MRI Artifacts/Quality for Accelerated Techniques (pMRI & SMS)

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Disclosure

I have nothing to disclose.

Outline

I. pMRI and SMS overview – a refresher
II. pMRI- & SMS-based Quality Issues
III. pMRI- & SMS-based Artifacts
    a. Original to pMRI, SMS
    b. Modifications of traditional artifacts

Parallel MR Imaging

Goal: to collect subset of image information to produce images in a shorter period of time.

Benefits:

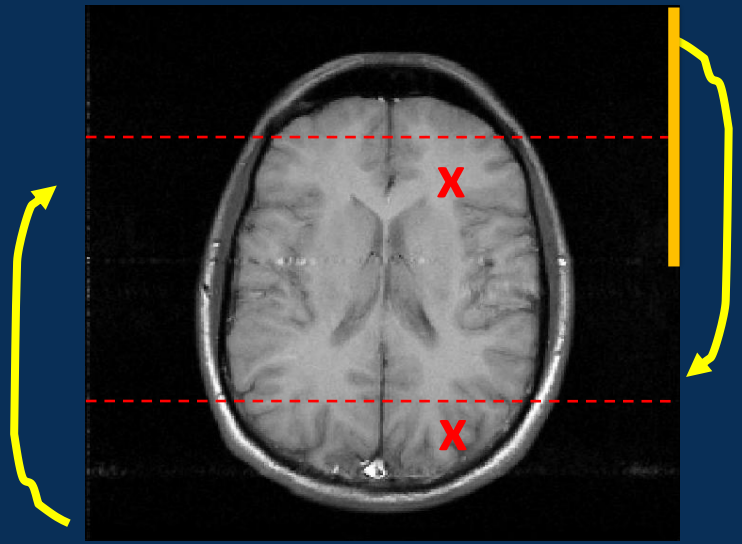
- *Faster image acquisition*
- *Higher-resolution imaging*
- *Some susceptibility mitigation*

How does it work?

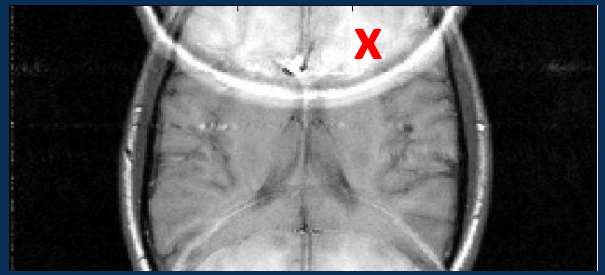
- ***Omit phase-encoding information and use coil element arrangement as a replacement***. *Undersampled k-space, but not sparse.*

pMRI Speed

less phase encodes = smaller FOV (with same resolution)



Smaller FOV



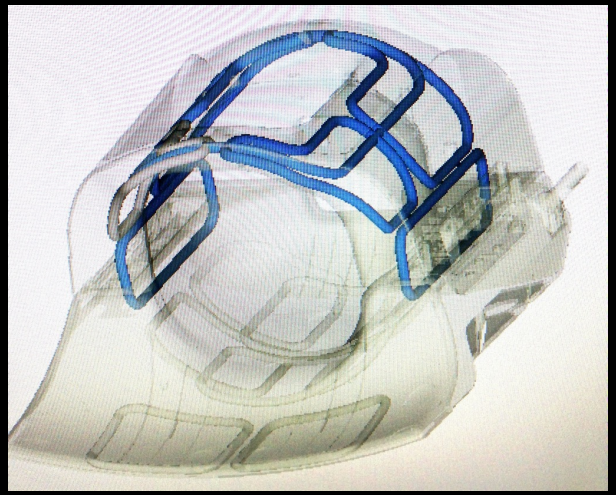
aliasing

1 out of 2 lines of k-space → ½ FOV

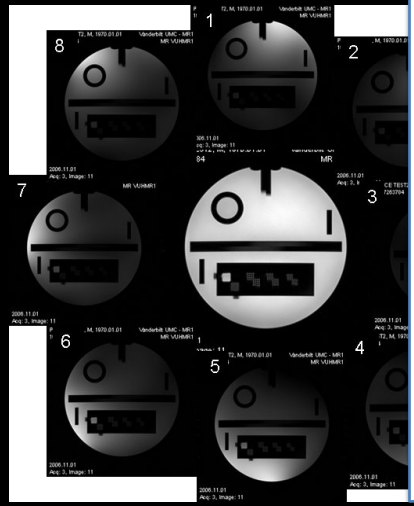
FOV "shrinkage" → undersampling (acceleration=R)

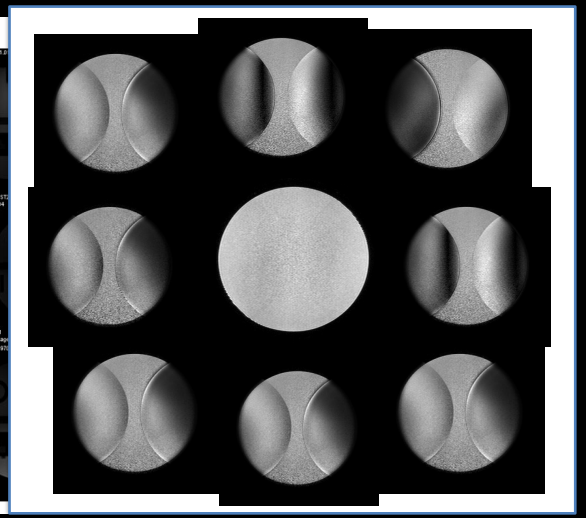
Parallel MR Imaging

Spatial sensitivity varies for each element → can use this in conjunction with undersampling. Can reduce phase encoding steps in both 2D and 3D imaging*.



Conventional use of phased-array (unaliased)



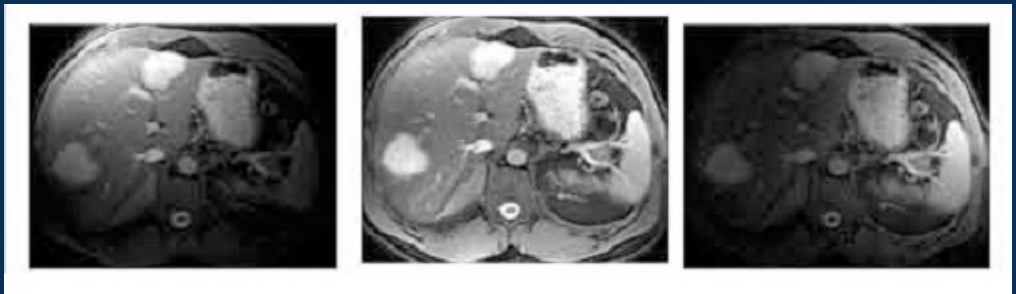


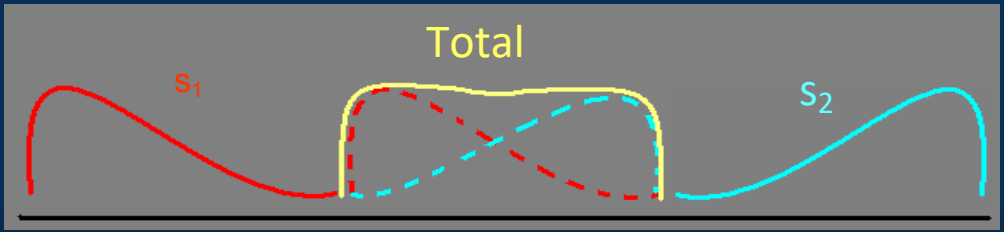
Parallel reconstruction of data (aliased)

*depending on coil

Sensitivity Map

Sensitivity map → spatial sensitivity of each coil element.
Sometimes, a ***calibration scan*** is usually required to calculate this.
Auto-calibration: acquire sensitivity information simultaneously with clinical image.

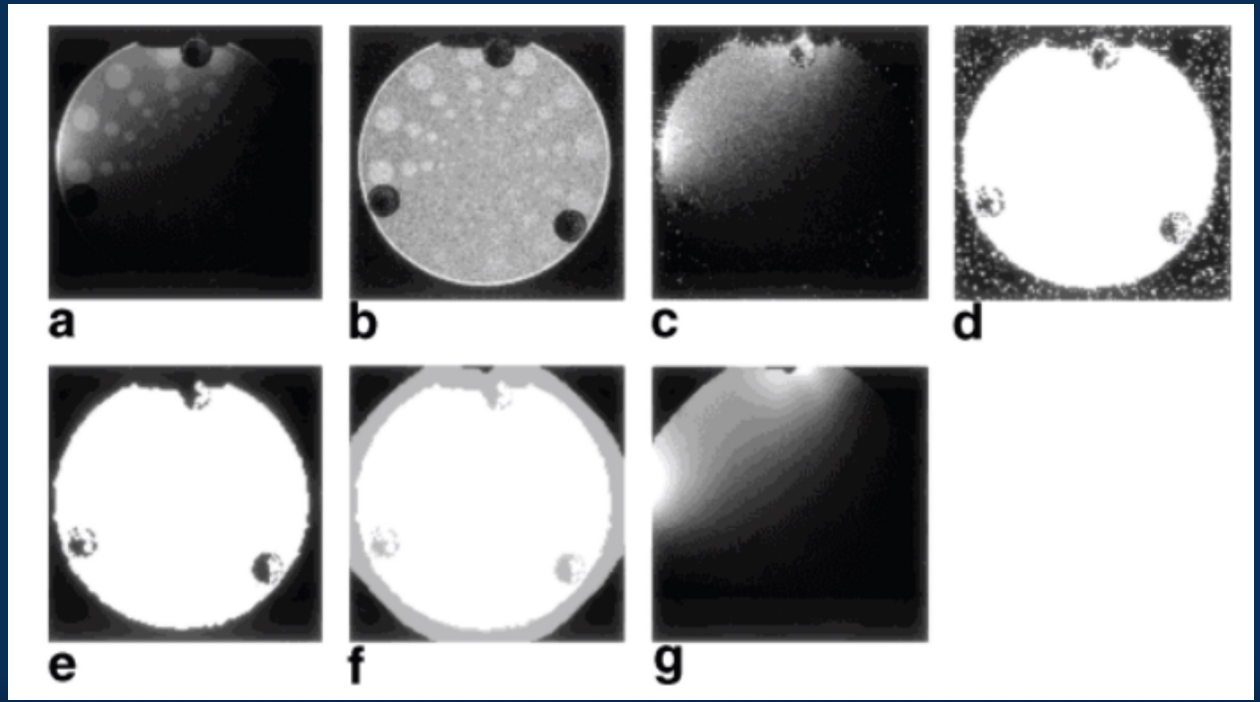




Might present different artifacts

Calibration Scan (SENSE method)

This takes a few seconds to acquire, at the beginning of a patient exam



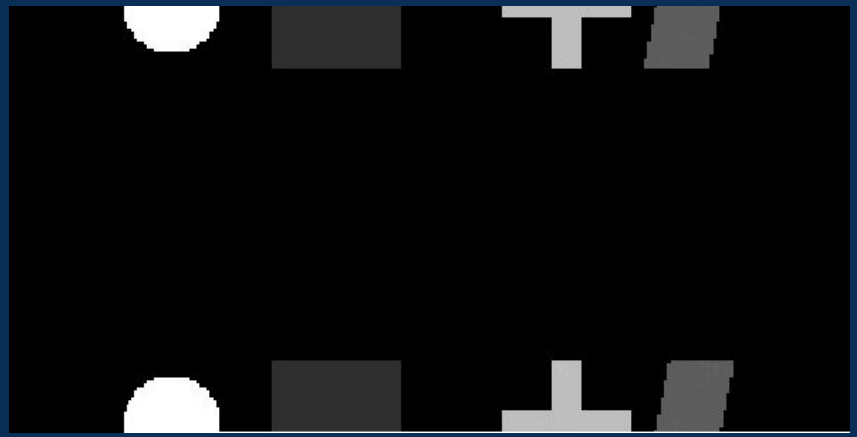
a) Individual element scan
b) Body coil scan
c) a/b
d) Threshold b → noise
e) Filtering
f) Dilate f
g) Polynomial fit: sensitivity map

Does this accurately represent sensitivity?

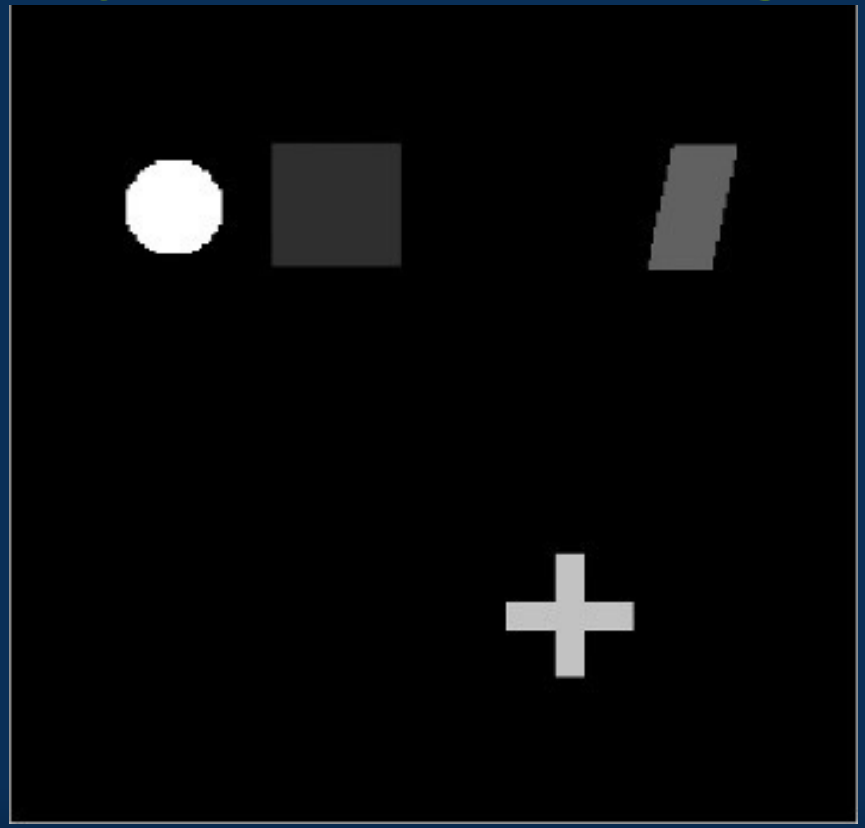
Pruessmann, et al. Magn Reson Med 1999

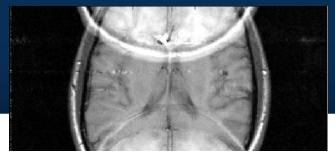
Example: Using Coil Sensitivity to Un-alias an Image

aliased

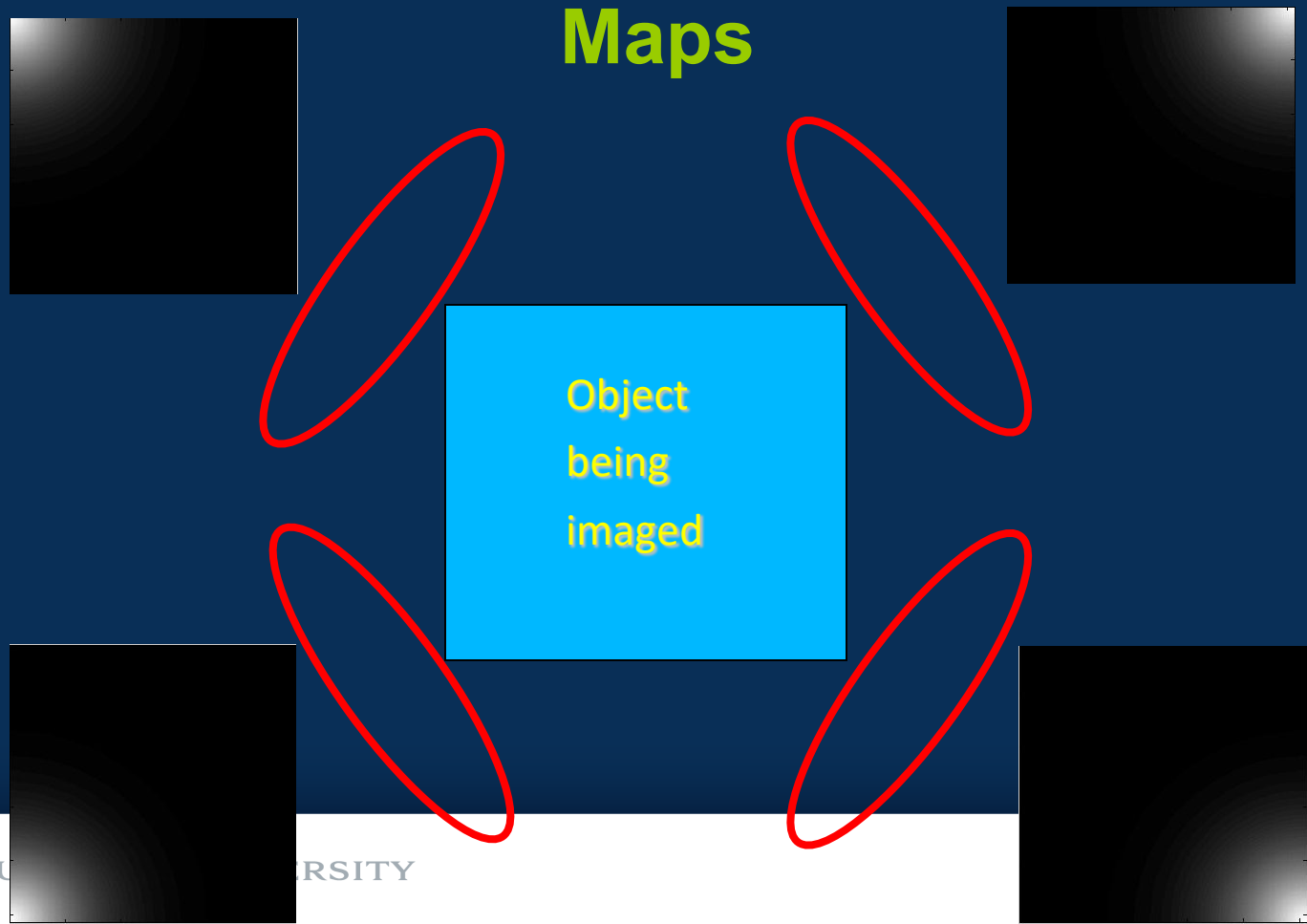


Unaliased
(maybe?)

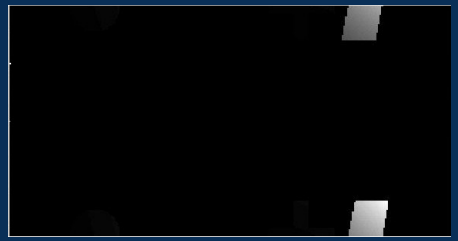


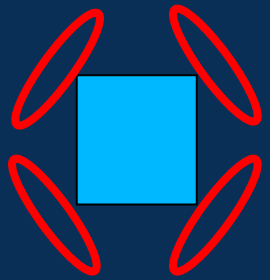


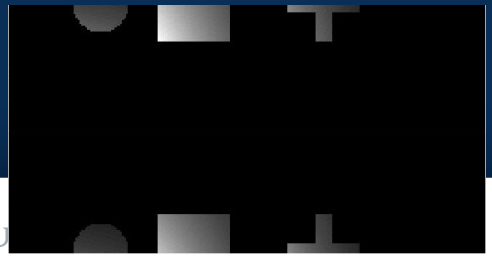
Coil Locations and Sensitivity Maps

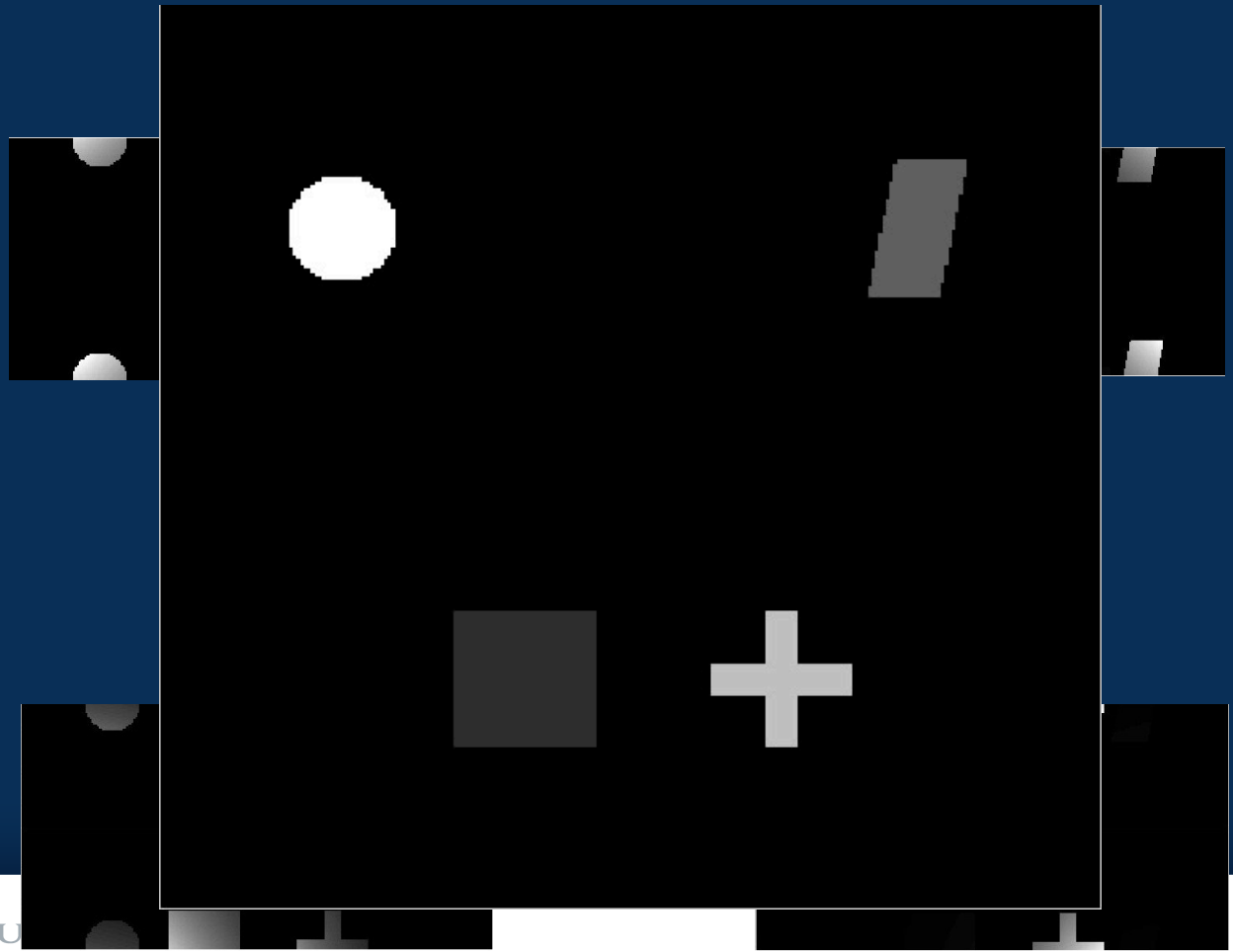


Using Coil Sensitivity to Un-alias an Image



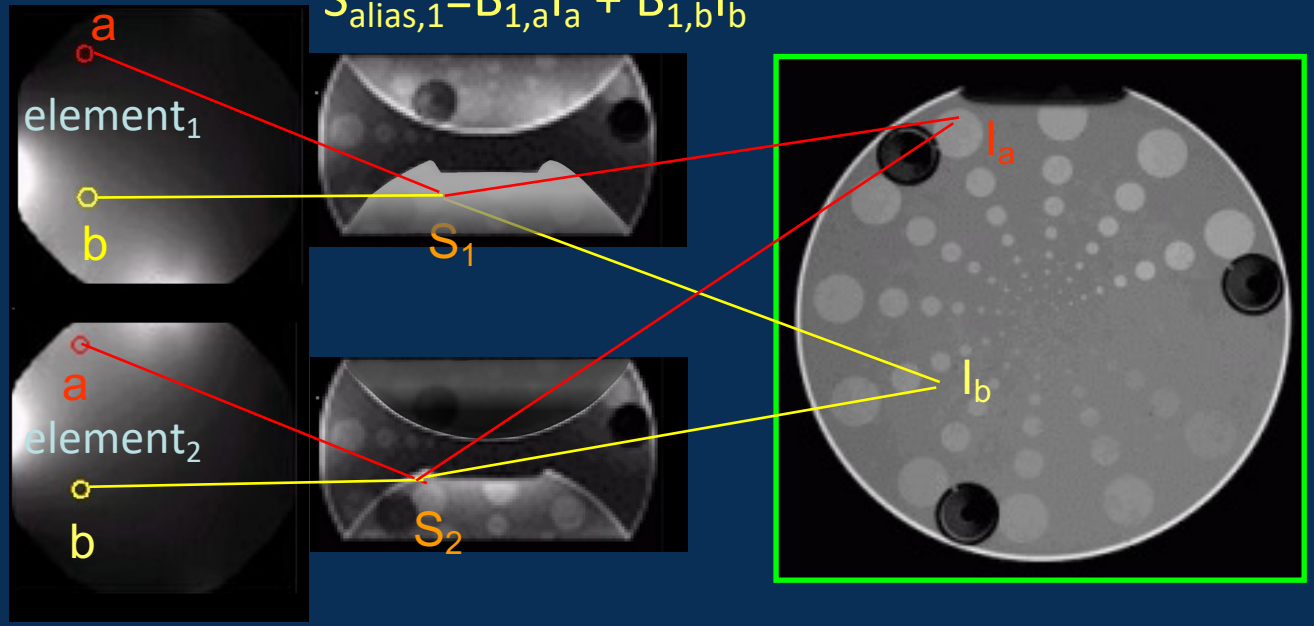






A Simplistic SENSE Example

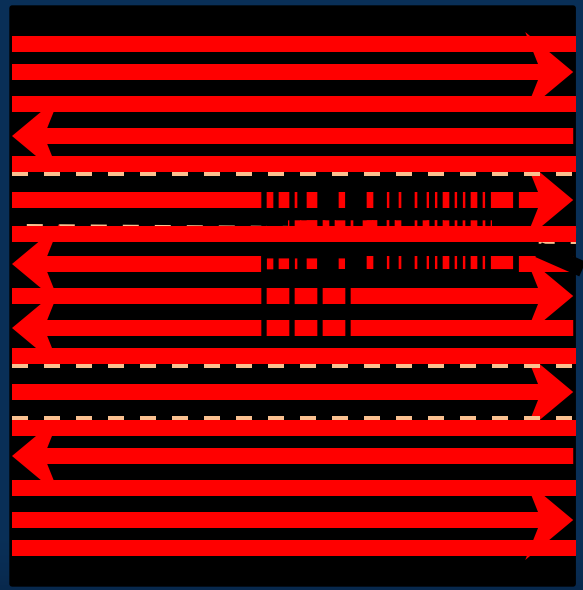
$S_{alias,1}=B_{1,a}I_a + B_{1,b}I_b$

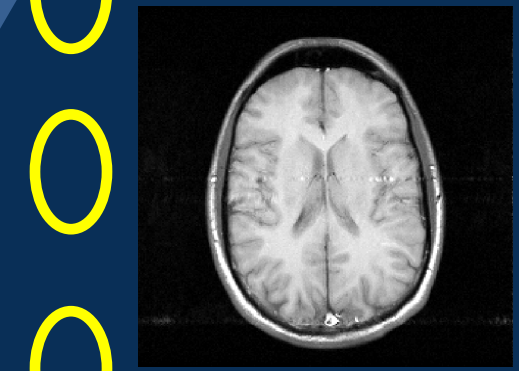


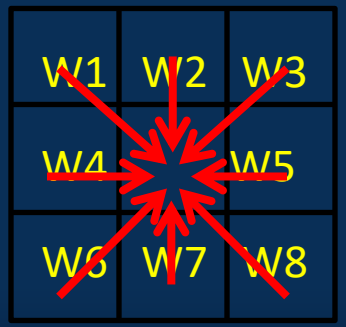
$S_{alias,2}=B_{2,a}I_a + B_{2,b}I_b$

GRAPPA

K-space for each individual element.



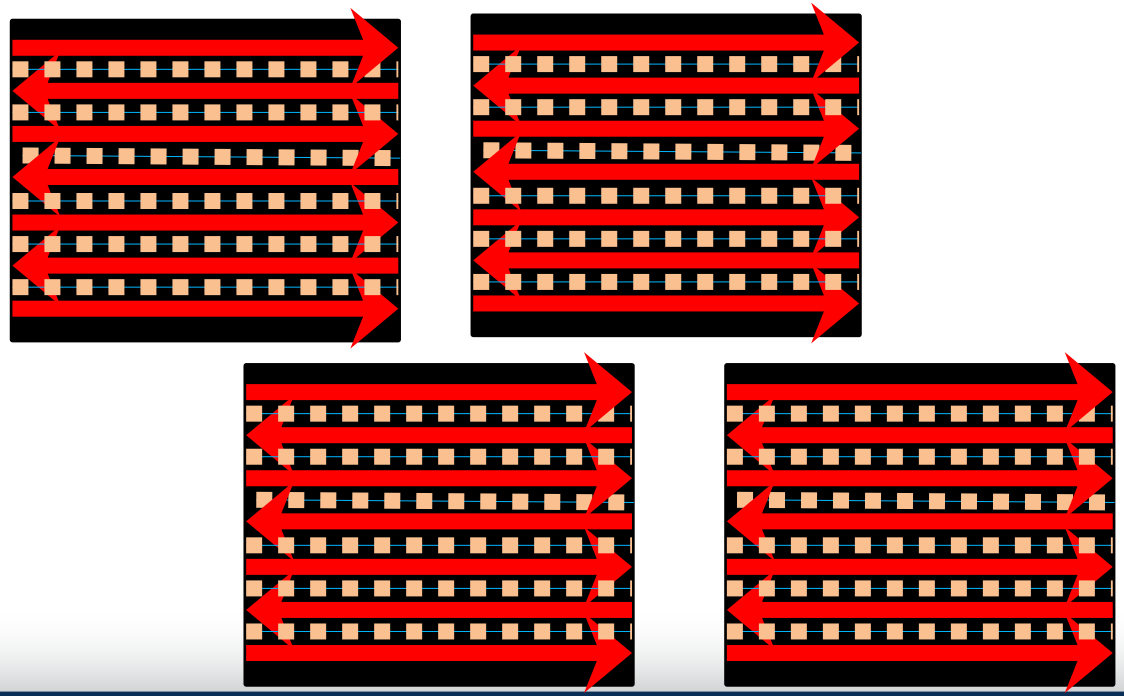


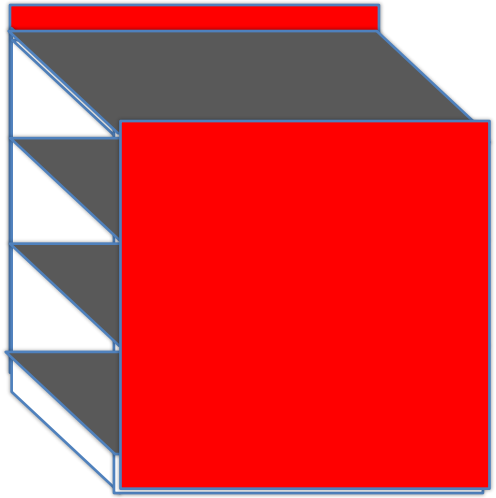


Weights come from auto-calibration data.

Parallel MR Imaging – Through-plane acceleration

3D Imaging: 2 possible directions of phase encoding (1 in-plane, 1 through-plane).

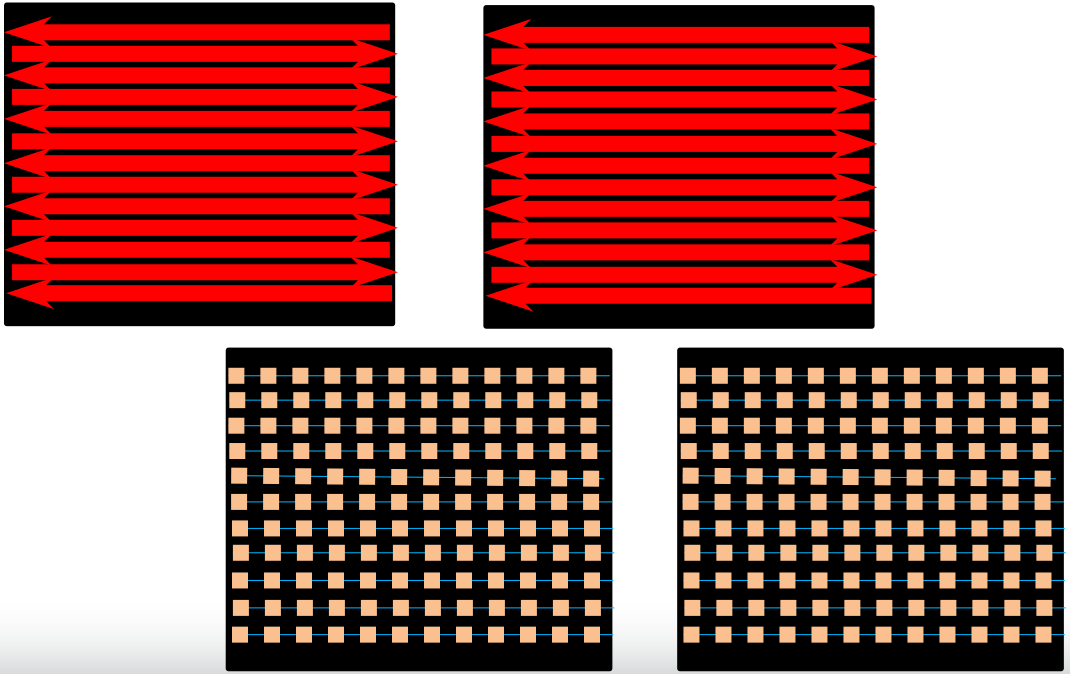


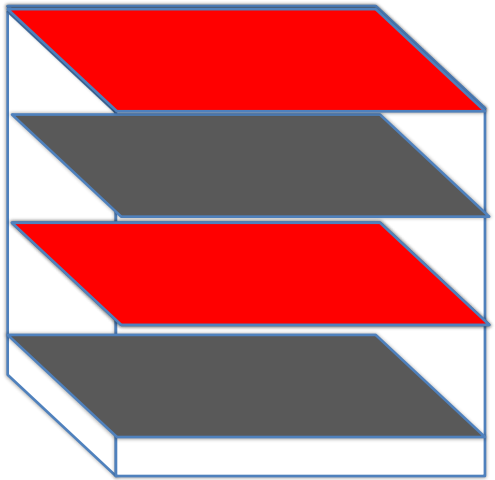


In-plane pMRI pattern (no 3D acceleration)

Parallel MR Imaging – Through-plane acceleration

3D Imaging: 2 possible directions of phase encoding (1 in-plane, 1 through-plane).

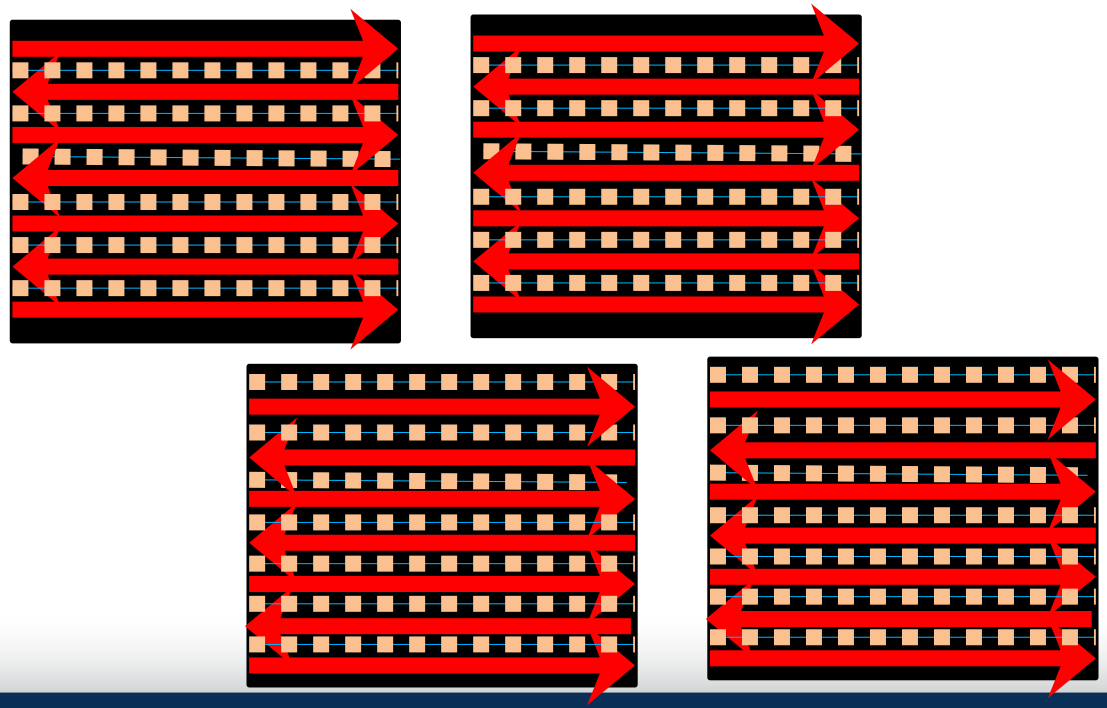


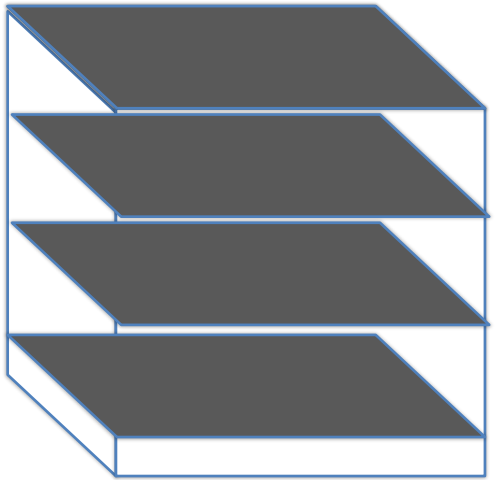


Through-plane pMRI pattern

Parallel MR Imaging – Through-plane acceleration

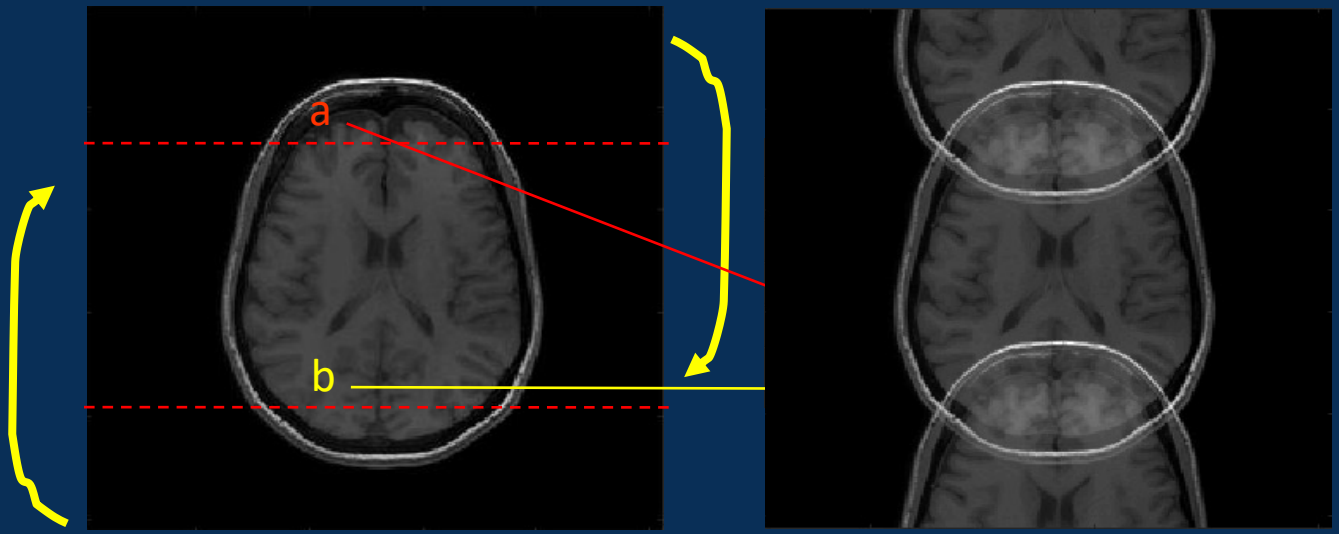
3D Imaging: 2 possible directions of phase encoding (1 in-plane, 1 through-plane).





Caipirinha pMRI pattern

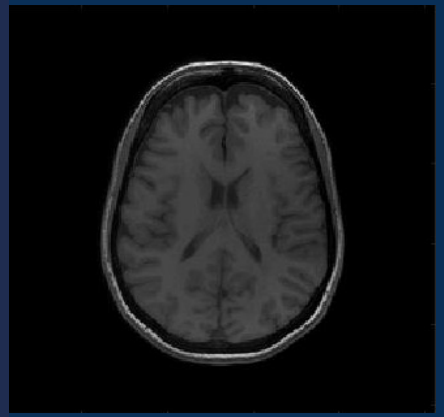
Simultaneous Multi-Slice Imaging (SMS): Comparison to pMRI

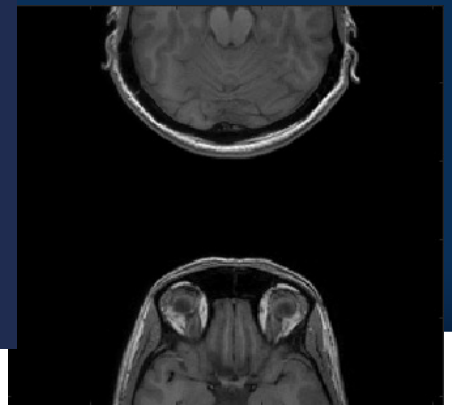


Smaller FOV

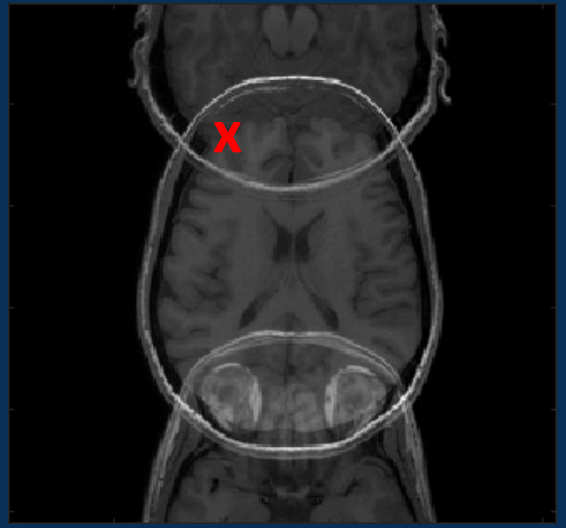
SMS Imaging (Controlled Aliasing – approach)

- Benefit: acquire N images in the time required for 1.
- Differences: Data summed over N image sets → SNR increase of $N^{1/2}$ (unlike pMRI).
- Reconstruction: somewhat analogous to pMRI image-based reconstruction**.
- Phase offset in k-space (slice shift)→ helps with the reconstruction (N=2 shown)
- RF pulses require tailoring and care (excite multiple slices, multiplex vs. simultaneous, high SAR and RF amplifier concerns)



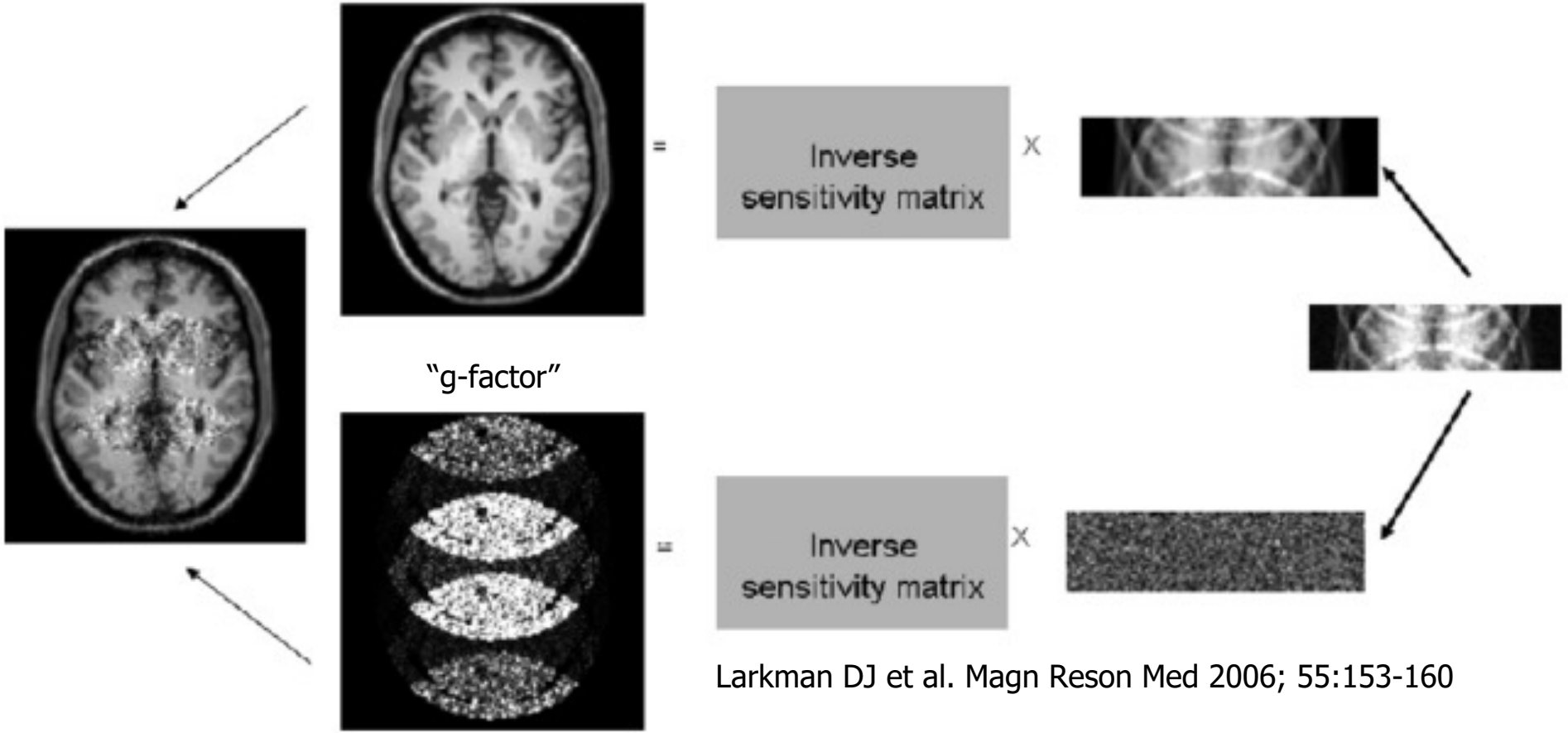


Think about how artifacts may propagate between slices



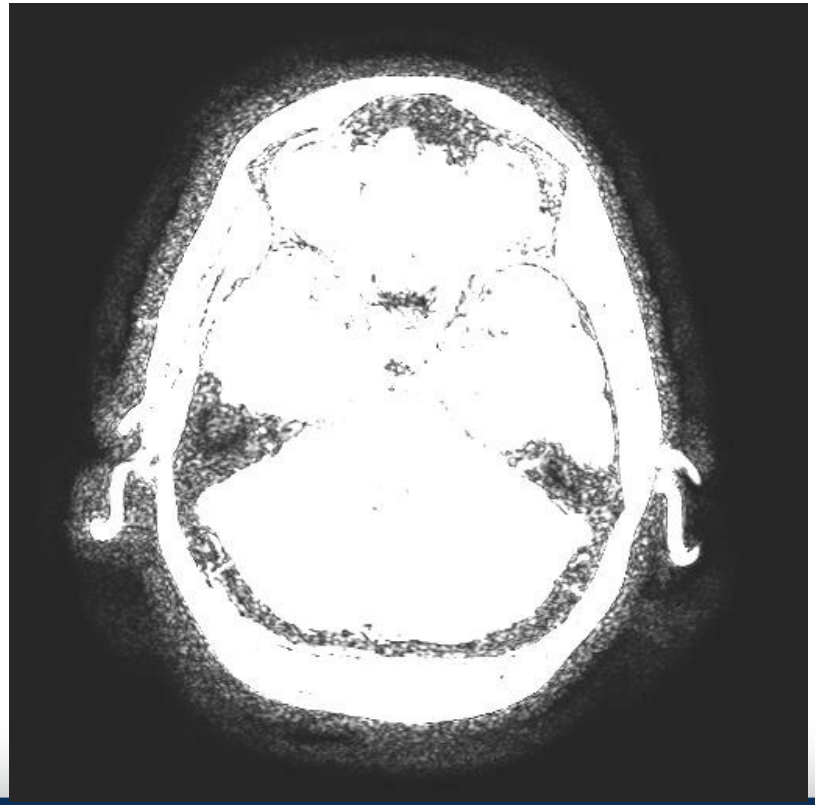
**Beyond the scope of this talk.

pMRI Quality Issues: non-uniform SNR (and SNR reduction by $(1/R)^{1/2}$)

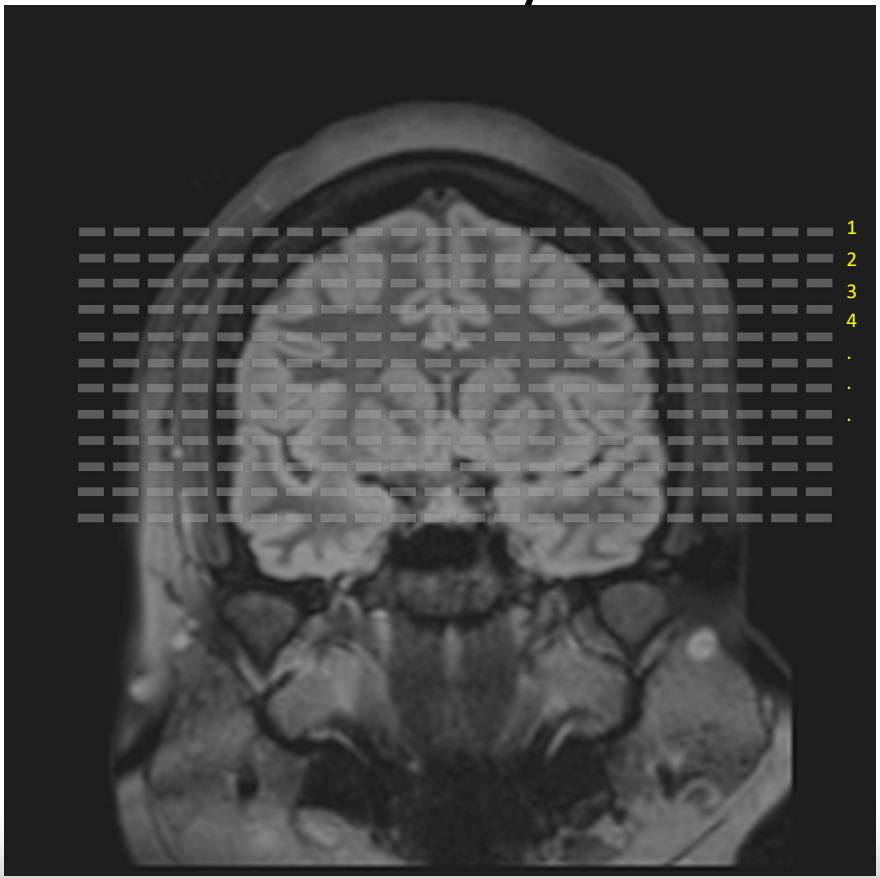


Larkman DJ et al. Magn Reson Med 2006; 55:153-160

pMRI Quality Issues: masking of sensitivity map → no noise in periphery

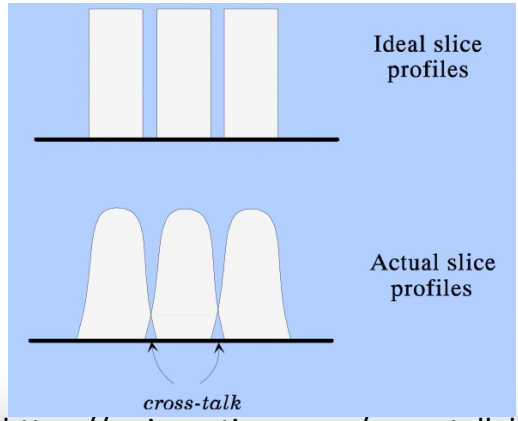


SMS Quality Issues: Saturation and Slice Ordering



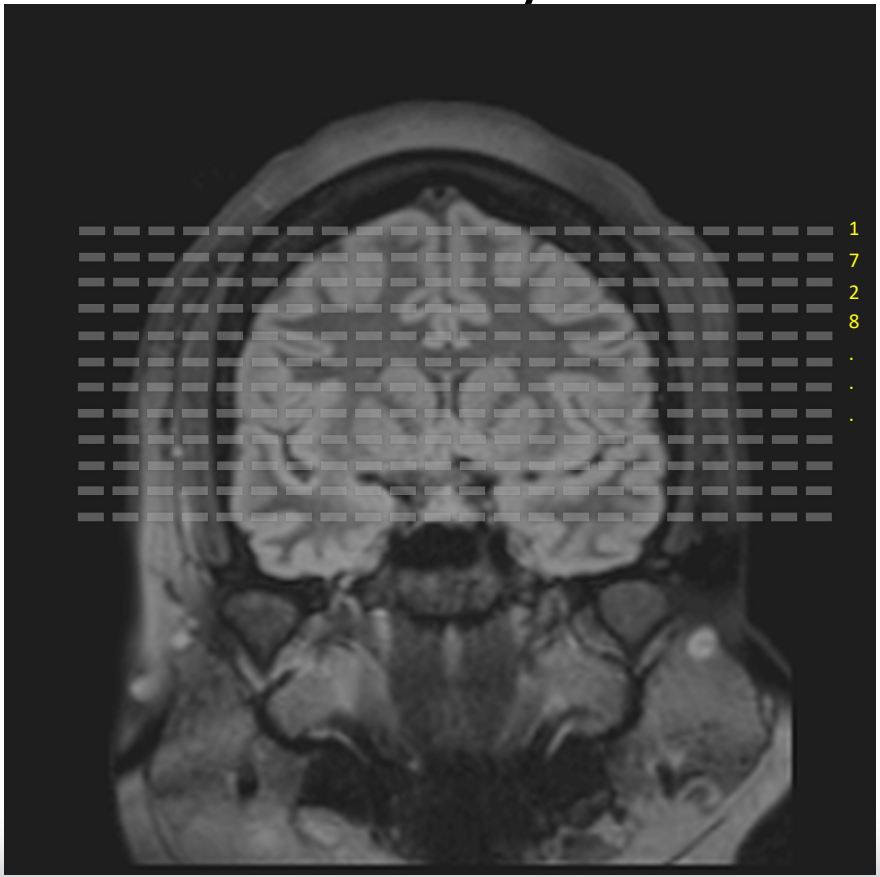
Example: Axial acquisition for non-SMS scanning (12 slices, with TR=2 sec, **no gap**)

Non-interleaved – can get saturation of slices (here, excitation difference = TR/12 → T1 effects between slices)



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

SMS Quality Issues: Saturation and Slice Ordering



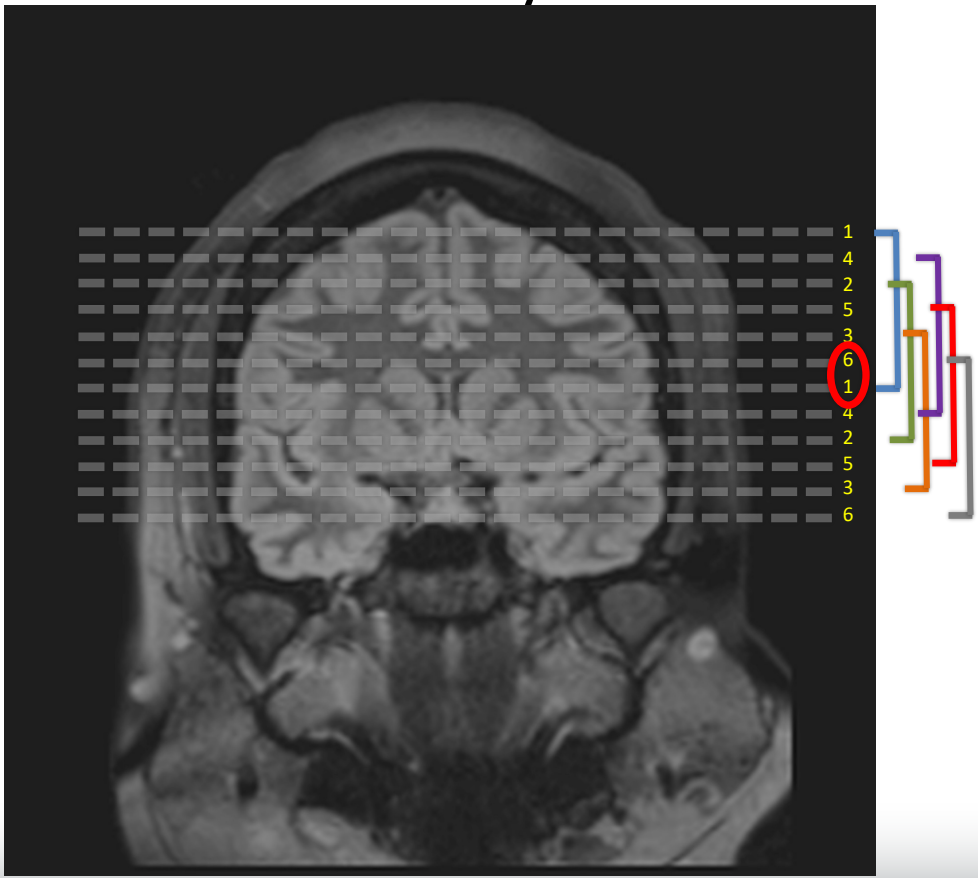
Example: Axial acquisition for non-SMS scanning (12 slices, with TR=2 sec, **no gap**)

Non-interleaved – can get saturation of slices (here, excitation difference = TR/12 → T1 effects between slices)

Interleaved – slices too far to saturate (here, excitation difference = TR/2)

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

SMS Quality Issues: Saturation and Slice Ordering



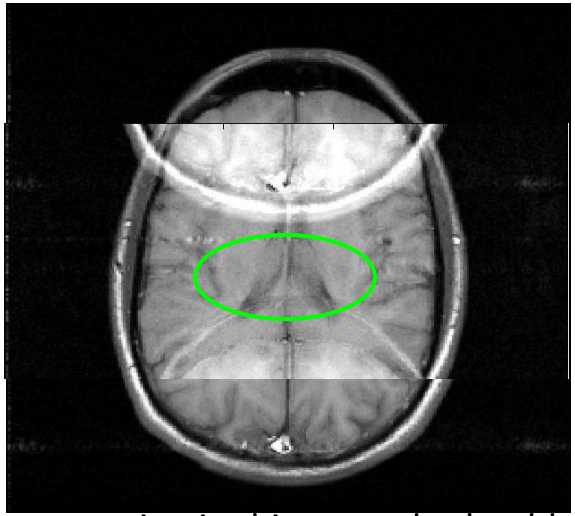
Example: Axial acquisition for SMS scanning (12 slices, with TR=2 sec, no gap, multi-slice N=2)

Interleaving for SMS: interaction effect between # of slices and N – can get saturation effects periodically in stack.

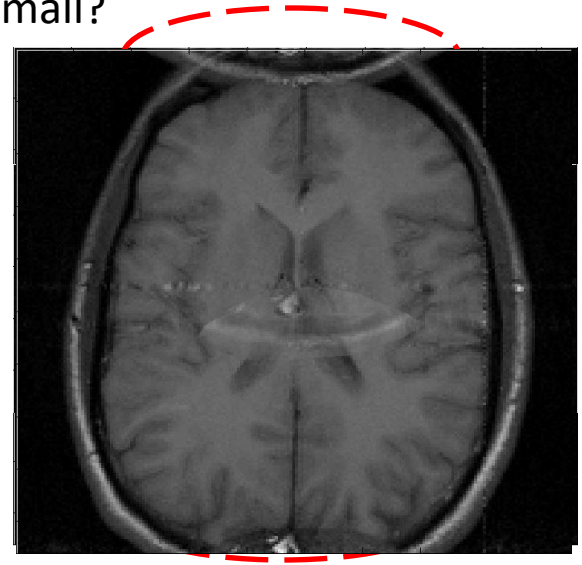
Artifacts

Tissue Outside of FOV (SENSE)—Wrap-around artifact

What happens when the FOV before acceleration is too small?



Center region in this example should be unaliased, for acceleration R=2.

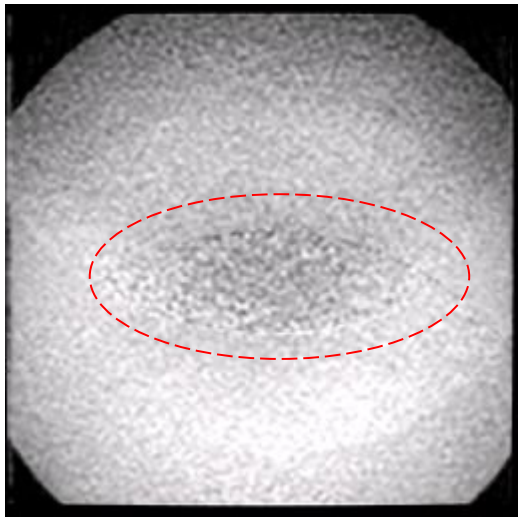


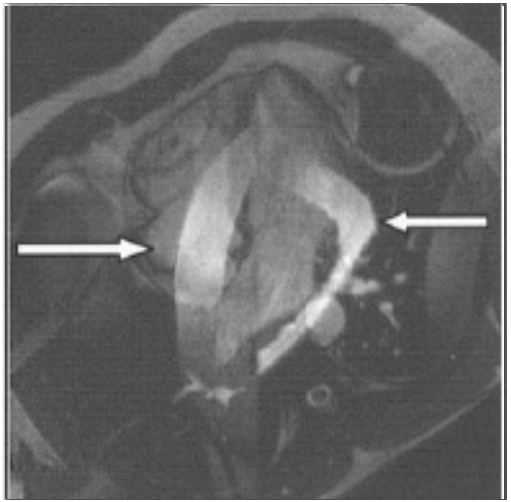
Treated as non-aliased tissue during reconstruction.

Tissue Outside of FOV

- With SENSE-based technique, tissue outside of the FOV yields “wrap-into” artifact

Goldfarb, JMagn Reson Imag. 2004

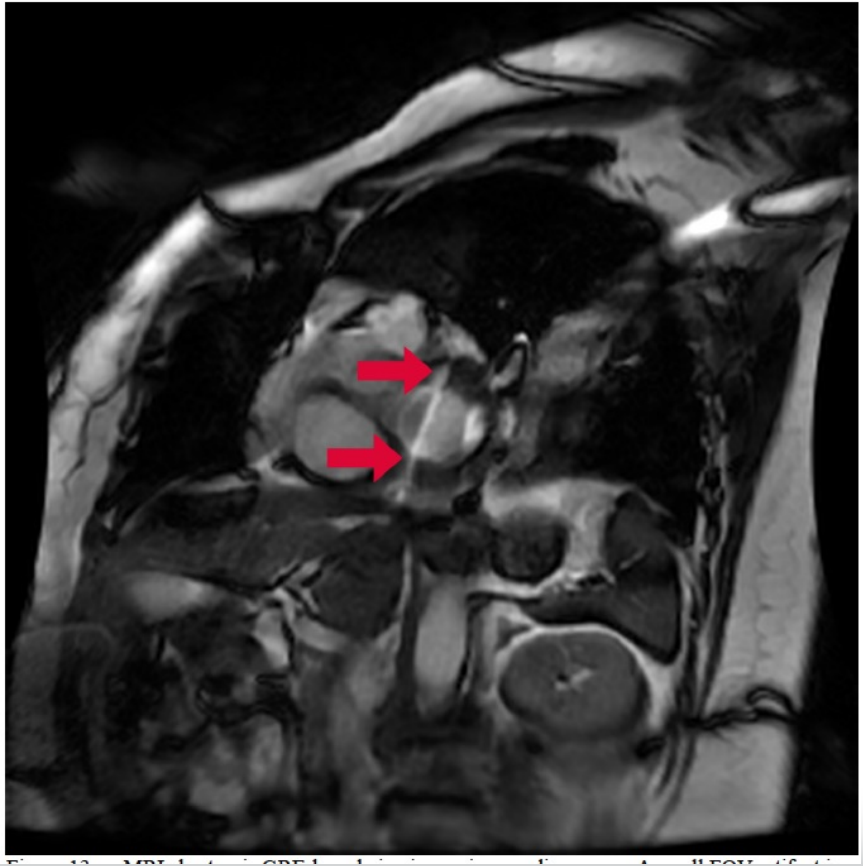




Normal FOV

Small FOV

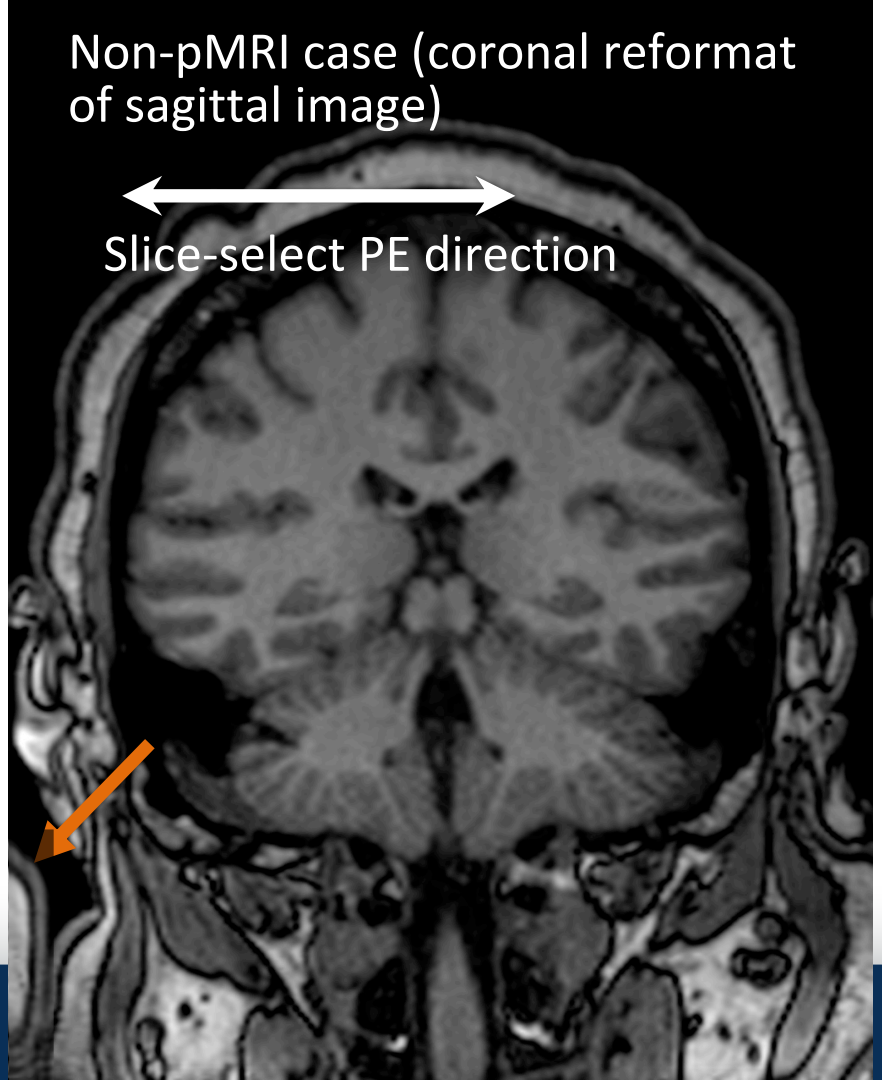
Tissue Outside of FOV



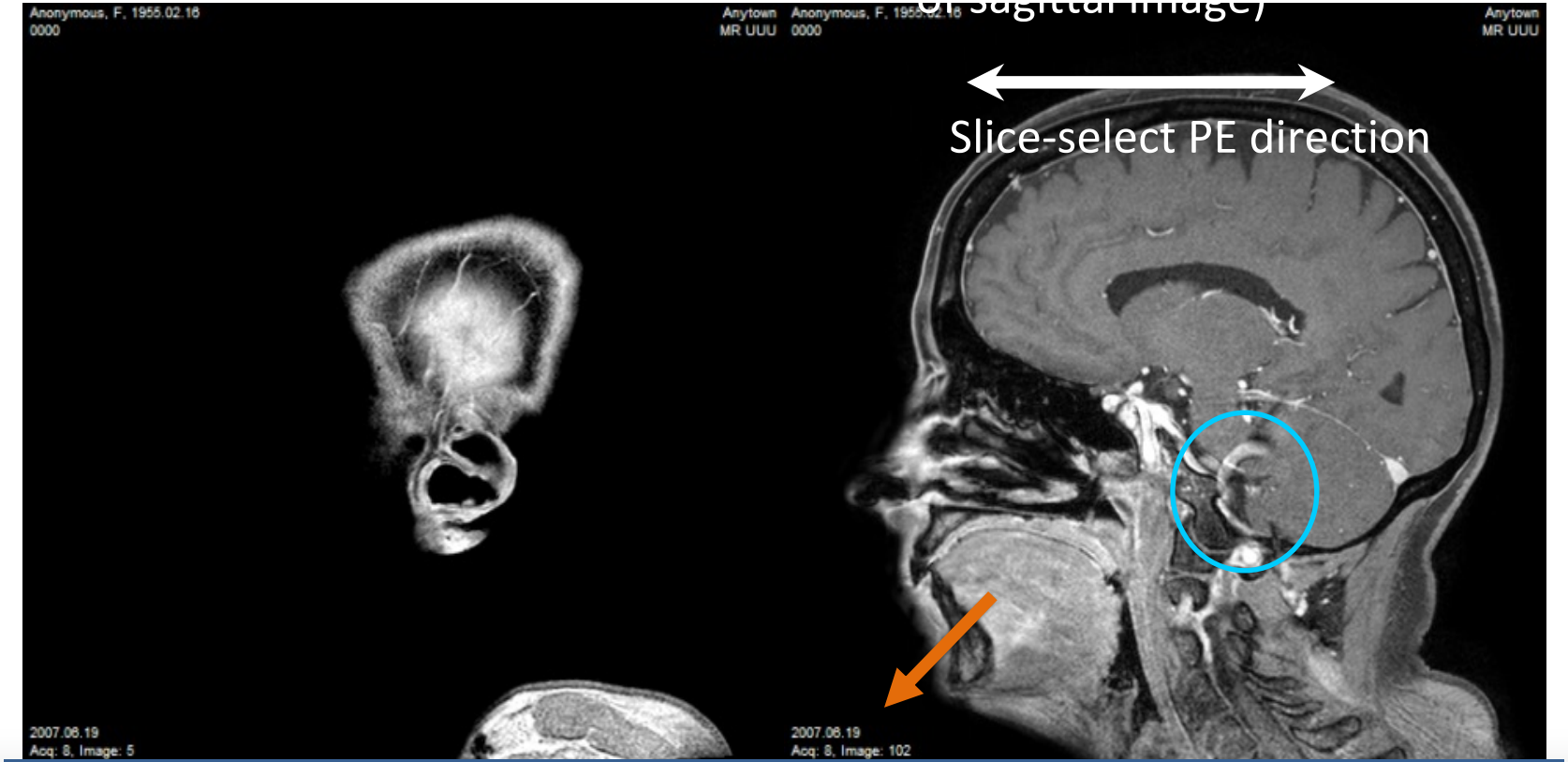
- Must open up the field of view, or potentially need to use a different angle.

Yanasak and Kelly, Radiographics, 2014

pMRI 3D FOV Clinical Artifact Example



pMRI 3D FOV Clinical Artifact Example

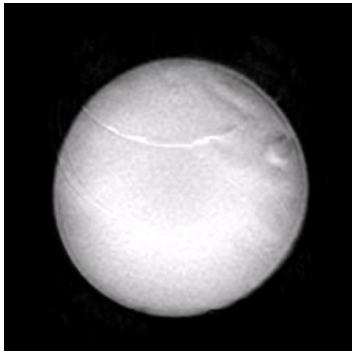


3D artifact: faint ghost near the middle of FOV that resembles structures located at the edges of scanned volume (nose, ear).

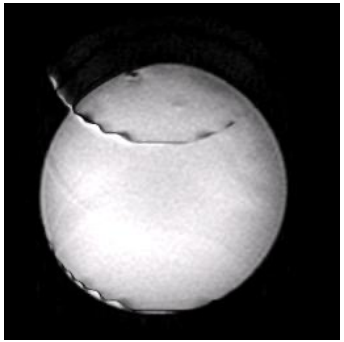
Motion After Calibration Scan (any non-auto-calibrated sequence)

Calibration scan must accurately represent tissue position.

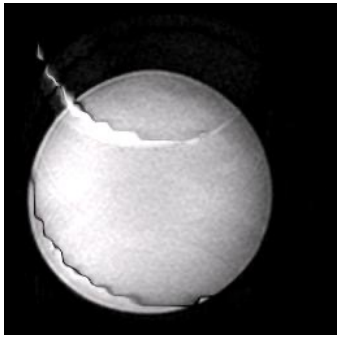
Here, phantom moved after calibration scan.



Small displacement



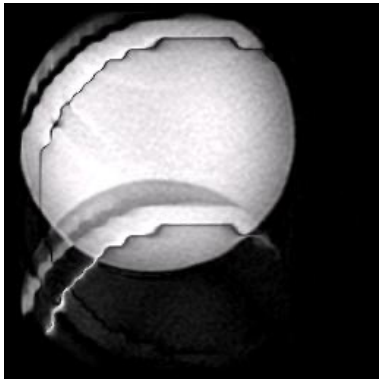
Medium displacement



Large displacement

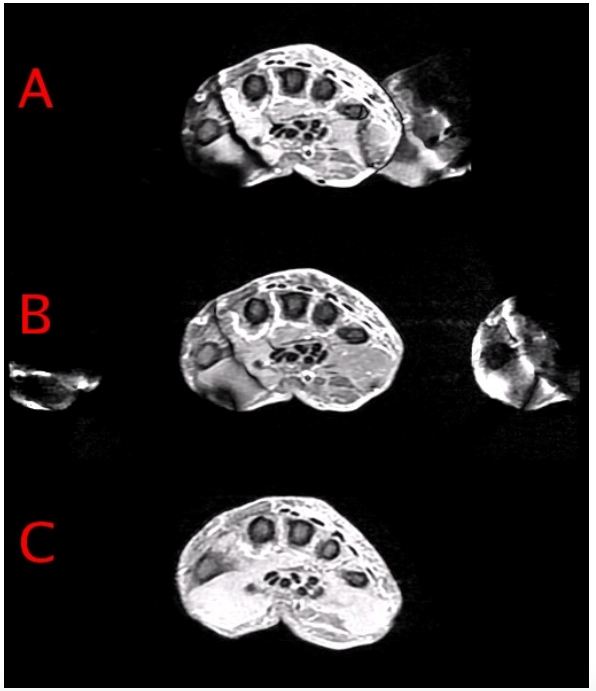
Motion After Calibration Scan (any non-auto-calibrated sequence)

Affected by FOV choice as well.



Small FOV

Large FOV



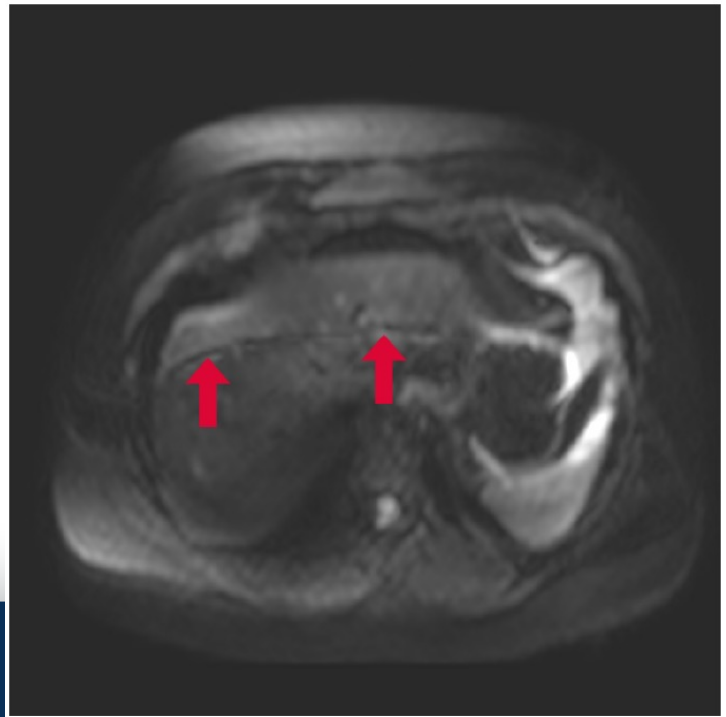
Motion After Calibration Scan - Breath-holds

This happens most often in abdomenal scans.

If the patient's chest is not in the same location as it was when the calibration was scanned, YOU WILL GET AN ARTIFACT.

Inhale vs. exhale?

Yanasak and Kelly, Radiographics, 2014



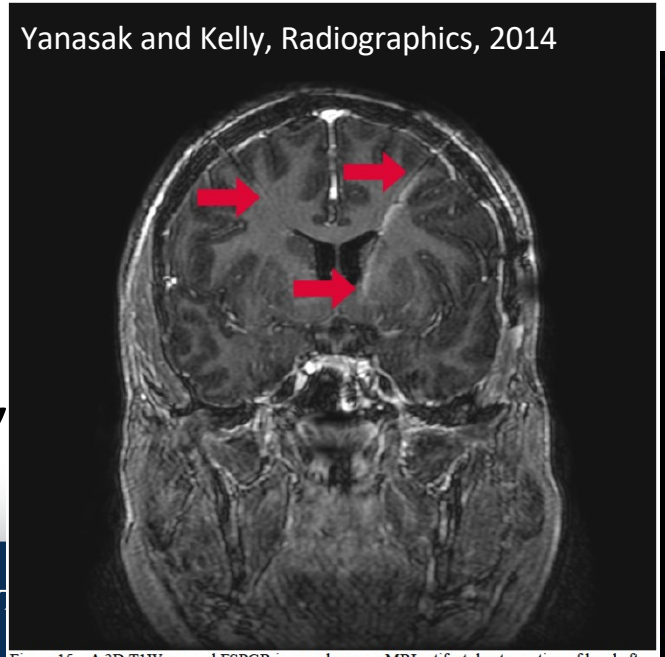
Motion After Calibration Scan (any non-auto-calibrated sequence)

What to do about these?

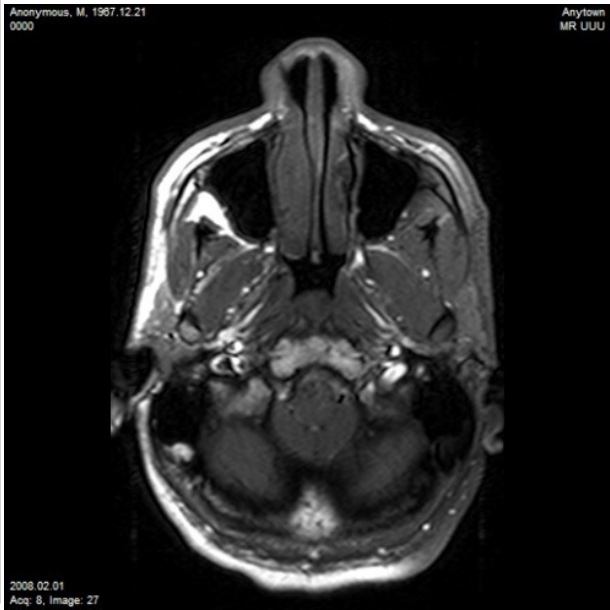
Rescan the calibration scan, then rescan the sequence again.

Or, use auto-calibration if you can.

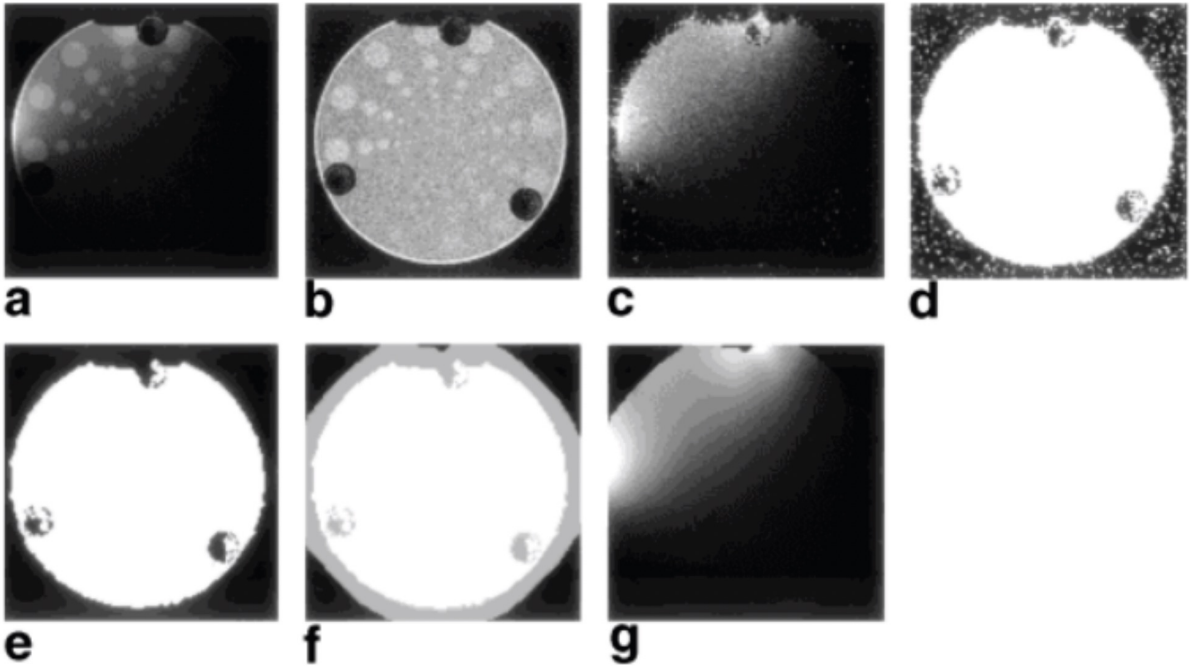
If a patient moves all the time, ***parallel imaging may not be for you.***

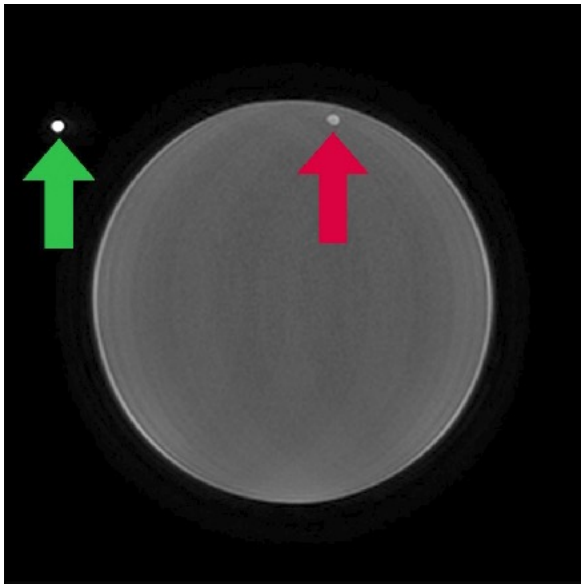


Pseudo-"failure" of fat sat: Patient moved between reference and SENSE scans



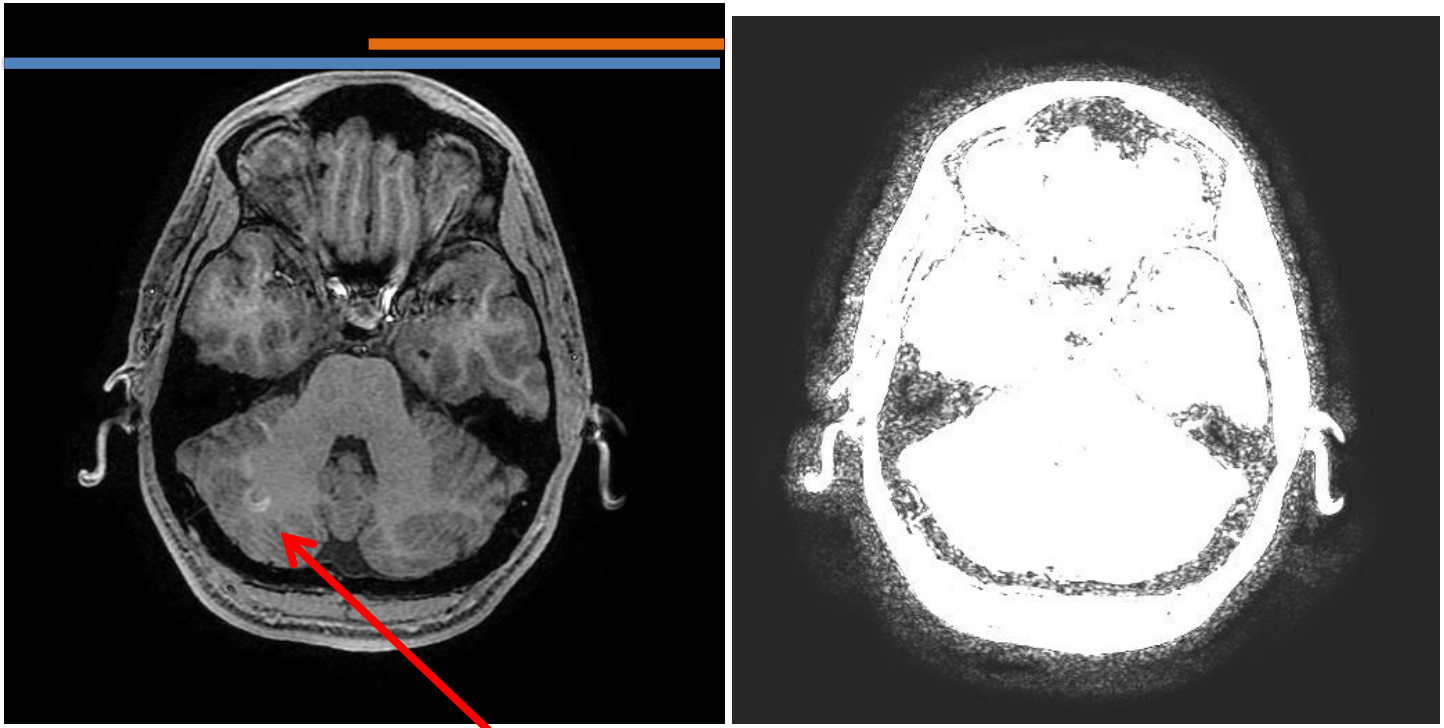
Sensitivity Map Mismatch Artifacts (“Thin Structures”)





Sometimes, small detail in regions of darkness get partially/fully masked or de-emphasized → non-accurate sensitivity in that region.

Sensitivity Map Mismatch Artifacts (“Thin Structures”)



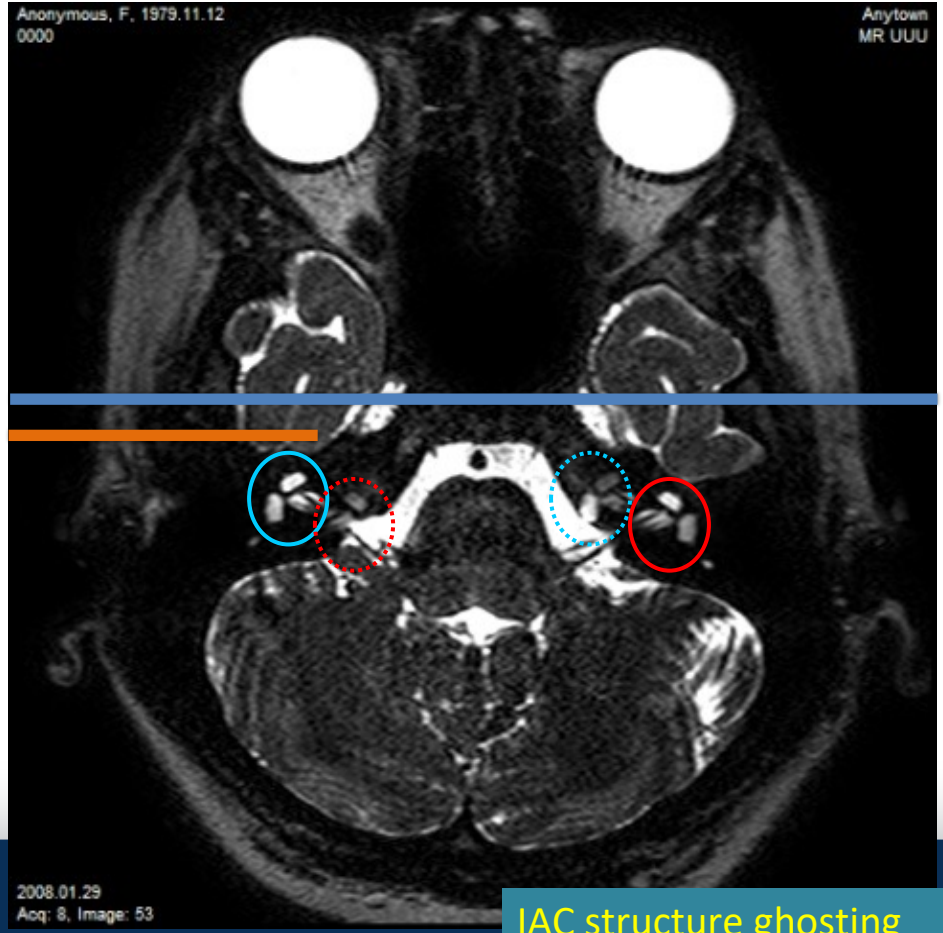
Thin, bright structures that are parallel to the FOV (Acceleration factor = 2) and anatomy.

Here, notice that the separation is about 1/2 of the FOV (Acceleration factor = 2).

pMRI Clincial “Thin Structures” Artifact

Separation related to amount of acceleration.

Here, notice that the separation is about 1/3rd of the FOV (acceleration = 3).



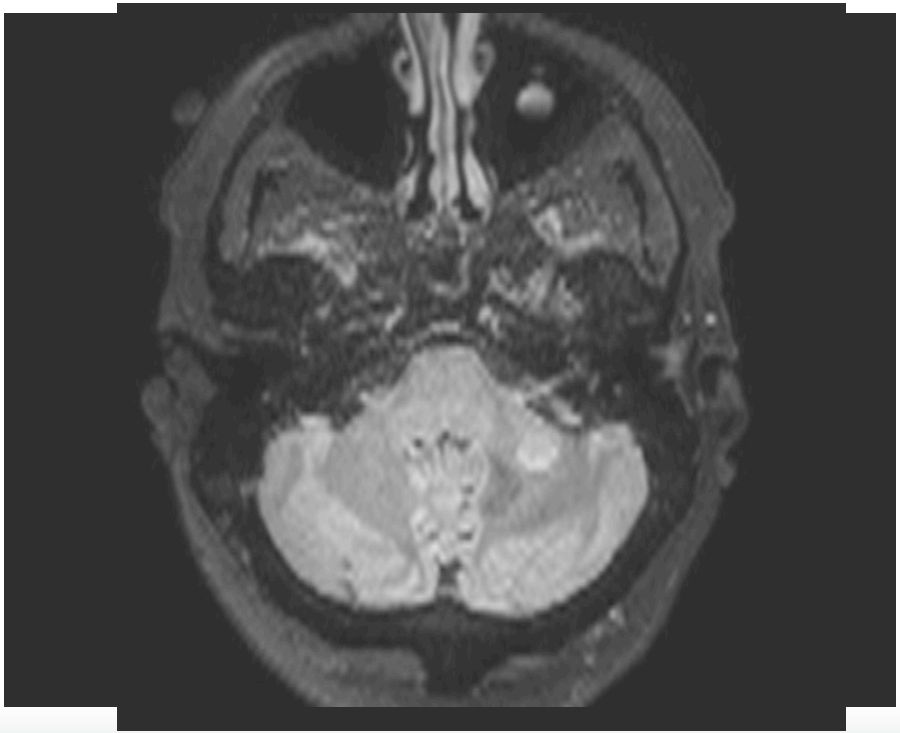
2D Acceleration and Sensitivity Map Mismatch Artifacts

Cerebellar lesion?

No … sensitivity map mismatch, projected in slice direction (PE #1),

...and in-plane phase-encoding direction (PE #2)

Note the separation (½ FOV, ½ stack)



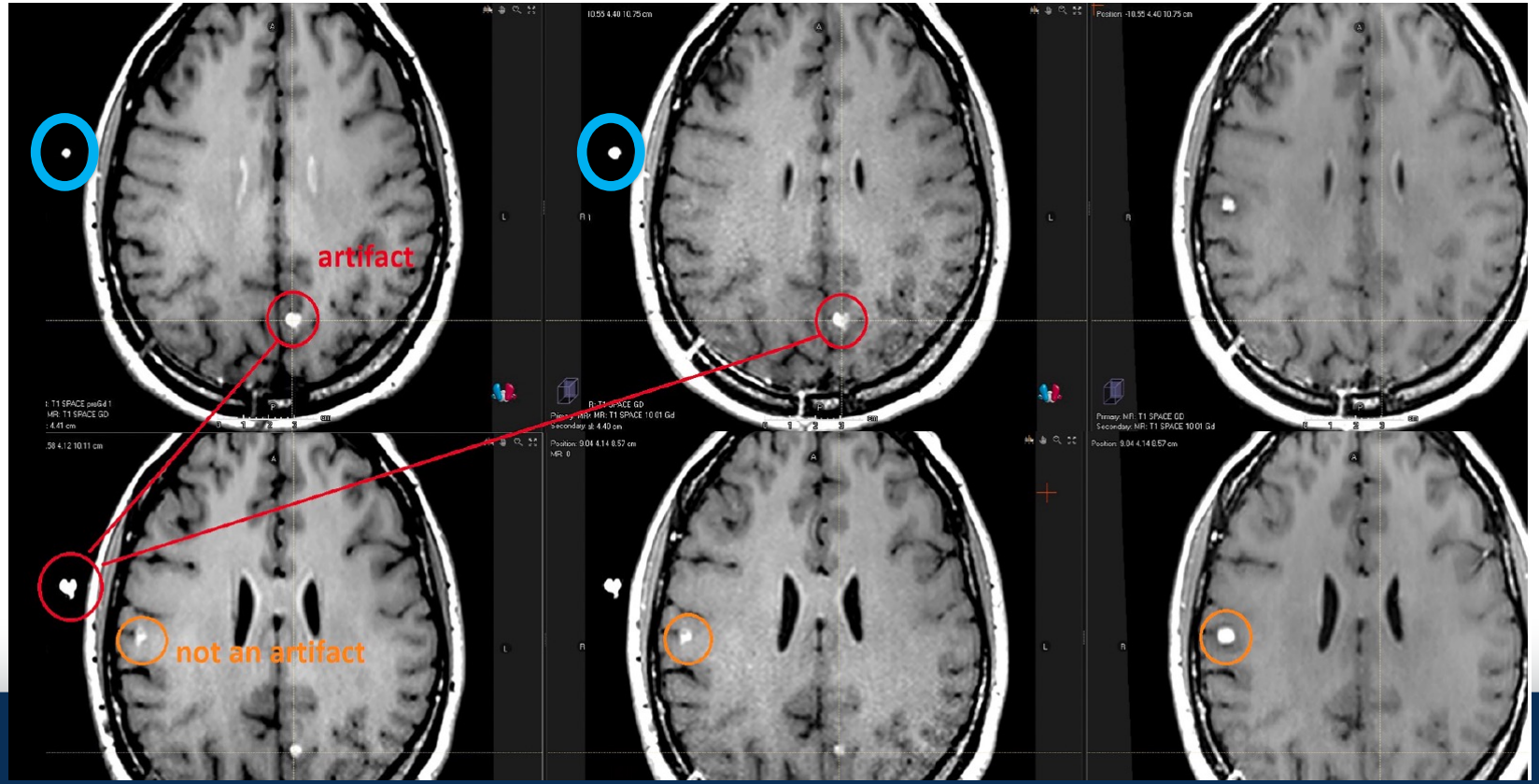
Lesion or no?

Check reformats!

pMRI Clinical Artifact Example (2D Caiparinha)

Fiducial is mirrored in two dimensions. Caipirinha sampling shifts its location.

Crop, et al., Physica Medica, 2021



Fiducial

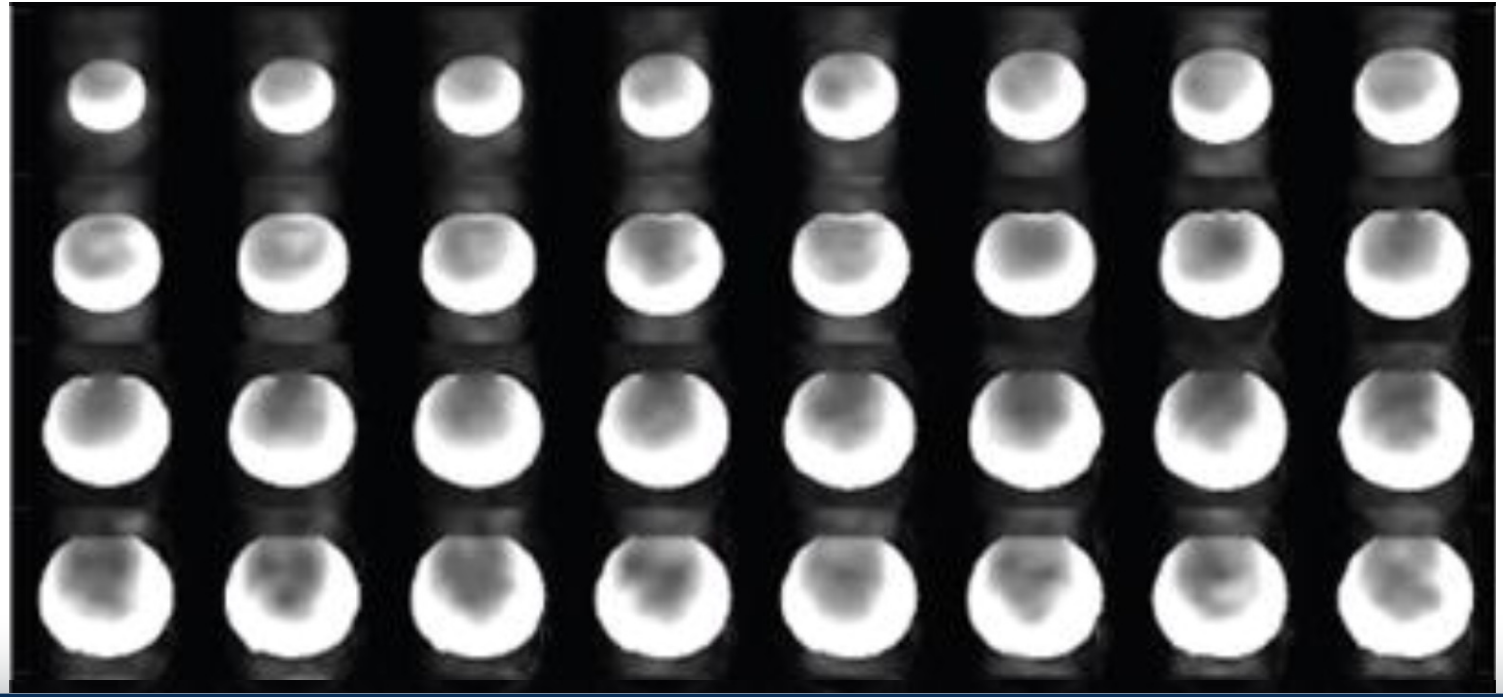
Artifact

Lesion

SMS Artifact: Leakage (similar to g-factor for pMRI)

Leakage: inaccuracies in separating slices during reconstruction.

Unlike pMRI (sensitivity mismatch → in-plane duplicates), leakage can be more subtle with multiple slices.



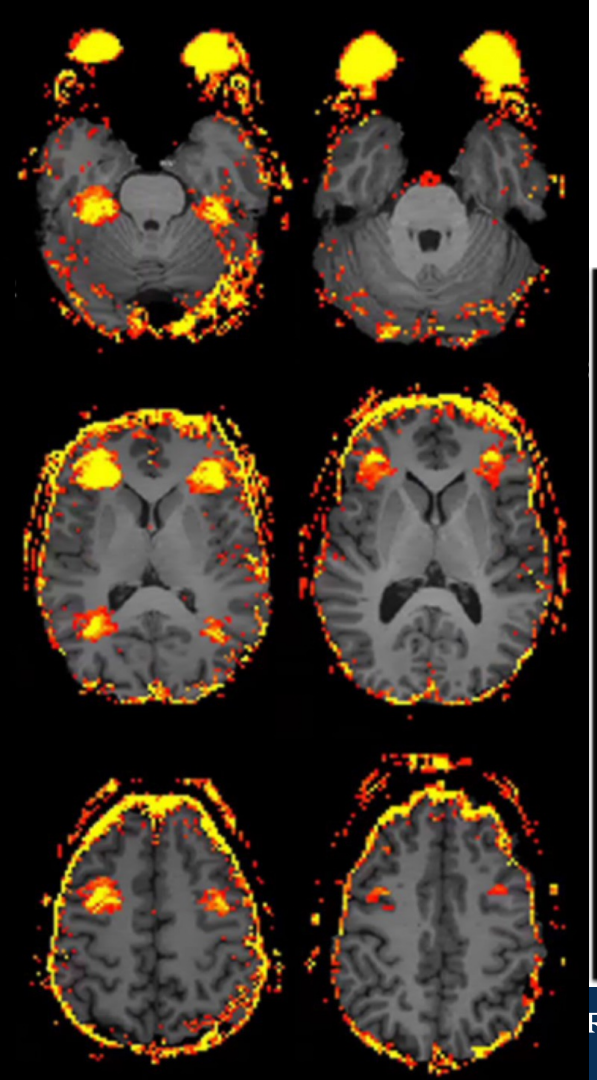
Cauley, et al. MRM, 2014

SMS Artifacts (leakage)

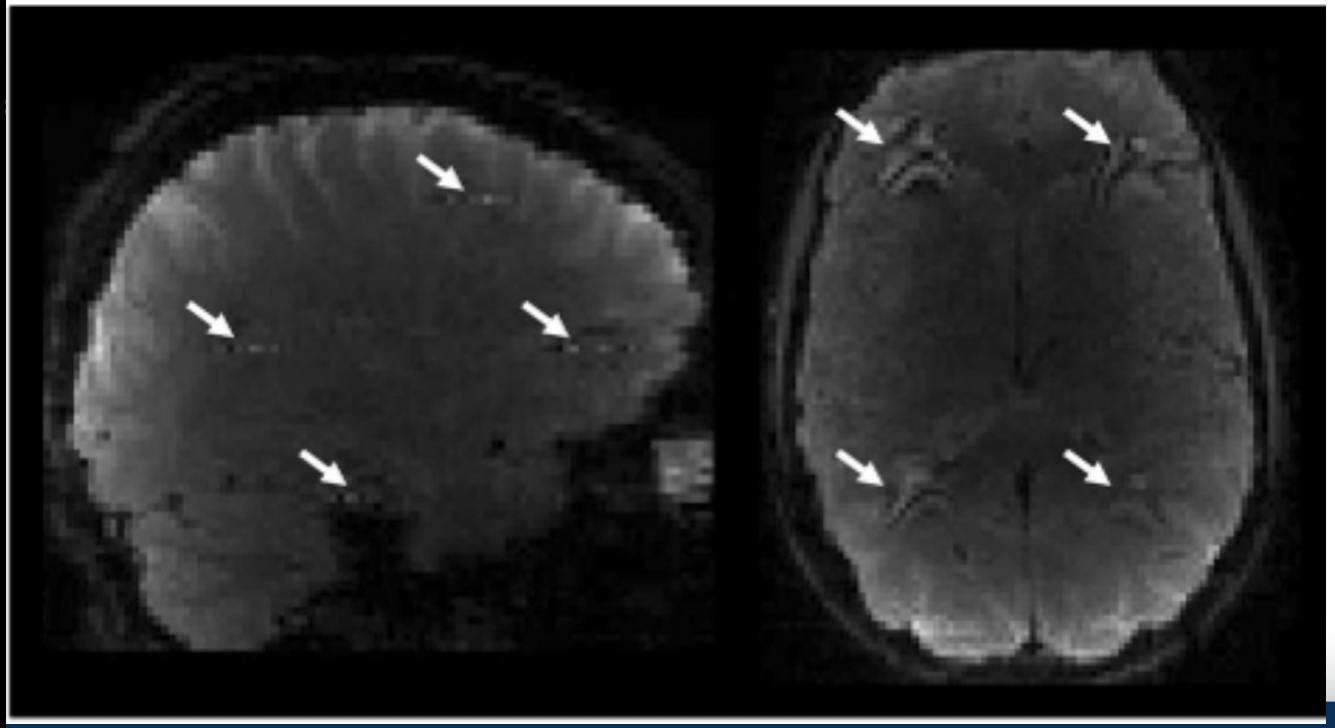
McNabb, et al. Brain Structure and Function, 2020

Grappa + SMS time series

(overlay: signal variance in images, natural eyelid motion)



Artifacts in single volume

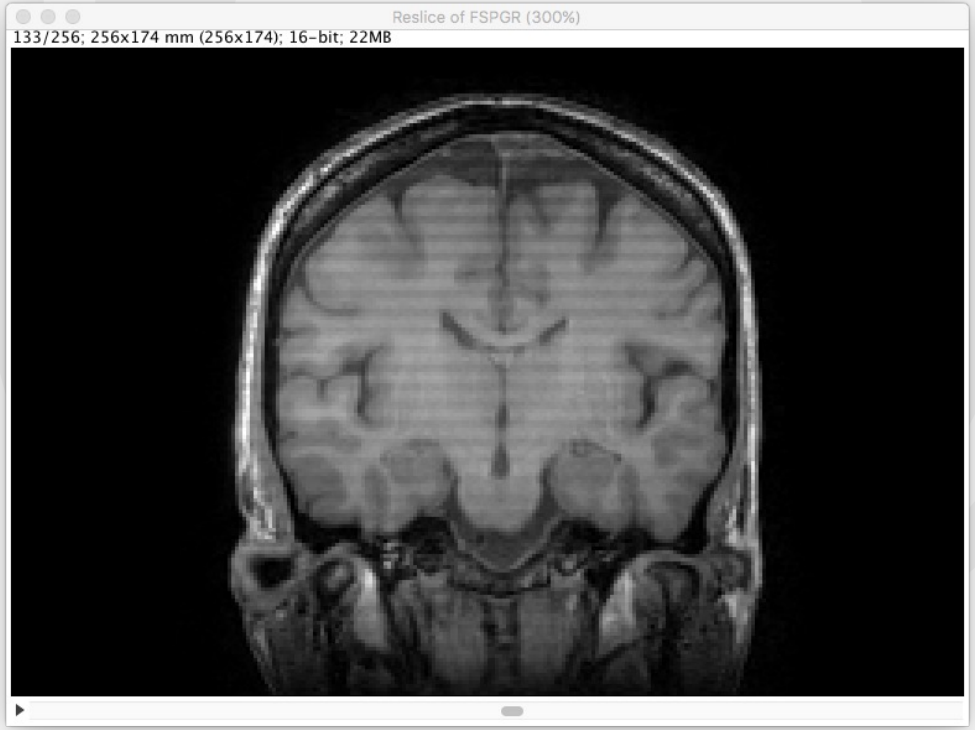


pMRI Sensitivity Map and Slice Thickness Interaction

Research group noticed a slice-to-slice striation in axial-acquired images.

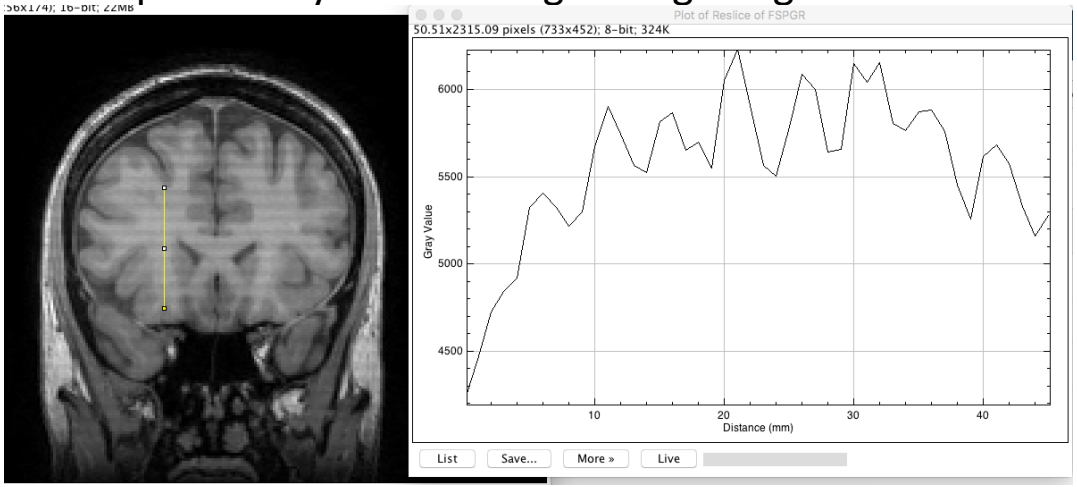
No obvious issues with interleaving, etc…

Turns out that calibration scan slice thickness (5mm) = integer # of slices (1mm).



pMRI Sensitivity Map and Slice Thickness Interaction

Measure the “periodicity” in the image using ImageJ:



Repeats about every 5 slices (@ 1mm slice thk, effect is 5mm).

Eureka! (and texting with Jason Stafford to think this through)

- 3D scan is non-oblique axially prescribed
- pMRI calibration scan purely in axial orientation…5mm slice thickness.

pMRI Sensitivity Map and Slice Thickness Interaction

Change calibration scan thickness

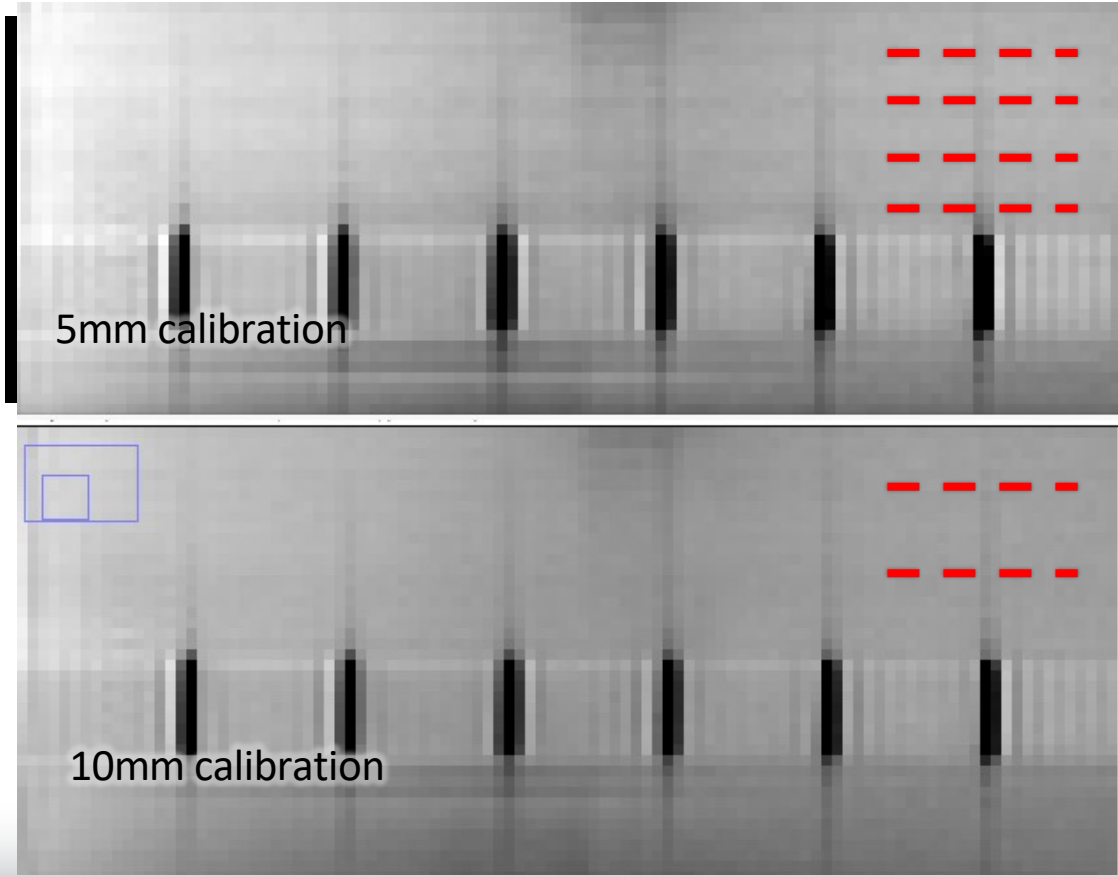
Phantom tests

Solution:

- Slight obliquity of calibration scan
- Force calibration slices to be non-multiple of imaging slice thickness.

Why did we never see this clinically?

Intersection of pure axial 3D scans and cal scans of certain thickness.



Slice 8 (T2, TE=80msec)

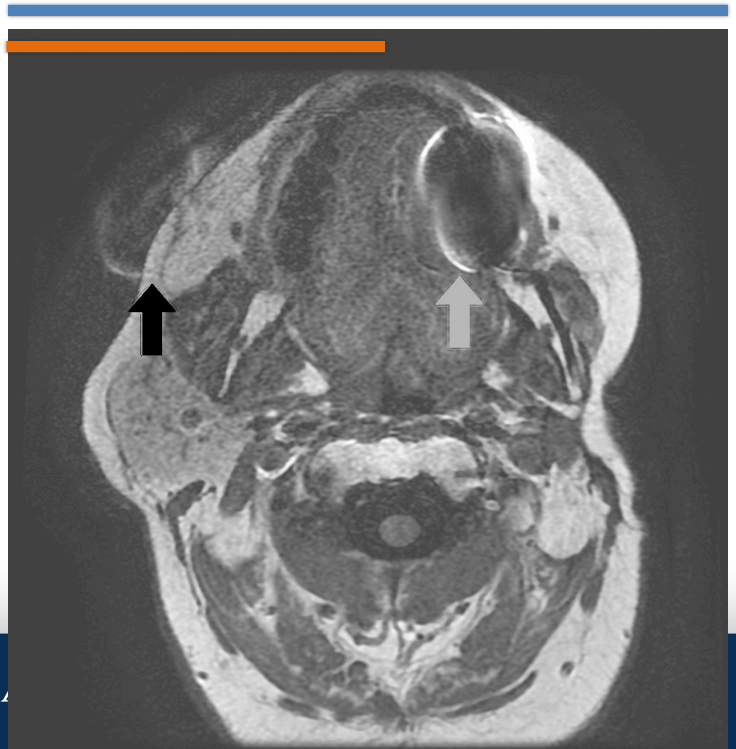
pMRI and Traditional Artifacts

pMRI and Traditional Artifacts: Susceptibility

Appearance of traditional artifacts may be modified by pMRI

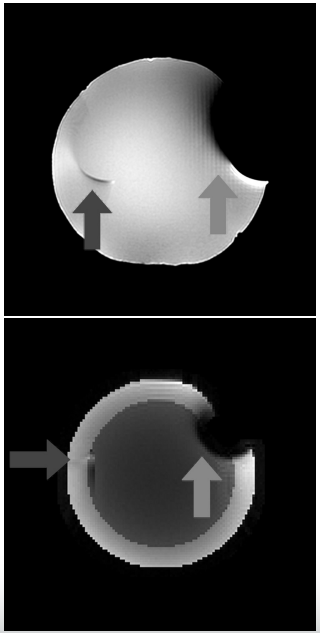
Susceptibility (artifact not perfectly represented on sensitivity map)

Yanasak and Kelly, Radiographics, 2014



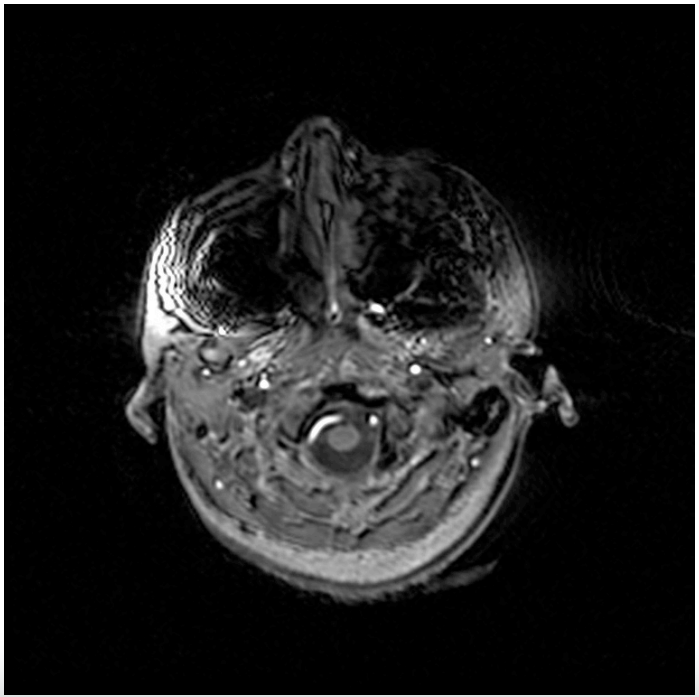
phantom

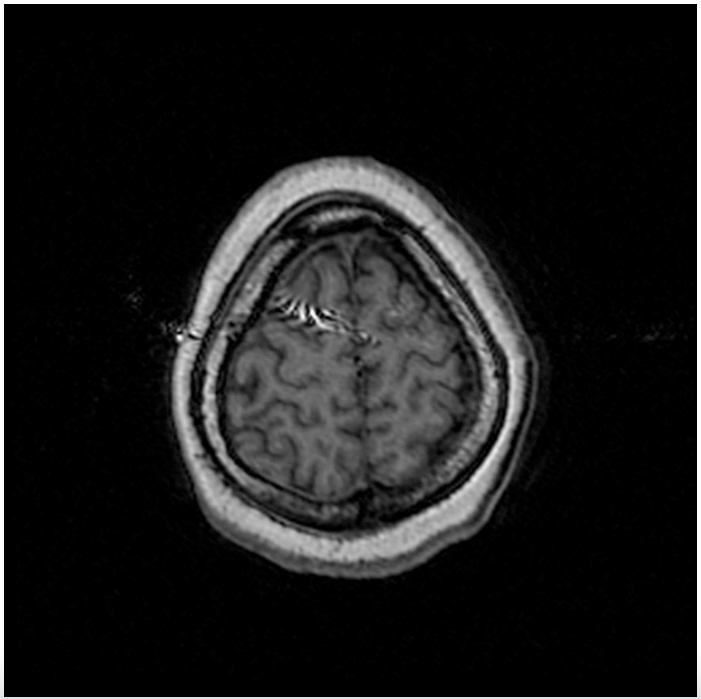
simulation



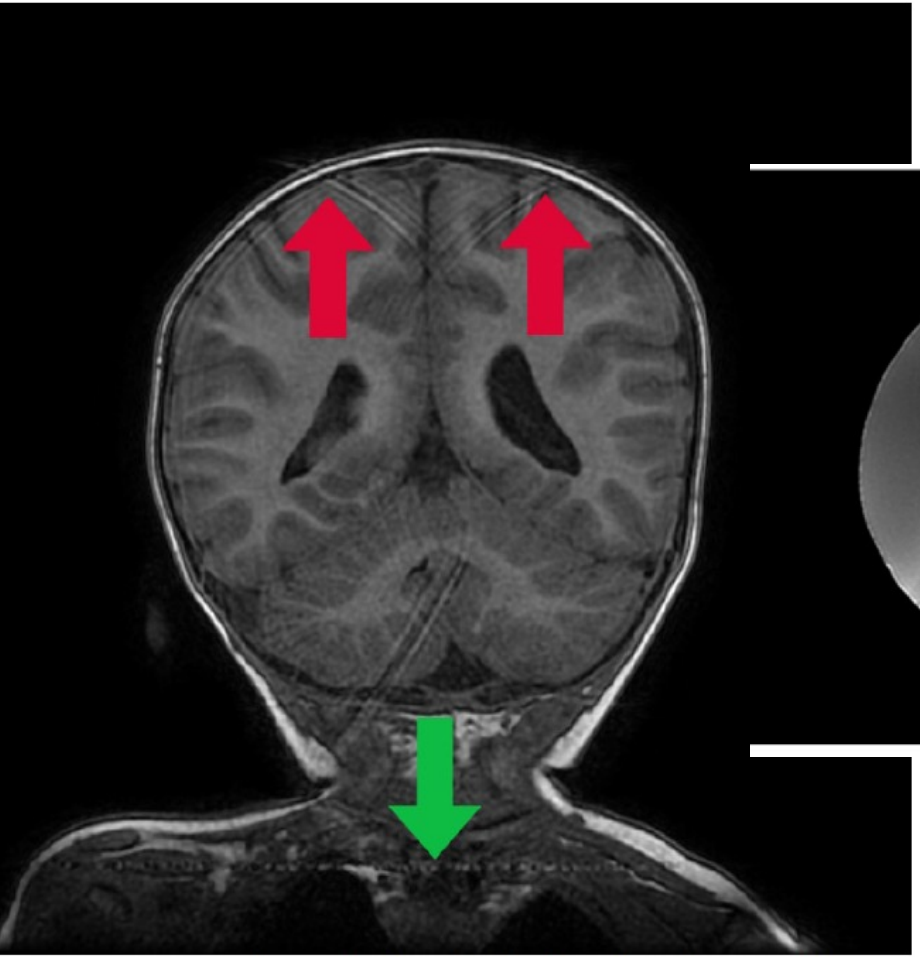
pMRI and Traditional Artifacts: 3D + Susceptibility

Another susceptiblity artifact for 3D scan, affecting a GEM 2D acceleration scan. Susceptibility affects reconstruction along slice-select phase encoding.

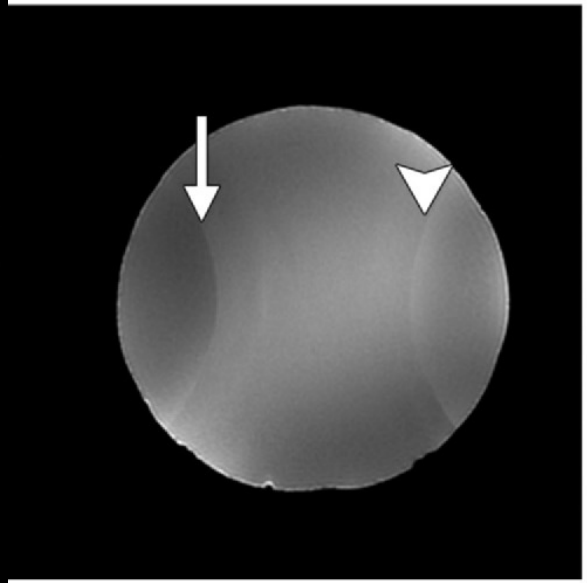


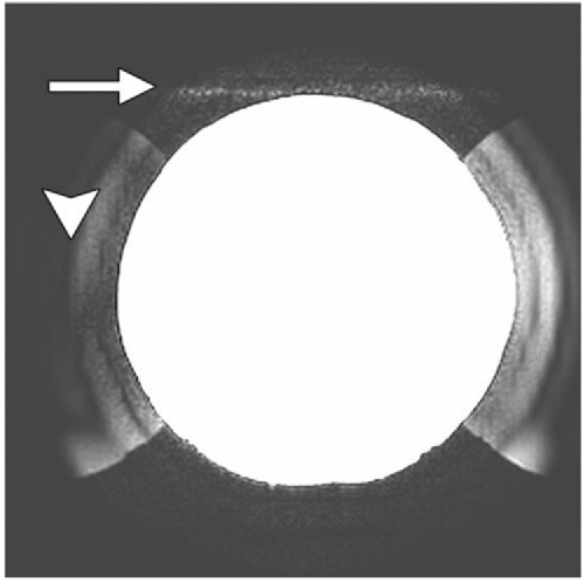


pMRI and Traditional Artifacts: Zippers



Zipper causes poor reconstruction.

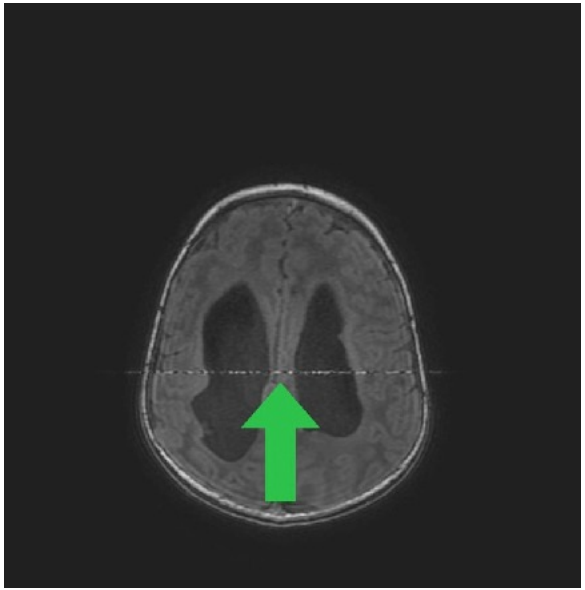




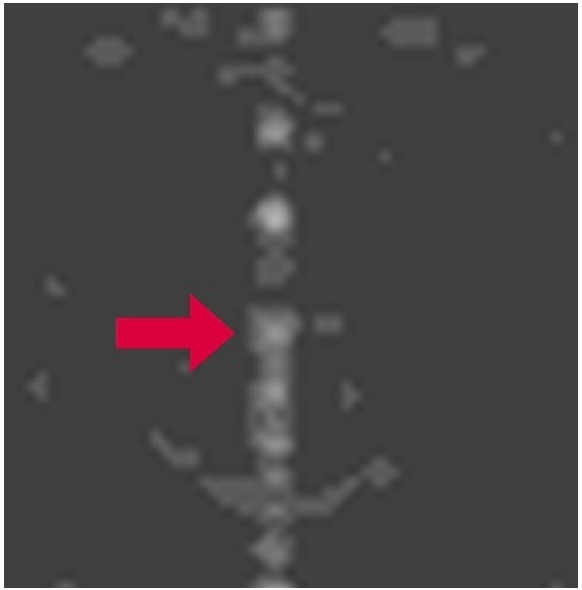
Yanasak and Kelly, Radiographics, 2014

pMRI and Traditional Artifacts: Zippers

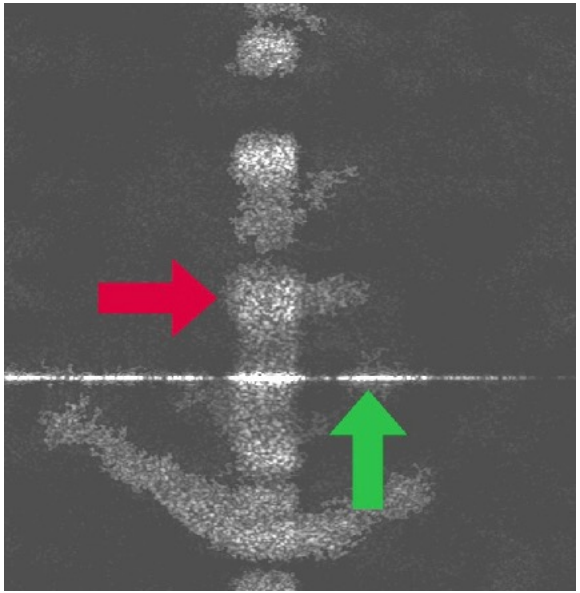
Zippers prevalent in ALL scans can also be a problem → sensitivity scan might have another zipper, in a different place.



Zipper, showing L-R PE direction



Zipper in calibration scan, showing A-P PE direction



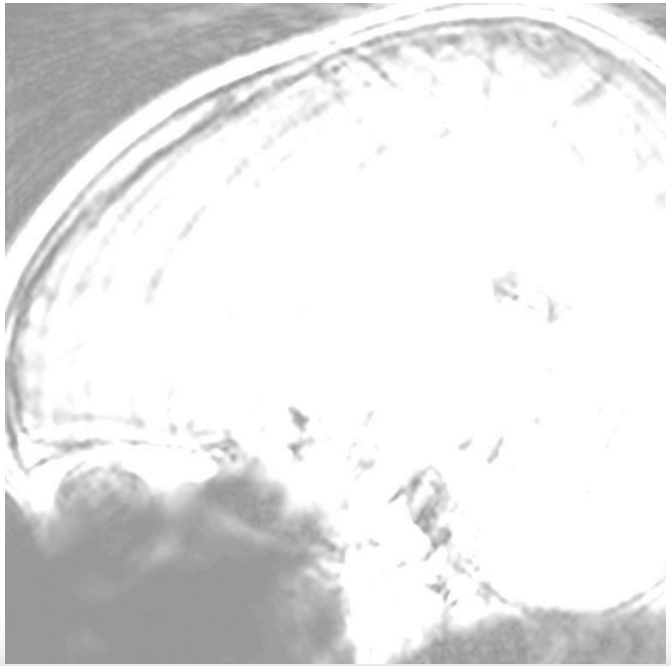
Zipper in SENSE scan, showing noise in A-P (red)

Yanasak and Kelly, Radiographics, 2014

pMRI and Traditional Artifacts

Appearance of traditional artifacts may be modified by pMRI

Profound motion is made much worse by pMRI.



Yanasak and Kelly, Radiographics, 2014

Coil Dropout Issues & pMRI

Two potential scenarios:

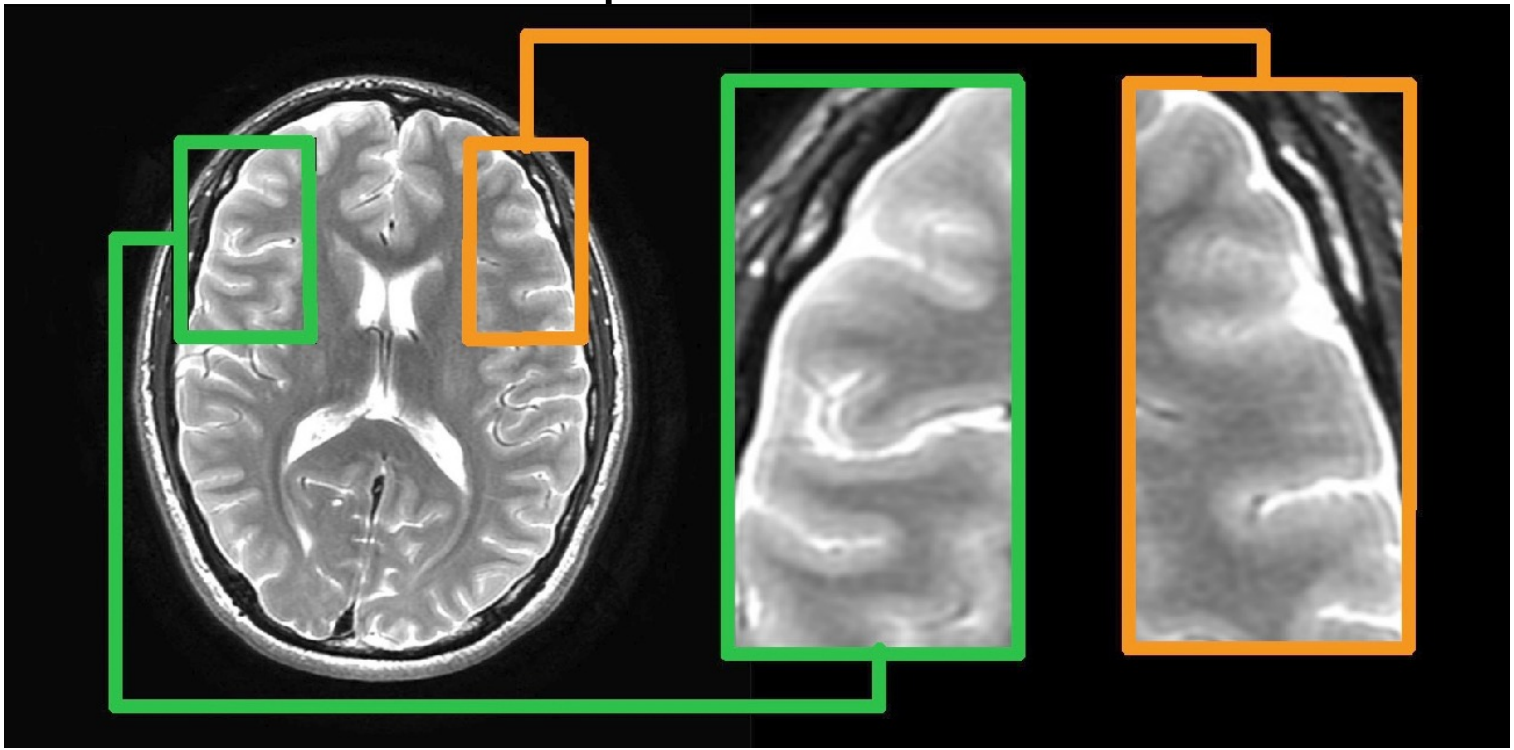
1) 1 or more coil elements are **completely dead** (might be ok w/ small # of elements).

No coil element data for both sensitivity map and for image data → coil element does not contribute to the image (but, dropout or decreased SNR).

2) 1 or more coil elements are **intermittent** or exhibit compromised performance (worst-case scenario)

Coil element data for both sensitivity map and for image data, but the gain may go up and down → sensitivity mismatch artifacts.

Coil Dropout Issues: Dead Elements

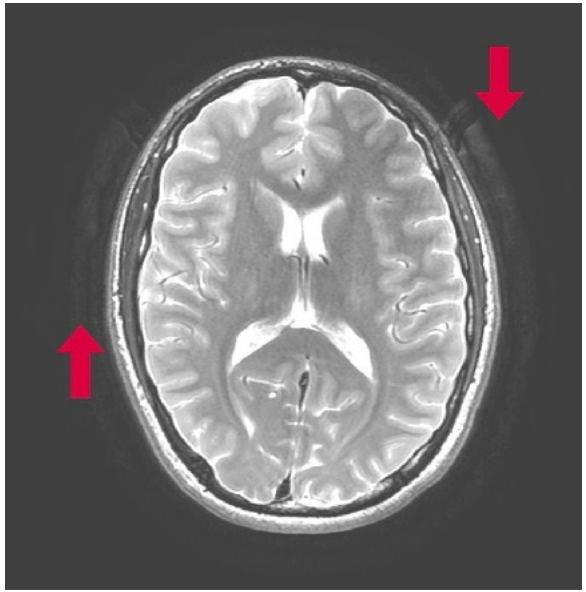


8-channel head coil.

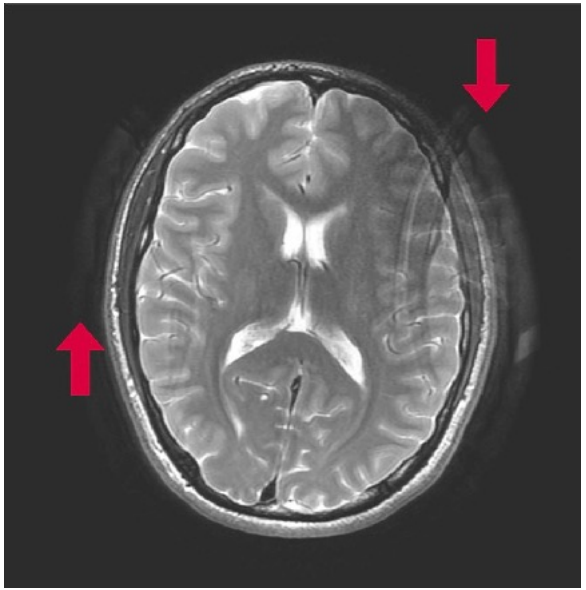
One coil element disabled for both imaging and calibration scan (image right)

Yanasak and Kelly, Radiographics, 2014

Coil Dropout Issues: Intermittent Element



1 disabled channel



2 disabled channels

8-channel head coil.

Normal sensitivity map + missing data during scan (worst case scenario).

Actual performance would be somewhat better.

Yanasak and Kelly, Radiographics, 2014

Summary

- Quality differences
  - pMRI: non-homogeneous noise distribution
  - SMS: leakage, and potential slice saturation issues if not careful.
- Any difficulties with using auxilliary information during reconstruction leads to artifacts
  - pMRI: FOV must be larger than tissue being imaged.
  - Sensitivity map mismatches (e.g., traditional artifacts changing between map and scan…susceptibility, thin bright objects) can lead to duplicate structures appearing in various parts of the image.
  - Shift of the duplicate structures related to acceleration factor (pMRI) and number of slices (SMS) and inter-slice phase shifting scheme.
  - Motion artifact is greatly enhanced.