Artifacts in MRI

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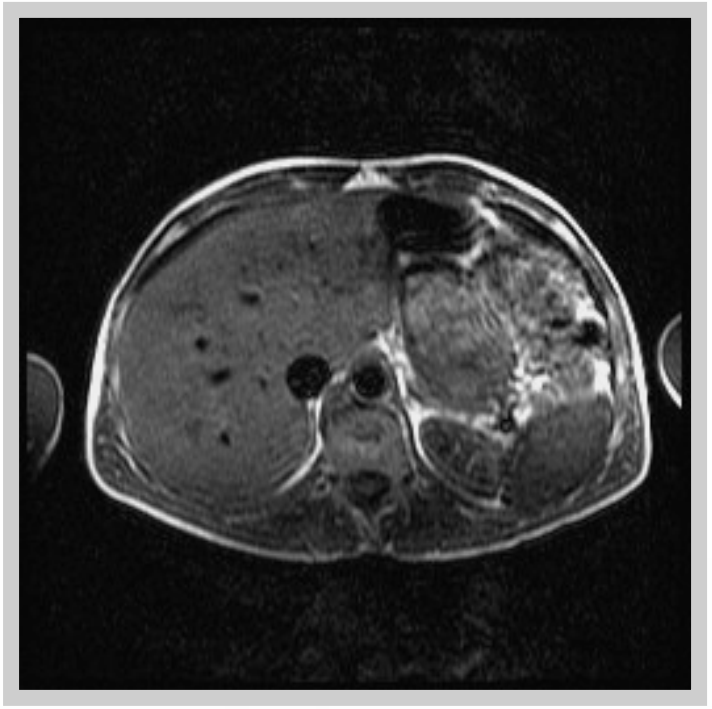
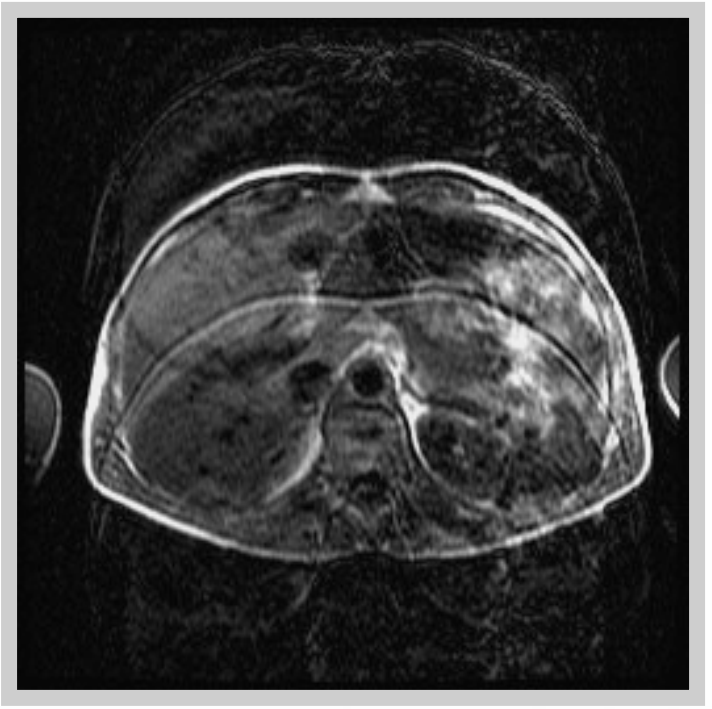
Image artifacts

- Something seen on an image that are not present in reality
  - Or in different position, shape, size…
- MRI has many kinds of artifacts!
  - Because the site is usually located at the basement?
  - Because of complicated imaging physics…

Example of MRI artifacts



Normal image



Ghost image

Visual artifacts

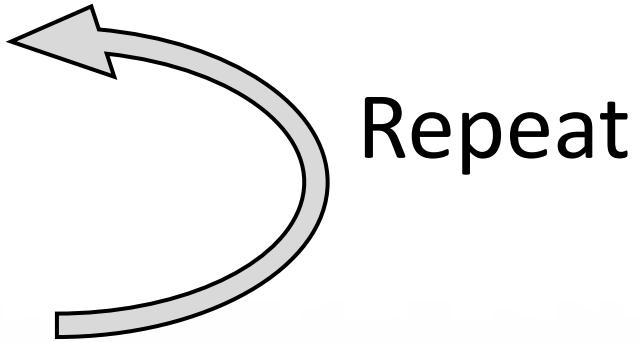
- The visual artifacts may influence interpretation of an MRI.
- So, it is important to avoid, minimize, or at least understand artifacts in MRI.

Why is there artifacts in MRI?

- In the complicated procedure of MR imaging, any signal received in an unexpected way could cause artifacts.
  - Could be tissue-related, signal-processing-related, or technique-related…

Imaging procedure of an MRI

- Magnetization
- RF excitation
- Spatial encoding
- Signal acquisition
- Image reconstruction



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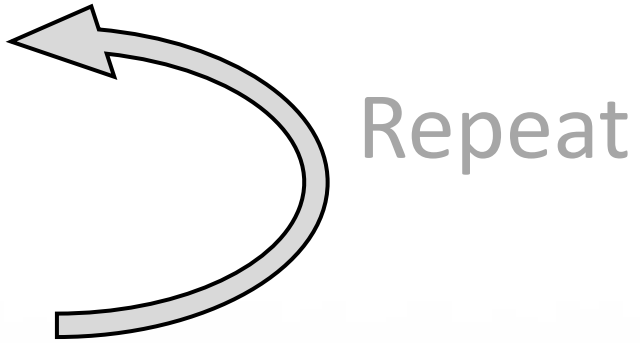

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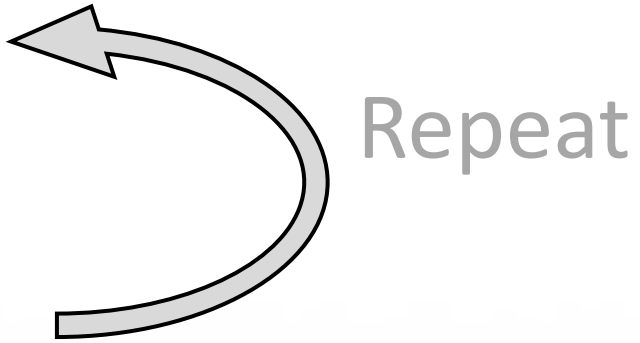


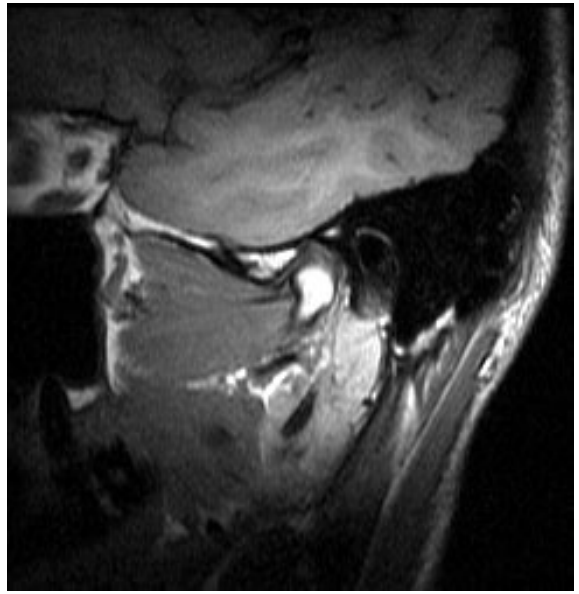
Inhomogeneity in B_0 and B_1 fields

- Inhomogeneous magnetization
- Inhomogeneous signal distribution
- In clinical routine, inhomogeneous signal in MRI can be almost neglected in visual perception, but still affect the quantization results.

Comparison of RF coils

Body coil

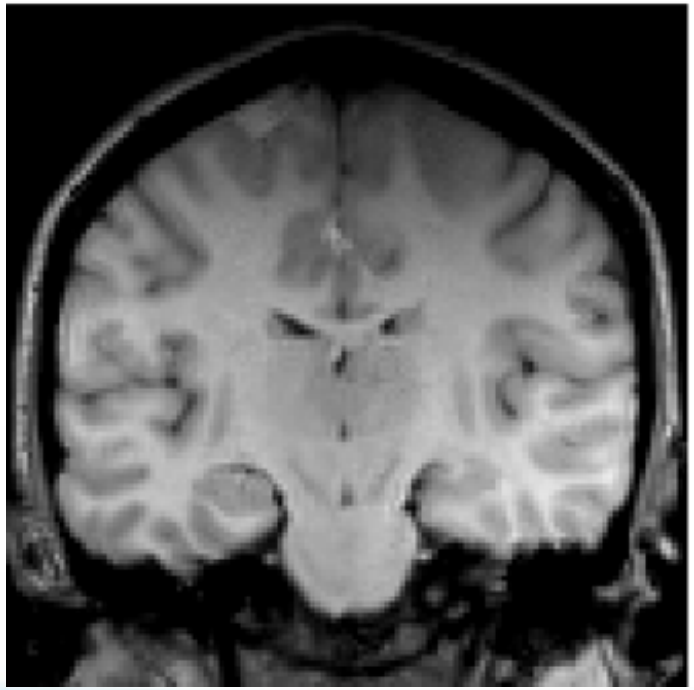
Head coil



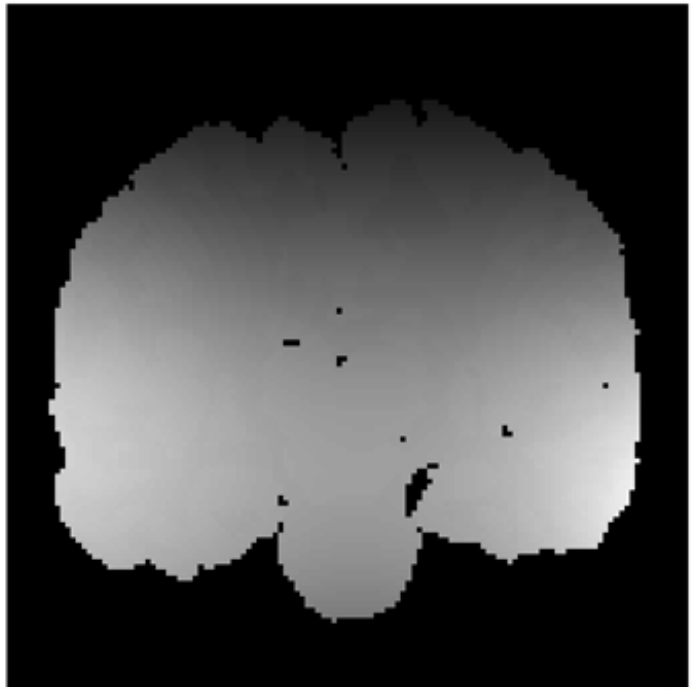
3” Surface coil

Intensity inhomogeneity in MRI

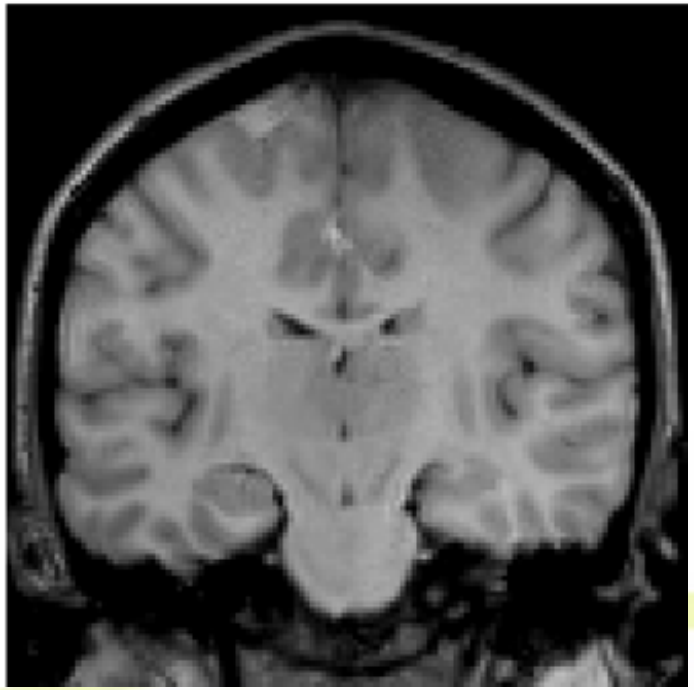
Original image



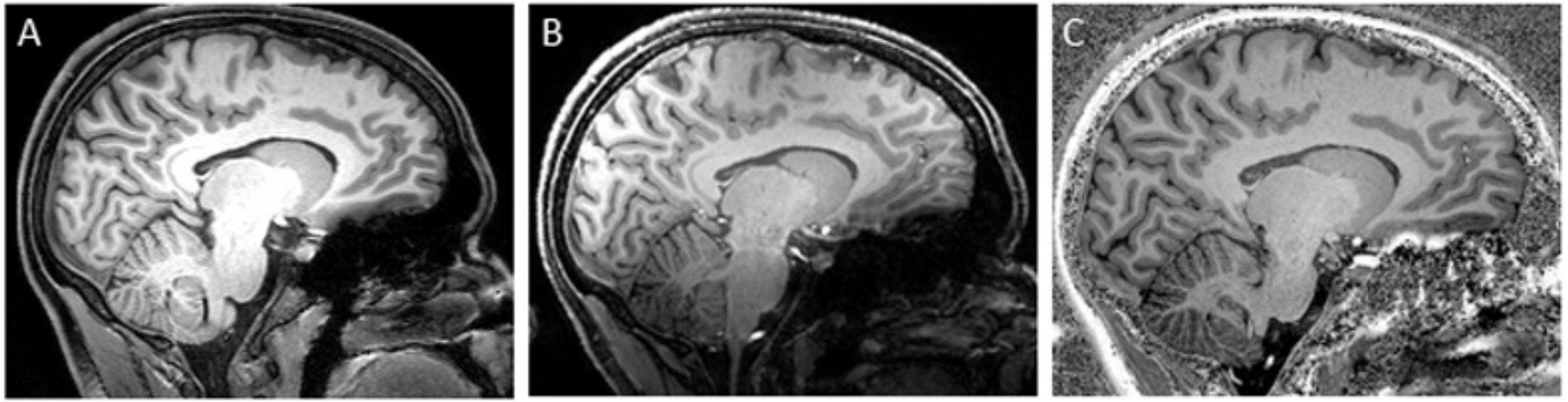
Inhomogeneity field



Corrected image



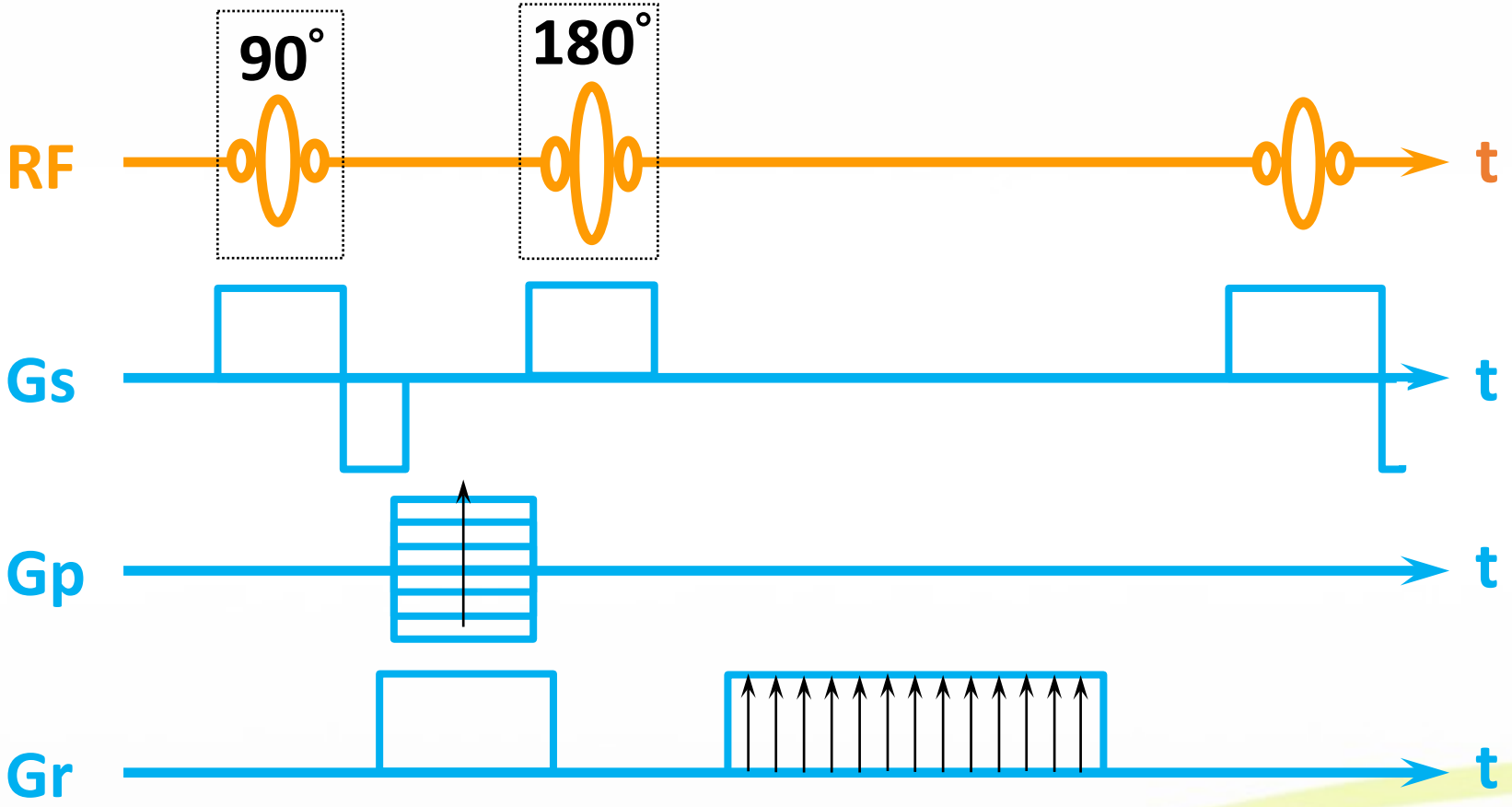
Intensity inhomogeneity at high fields



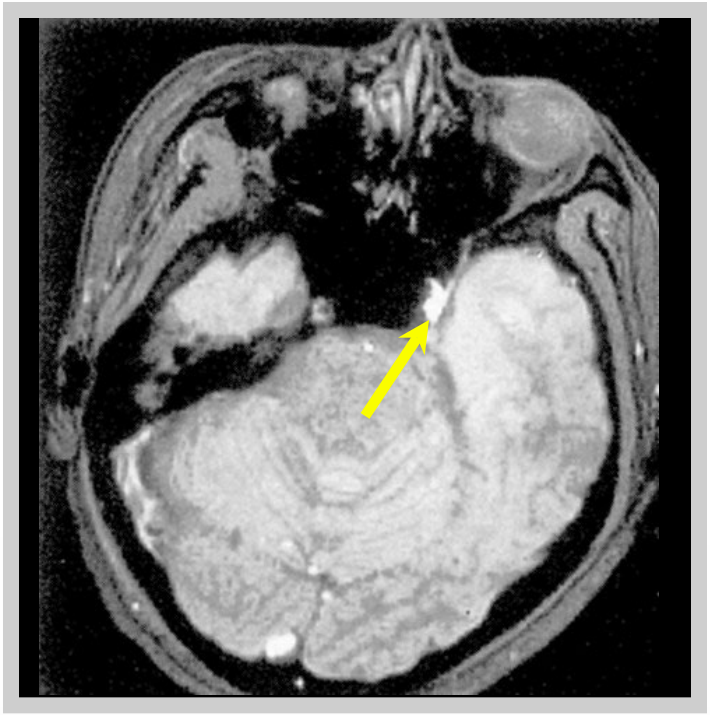
RF-related artifacts: flow void

- Spin-echo sequence: 90° + 180° pulses
- In case of blood flow, these two pulses might tag different portions of spins.
  - Depending on flow velocity and direction

2D Spin echo



Bright blood and dark/black blood



Bright blood in gradient echo

Dark blood in spin echo

Flow void in spin echo

- 90° - 180° - data sampling
- Blood excited by 90° RF pulse could leave the slice during inversion pulse.
  - Not refocused spins → signal drop
- Low signal for through-plane flow (flow void)

Imaging procedure of an MRI

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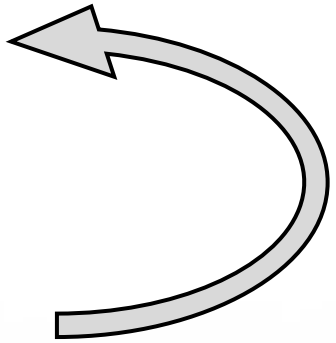


Repeat

Artifacts of inaccurate spatial encoding

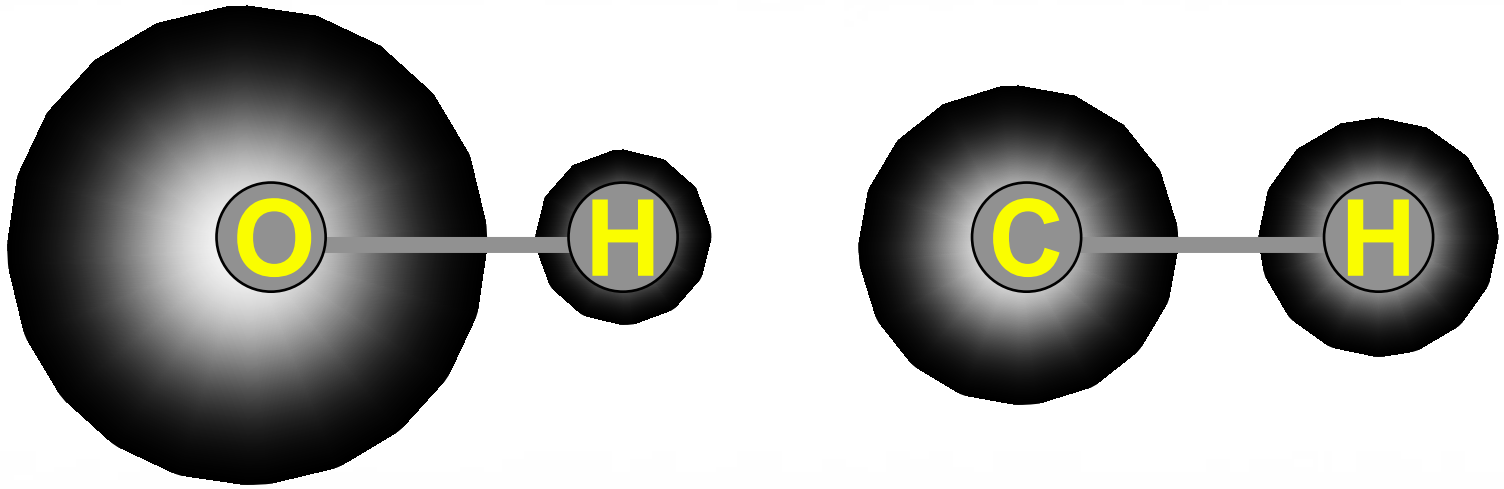
- Magnetic field – Resonant frequency – Location
  - Linear relationship
- Unexpected change in frequency may cause positioning error.
  - Chemical shift
  - Susceptibility

Chemical shift

- The resonant frequencies of water and fat are slightly different!
  - Due to different molecular environments of nuclei, which are shielded by electron clouds

Chemical shift of ^{1}H nuclei

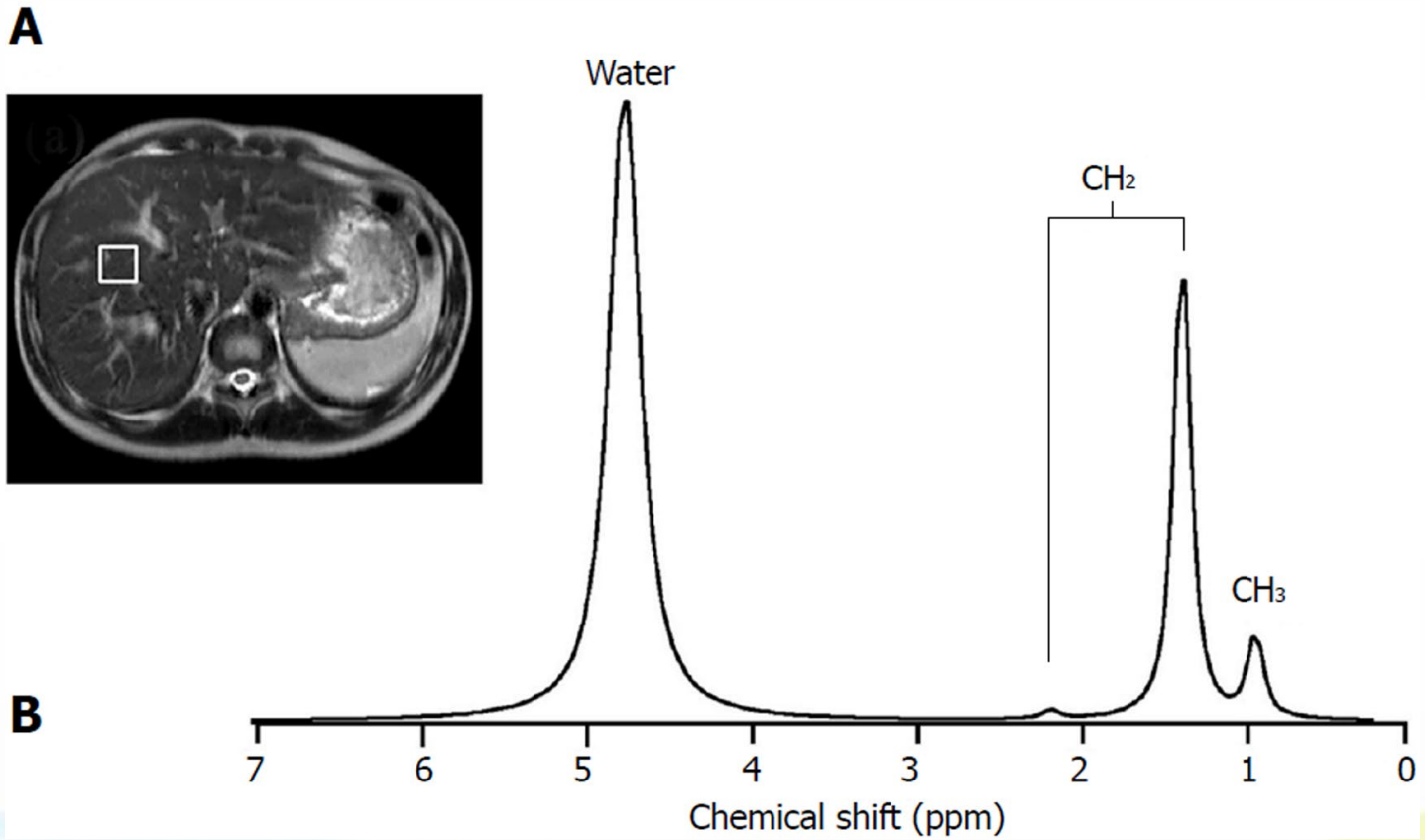
O: stronger affinity to electrons pull away more electron clouds from H



Water

Fat

MR spectroscopy of protons



Pasanta D, et al. Body mass index and its effects on liver fat content in overweight and obese young adults by proton magnetic resonance spectroscopy technique. World J Hepatol 2018; 10(12): 924-933

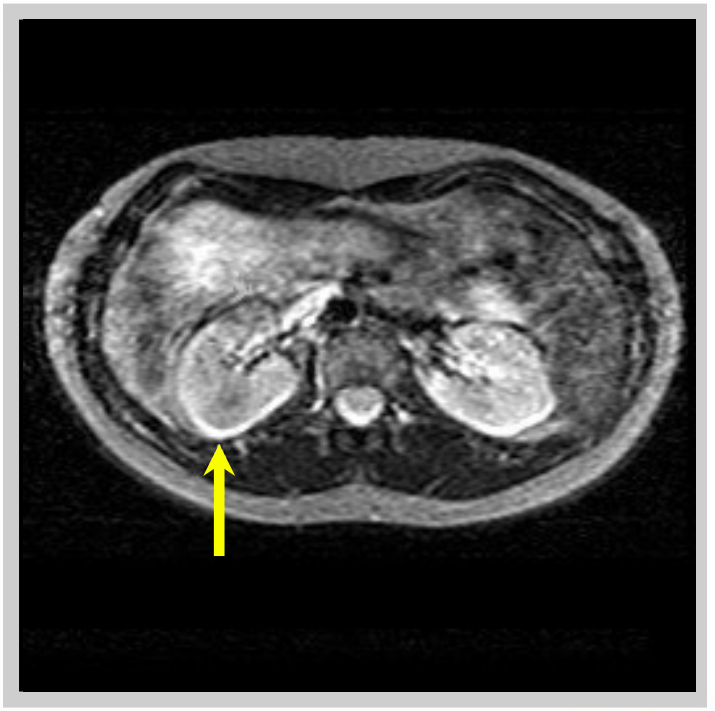
Reference: TMS (四甲基硅烷)

Chemical shift artifact

- The resonant frequencies of water and fat are intrinsically different.
  - By 3.35-3.5 ppm
- Shift in resonant **frequency** leads to shift in positioning along **frequency** encoding direction.

Chemical shift artifact

Horizontal freq. encoding

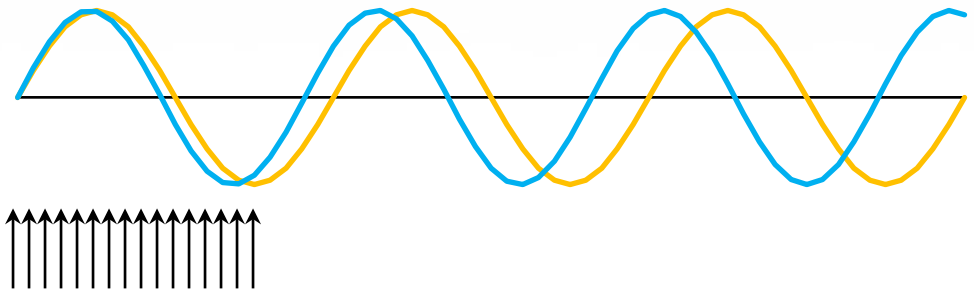


Vertical freq. encoding

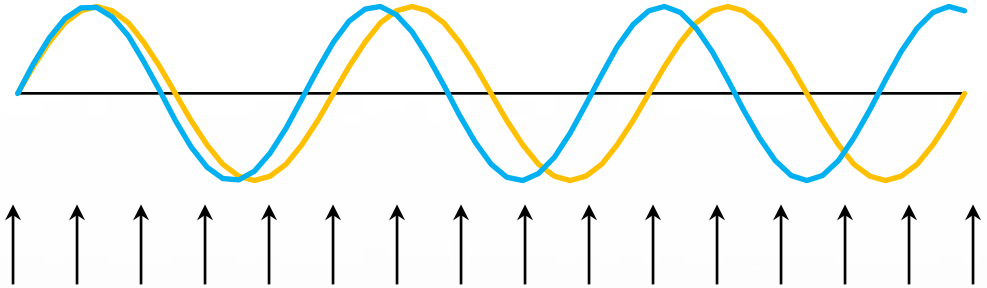
Spatial shifting in chemical shift artifact

- The distance is directly related to sampling frequency.
- Faster collection of data (higher fs) …
  - reduce the difference of water and fat in waveform
  - less spatial shift

Chemical shift artifact and sampling



Fast sampling



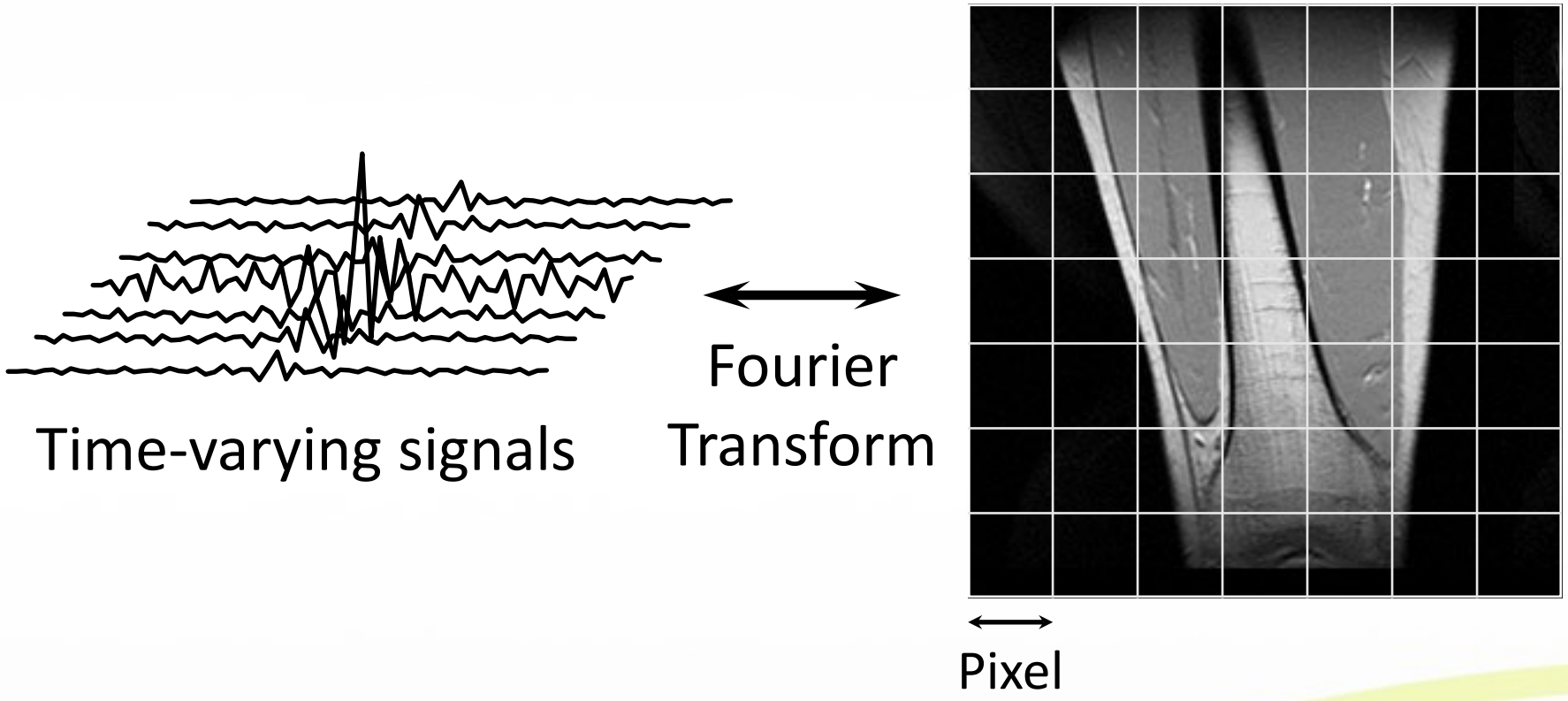
Slow sampling

Spatial shifting in chemical shift artifact

- Pixel bandwidth (BW/Px): bandwidth distributed to each pixel
  - Total BW divided by pixel number in FE direction
- Chemical shift (in unit of pixels):

$$\frac{\Delta f}{\text{Pixel bandwidth}}$$

Image = spectrum

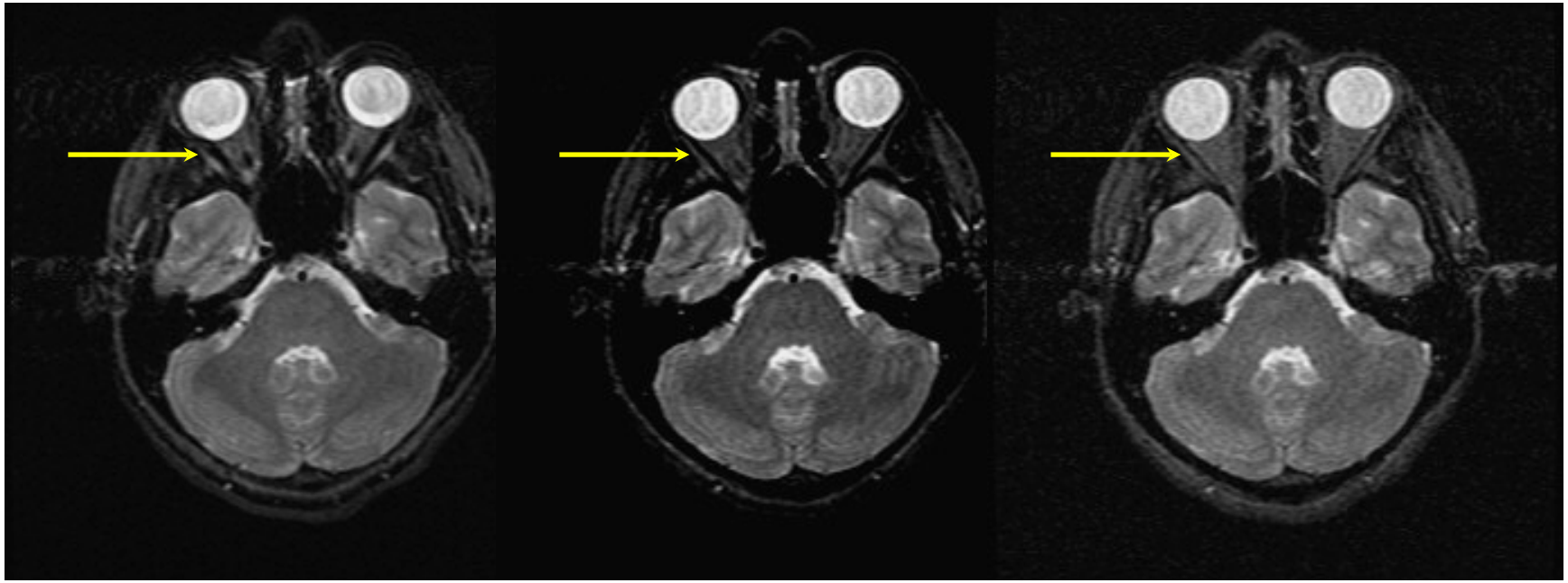


Each pixel in image corresponds to a section of spectrum.

Spatial shifting in chemical shift artifact

- Difference in water-fat frequency: ~220 Hz @1.5 Tesla
- Given fs = 32 kHz for a 256 matrix,
  - Pixel bandwidth = 32k/256 = 125 Hz/Pixel
  - Chemical shift = 220/125 ~ 2 pixels

Chemical shift artifact and bandwidth



32 Hz/Pixel 64 Hz/Pixel 128 Hz/Pixel

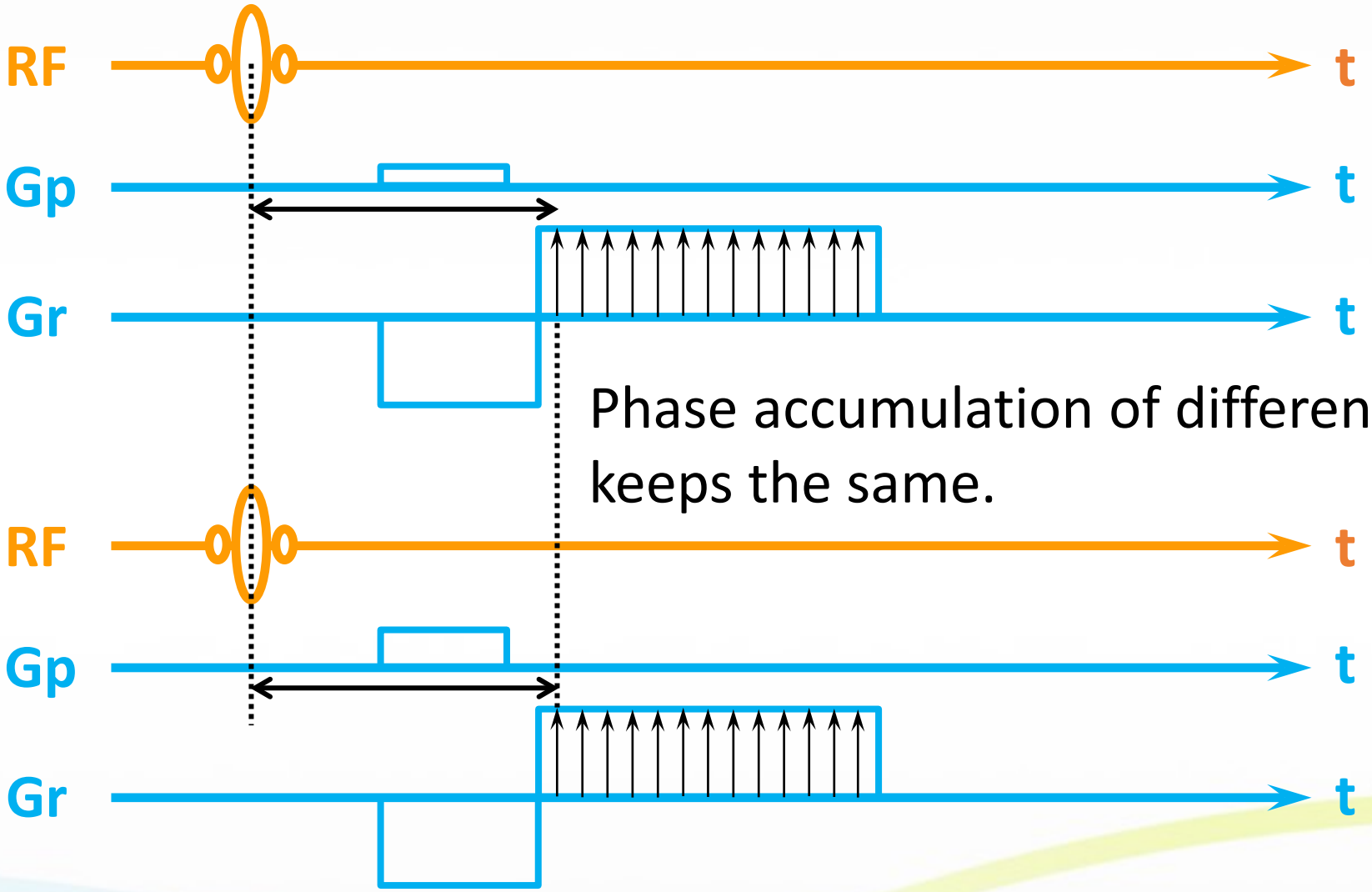
Also note SNR difference

Chemical shift artifact and SNR

- Higher sampling frequency: smaller shift but lower SNR
- Slower sampling frequency: higher SNR but larger shift

Frequency and phase encoding

- So far, chemical shift is only shown in frequency encoding direction.
- No chemical shift in phase encoding direction!
  - Phase accumulation due to chemical shift is not changed by phase encoding gradients



Phase accumulation of different PE keeps the same.

Chemical shift of fat

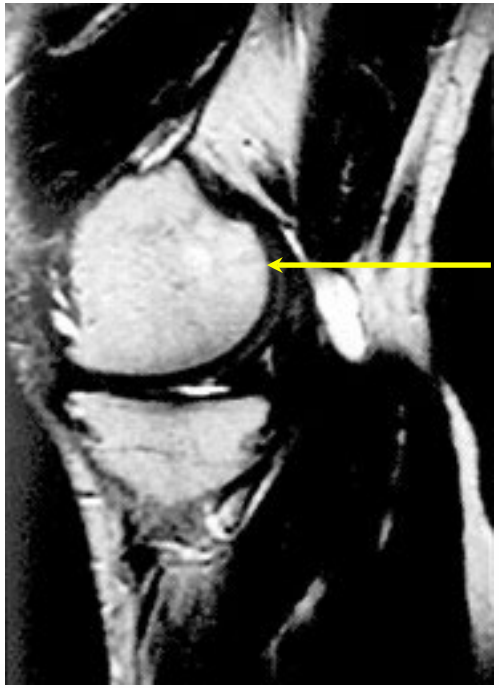
- Fat usually appears in high intensity, especially in T1WI
  - T1/T2 = **260**/80 ms @ 1.5 Tesla
- Bright and shifted lipid tissue could interfere clinical diagnosis

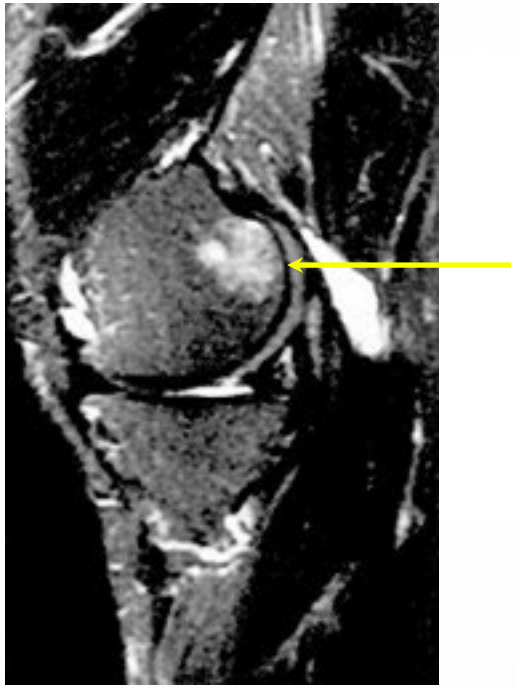
Solutions

- To remove fat signals
  - Fat suppression (Fat SAT)

- To preserve fat signals as comparison
  - Fat-only and/or water-only image

Before and after fat suppression





Bone tumor can only be observed after fat suppression.

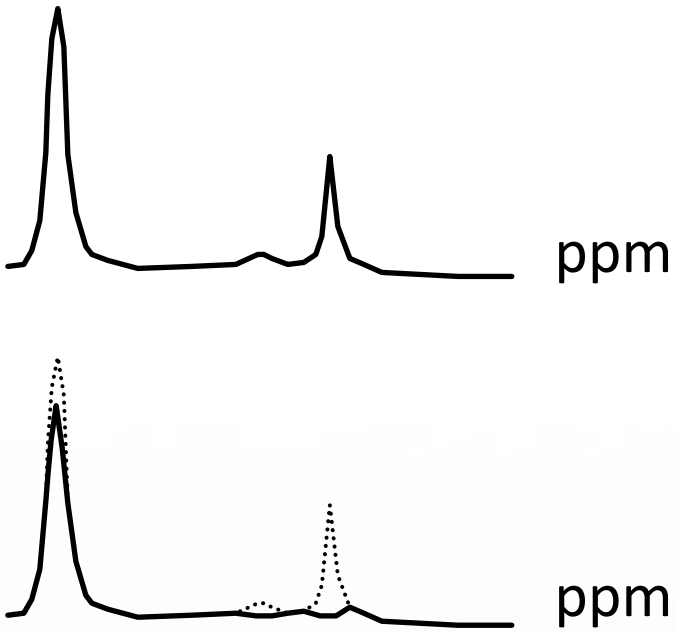
How to do fat suppression?

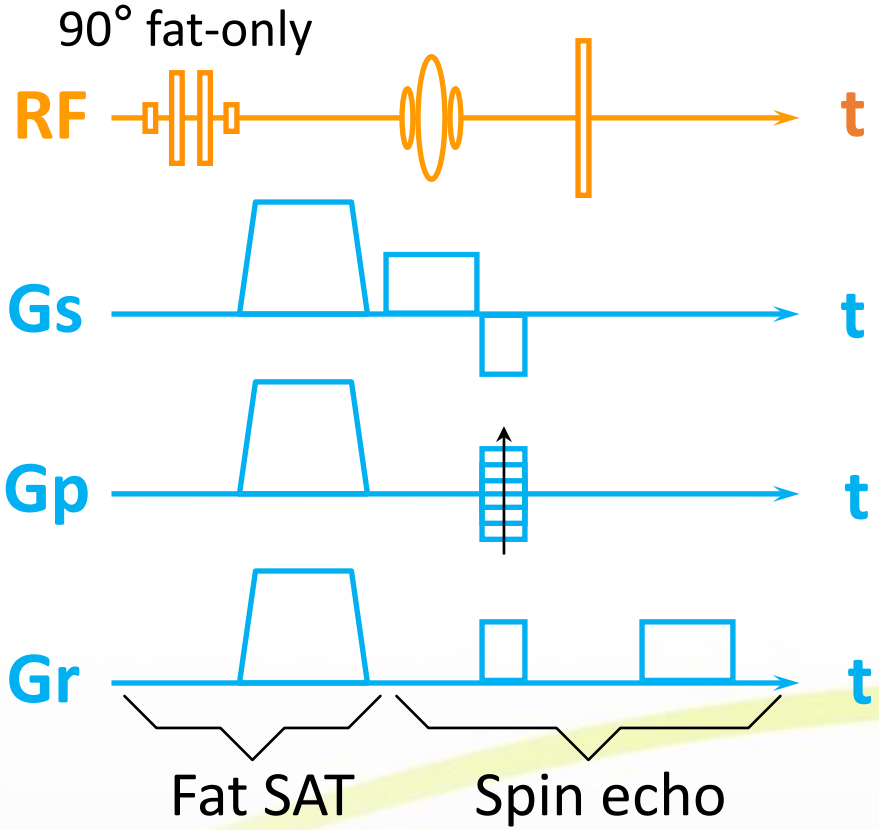
- Making use of the facts that induce this artifact
  - Difference in resonant frequency

CHEmical Shift Selective method (CHESS)

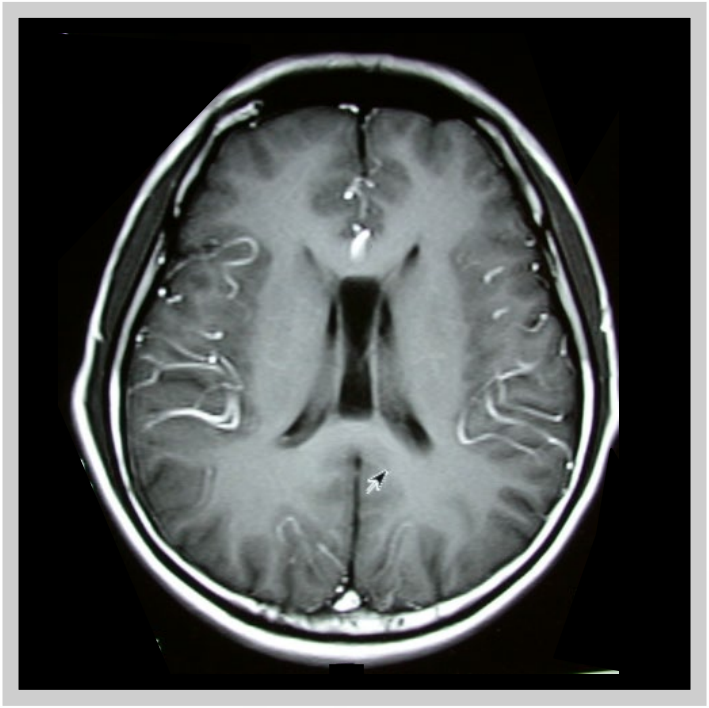
- Frequency-selective 90° pulse: excite fat tissue only and leave water intact
- Saturate the fat signal immediately by applying strong gradients
  - Spoiler gradient

CHESS pulse sequence

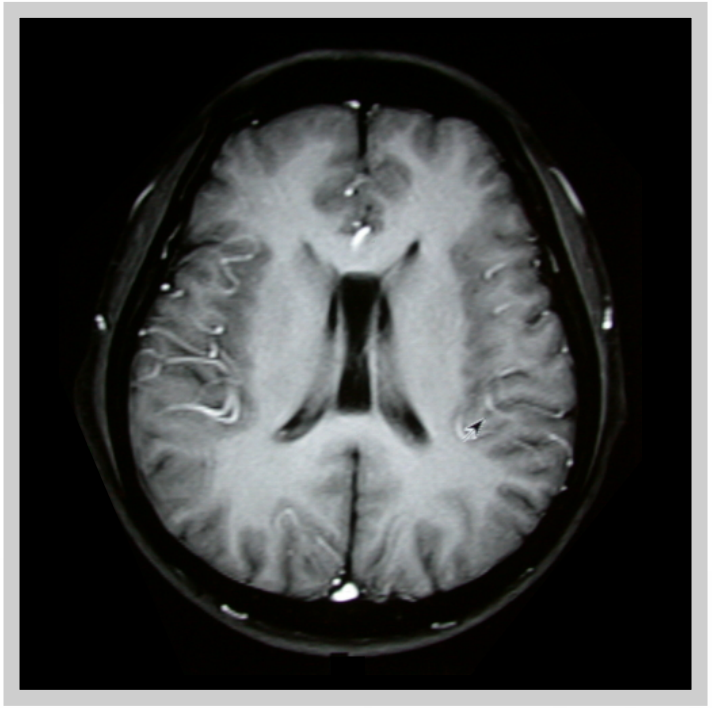




Fat suppression using CHESS pulse



No Fat SAT

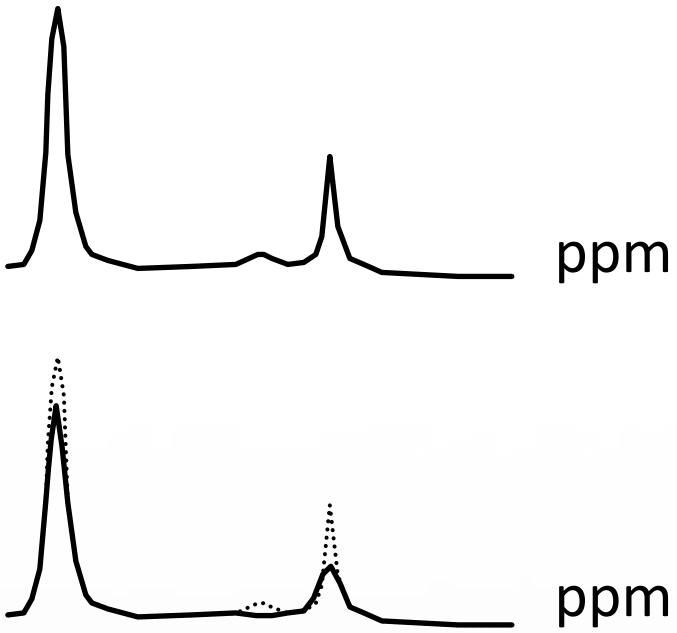


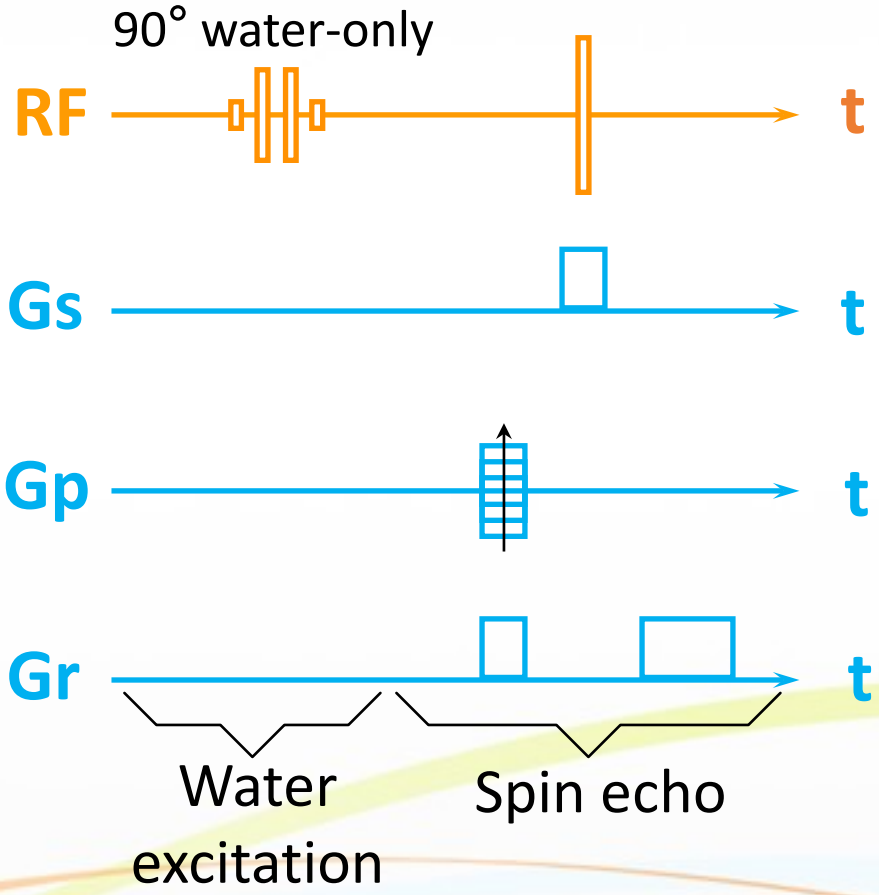
With Fat SAT

CHESS: water excitation

- Frequency-selective 90° pulse: excite water only (instead of fat tissue)
- Collect signal for imaging directly
- Narrow BW is required
  - Or fat tissue gets partially excited

CHESS: water excitation

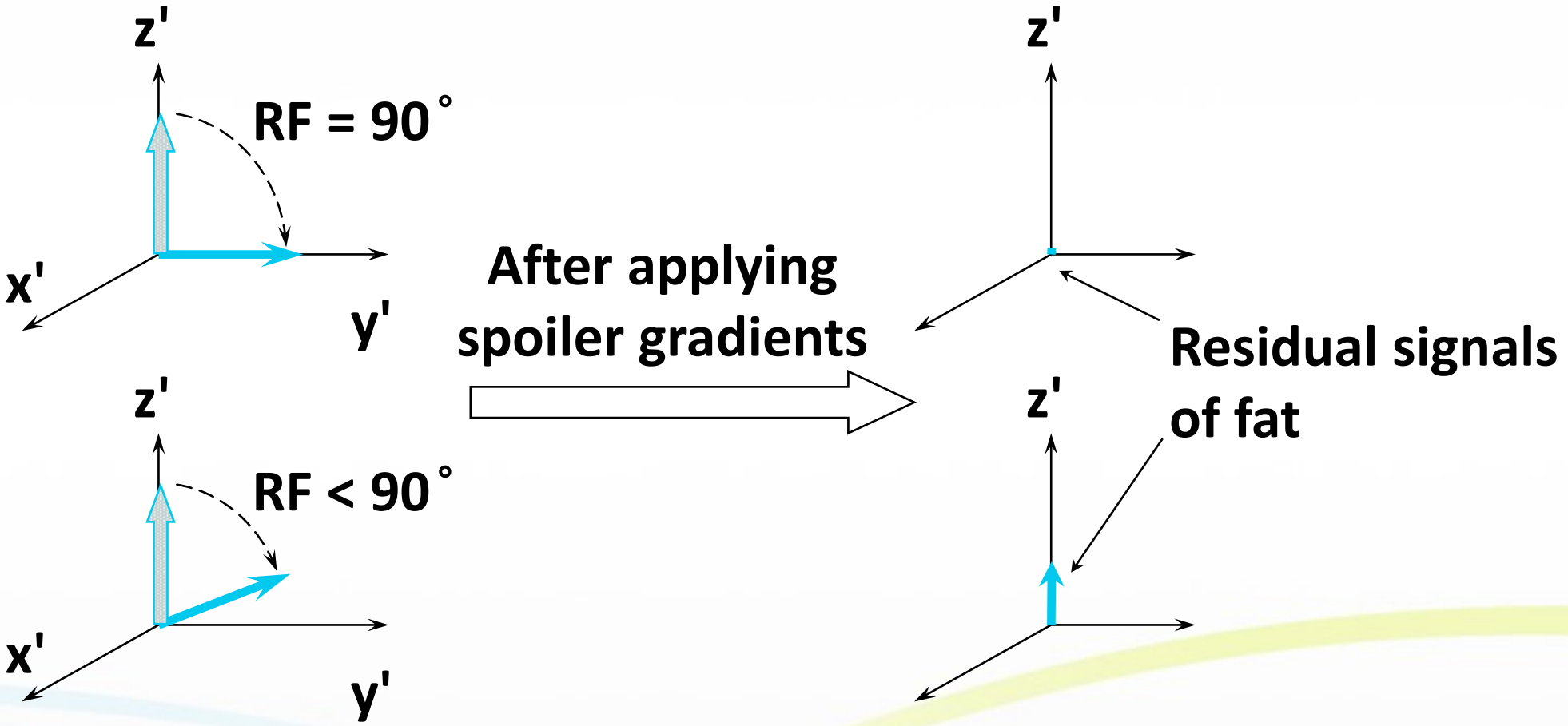




Requirement for B_0 and B_1 fields

- B_1 field has to be homogeneous for uniform excitation
  - Homogeneous volume coil for excitation
- B_0 field has to be homogeneous for uniform resonant frequency
  - Shimming

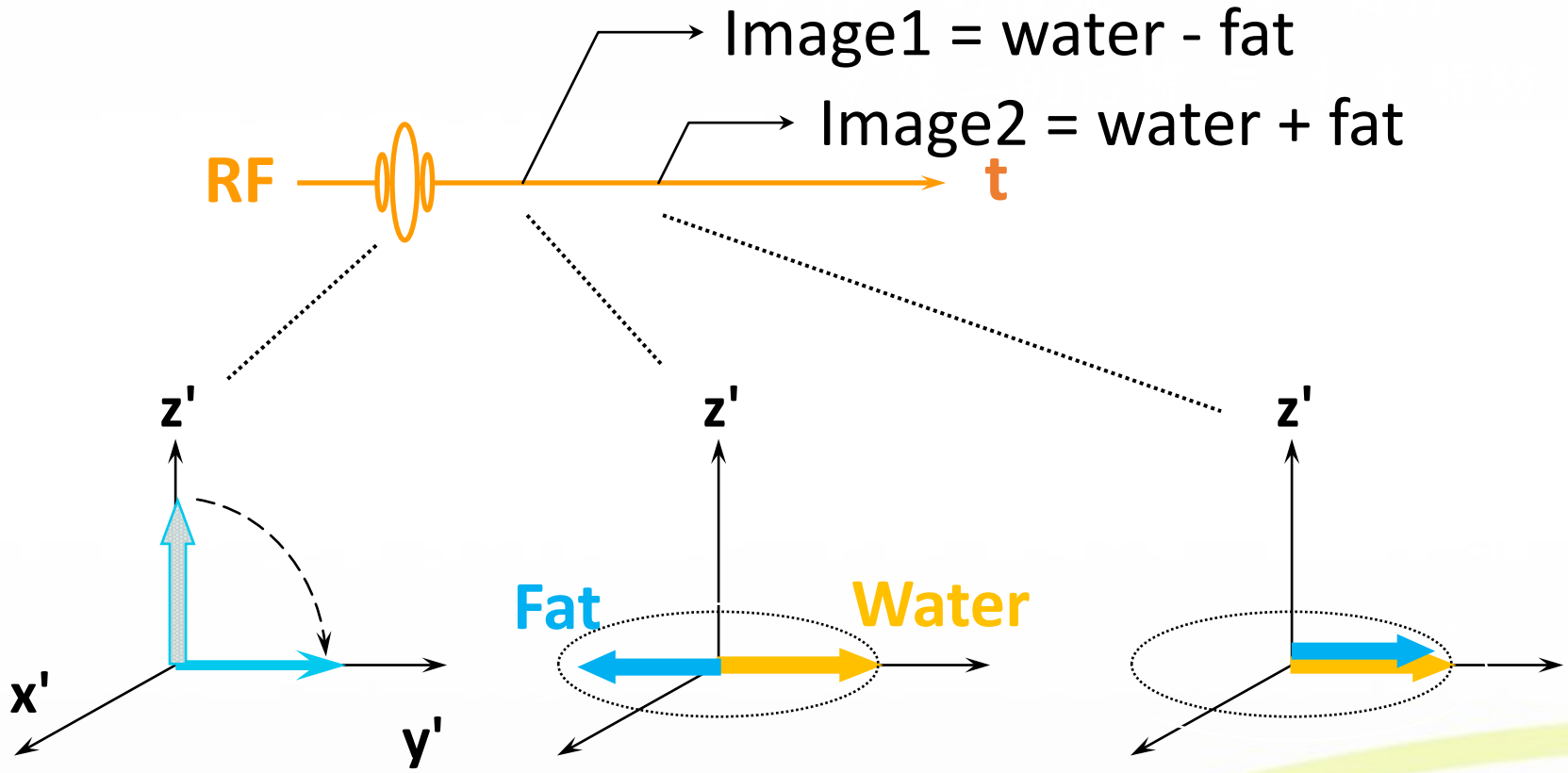
Homogeneity in B_1 field



In-phase and out-of-phase image

- Phase effects of chemical shift
- Adjusting TE to acquire in-phase (water + fat) and out-of-phase (water - fat) image
  - Water image: in-phase + out-of-phase
  - Fat image: in-phase – out-of-phase

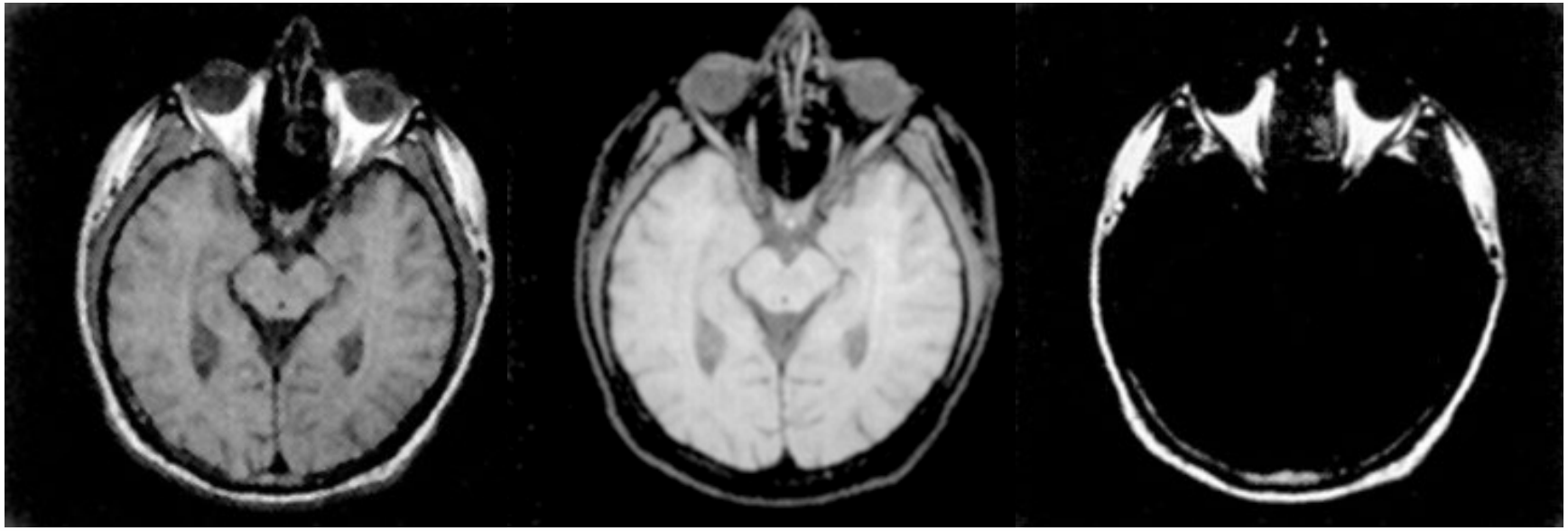
In-phase and out-of-phase



Dixon method

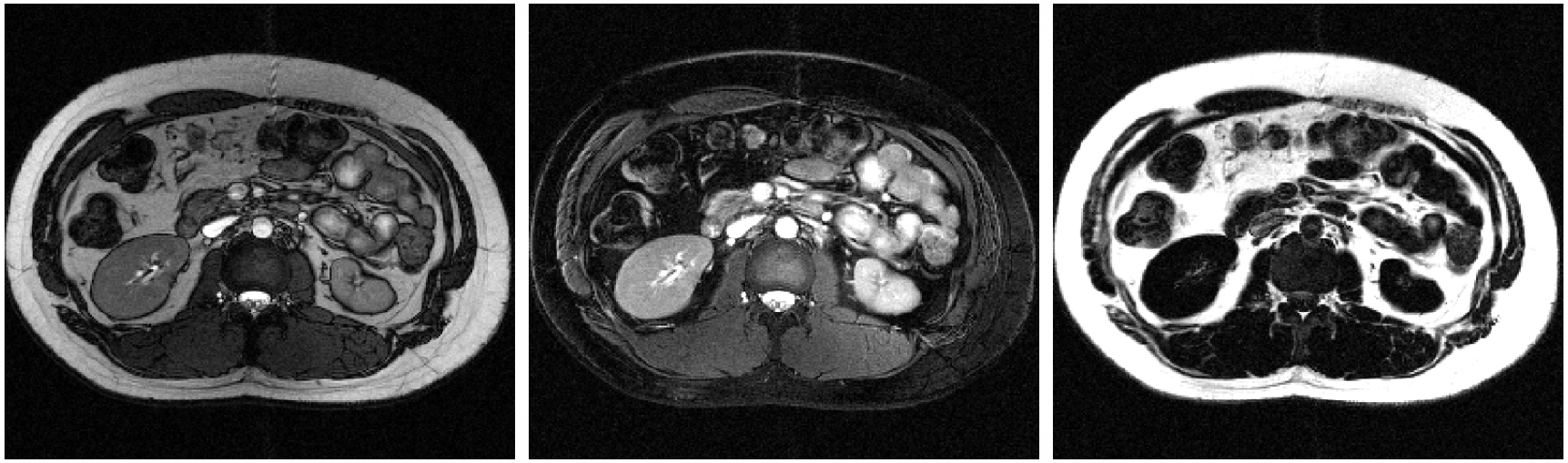
- Sum-difference problem
- Homogeneous B_0 field is required
- Double scan time: in/out-phase images

Water and fat images: brain



In-phase Water image Fat image

Water and fat images: abdomen



Out-phase Water image Fat image

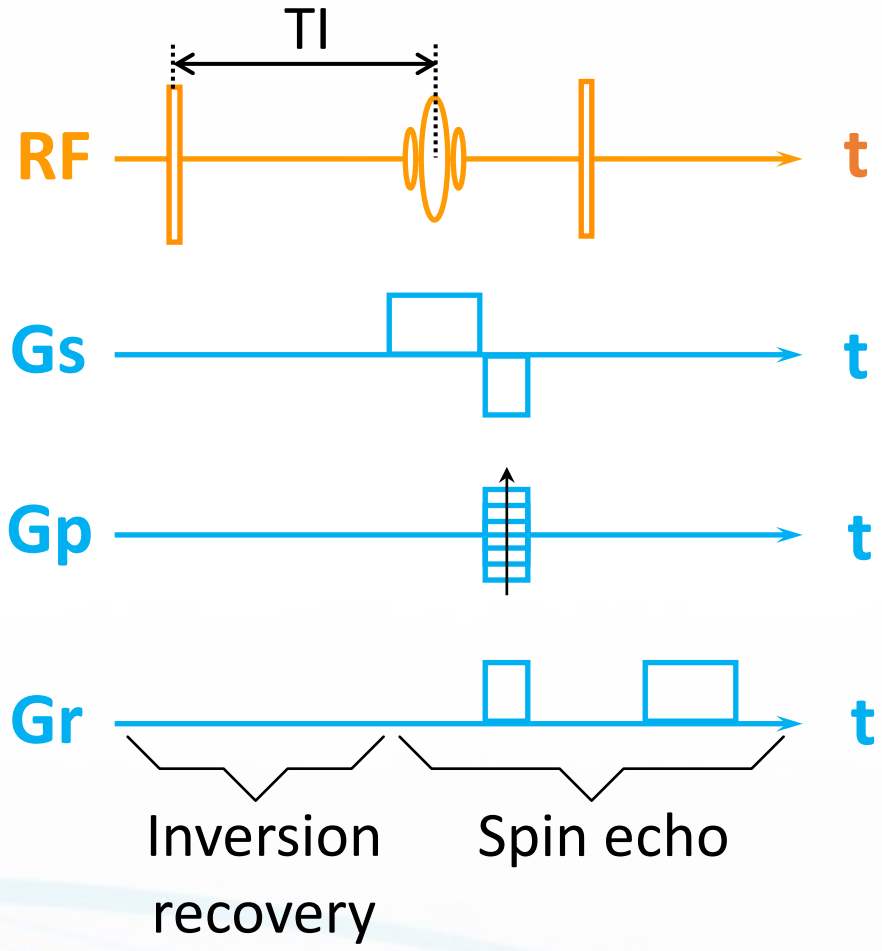
How to do fat suppression?

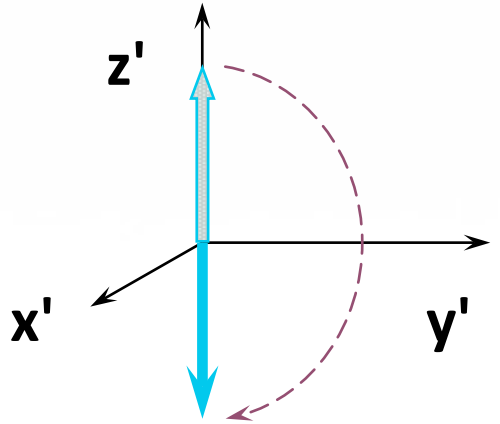
- Making use of the facts that induce this artifact
  - Difference in resonant frequency
  - Difference in T1

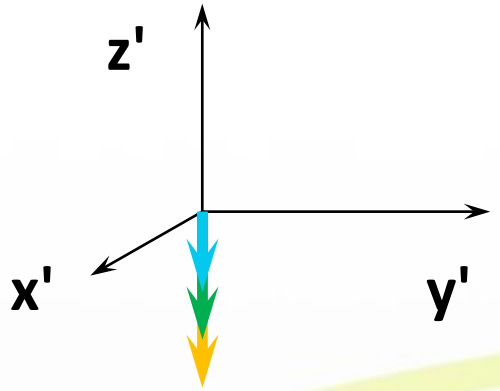
Short TI Recovery (STIR)

- Inversion pulse is applied first to invert magnetization of all tissues
- T1 recovery…
- Acquire the image when fat signal is recovered to the null point
  - Inversion time (TI): 160-180 ms @ 1.5 Tesla

STIR







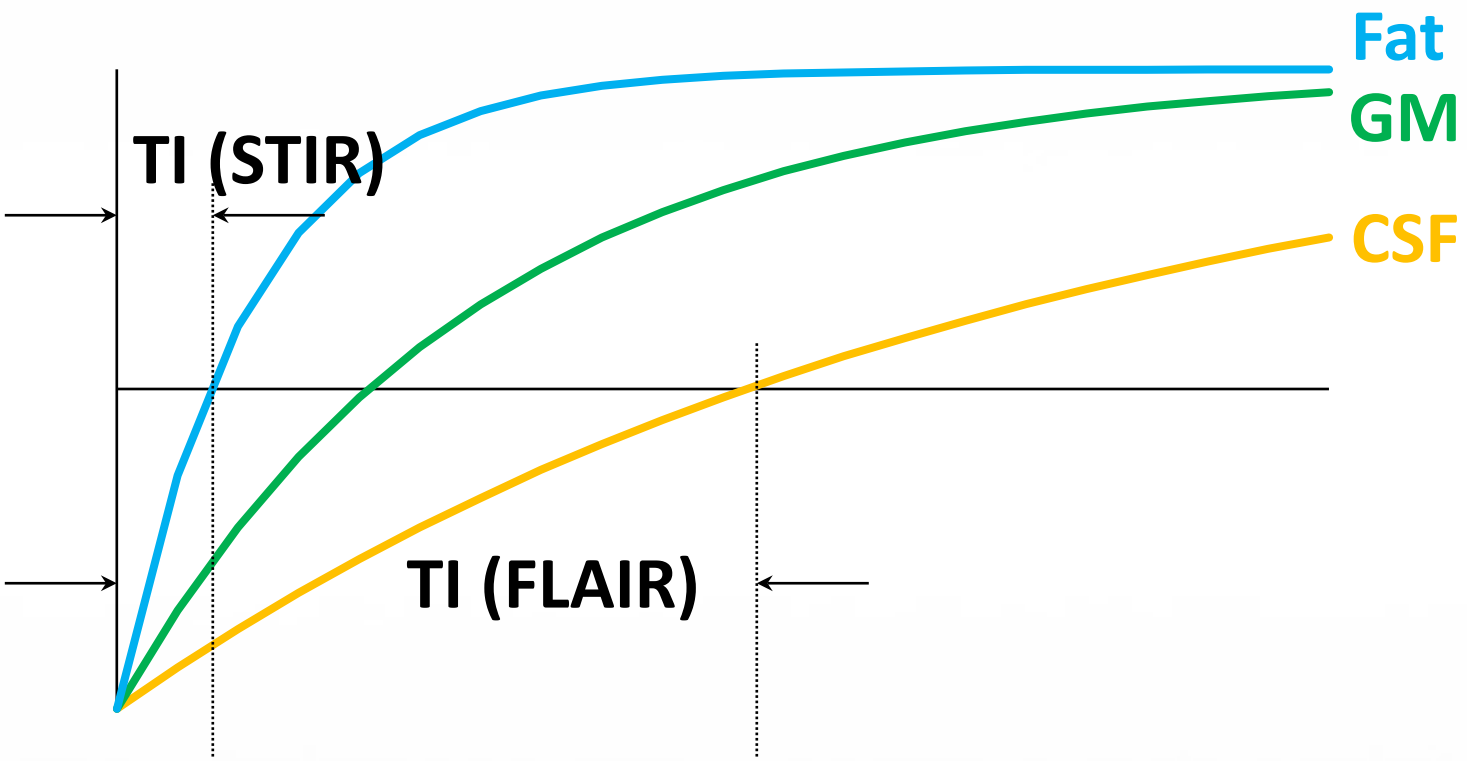
Fat
GM
CSF

STIR image: lipoma

T1WI

STIR image

STIR vs FLAIR

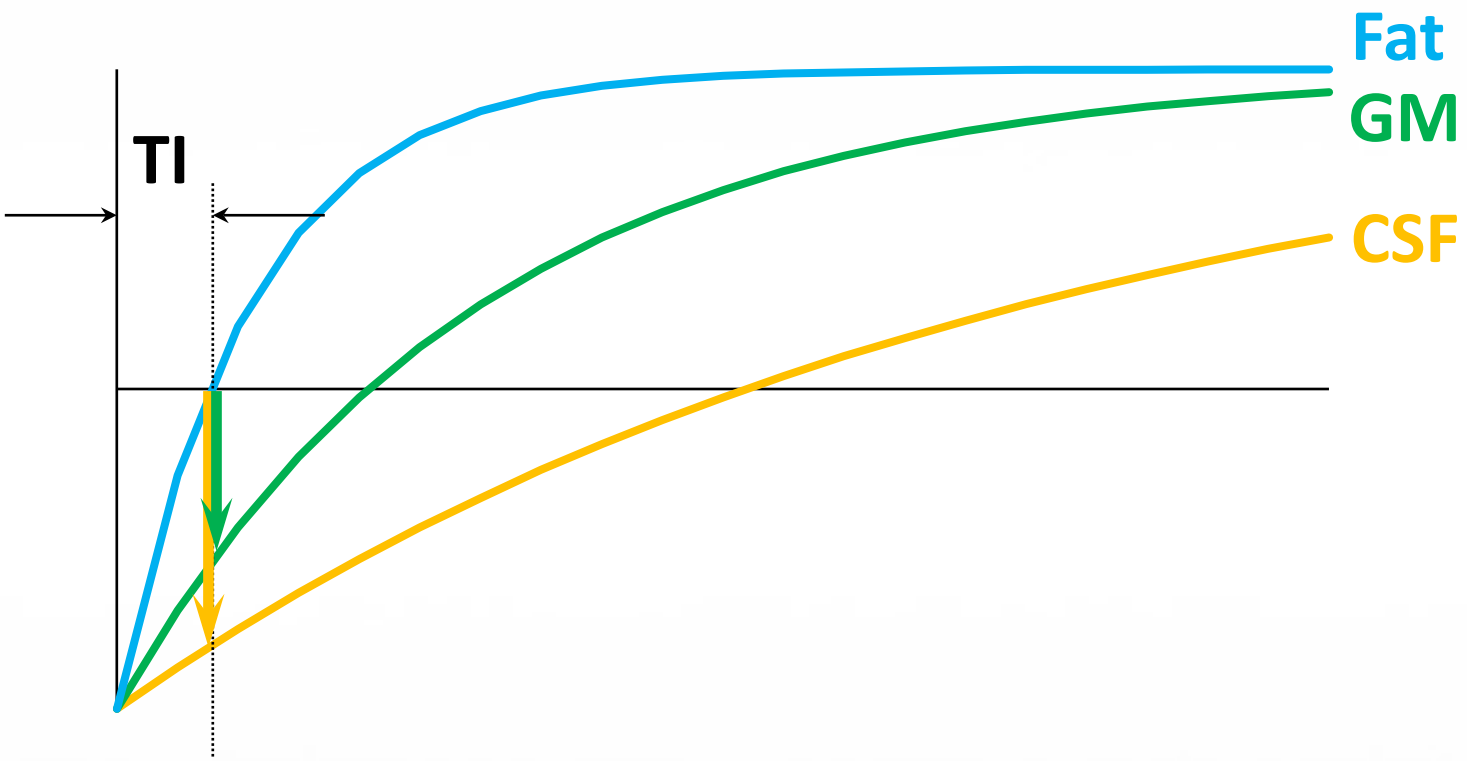


TI is chosen appropriately to suppress the specific tissue.

STIR

- Homogeneous B_0 fields is not necessary
- Inverse T1-weighting
  - Long T1 tissue: bright
  - Short T1 tissue: dark
  - CSF > GM > WM

Inverse T1 weighting



Long-T1 tissue (CSF) recovers slowly, exhibiting strong signal at short TI

STIR Fat-SAT spin-echo

1.5 Tesla
IR Spin-echo
TI = 150 msec
TR = 2000
TE = 20

Periorbital fat is suppressed

Comparison of fat SAT methods

- CHESS: Both B_0 and B_1 fields have to be homogeneous
- Dixon: double scan time (?)
- STIR: inverse T1 contrast

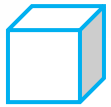
Artifacts of inaccurate spatial encoding

- Magnetic field – Resonant frequency – Location
  - Linear relationship
- Unexpected change in frequency may cause positioning error.
  - Chemical shift
  - Susceptibility

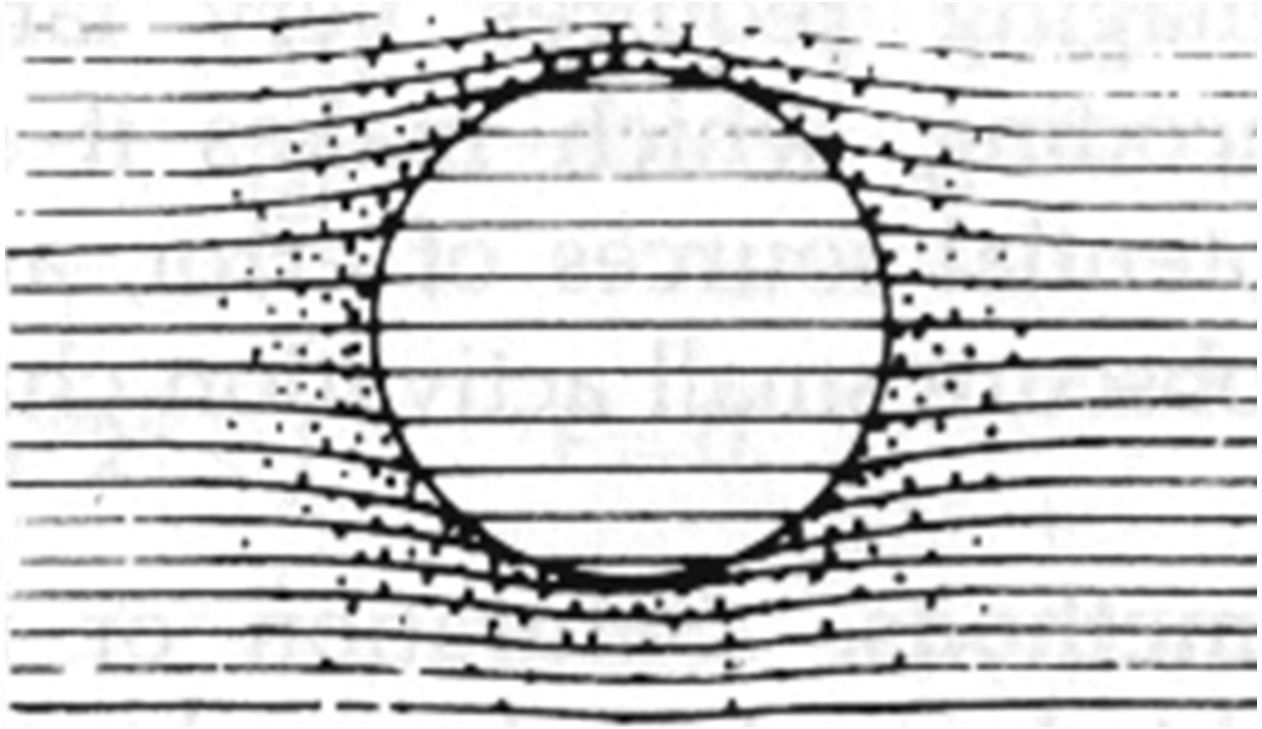
Spatial distortion due to field interference

- Off resonance may cause error in spatial encoding
  - The higher sampling frequency, the less shift in FE direction.
  - Not only induced by chemical shift
  - Distortion is proportional to the off resonance

Macroscopic inhomogeneity by susceptibility

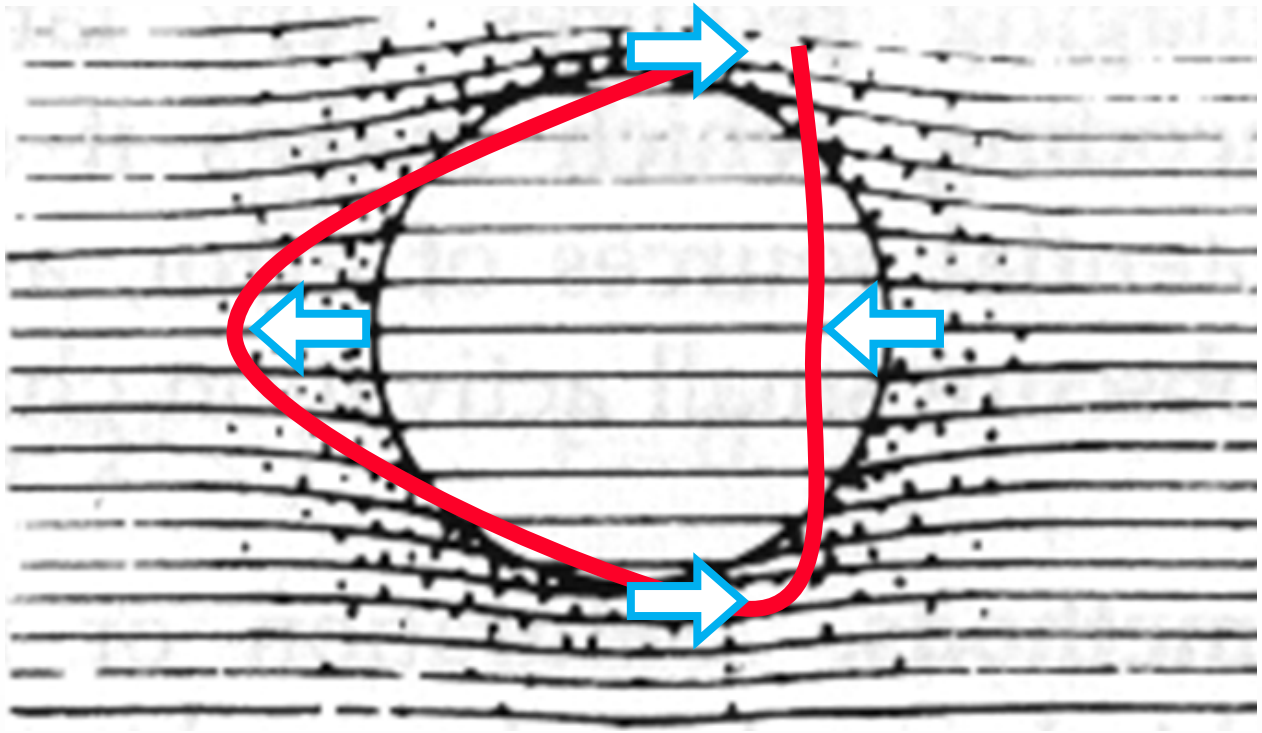


An image voxel



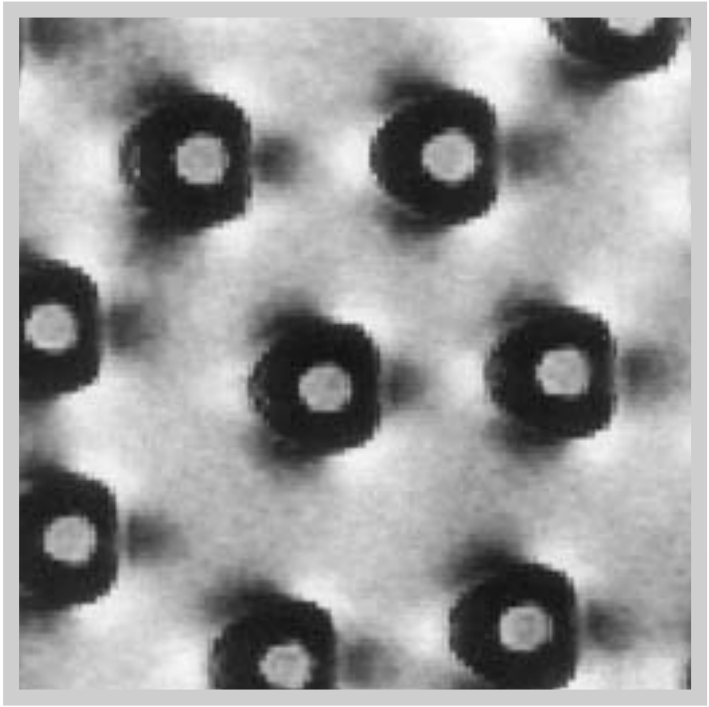
Off resonance: diamagnetic sphere surrounded by paramagnetic tissues

Susceptibility-induced spatial distortion



Not a circular boundary anymore!

Susceptibility-induced spatial distortion

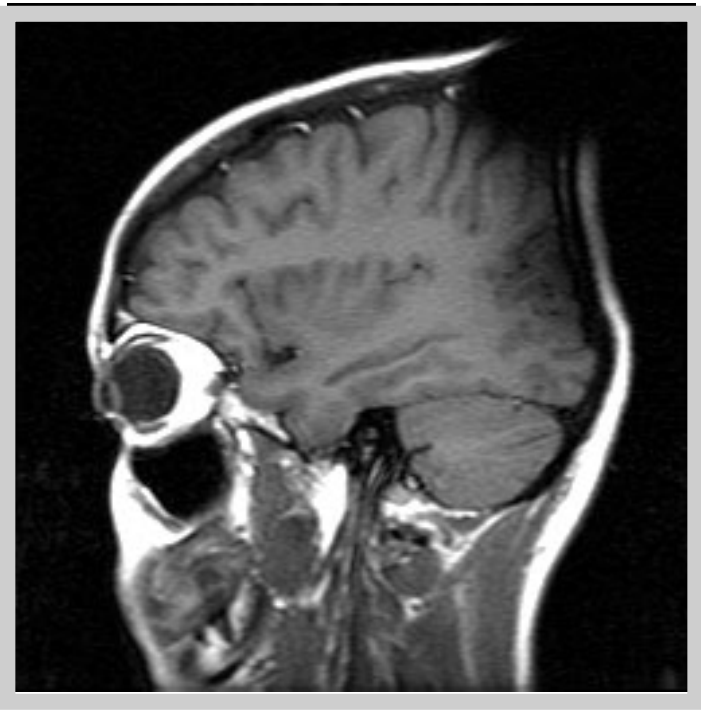


Glass tubes (diamagnetic)
immersed in $CuSO_4$
solution (paramagnetic)

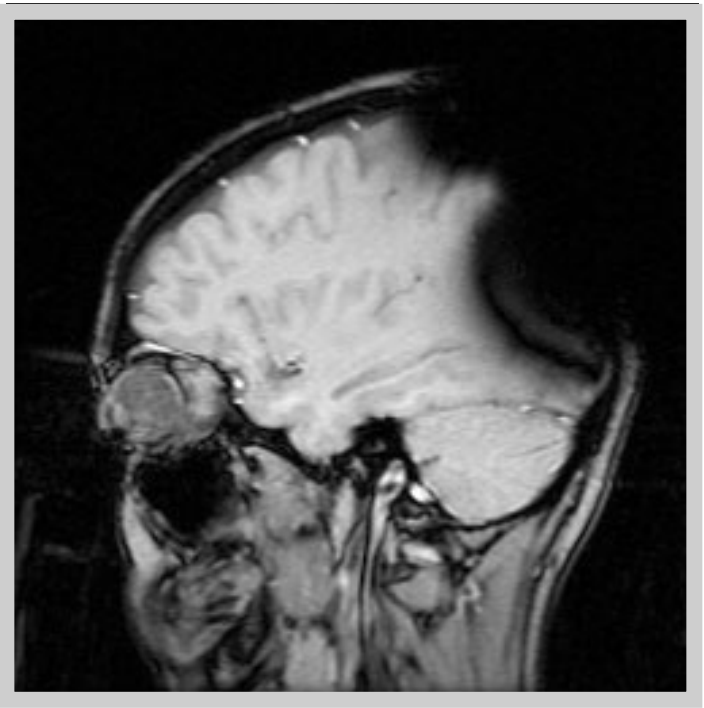
1.5 Tesla
Gradient echo

From a circular shape to an arrow shape

Susceptibility artifact due to iron hairpins



Spin echo



Gradient echo

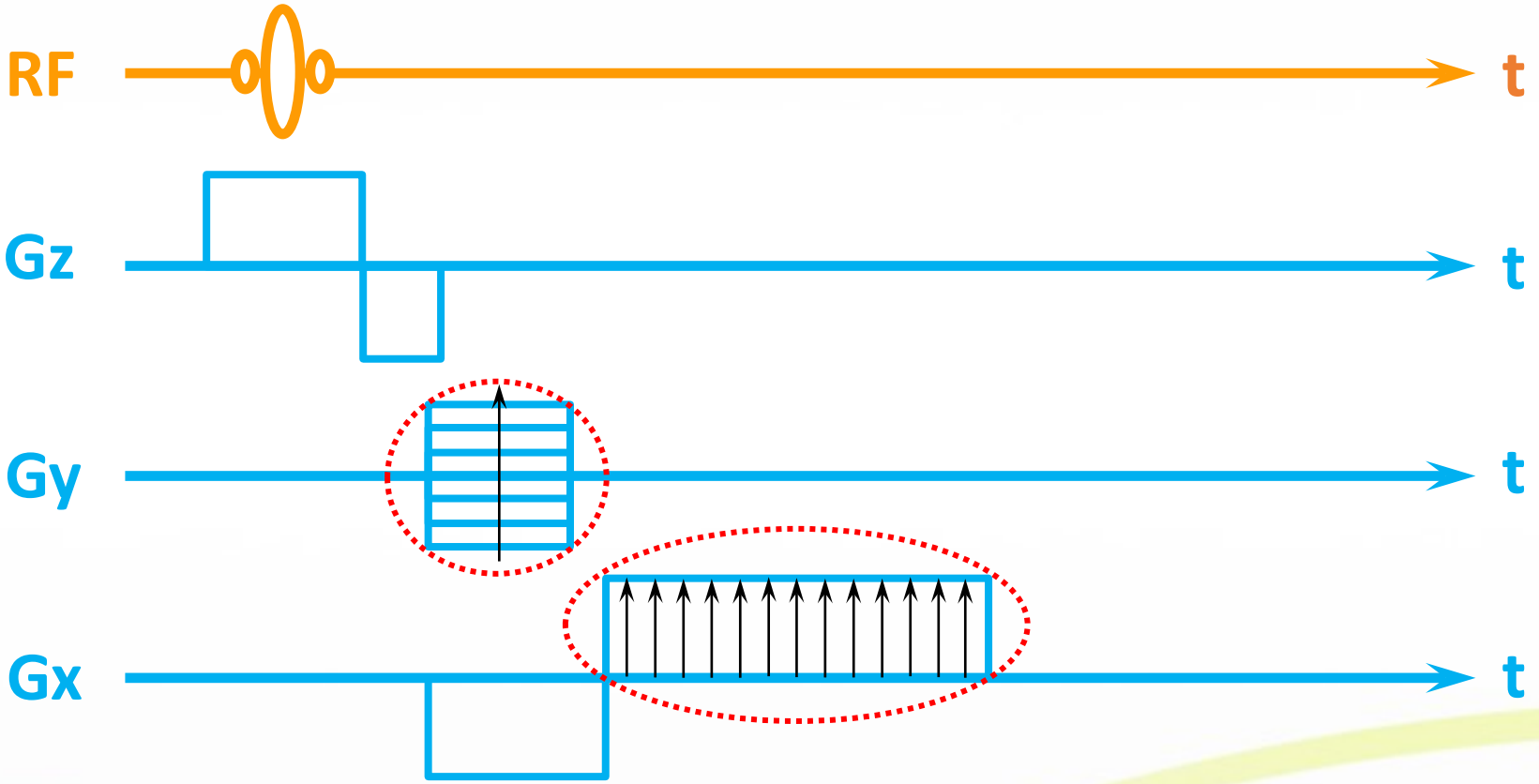
Artifacts of inaccurate spatial encoding

- Magnetic field – Resonant frequency – Location – Linear relationship
- Unexpected change in frequency may cause positioning error.
- Mismatch of frequency encoding and phase encoding

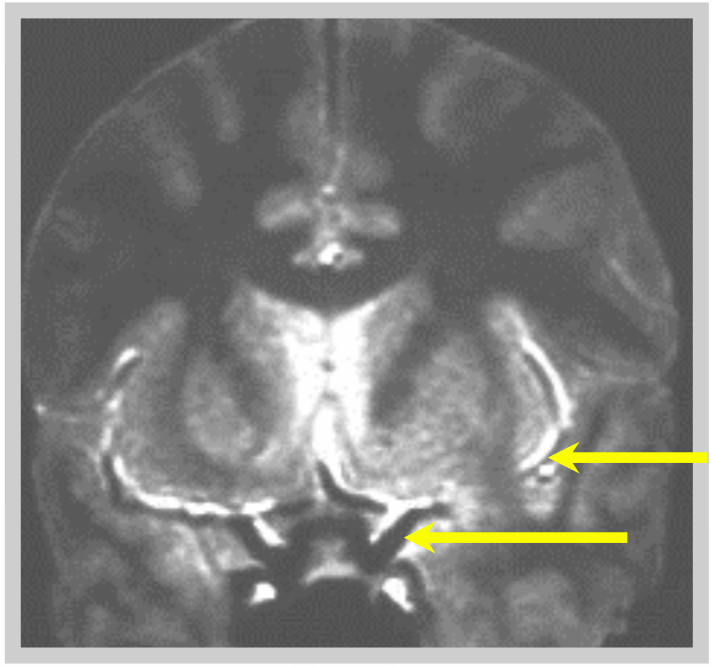
Displacement artifact of flow

- Phase encoding and frequency encoding is not performed simultaneously
- Flow moving between applications of PE and FE gradients
  - Mis-registration depends on the direction and velocity of flow

2D gradient echo



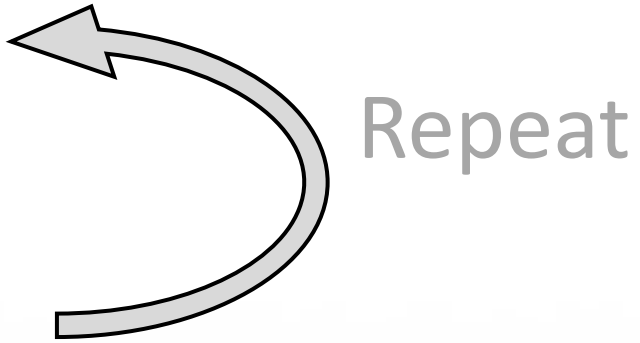
Displacement artifact



Mis-registration of an in-plane flow, especially notable in diagonal direction.

Imaging procedure of an MRI

- Magnetization
- RF excitation
- Spatial encoding
- Signal acquisition
- Image reconstruction



RF leakage

- Interference of external EM waves
  - For example, FM bands
- RF shielding of the scan room
- The door of scan room should be closed tightly during MRI scan

RF leakage

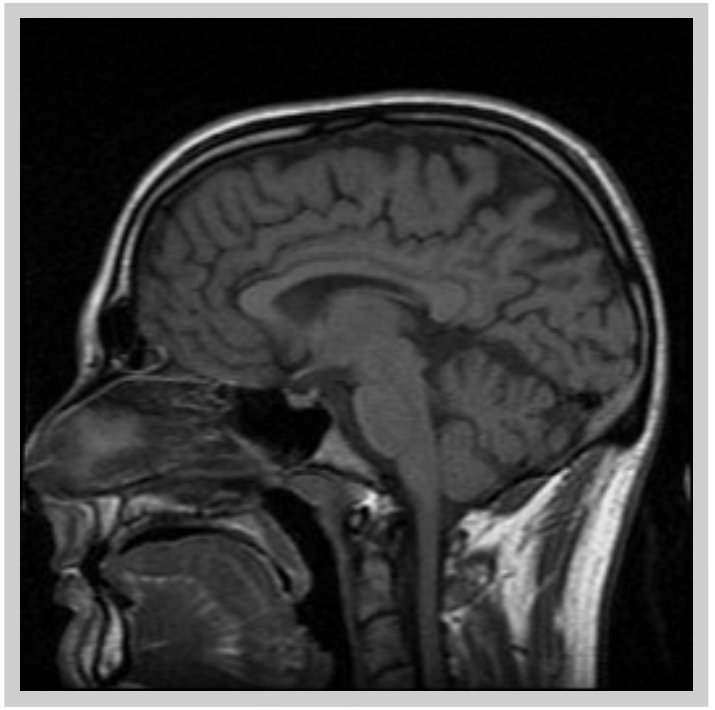
Horizontal: frequency encoding direction
Vertical: phase encoding direction

Zipper artifact along phase encoding direction Q

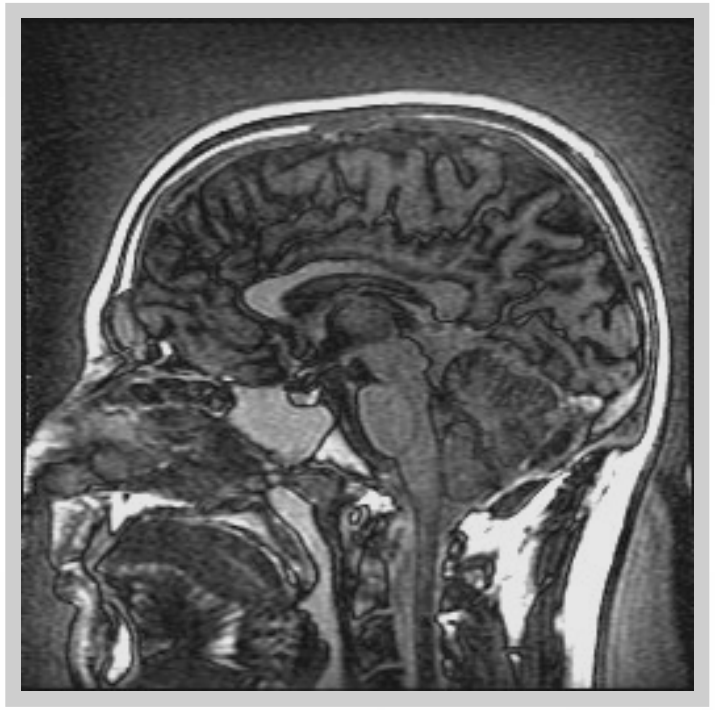
Inappropriate receiver gain

- MR signal has to be amplified during acquisition
- Automatic calibration
- A gain set too high or too low could introduce artifacts
  - Too high: data clipping of low-frequency signals
  - Too low: loss of high-frequency info, smoothing

Inappropriate receiver gain



Normal gain

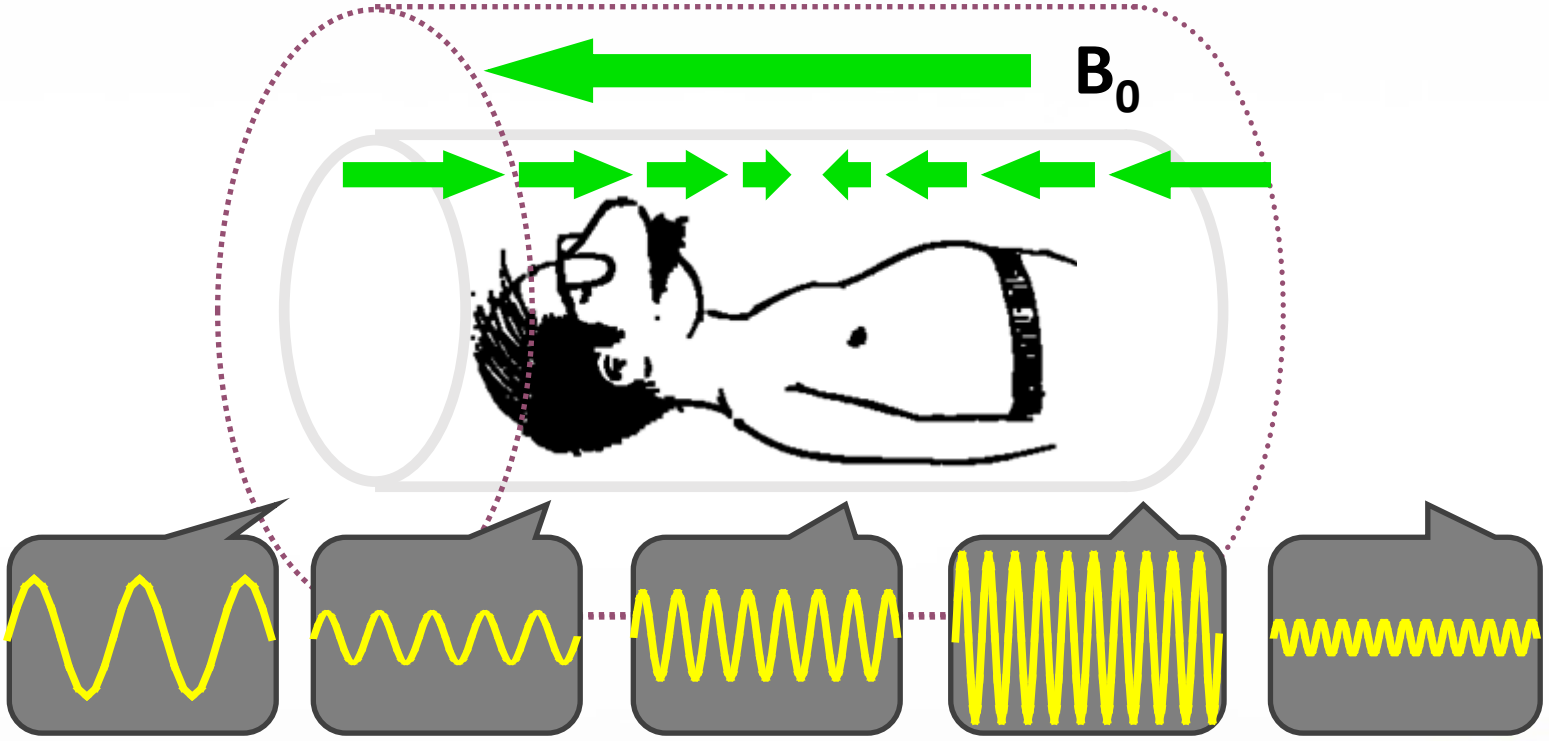


Gain too high

Aliasing artifact

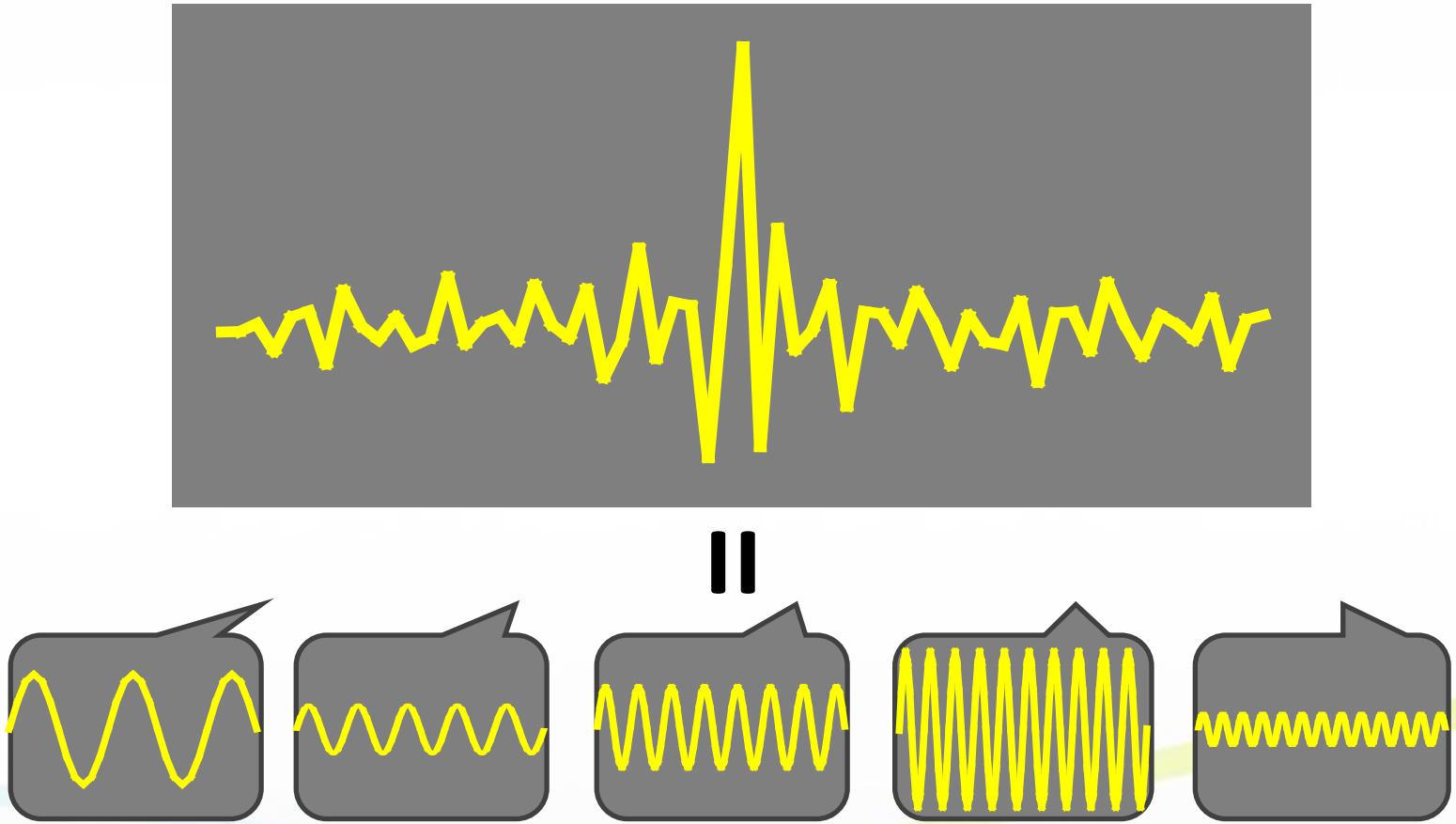
- When sampling frequency is not high enough…
  - Fail to obey sampling theorem
  - High-frequency components would be mistaken as low-frequency components
  - Image signal beyond the FOV would be folded to another side

Spatial-dependent frequency

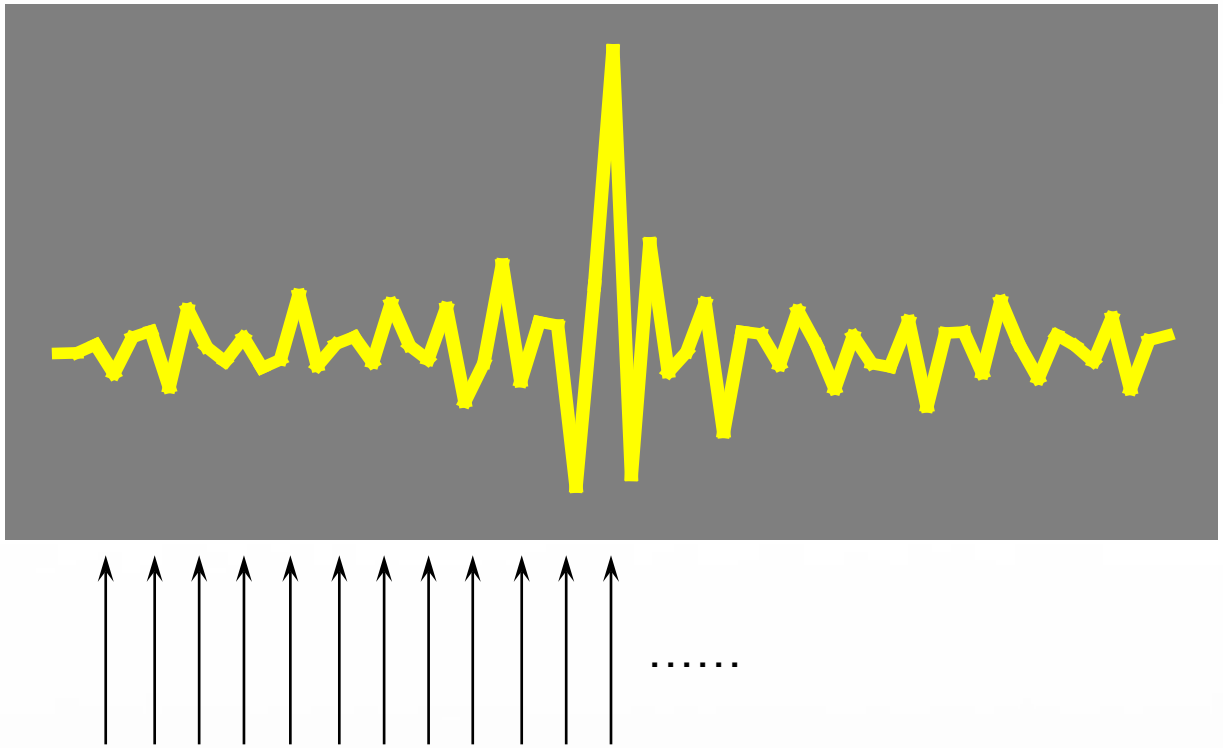


Frequency: location Amplitude: proton density

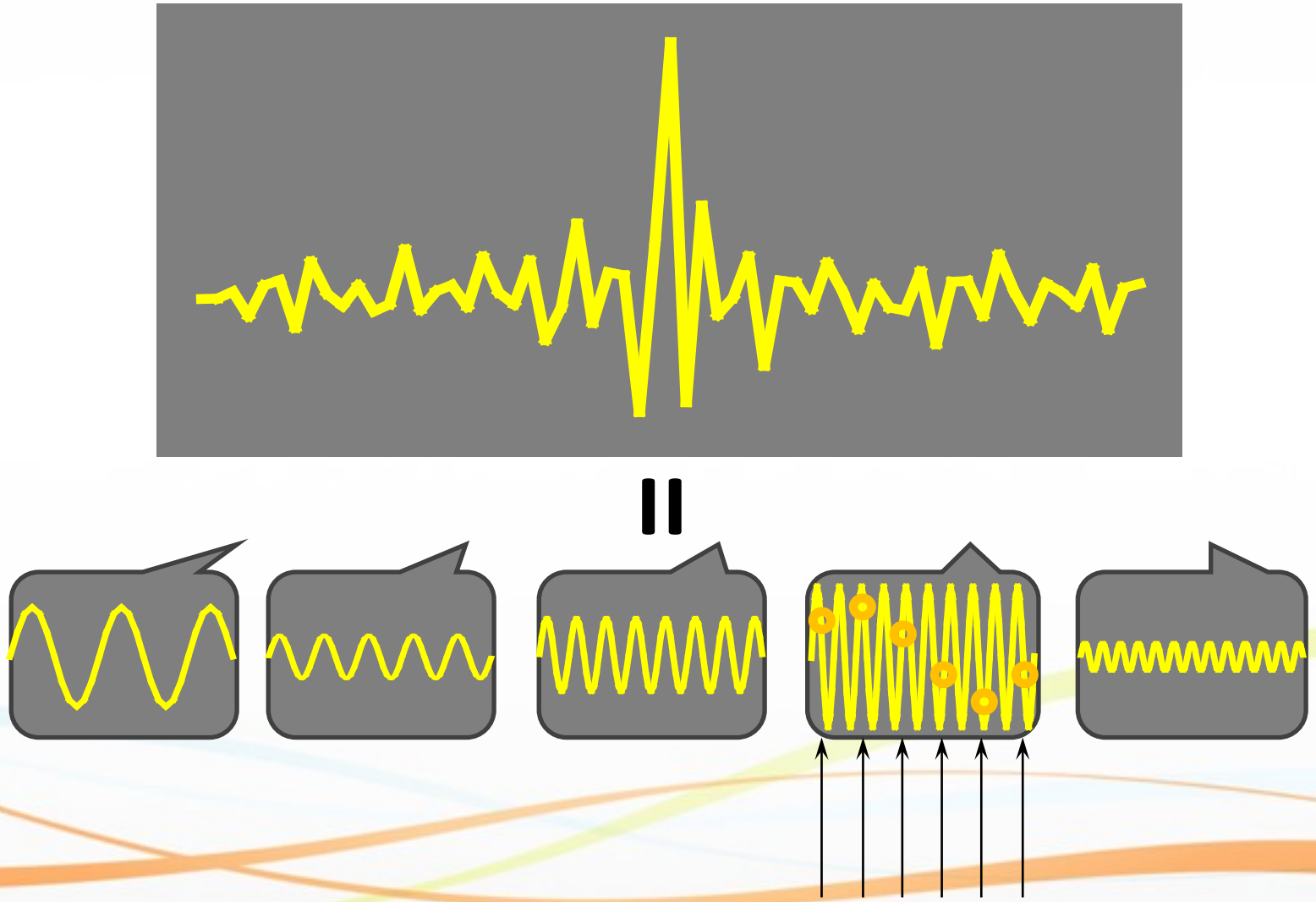
Combination of all frequencies



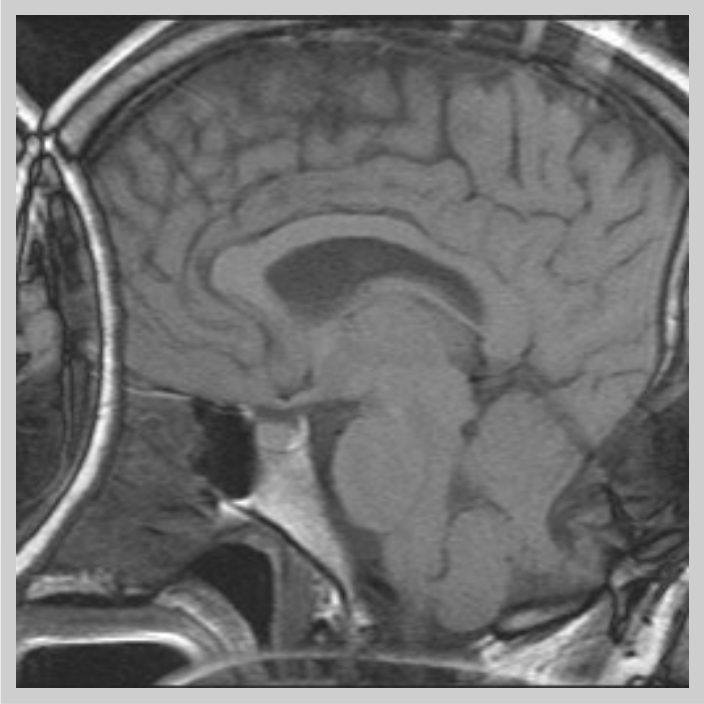
Data acquisition



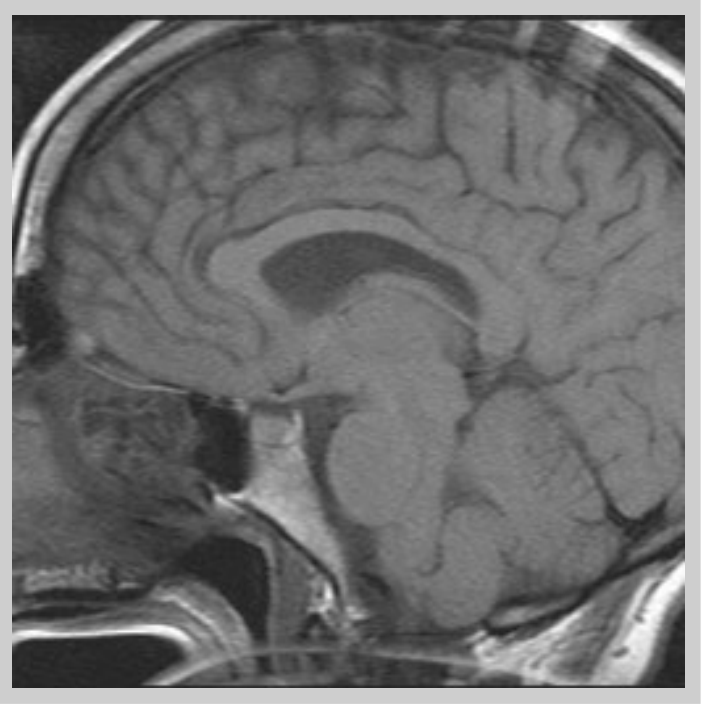
When sampling frequency is set too low...



Aliasing (wrap-around) artifact in MRI



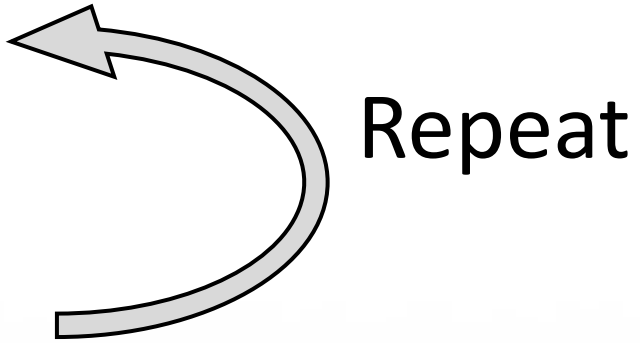
Aliasing



Oversampling

Imaging procedure of an MRI

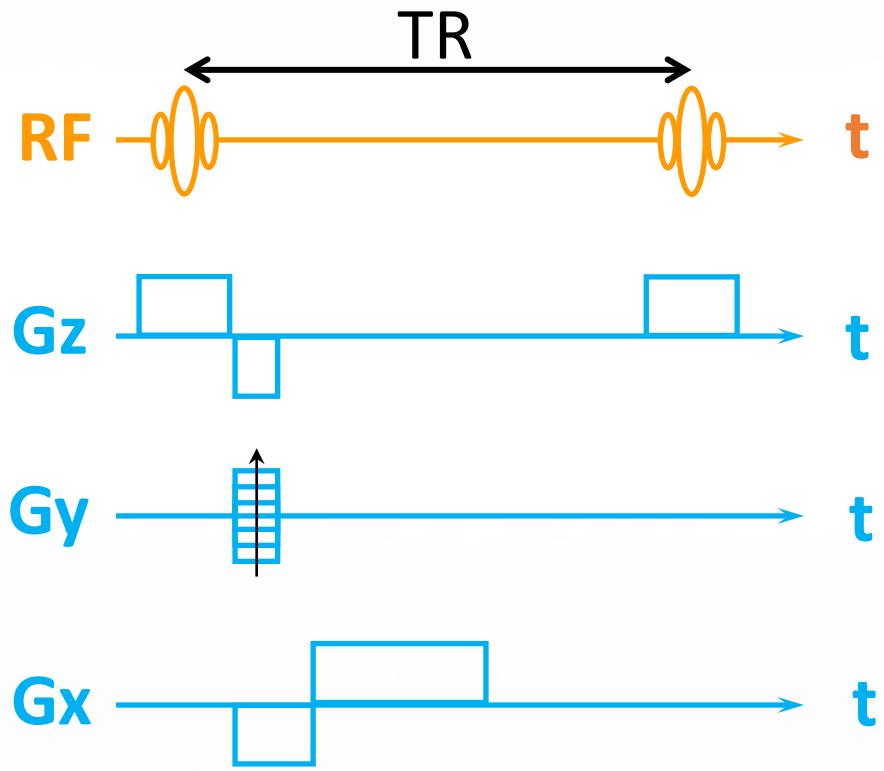
- Magnetization
- RF excitation
- Spatial encoding
- Signal acquisition
- Image reconstruction

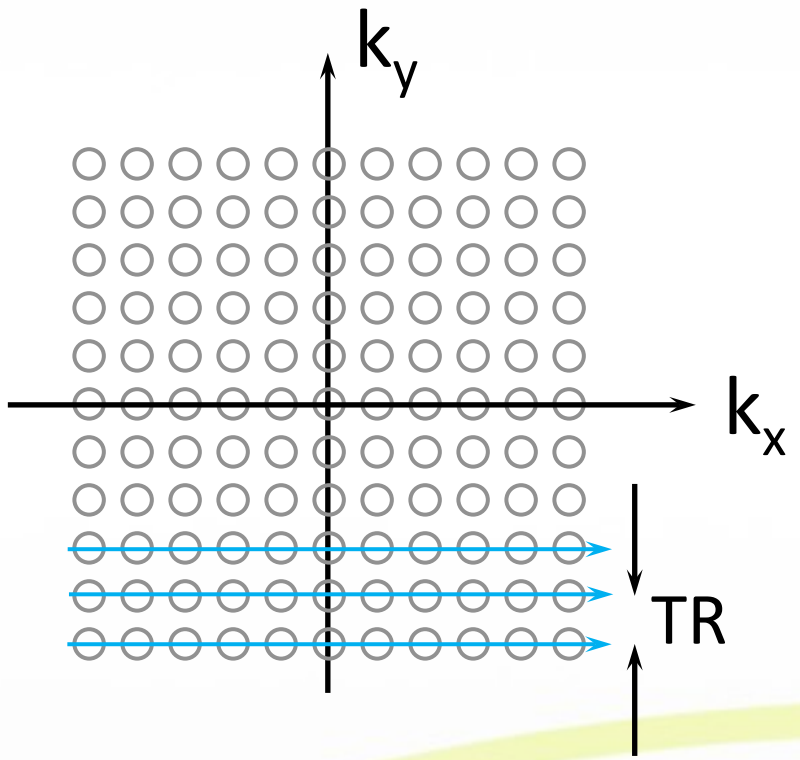


Motion artifact

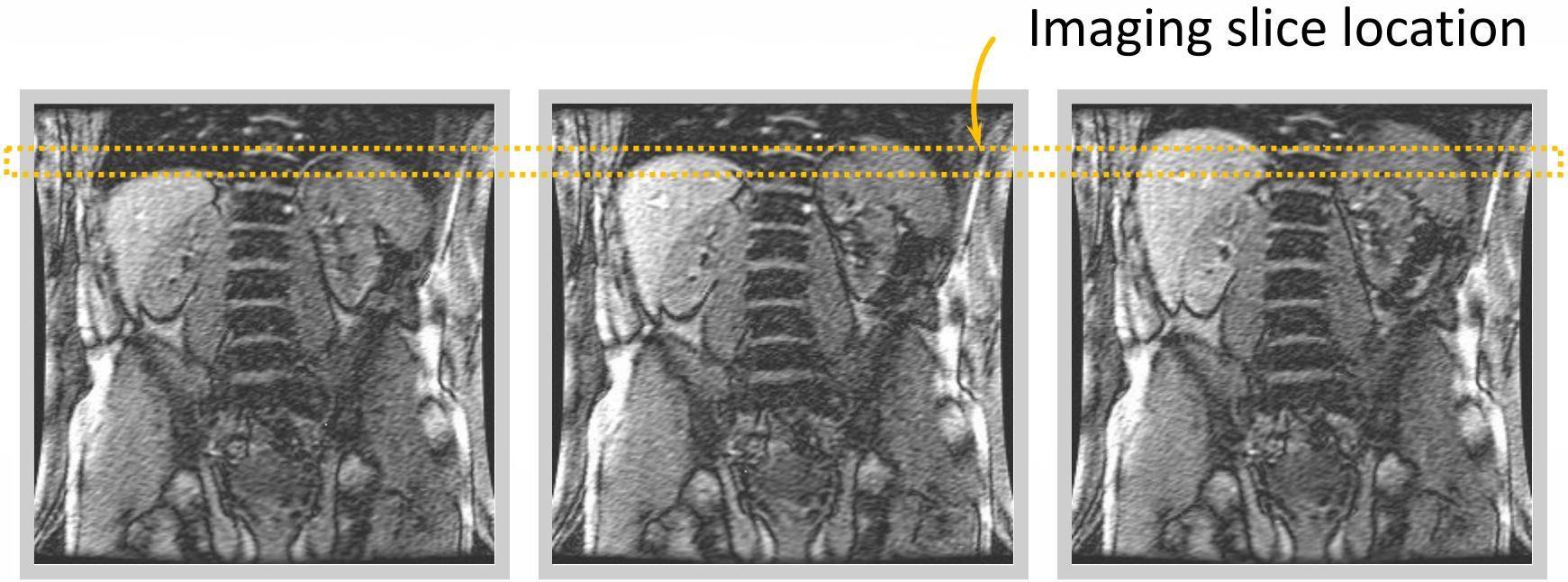
- Signal inconsistency in the repeated process
- All k-lines are not corresponding to the identical object
  - Periodic motion
  - Non-periodic motion

Pulse sequence and k-space





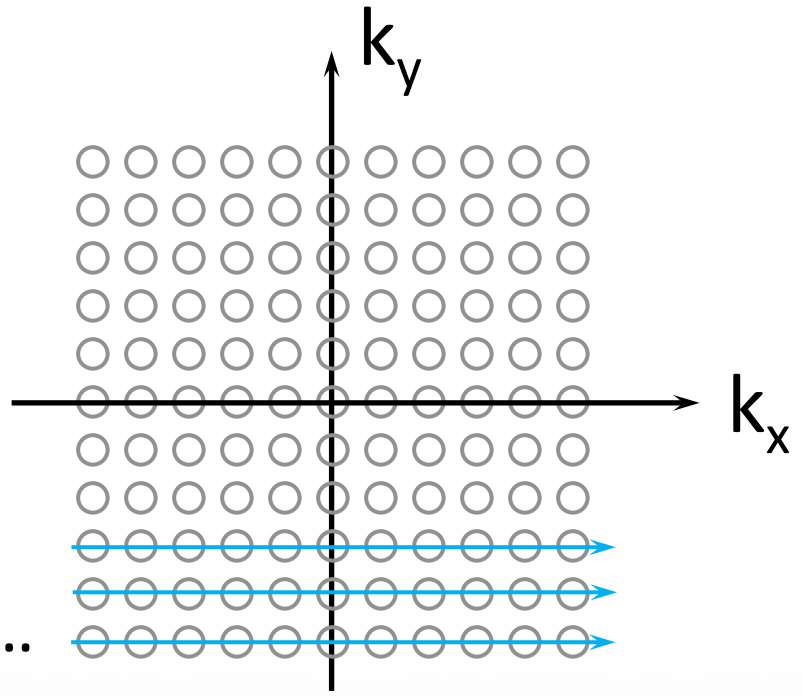
Respiratory motion



Signal changes in a period of respiration

K-space signal

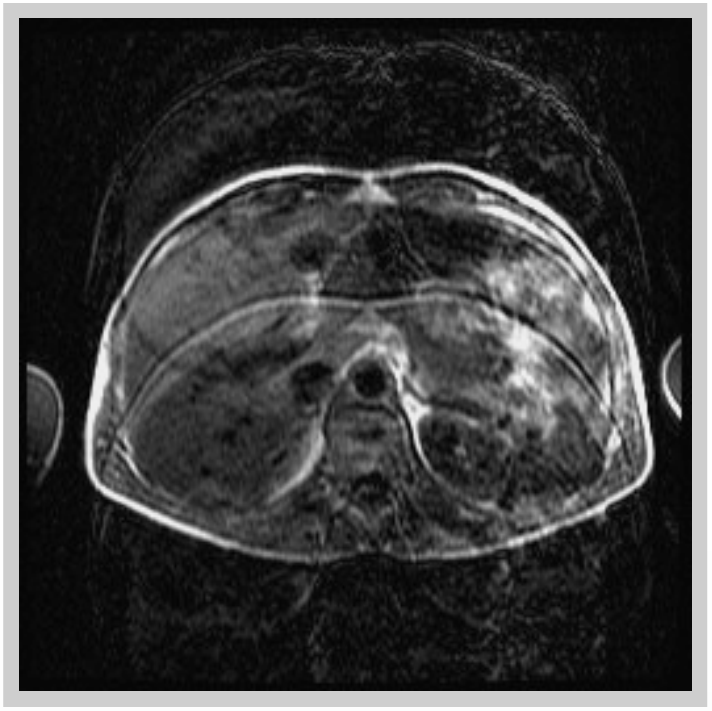
Signal ups
and downs…



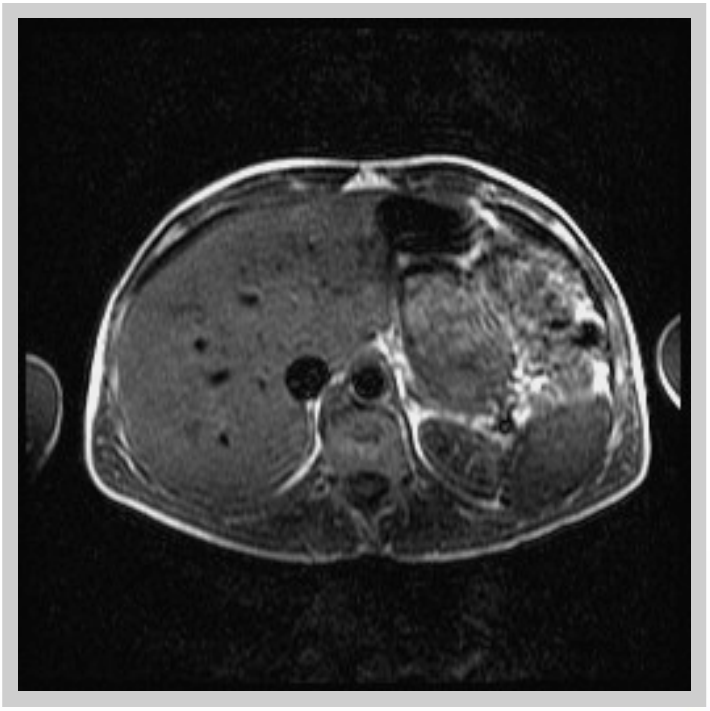
Motion-induced variation

- Periodic motion: clear ghost
  - Modulation by a periodic function in k-space
  - Appearance in PE direction
- Non-periodic motion: irregular overlapping of artifacts in PE direction

Motion ghost due to periodic motion



Ghost

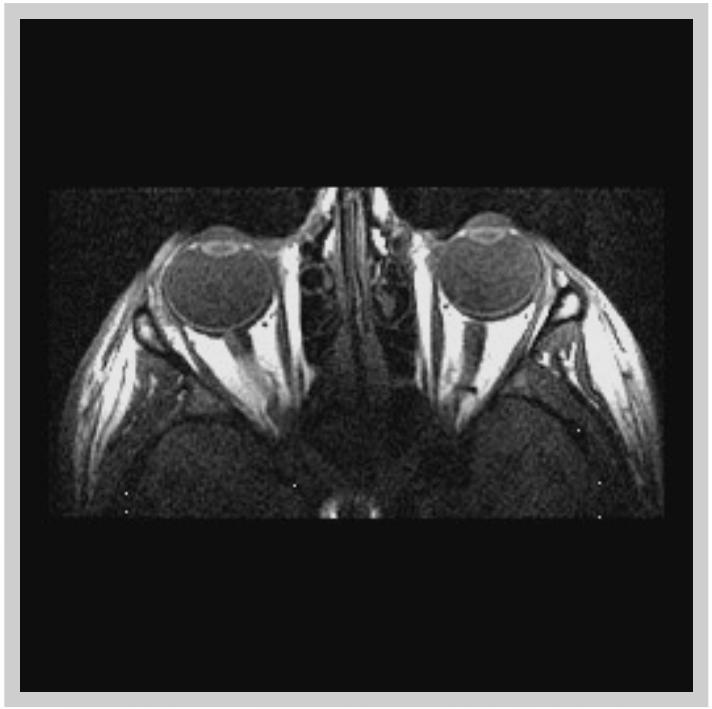


Respiratory-gating

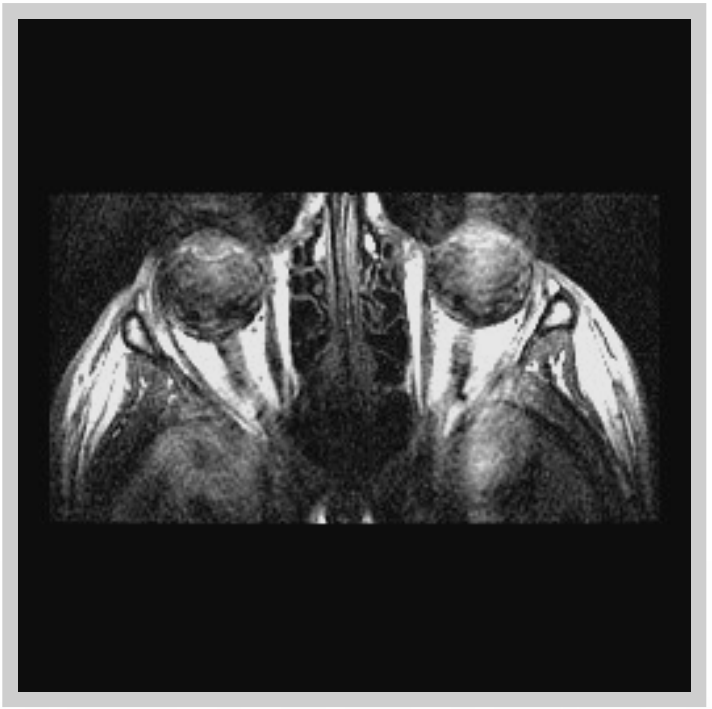
Motion ghost due to periodic pulsation

Only moving part (aorta) has ghosts, which appears in PE direction.

Motion ghost due to non-periodic motion



No eye motion



Irregular motion

Possible remedies to motion artifacts

- Minimization of motion
  - Instruction for stabilization
  - Breath holding
- Suppression of moving tissues (e.g., flow)
  - Suppression of upstream flow

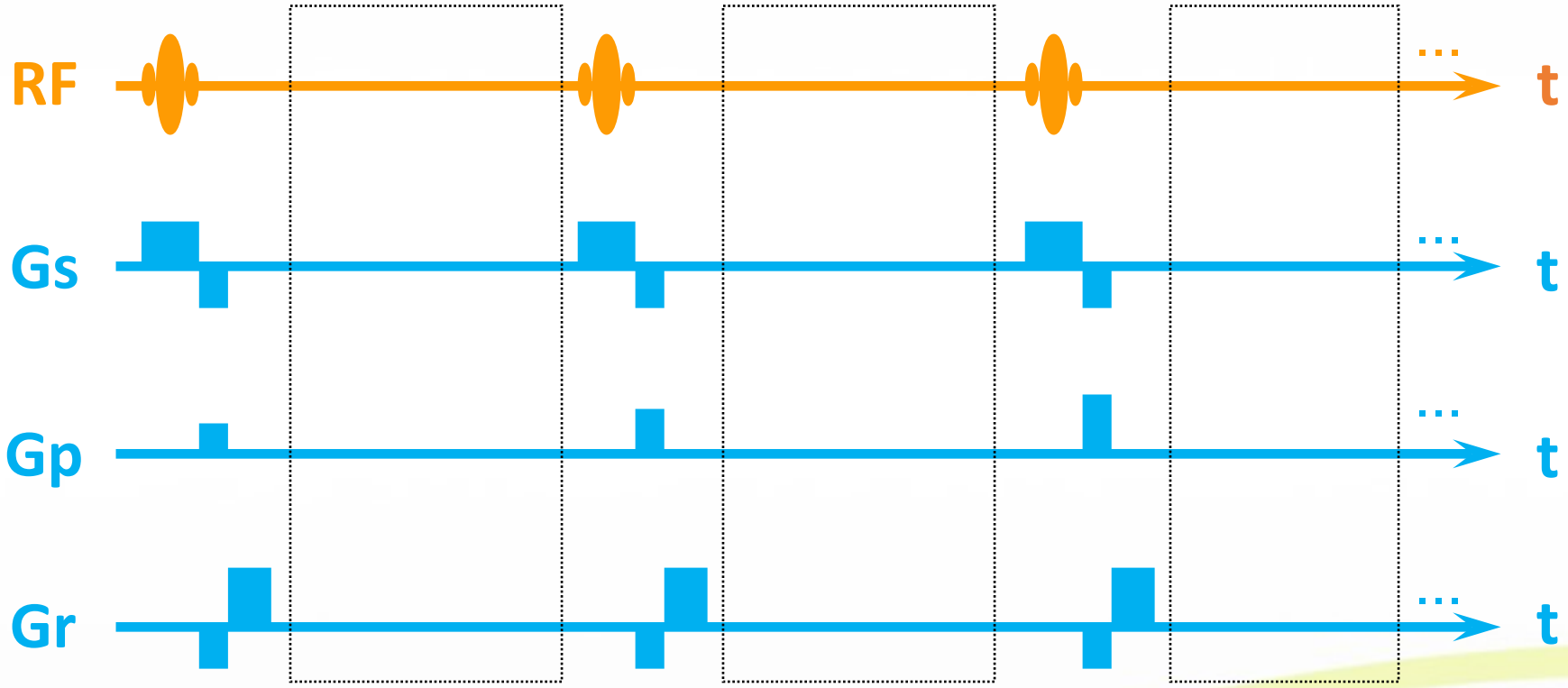
Possible remedies for motion artifacts

- Motion compensation
  - Gating for periodic motion, such as respiration or cardiovascular motion
  - Special sequences: navigator echo, PROPELLER,…

Cross talk

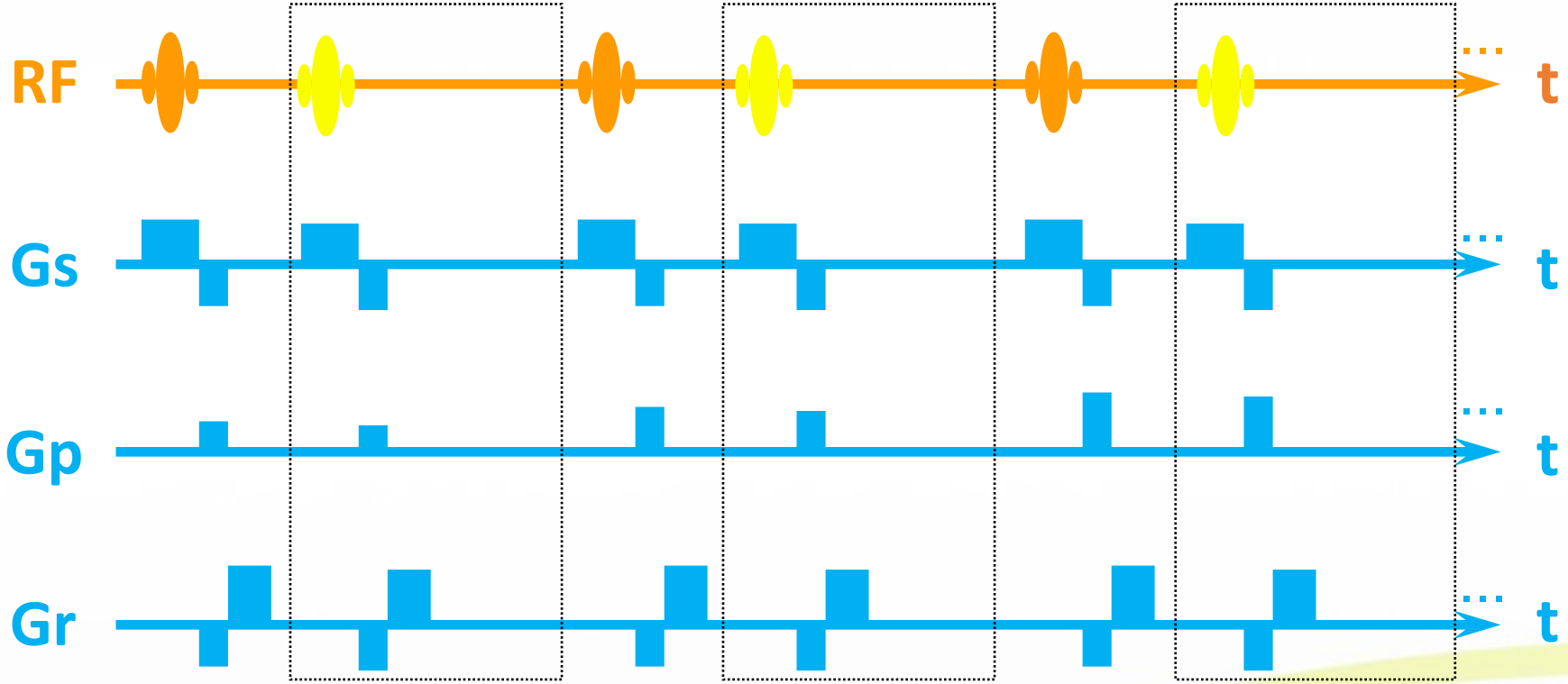
- Multiple excitations may occur on the same spins in one TR
  - For example: multi-slice multi-angle imaging, imperfect excitation without inter-slice gap…
- Decrease of effective TR limits the T1 recovery
  - Lower signal intensity

Single slice



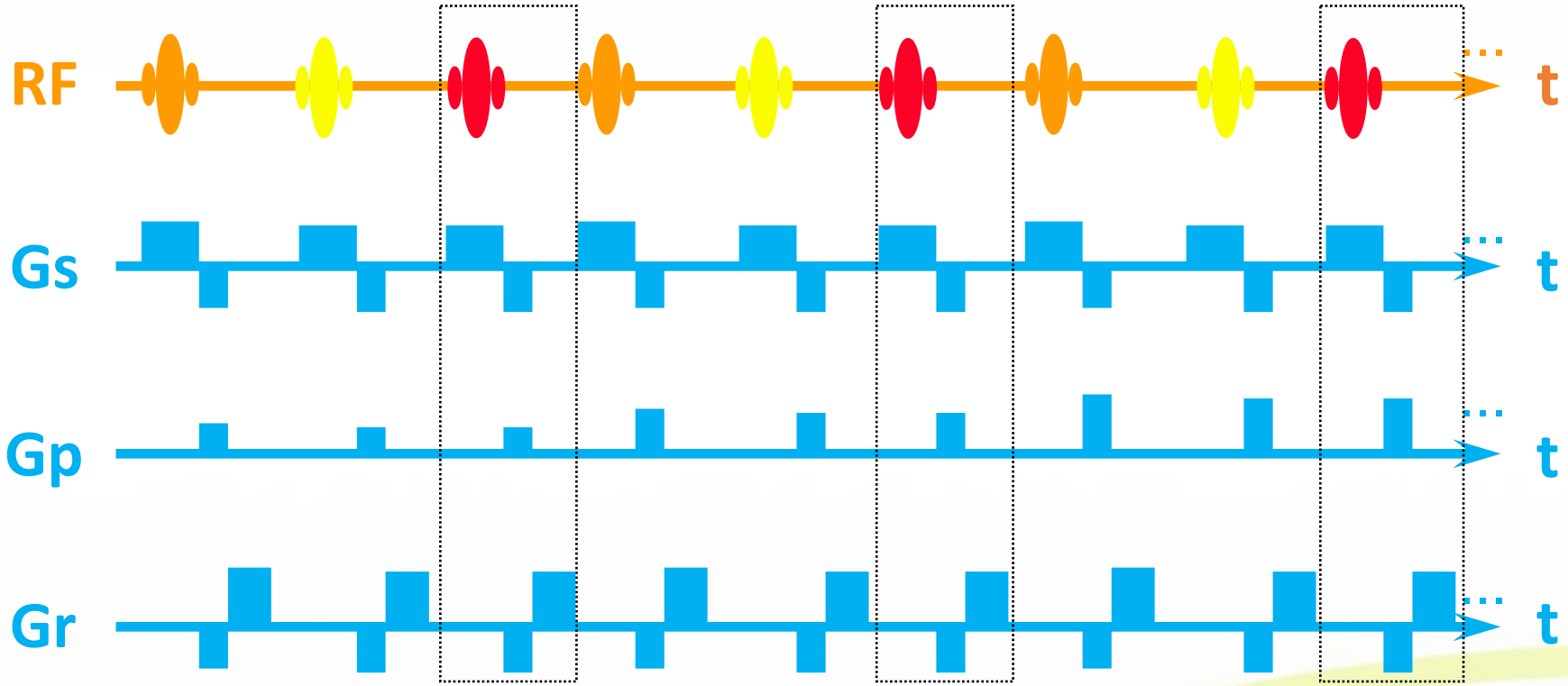
TE >> TR: do nothing for most of time

Insertion of another slice



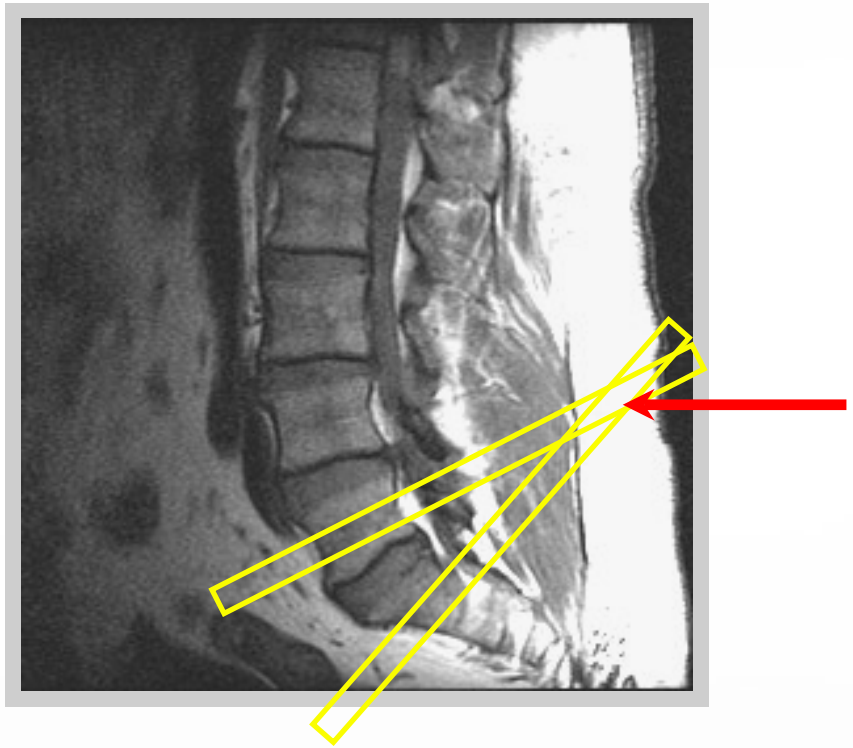
Taking advantage of the spare time

Insertion of one another slice



Multi-slice imaging

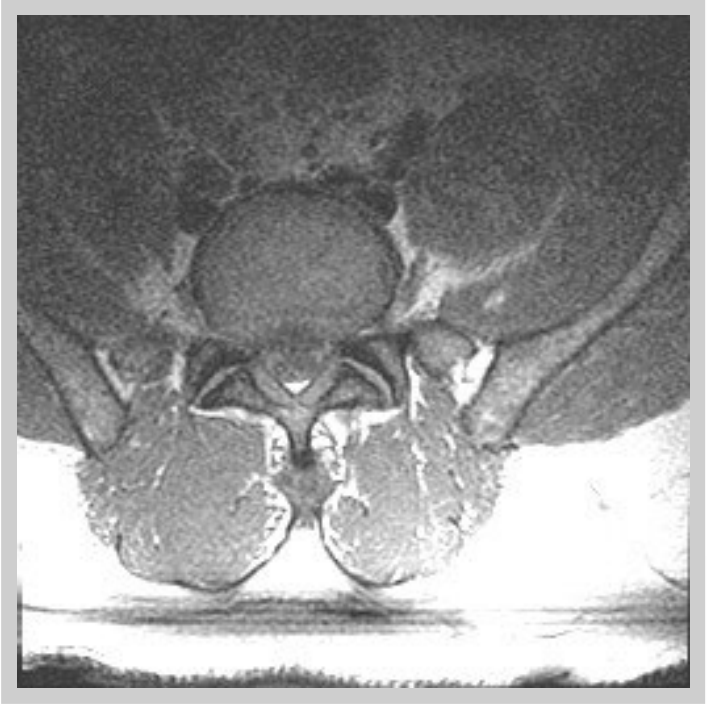
Cross talk



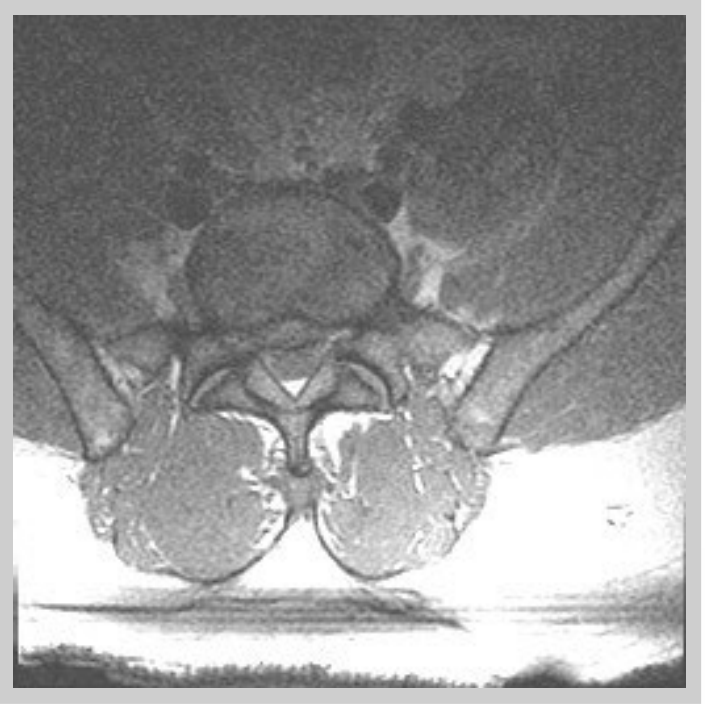
Excited by both slices

→ Effective TR is reduced to half

Cross talk



Lumbar

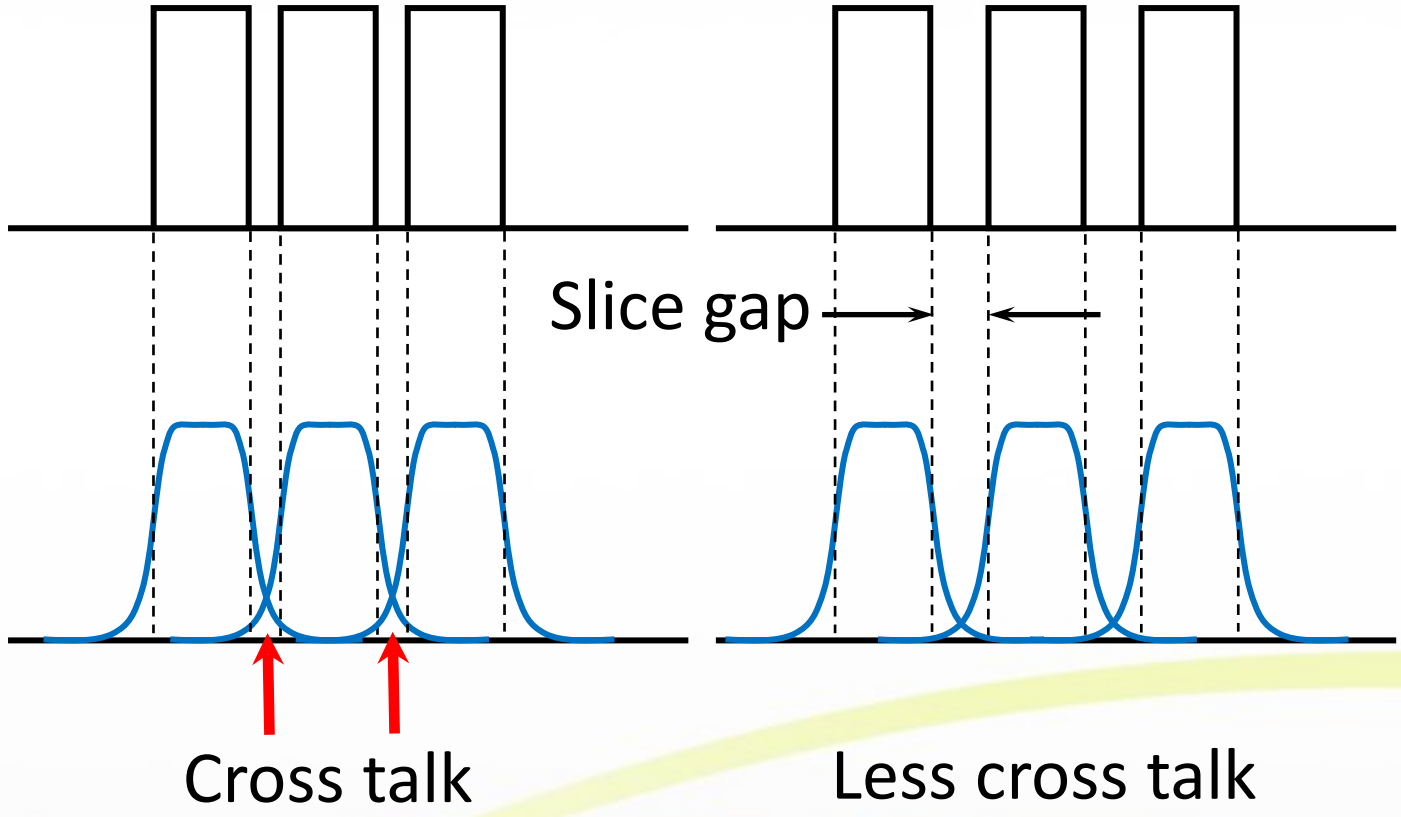


Sacrum

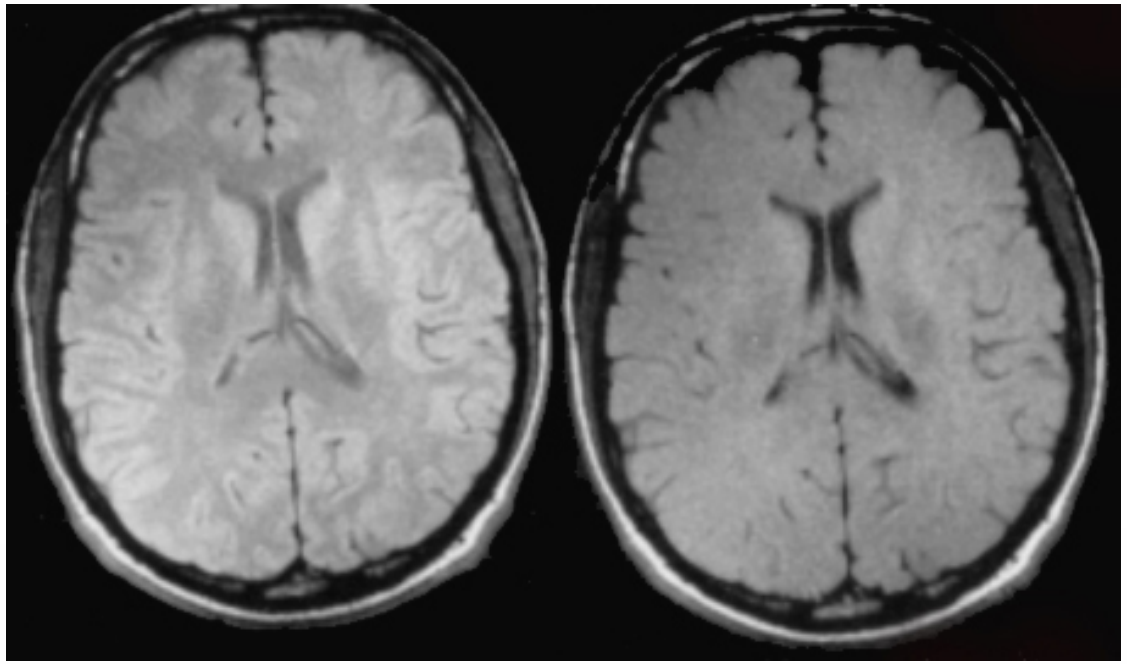
Cross talk due to imperfect profiles

Ideal slice profiles

Actual slice profiles



Cross talk due to imperfection profiles



50% gap 0% gap

Spin echo (PDWI)
TR/TE = 2000/20 ms

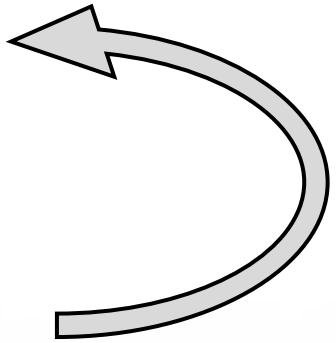
Reference: https://mriquestions.com/cross-talk.html

How to reduce cross talk?

- Increase slice interval/gap
  - Better slice profile also helps at the cost of pulse duration
- Adjust the order of slice excitation: interleaving instead of sequential

Imaging procedure of an MRI

- Magnetization
- RF excitation
- Spatial encoding
- Signal acquisition



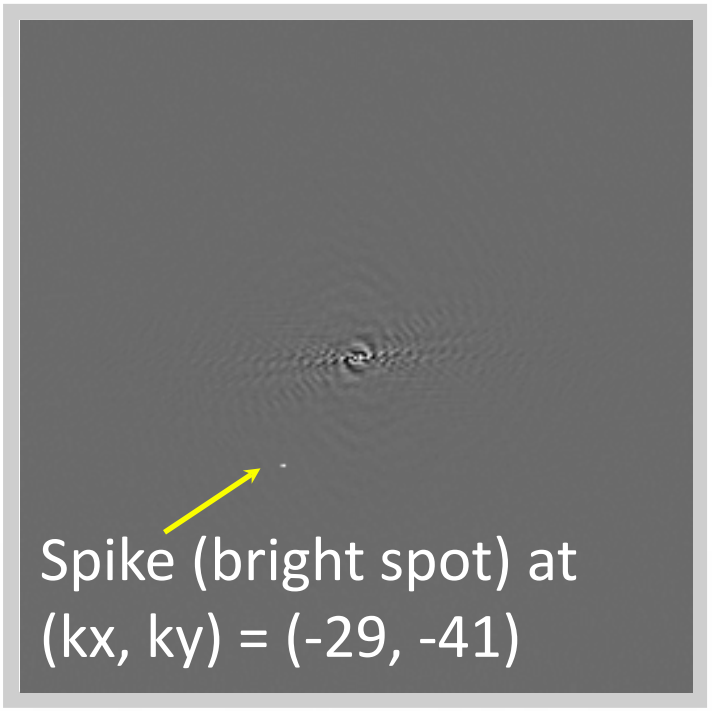
Repeat

- Image reconstruction

Discontinuity in k-space

- Spike noise in k-space
- Zero padding in k-space

Spike noise in k-space: banding artifacts



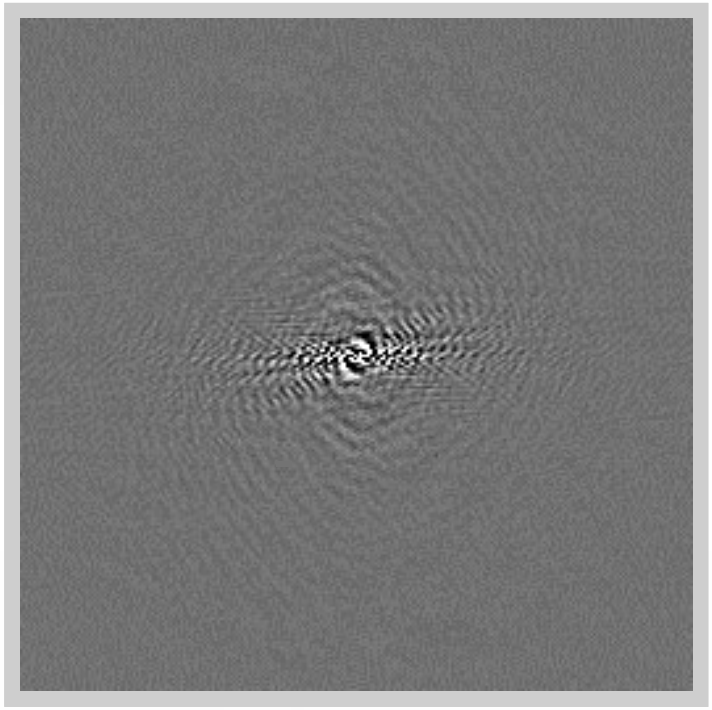
k-space

MRI

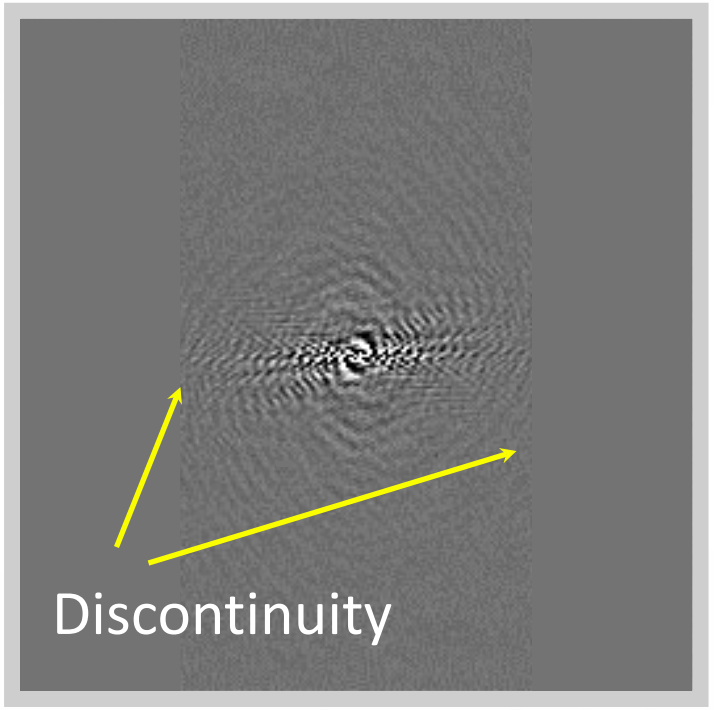
Correction of spike noise

- Only occur in few points in k-space
- Replaced by corrected values
  - Complex conjugate symmetric
  - Interpolation in k-space

Discontinuity in k-space sampling

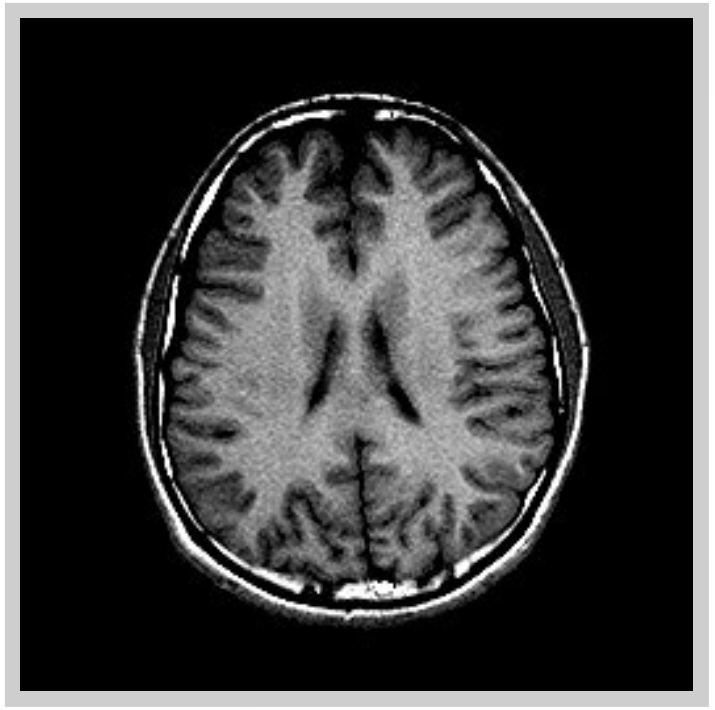


Full k-space

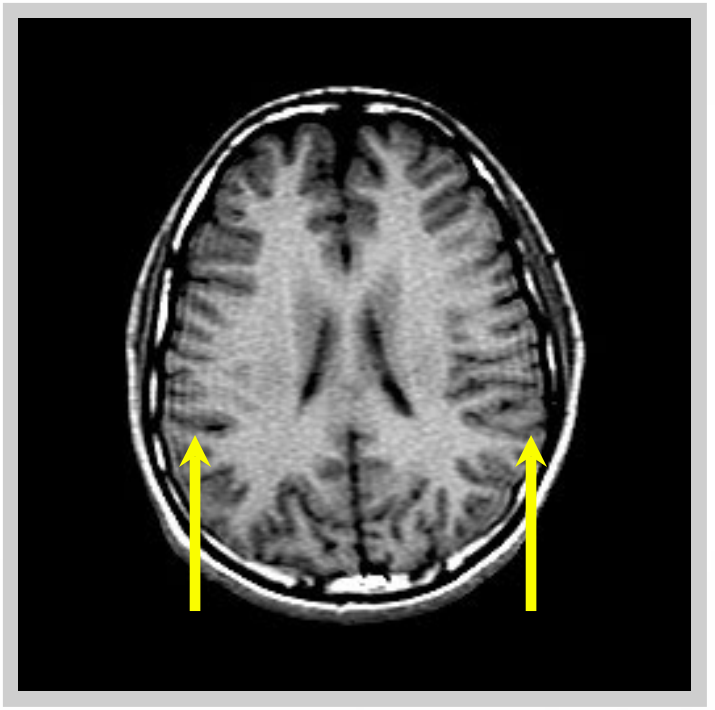


Limited k-space

Gibb's ringing (Ringing artifact)



256 x 256

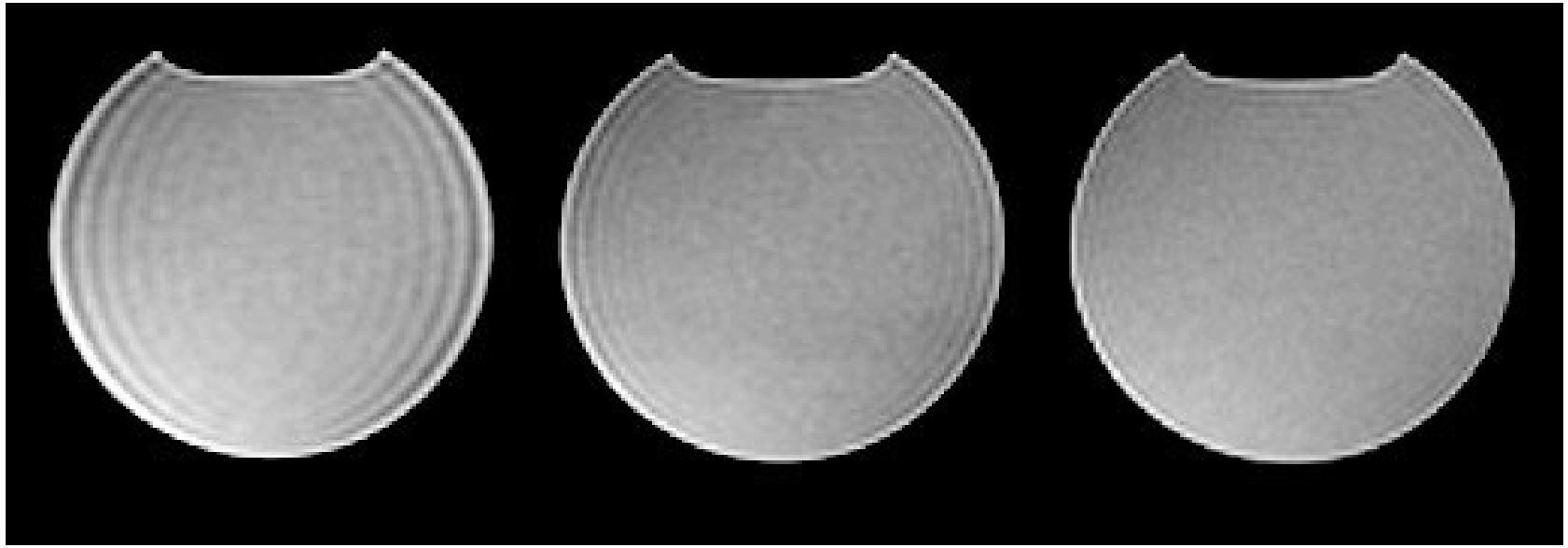


256 x 128

Gibb's ringing

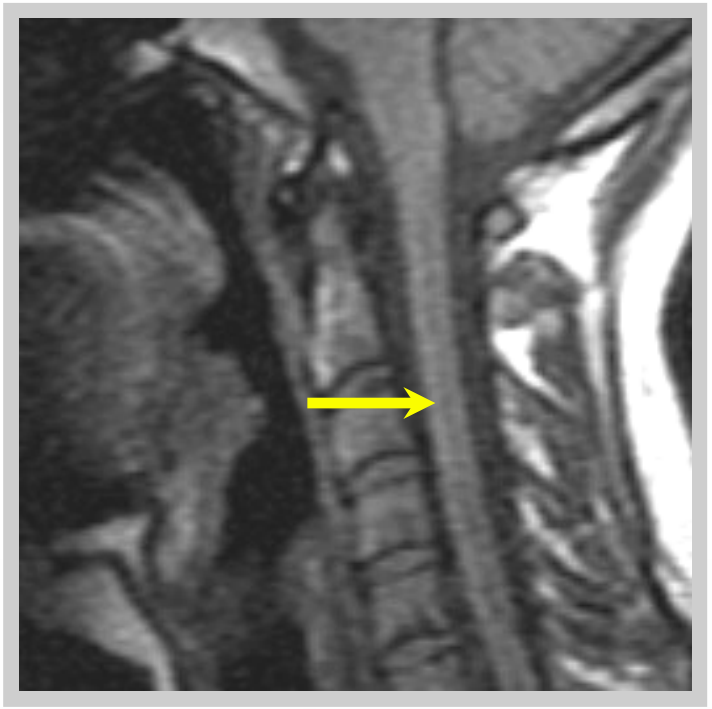
- K-space discontinuity due to zero padding
  - Also known as truncation artifact
  - Appear as fine lines parallel to interfaces
  - Usually more prominent in PE direction
- Reduced by increasing number of encoding steps

Gibb’s ringing



256 x 128 256 x 192 256 x 256

Syringomyelia or pseudo-syrinx in spine?

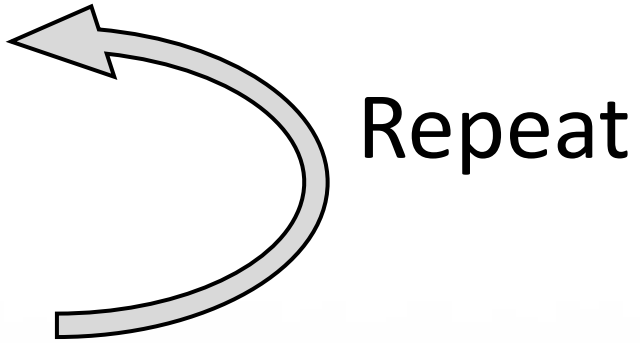


256 x 128

256 x 256

Finished? There’re still more…

- Magnetization
- RF excitation
- Spatial encoding
- Signal acquisition
- Image reconstruction



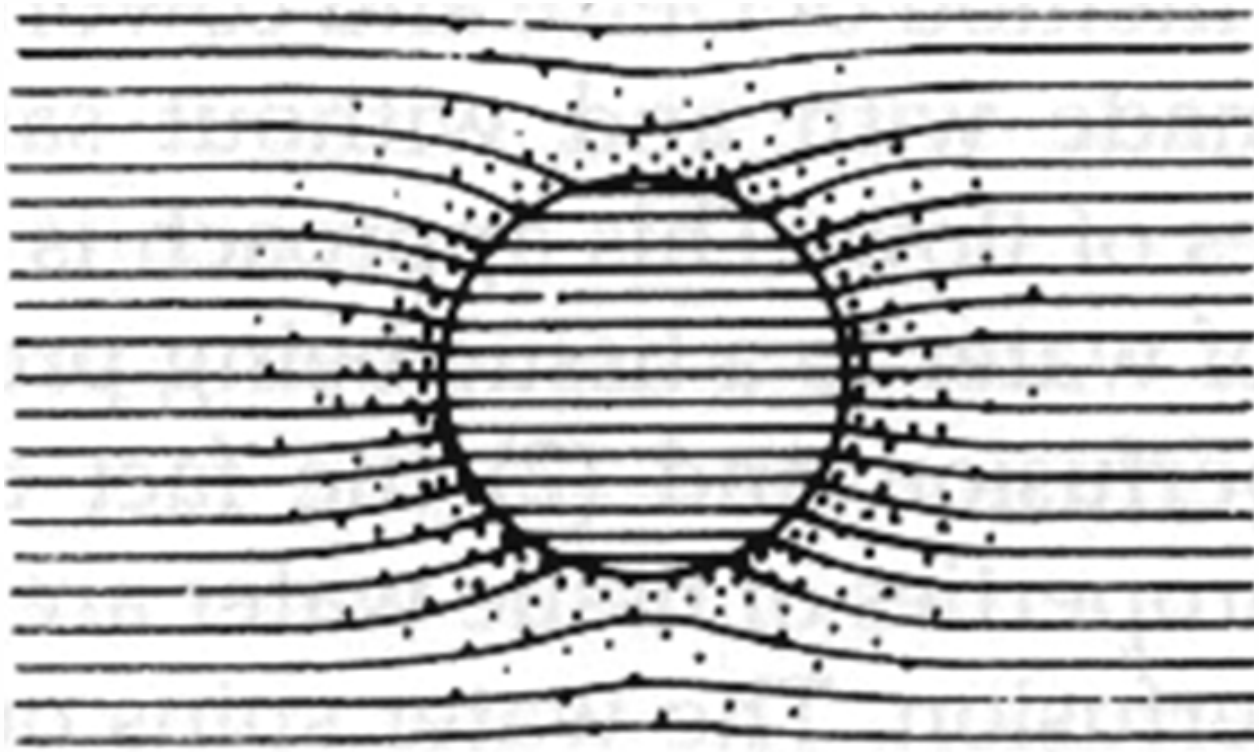
Intra-voxel phase dispersion

- Each voxel contains numerous H nuclei
- Signal intensity of each voxel reflects net magnetization
  - Net vector formed by all nuclei
- What if off resonance occurs non-uniformly in single voxel?

Intra-voxel phase dispersion

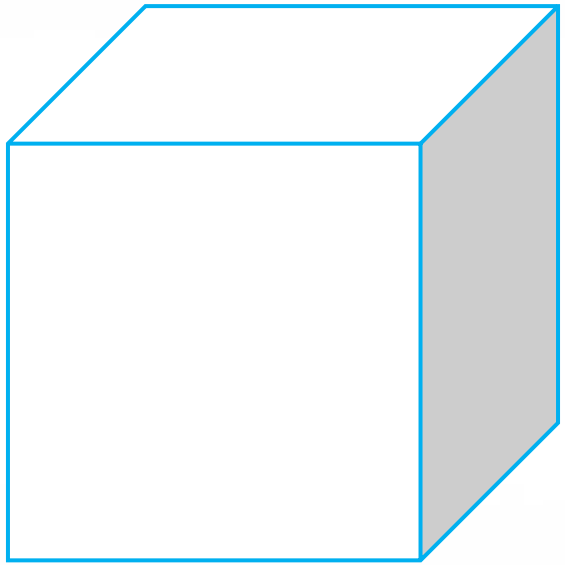
- Non-uniform off resonance in one single voxel
  - Inconsistent resonance frequency
  - Incoherent phase: intra-voxel dephasing
  - Signal attenuation: low intensity in image

A typical scenario…

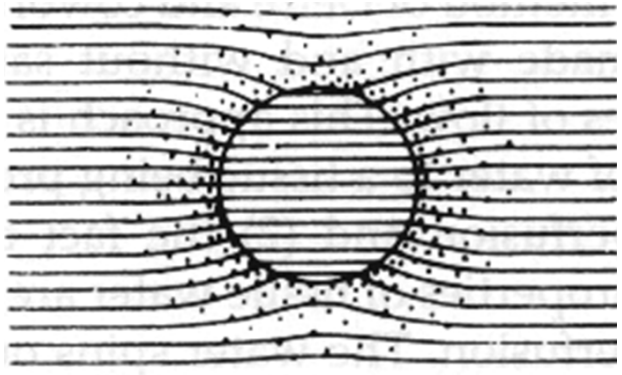


Off resonance: paramagnetic air space surrounded by diamagnetic tissues

Microscopic inhomogeneity by susceptibility

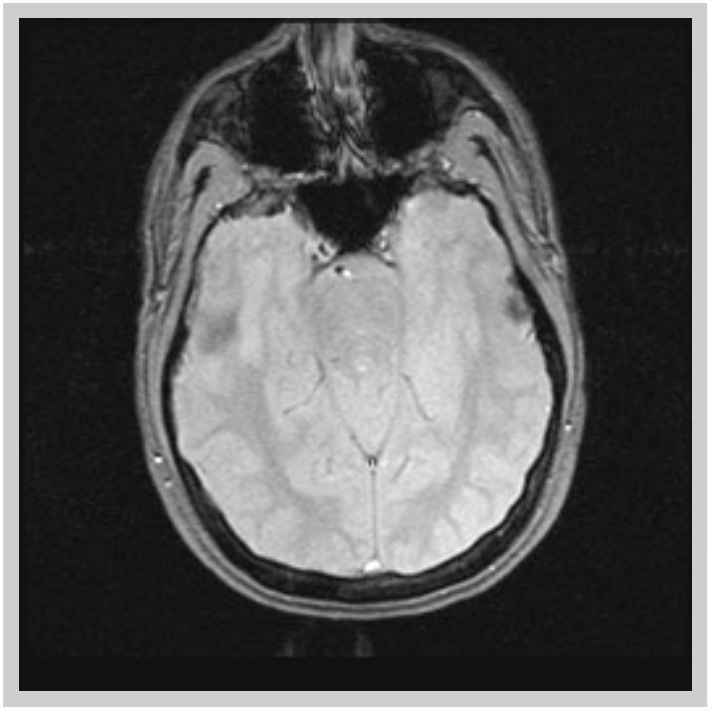


An image voxel

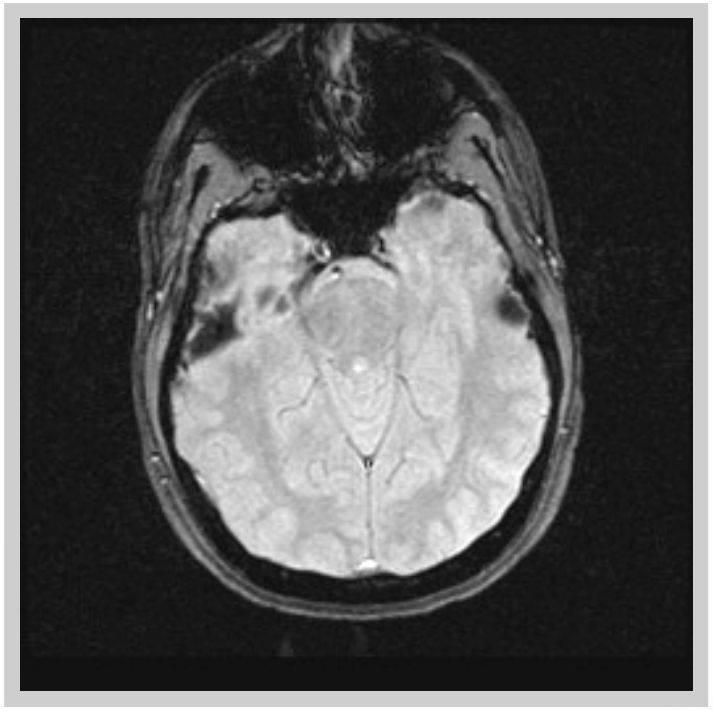


Intra-voxel field inhomogeneity: T2* attenuation

Signal attenuation of intra-voxel dephasing



TE = 9 msec



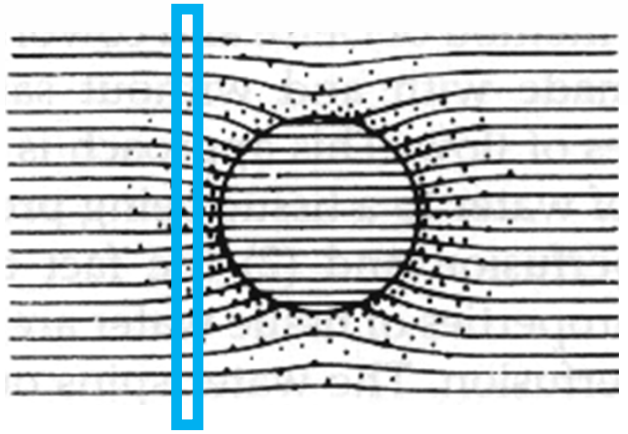
TE = 18 msec

Signal attenuation of intra-voxel dephasing

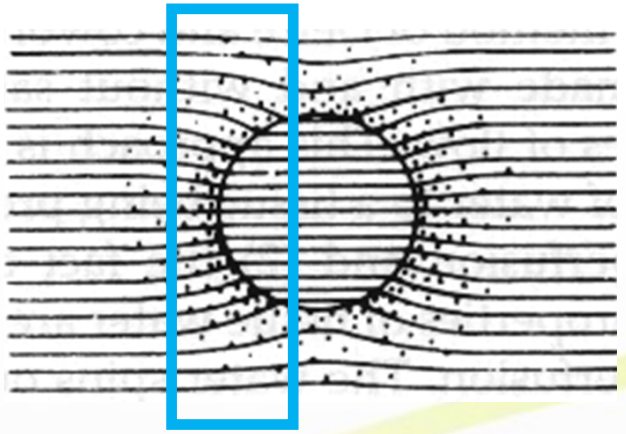
- Described as shortened T2*
  - Signal loss in gradient echo
  - Attenuate more with longer TE
  - Not only related to spatial distribution of tissues, but also the voxel size
  - Recovered in spin echo sequence

Field inhomogeneity at different dimensions

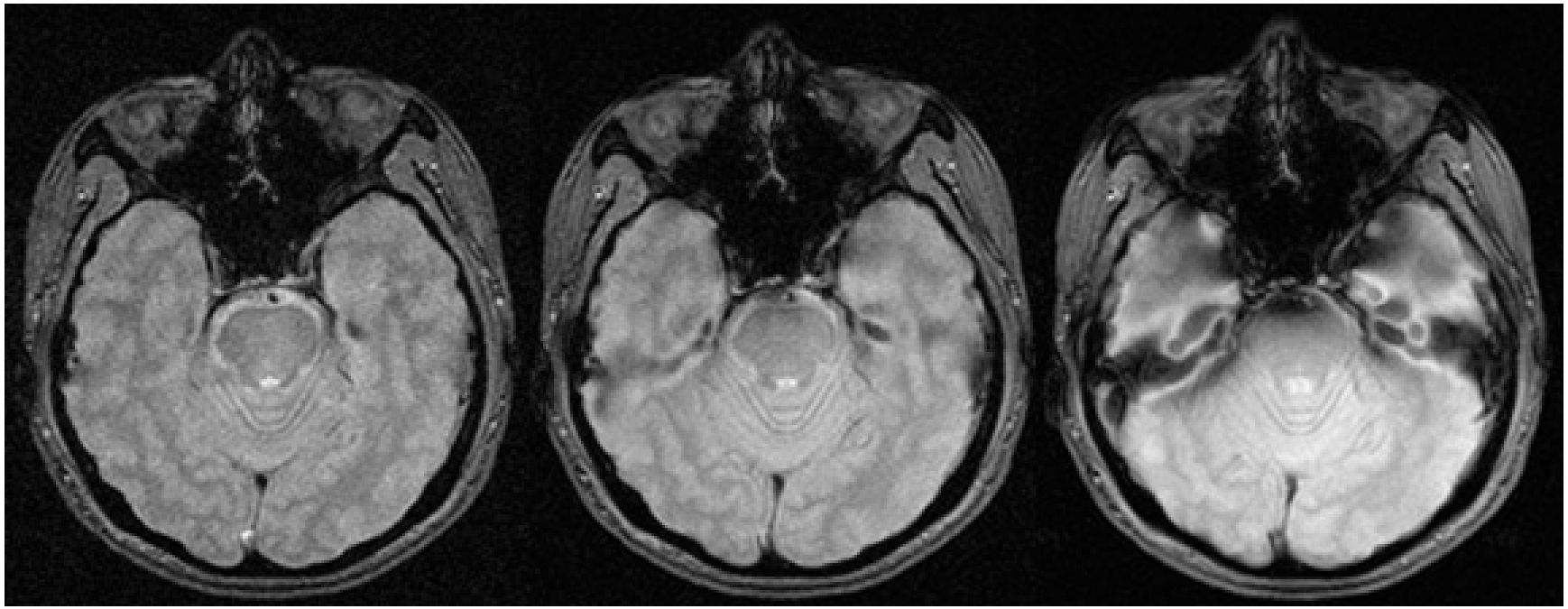
Thin slice



Thick slice

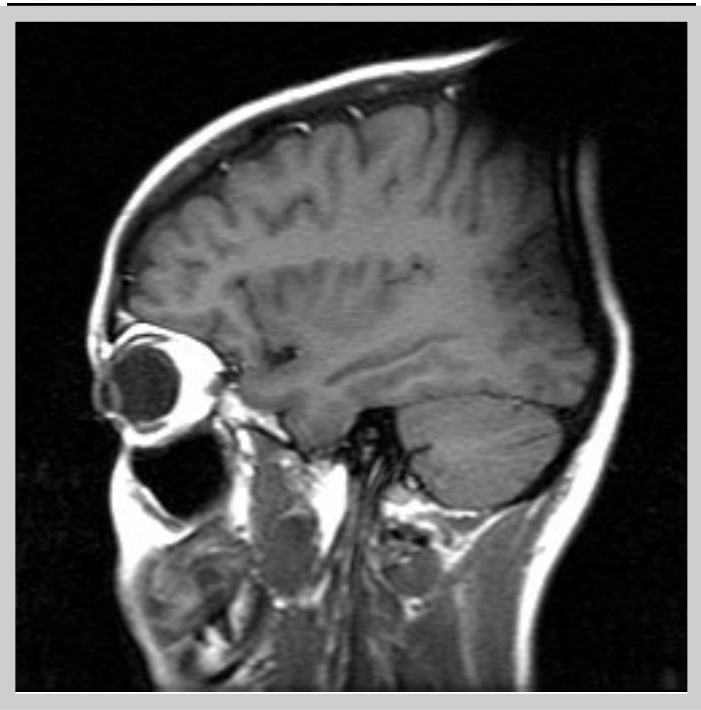


Comparison of different thickness

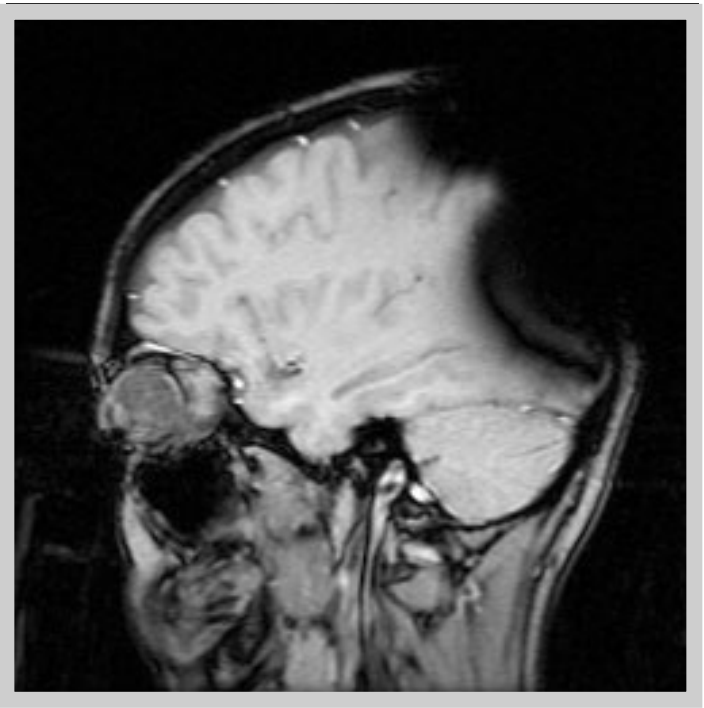


3 mm 5 mm 10 mm

Remember these images?

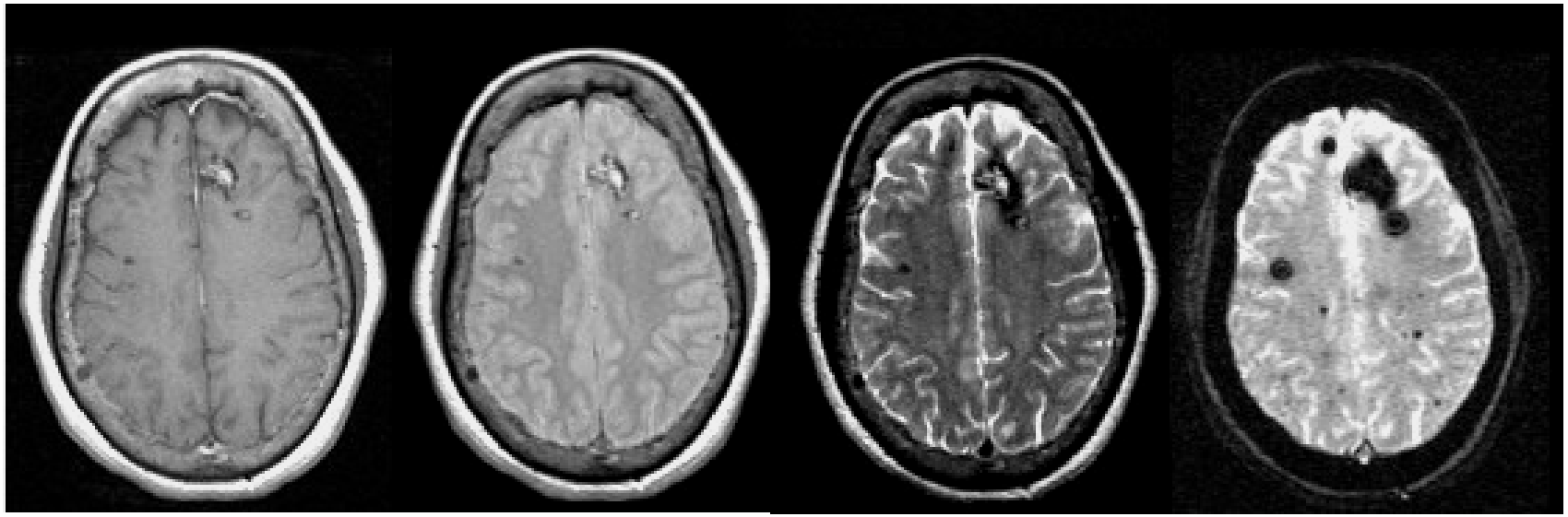


Spin echo



Gradient echo

T2* loss in hemorrhage

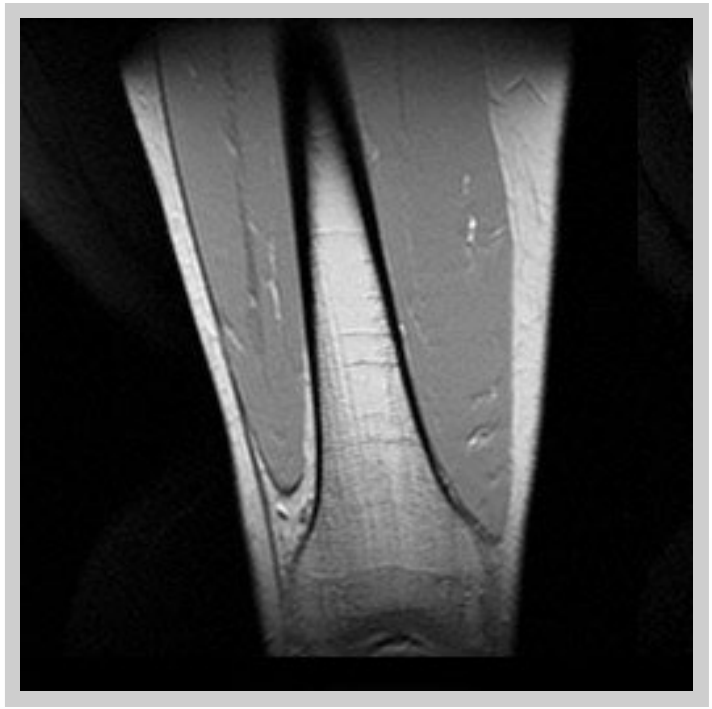


T1 PD T2 T2*
(Gradient echo)

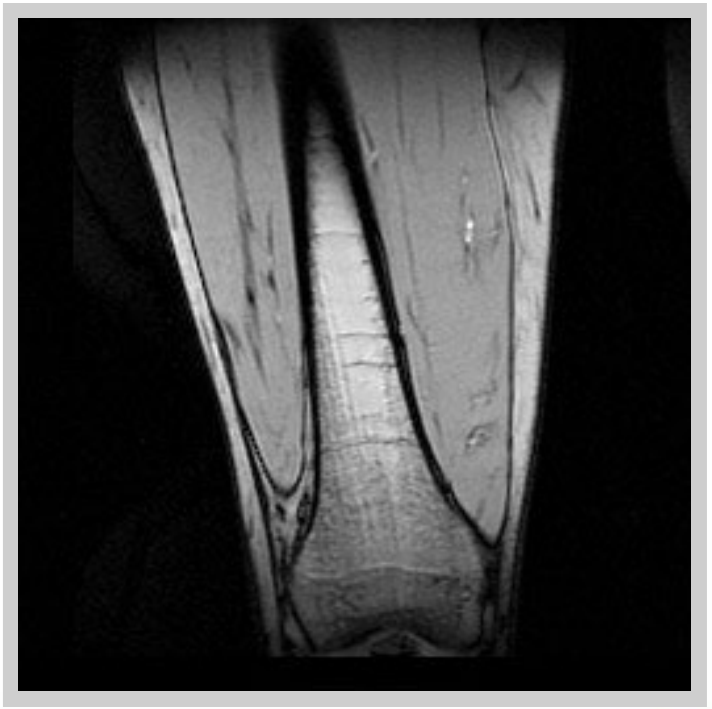
Intra-voxel dephasing in water-fat interfaces

- Water-fat chemical shift: ~220 Hz @ 1.5T
- It takes only 2.27 msec from in-phase to out-of-phase
- Intra-voxel dephasing happens at the voxel of the water-fat interface

Water-fat chemical shift



In-phase

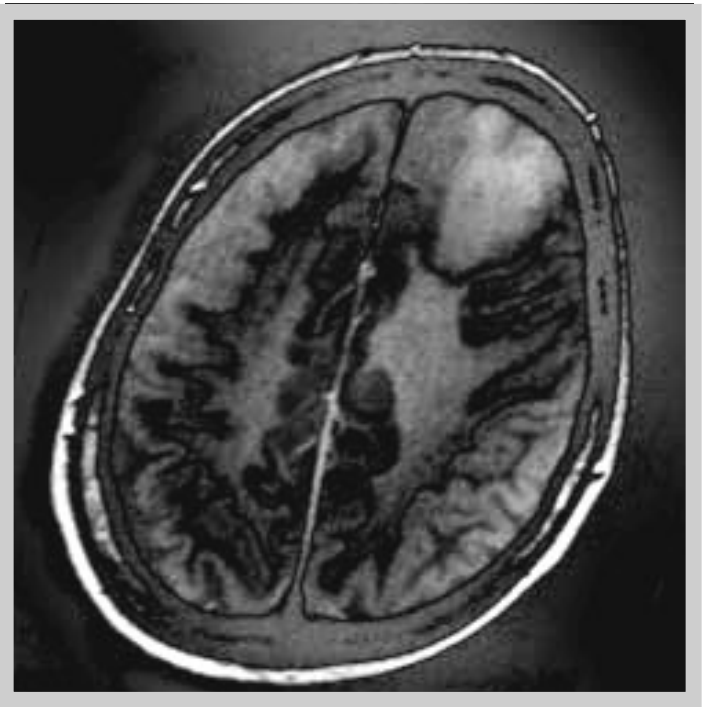


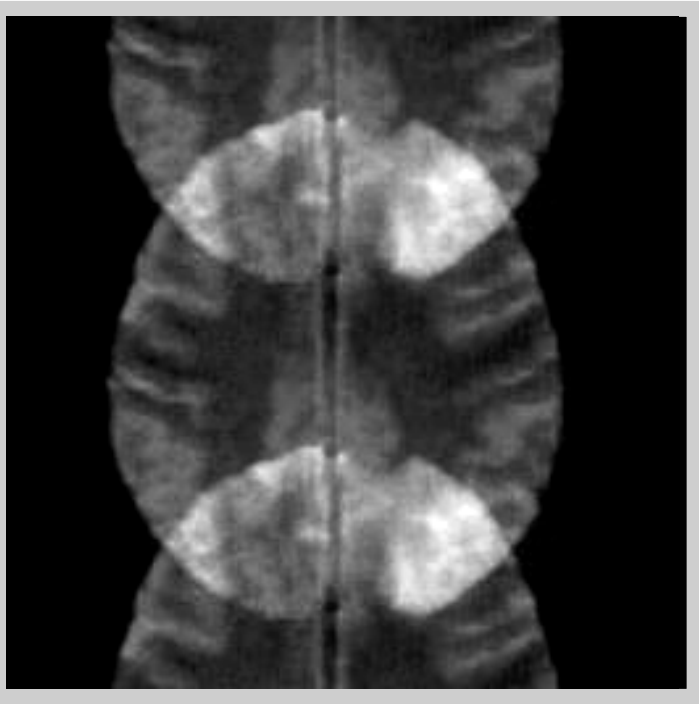
Out-of-phase

Other artifacts not mentioned…

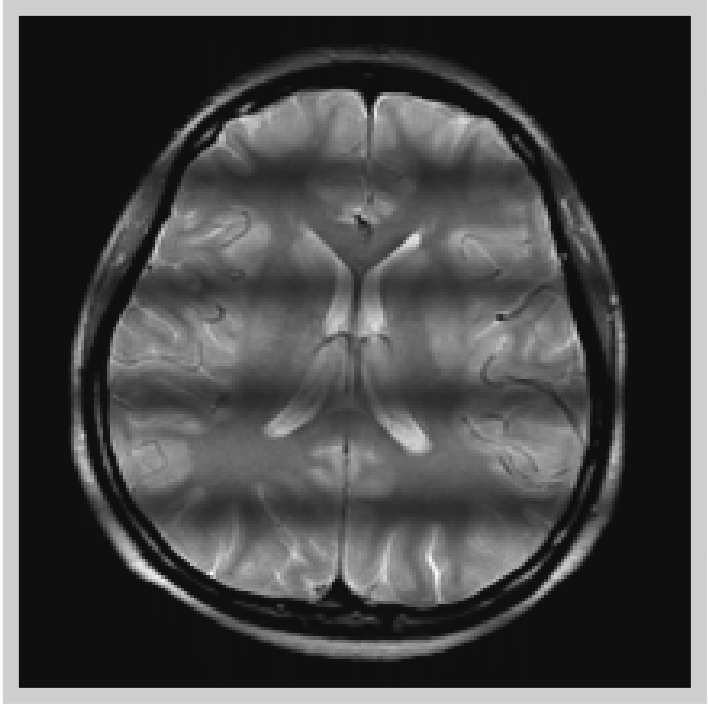
- There are still more…
- Many of them can not be perfectly explained
  - Just like diseases of human
- What if a bizarre artifact is encountered?

For example…





More examples…



Basic rules

- First of all, confirm reproducibility of the artifact
- Deduce or rule out possible factors by comparison of various parameters
- Usually costing lots of efforts
- Contact maintenance?
  - Usually cost more time or/and money…

Artifacts in MRI