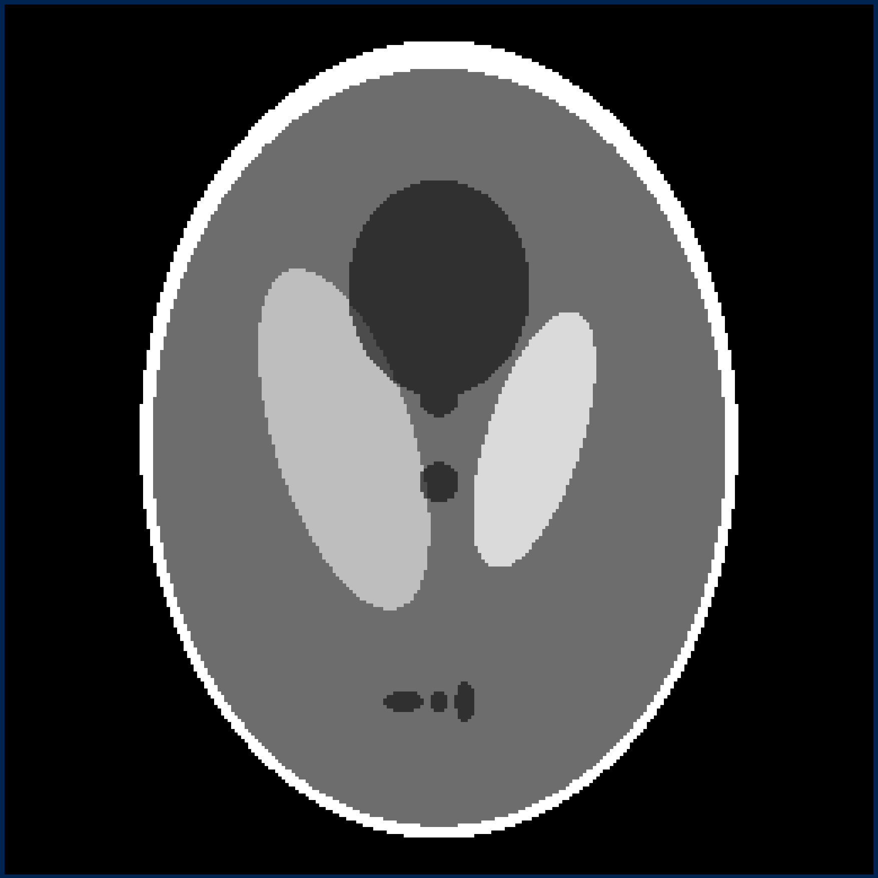
Images Courtesy of http://chickscope.beckman.uiuc.edu/roosts/carl/artifacts.html

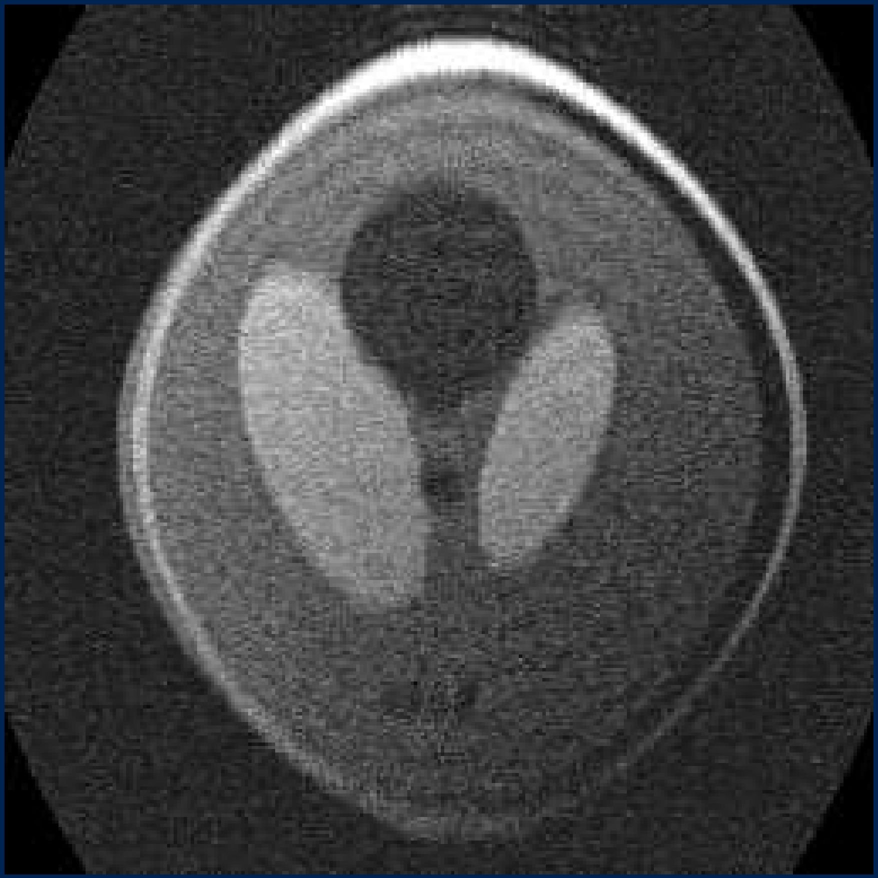
How many artifacts can you see?





How many artifacts can you see?





Noise
Gradient Distortion
Gibb's Ringing
Chemical Shift
Coil shading

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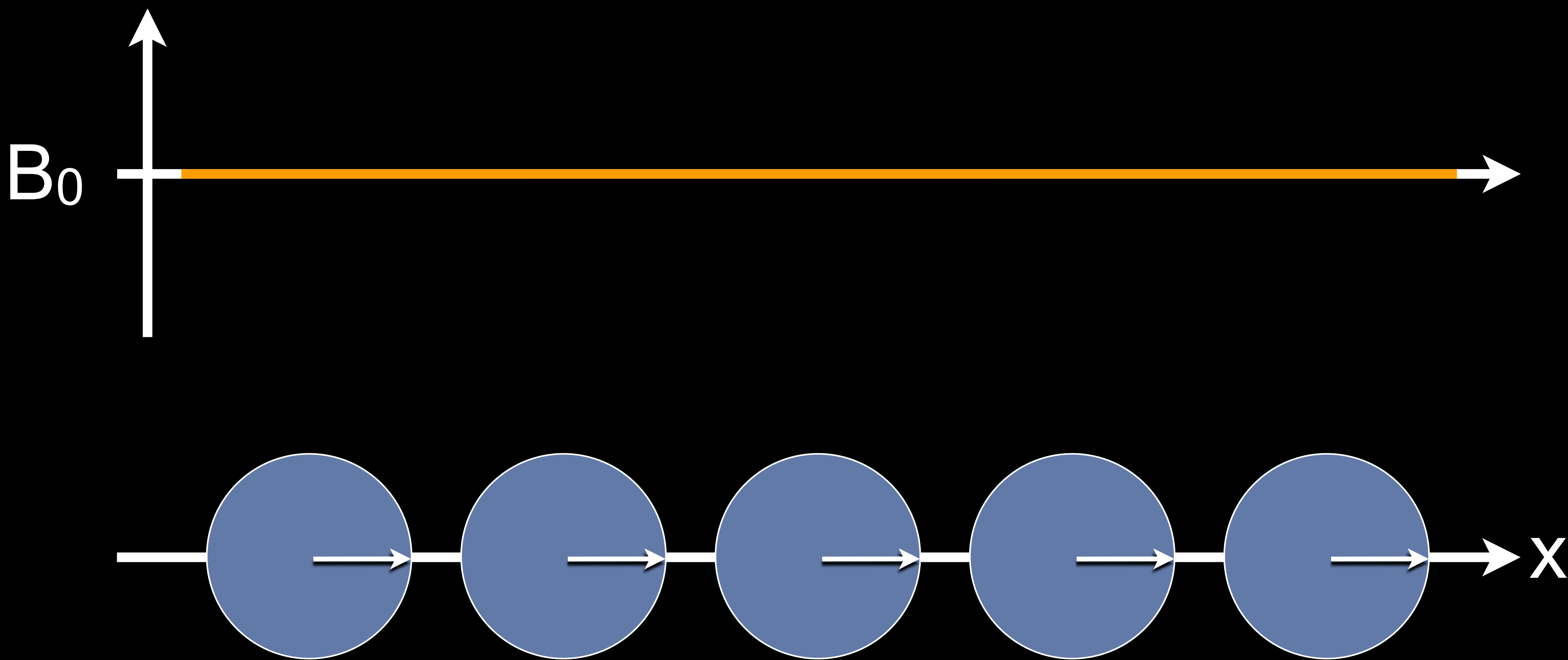
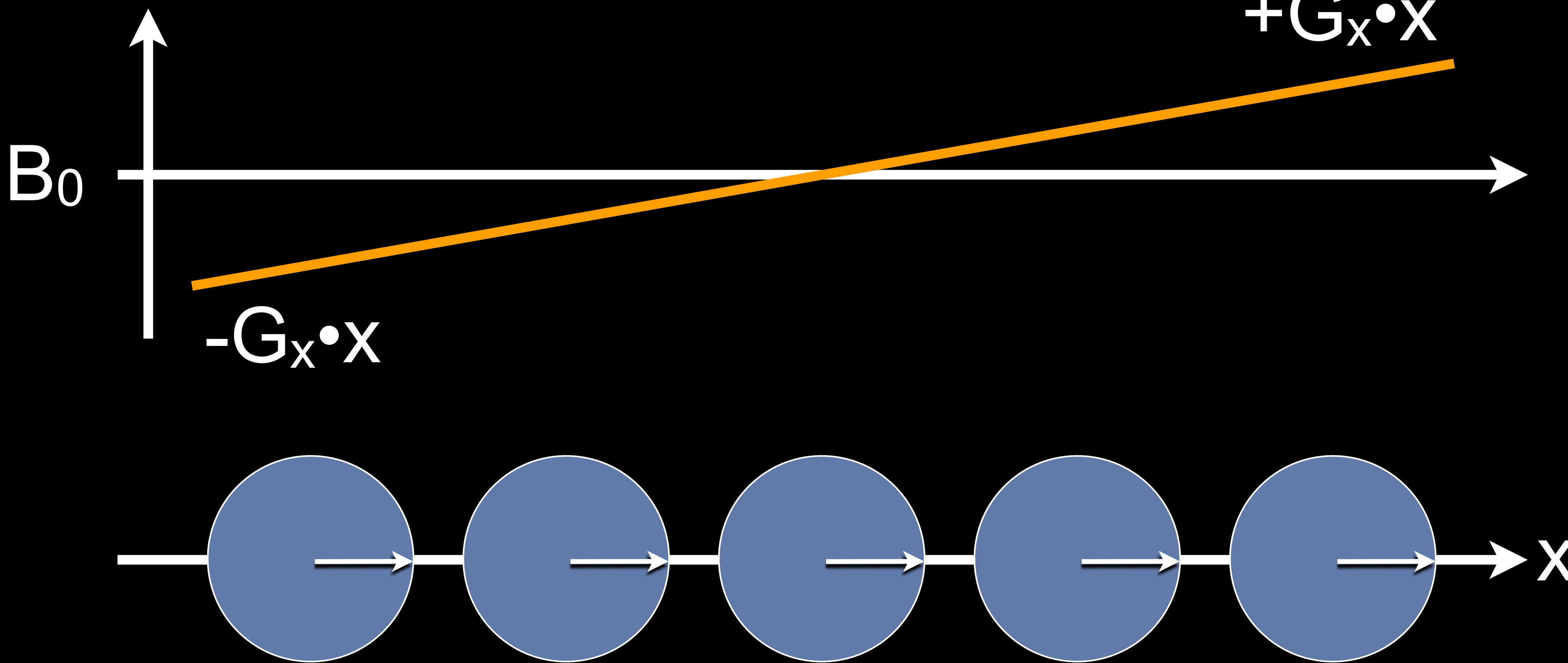
Gradient Echoes & Fat

GRE & Fat/Water Frequency



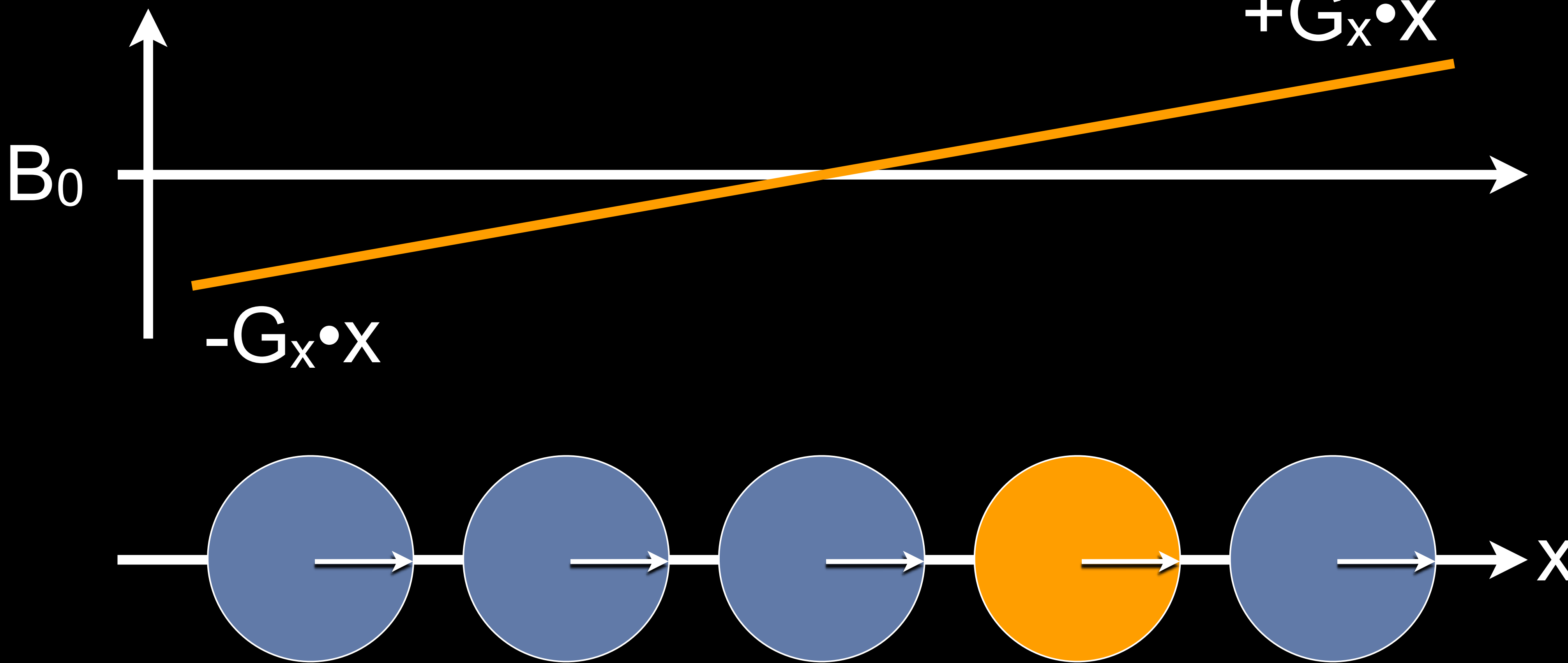
Water Spins in a Uniform Field

GRE & Fat/Water Frequency



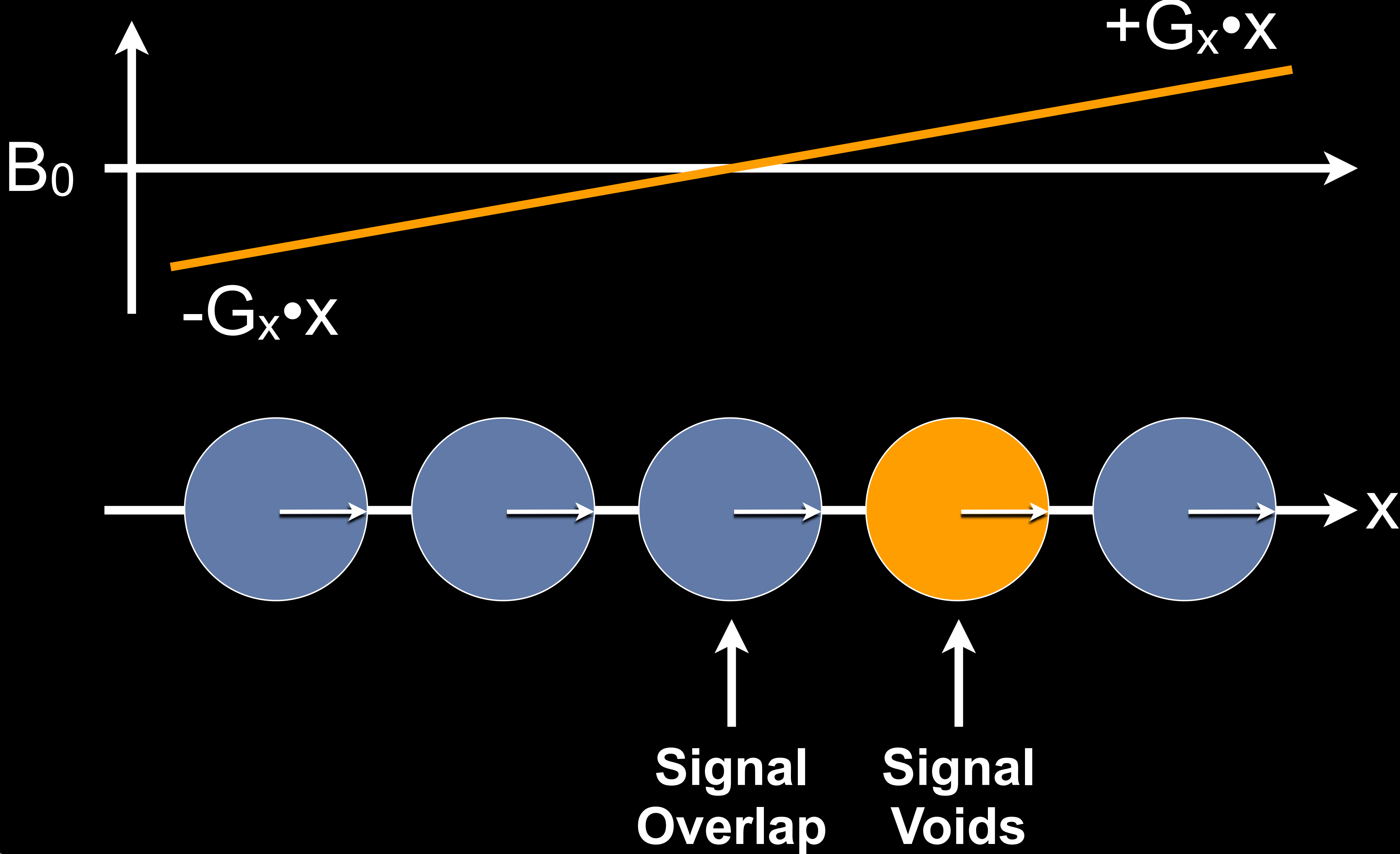
Water Spins in a Gradient Field

GRE & Fat/Water Frequency

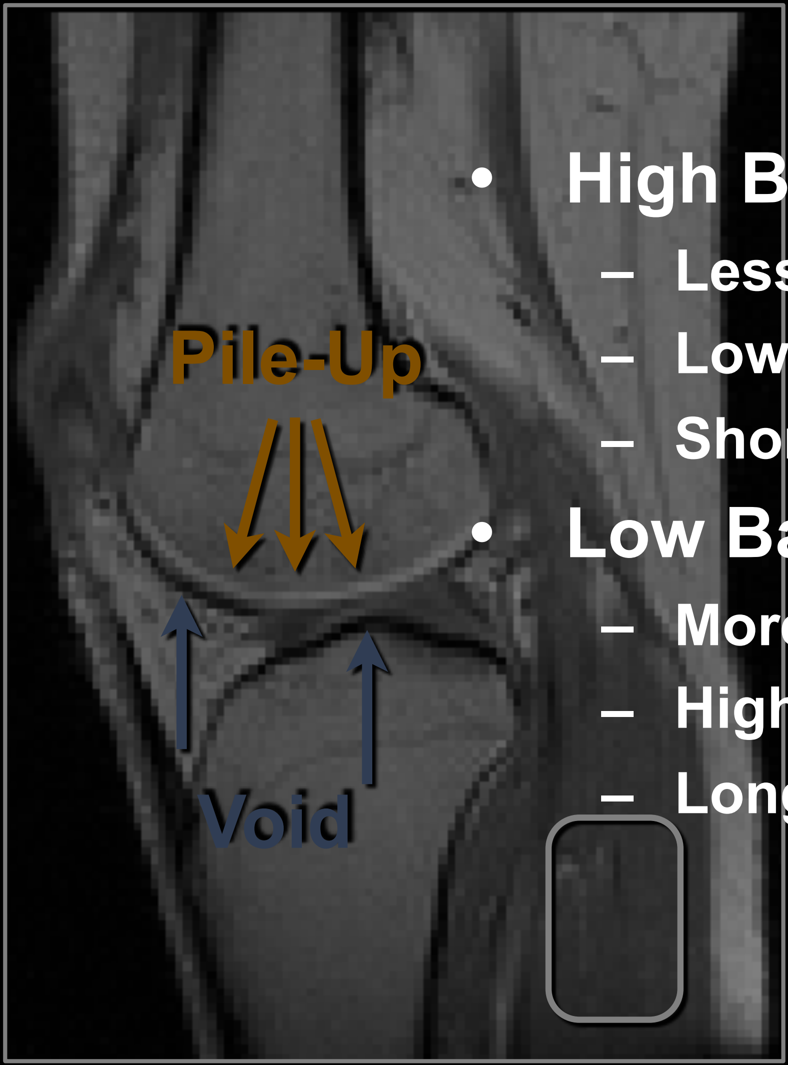


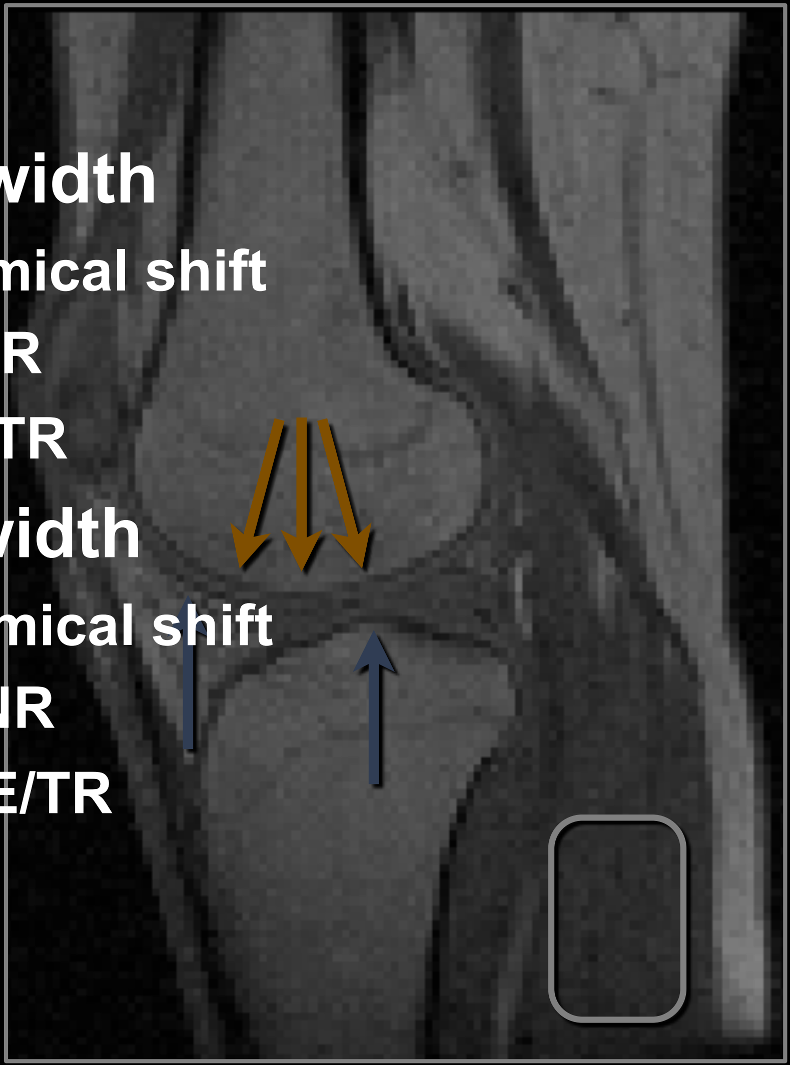
Water & Fat Spins in a Gradient Field

GRE & Fat/Water Frequency



GRE & Fat/Water Frequency

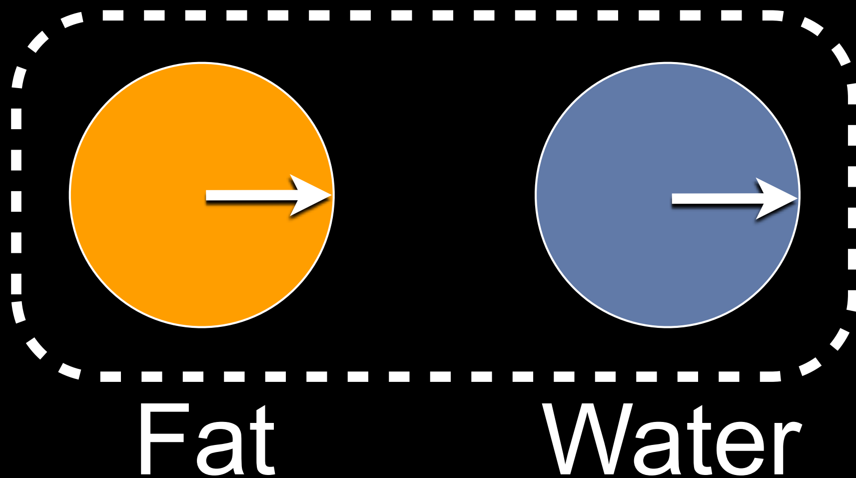




- **High Bandwidth**
  - Less chemical shift
  - Lower SNR
  - Short TE/TR
- **Low Bandwidth**
  - More chemical shift
  - Higher SNR
  - Longer TE/TR

GRE and Fat/Water Phase

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

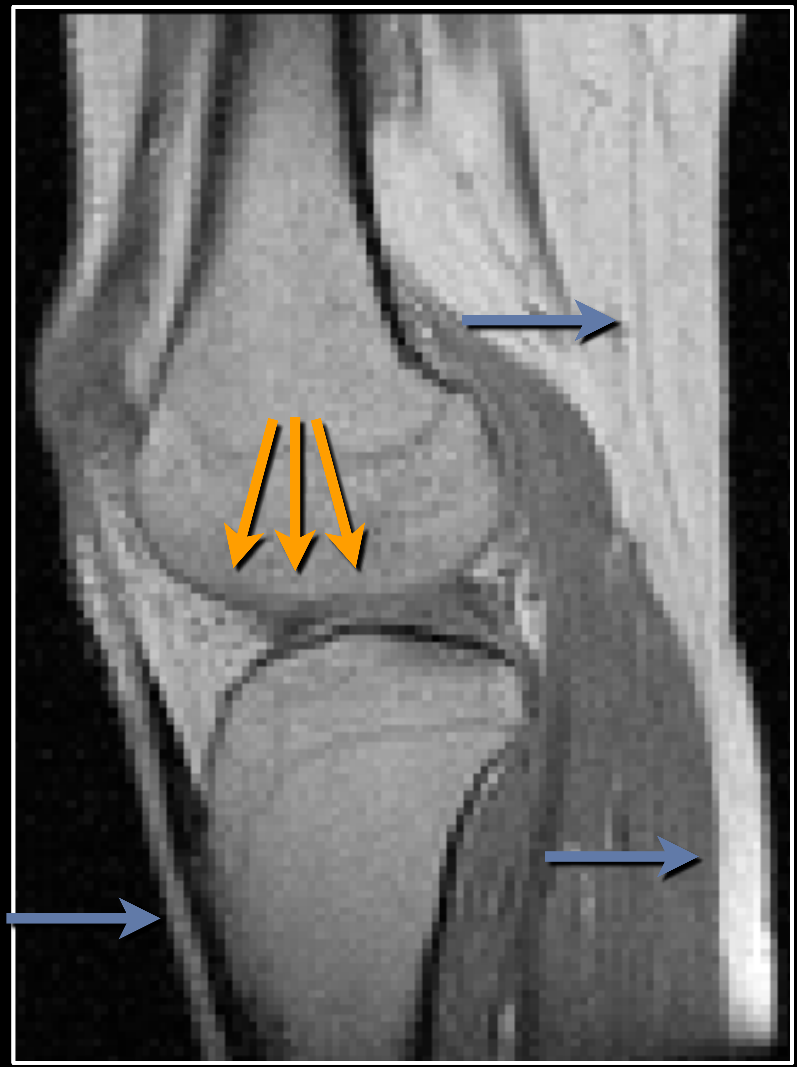


In-Phase	**Opposed-Phase**
→ + → >0	**← + → =0**

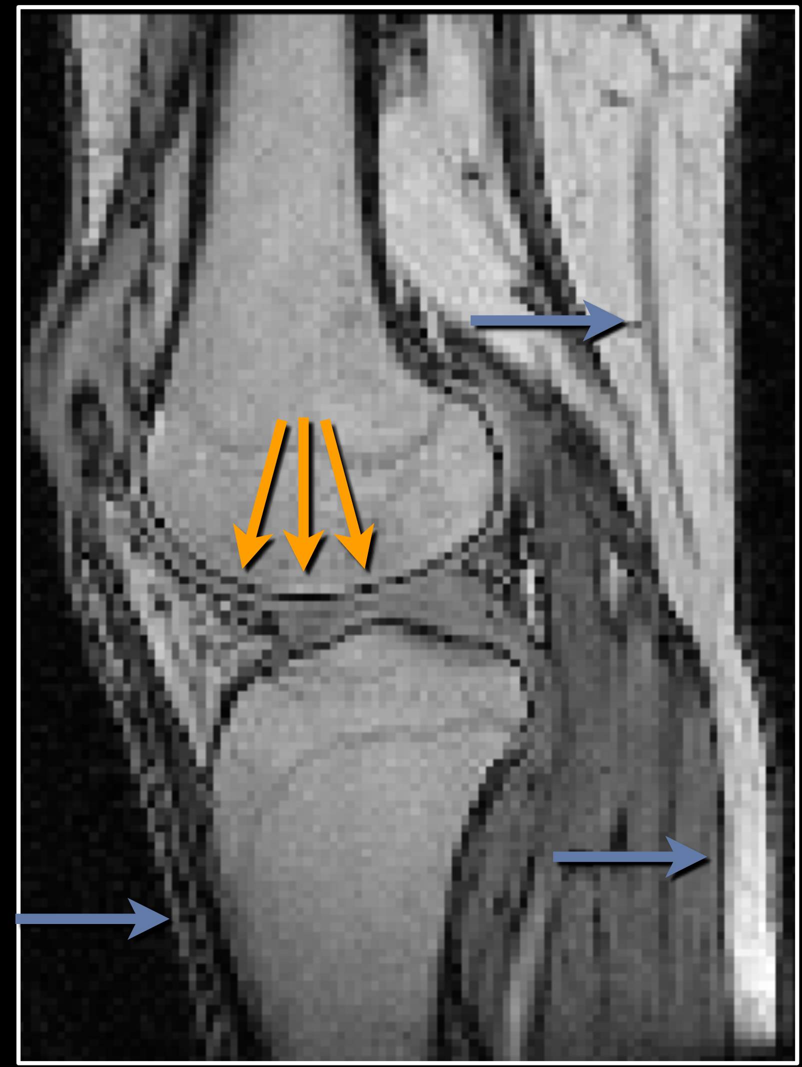
The TE controls the phase between fat and water.

GRE and Fat/Water Phase

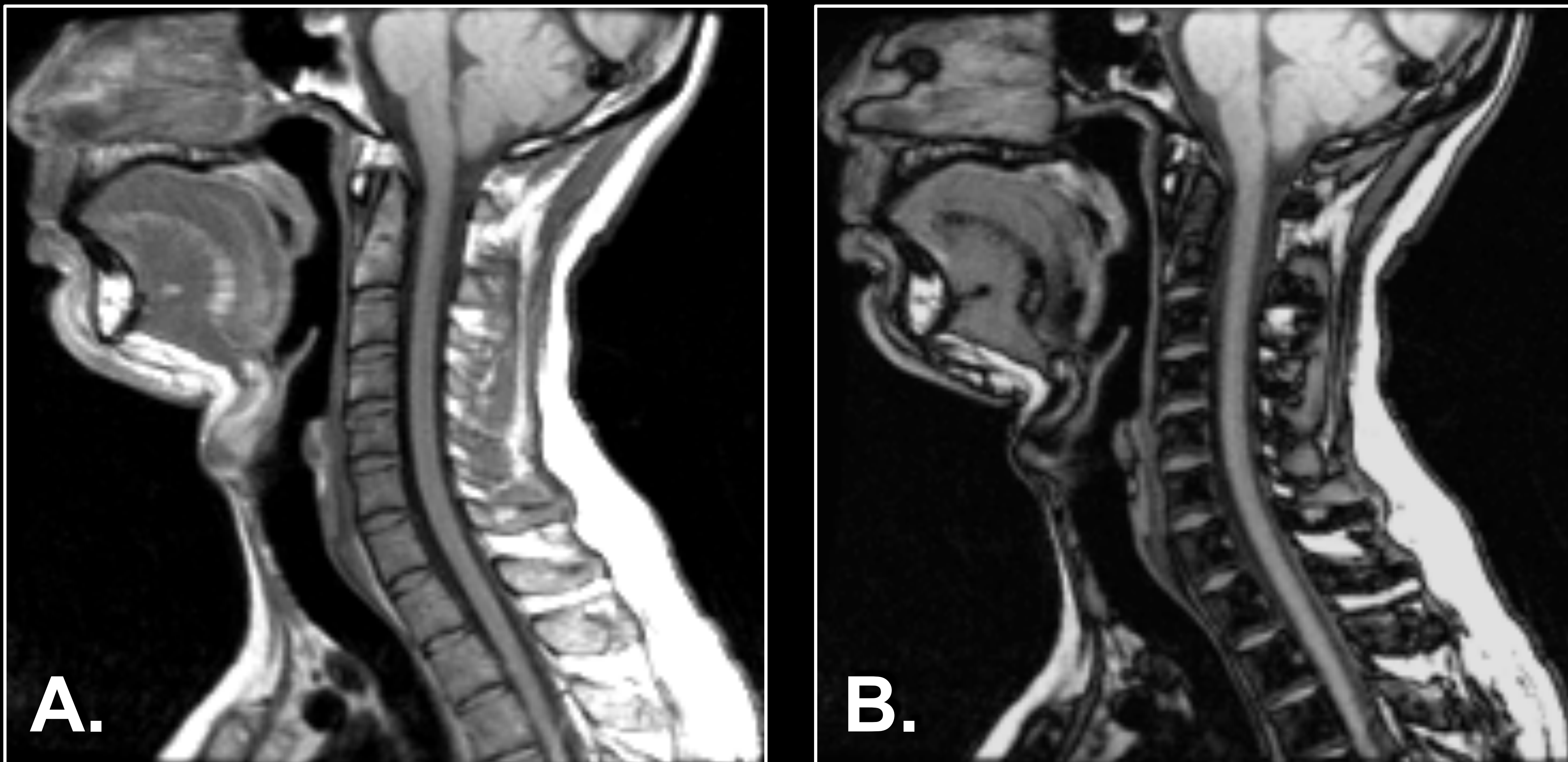
In-Phase



Opposed-Phase



Which image is the in-phase image?



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Images Courtesy of Scott Reeder

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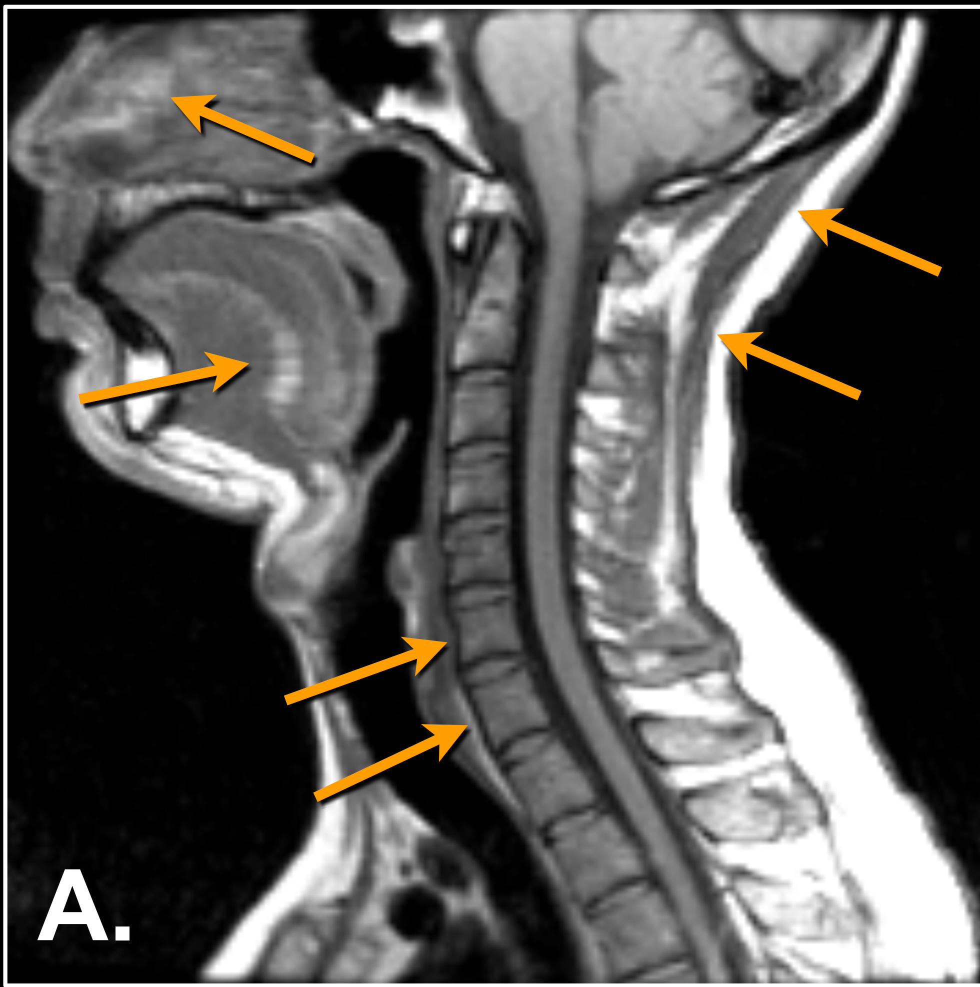
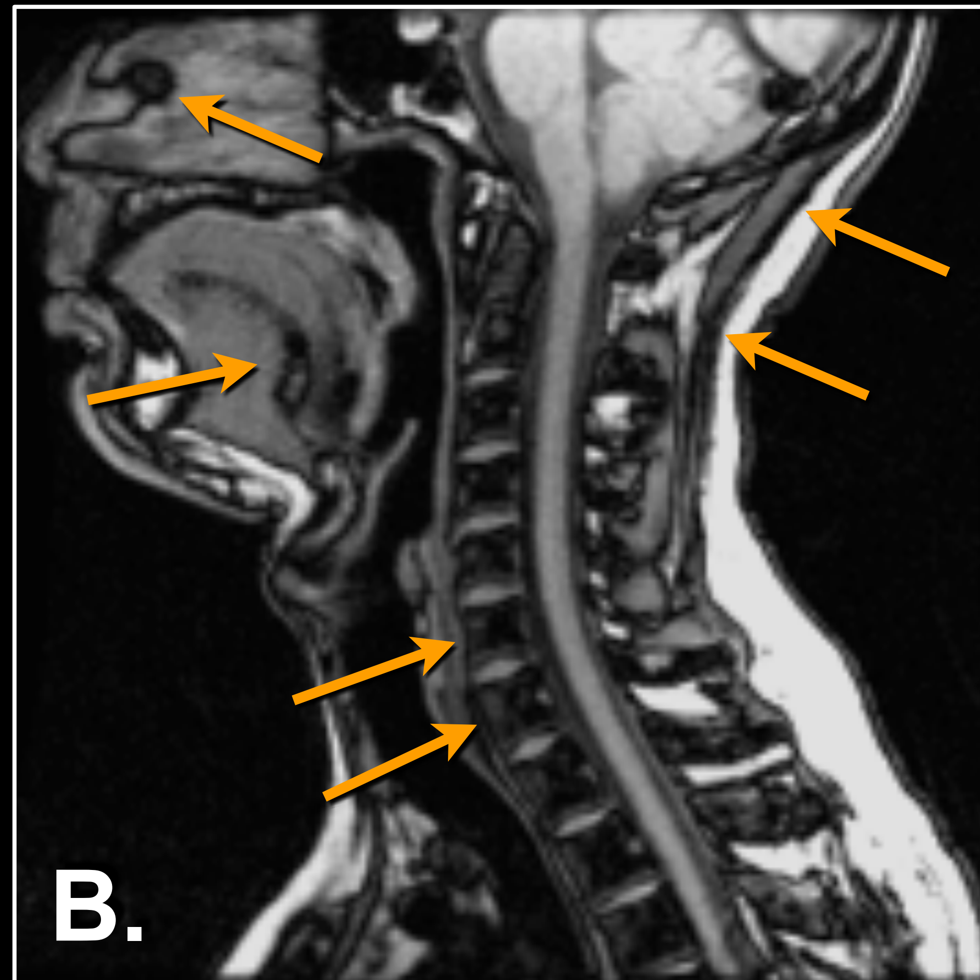
Which image is the in-phase image?



In-Phase



Opposed-Phase

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

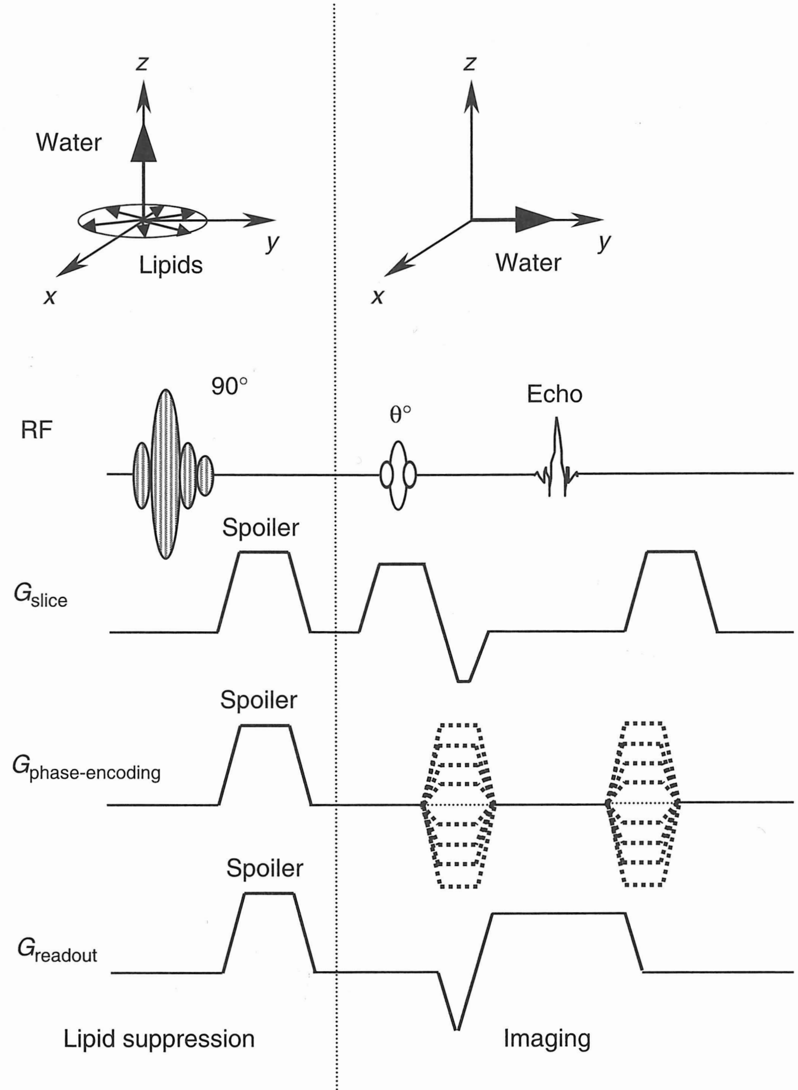
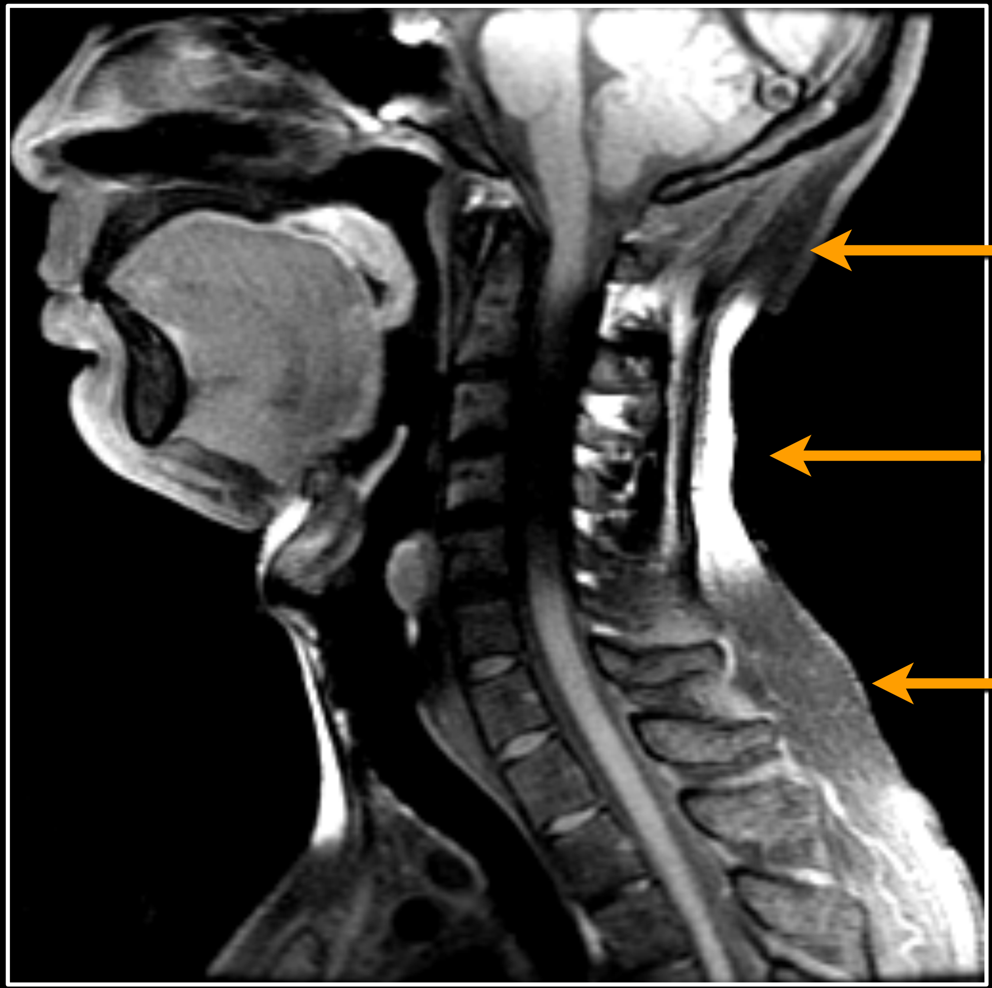


FIGURE 4.15 An example of using a spectrally selective pulse to suppress lipid signals in an imaging sequence. The 90° spectrally selective pulse (shaded area to denote the frequency offset), usually with maximal phase dispersion, is applied ~217 Hz off-resonance with respect to the water resonant frequency 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).

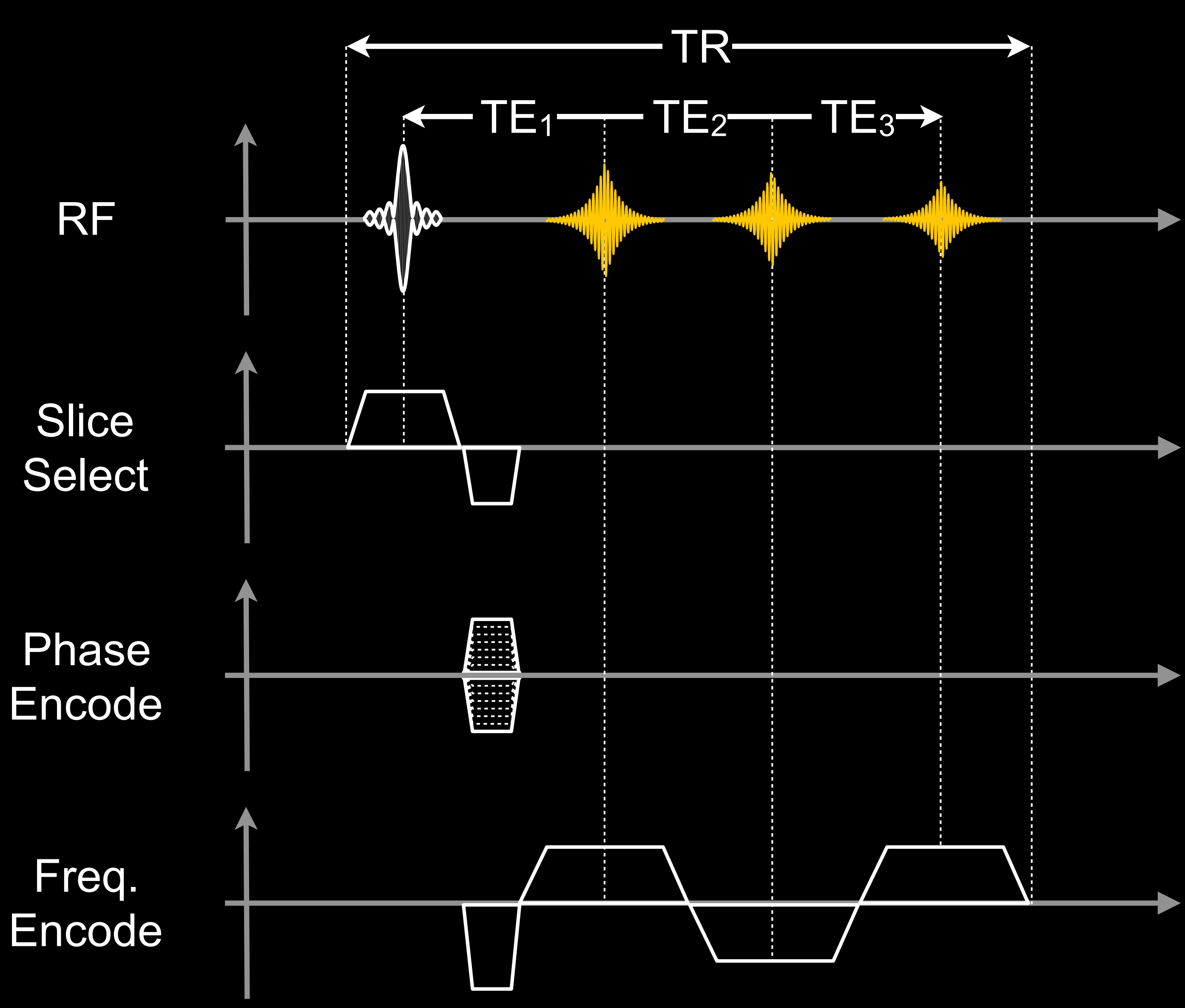
Fat Suppression

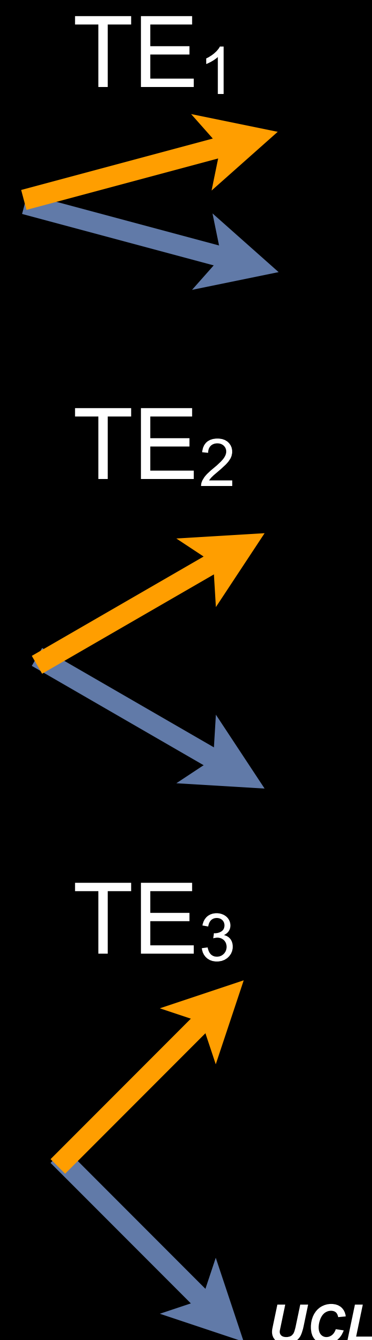


Fat-Sat Image

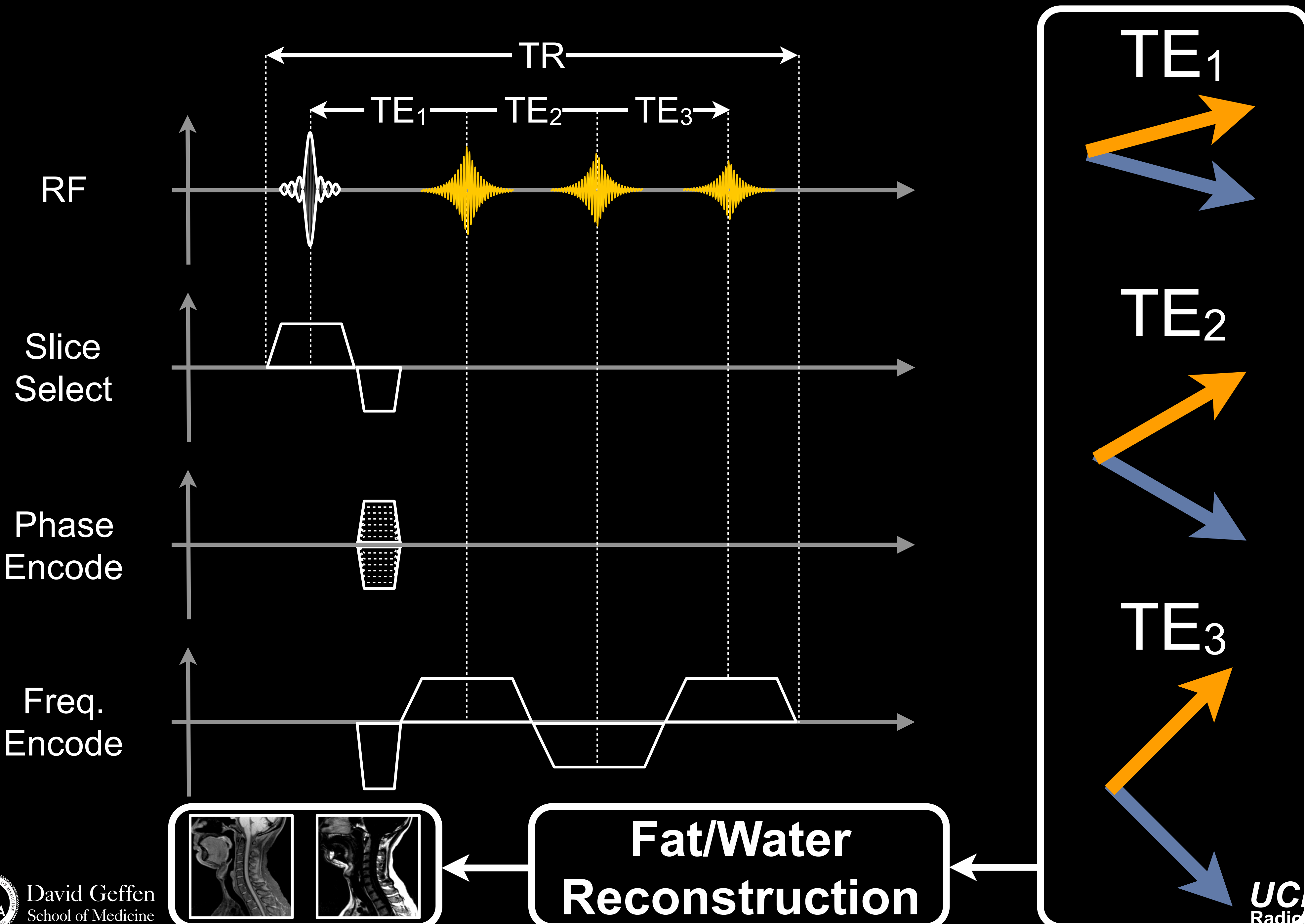
Fat-Sat Can Be Spatially Non-Uniform

GRE & Fat/Water Separation - How?





GRE & Fat/Water Separation - How?



Gradient Echoes & Fat/Water Separation

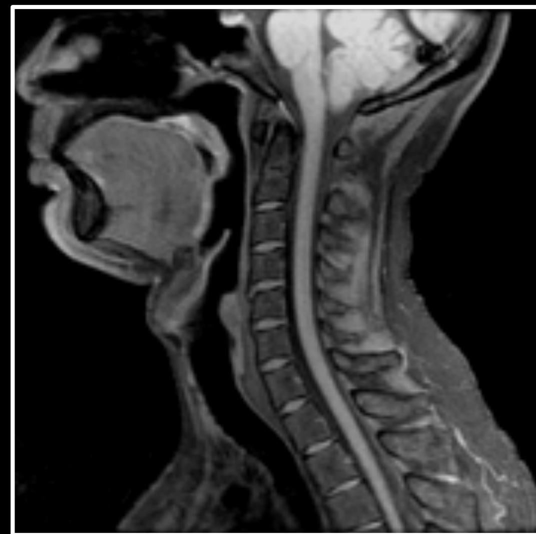
Water Image

Fat Image

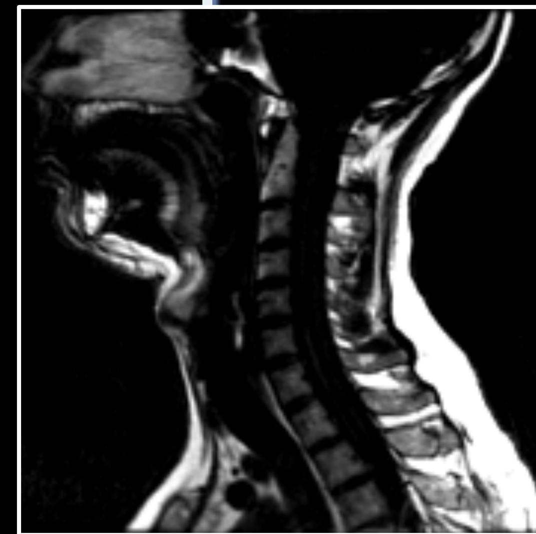
Images Courtesy of Scott Reeder

Gradient Echoes & Fat/Water Separation

Imperfect Fat Sat

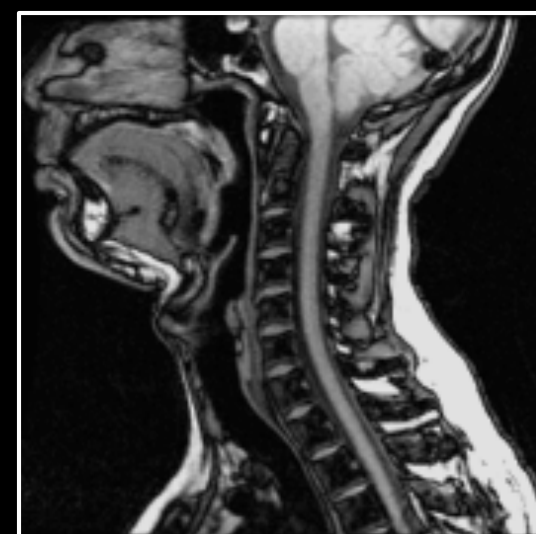


Water Image



Fat Image

In-Phase



Opposed-Phase

Images Courtesy of Dr. Scott Reeder

Thanks

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