Parallel Magnetic Resonance Imaging (pMRI): How Does it Work, and What is it Good For?

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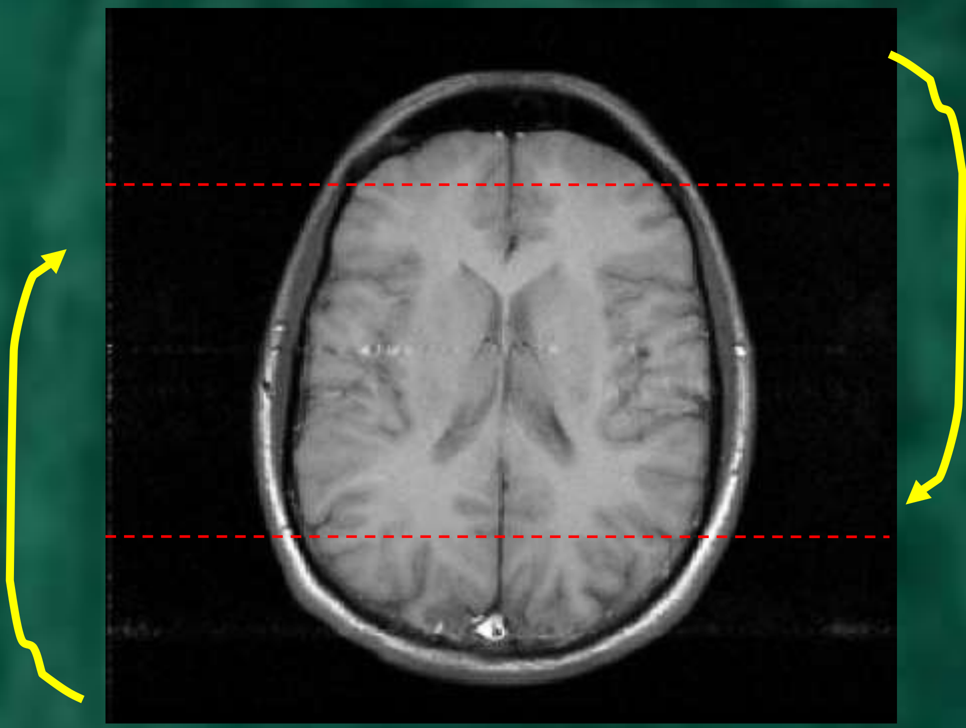
Overview

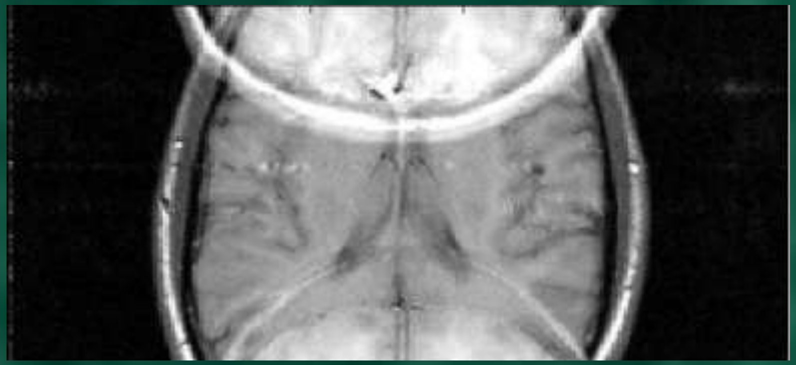
- Phased-array coils
- General Description of Parallel Imaging
- Different pMRI methods
- Applications of pMRI
- How NOT to use pMRI

What is pMRI?

- Uses spatial information obtained from arrays of RF coil elements sampling data in parallel
- Information handles *some portion* of spatial encoding performed using gradient fields (typically phase-encoding gradient)
- ***Speeds up MRI acquisition times***
  - without needing faster-switching gradients
  - without additional RF power deposited (key for higher field MR)

pMRI speed: less phase encodes = smaller FOV (with same resolution)





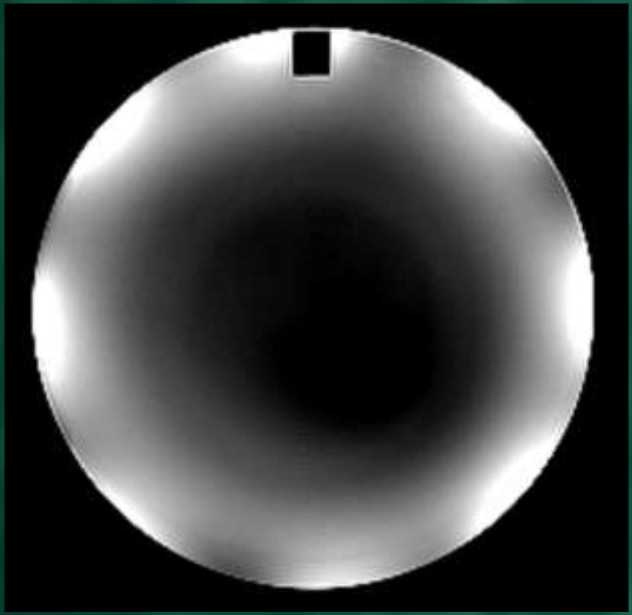
aliasing

Smaller FOV

Properties of Phased Arrays (PA) of Surface Coil Elements

What capabilities do PA coils have to localize signal?

- Each element is sensitive only to local spins



Uneven SNR throughout volume, but …

- Very high SNR at edge
- Lower SNR in middle
- SNR in middle is generally better than comparable volume coil.

SNR: Surface Coil vs. Volume Coil

Surface Coil (single element)

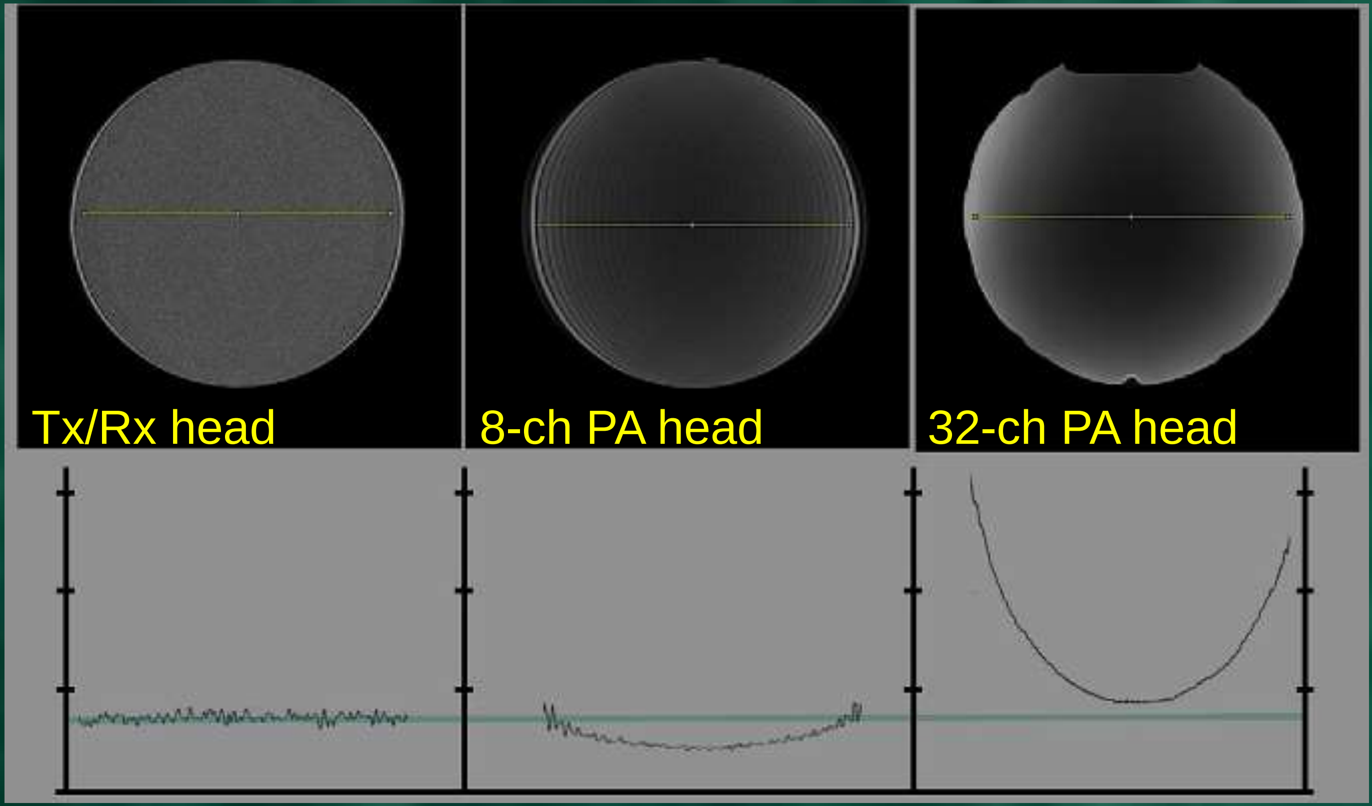
- Non-uniform SNR
- Great SNR up close

Phased-Array Coil

- Non-uniform SNR
- SNR generally high

Volume Coil

- Uniform SNR
- Average SNR



Bottom line: spatial localization of signal depends on PA element location (and size). Critical for pMRI.

Multichannel Coils

8- and 15-channel head coils

Multi-element body coils

Uniformity Tests and PA Coil Concerns

- ACR Uniformity test was specified during the era of volume coils.
- Effect of intrinsic non-uniformity of phased-array coils on QA?
- Uniformity test with 32-channel coil (3T) -- 32 tests with one element turned off (filter on)
  - Uniformity failures: 0
  - All elements: PIU=89.6%
  - One missing element: $\langle PIU \rangle_{N-1}$=89.6%
  - $\sigma_{PIU,N-1}$=0.5% (SEM~0.1%)

$PIU_{N-1,min}$=88.0%; $PIU_{N-1,max}$=90.2%

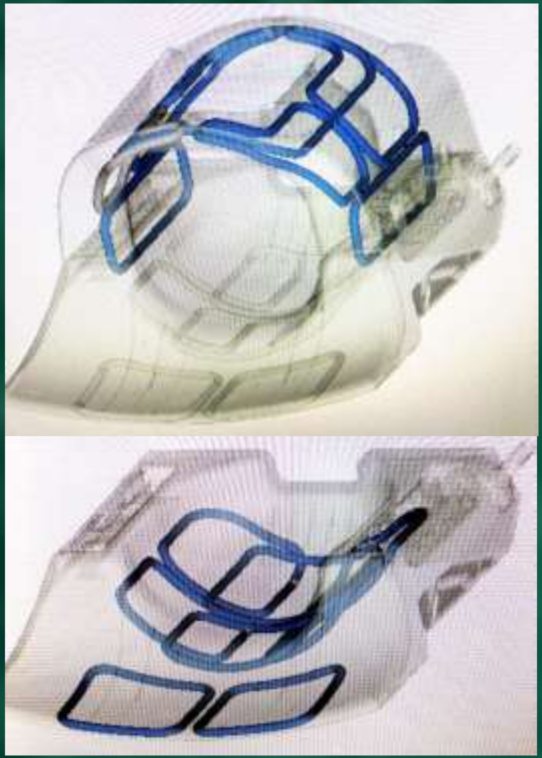
Uniformity and PA Coils

Let’s try that again with 15-channel coil (GRU workhorse).

15 tests with one element turned off (filter on)

- Uniformity failures: 0
- All elements: PIU=90.6%
- One missing element: $<PIU>_{N-1}=90.1\%$
- $\sigma_{PIU,N-1}=0.7\%$ (SEM~0.2%)

$PIU_{N-1,min}=88.7\%$; $PIU_{N-1,max}=91.3\%$



Uniformity and PA Coils

- One last time with an 8-channel coil (another GRU workhorse).

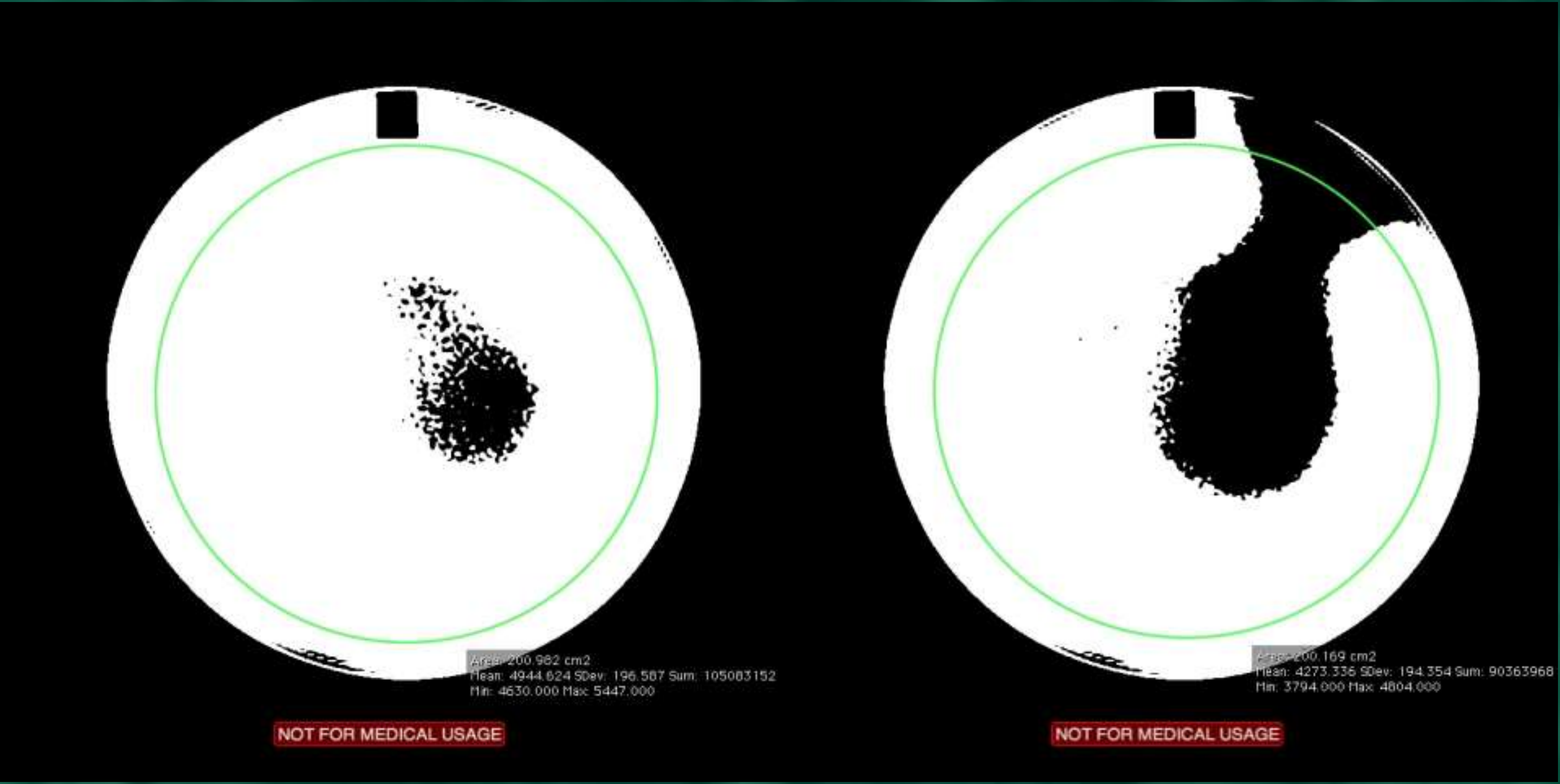
1 test with one element turned off (symmetry in coil)

- All elements: PIU=93.6%
- One missing element:

  PIU_{N-1}=91.5%

- Spatial distribution different, even with filter on.

Uniformity and PA Coils



All elements

7 elements

Uniformity and PA Coils

Observations:

Mean uniformity lower for higher # of elements.

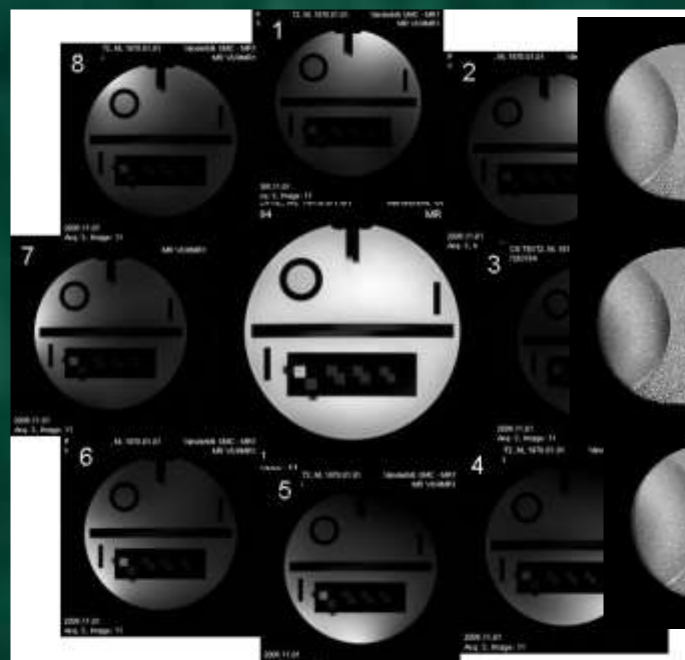
Uniformity degradation for coils with broken elements worse with smaller # of elements.

Obvious changes in spatial uniformity with 8-channel.

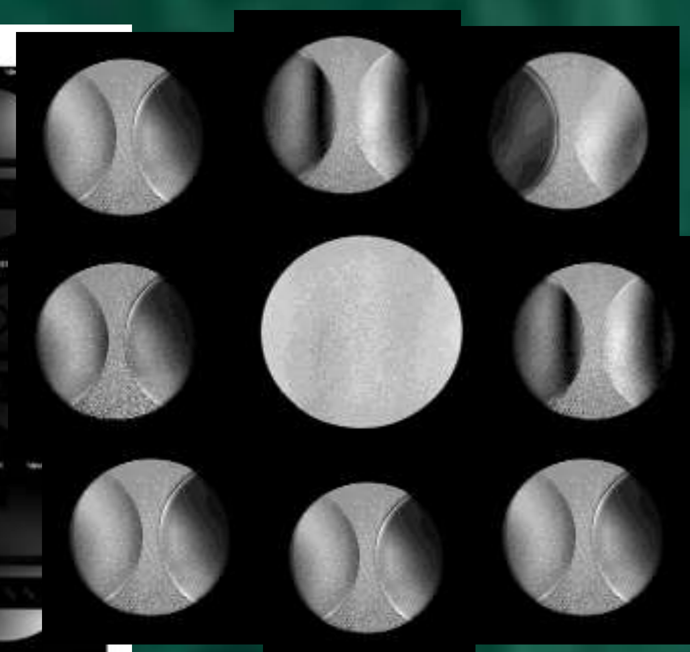
- What does this suggest for ACR testing of PA coils? Phantom issue? Protocol? Specs?
- For patient care?
- pMRI performance even more dependent on PA coils.

Use of Phased Array Coil in Parallel Imaging

Spatial sensitivity varies for each element → can use this in conjunction with undersampling.



Conventional use of phased-array (unaliased)



Parallel reconstruction of data (aliased)

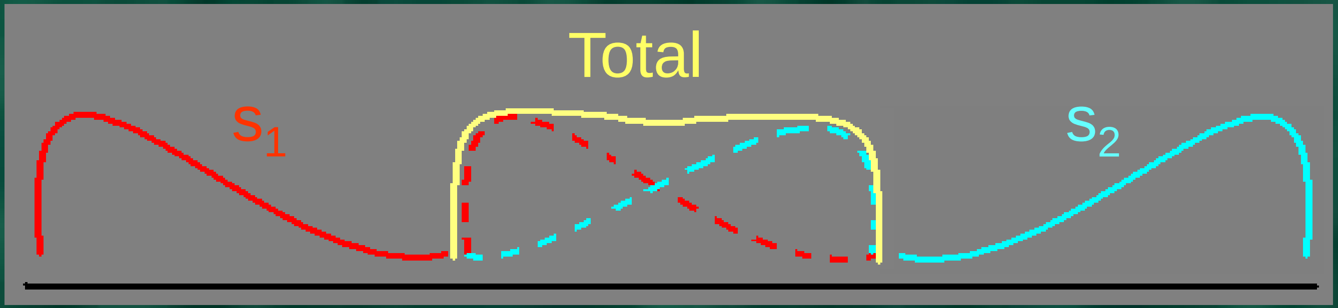
Coil Sensitivity Profiles

- Different approaches to solving the inverse problem that recovers spatial information.
- The key information always required to solve this problem is information on the spatial distribution of the RF coils' sensitivity.
- How you collect and use this information → different pMRI methods.

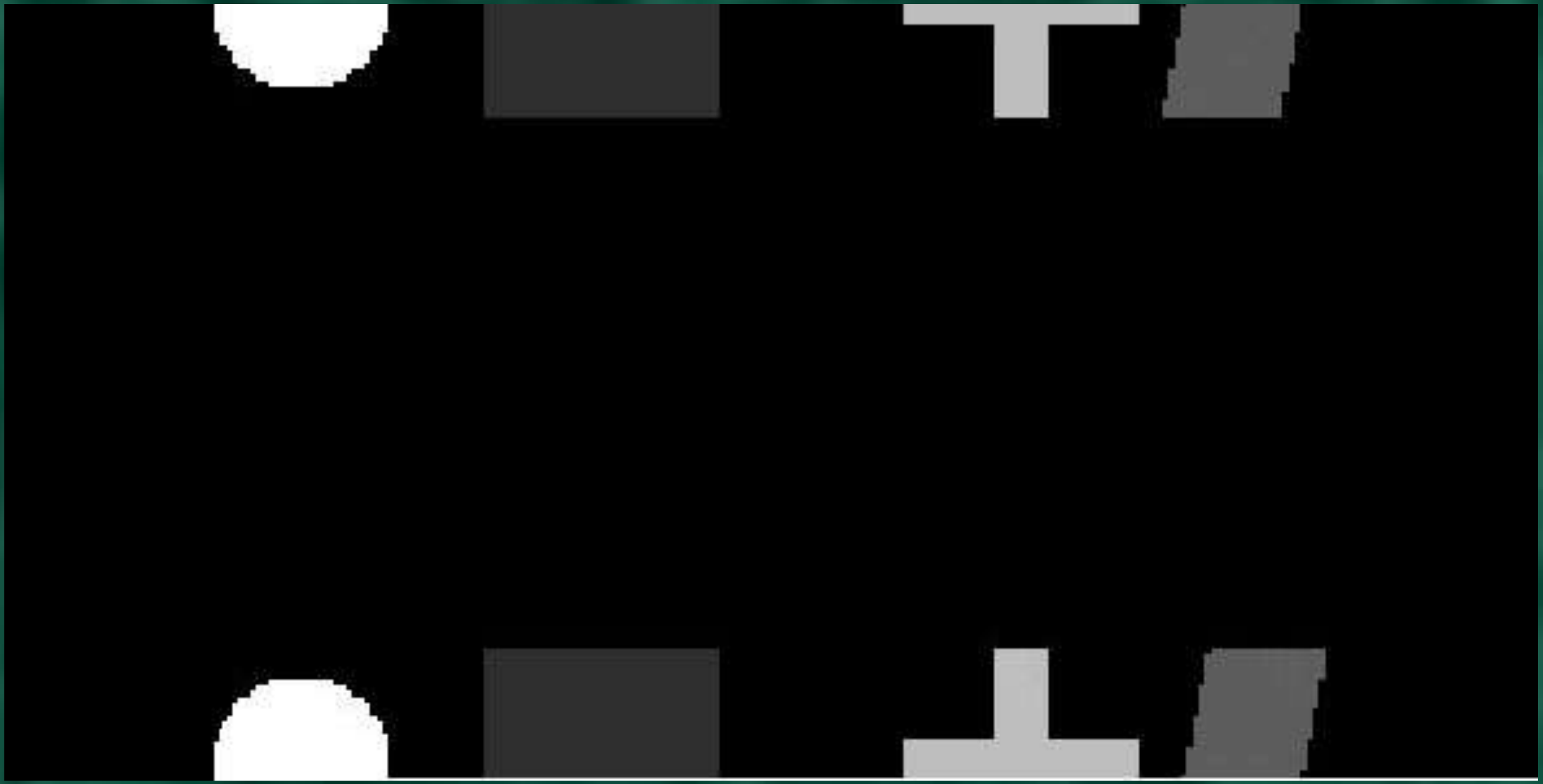
Sensitivity Map

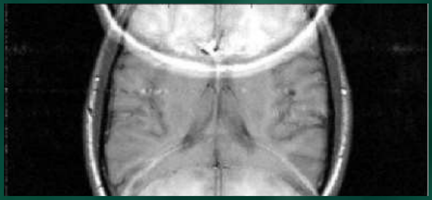
The spatial sensitivity of each coil element = sensitivity map.

A calibration scan may be required to calculate this.

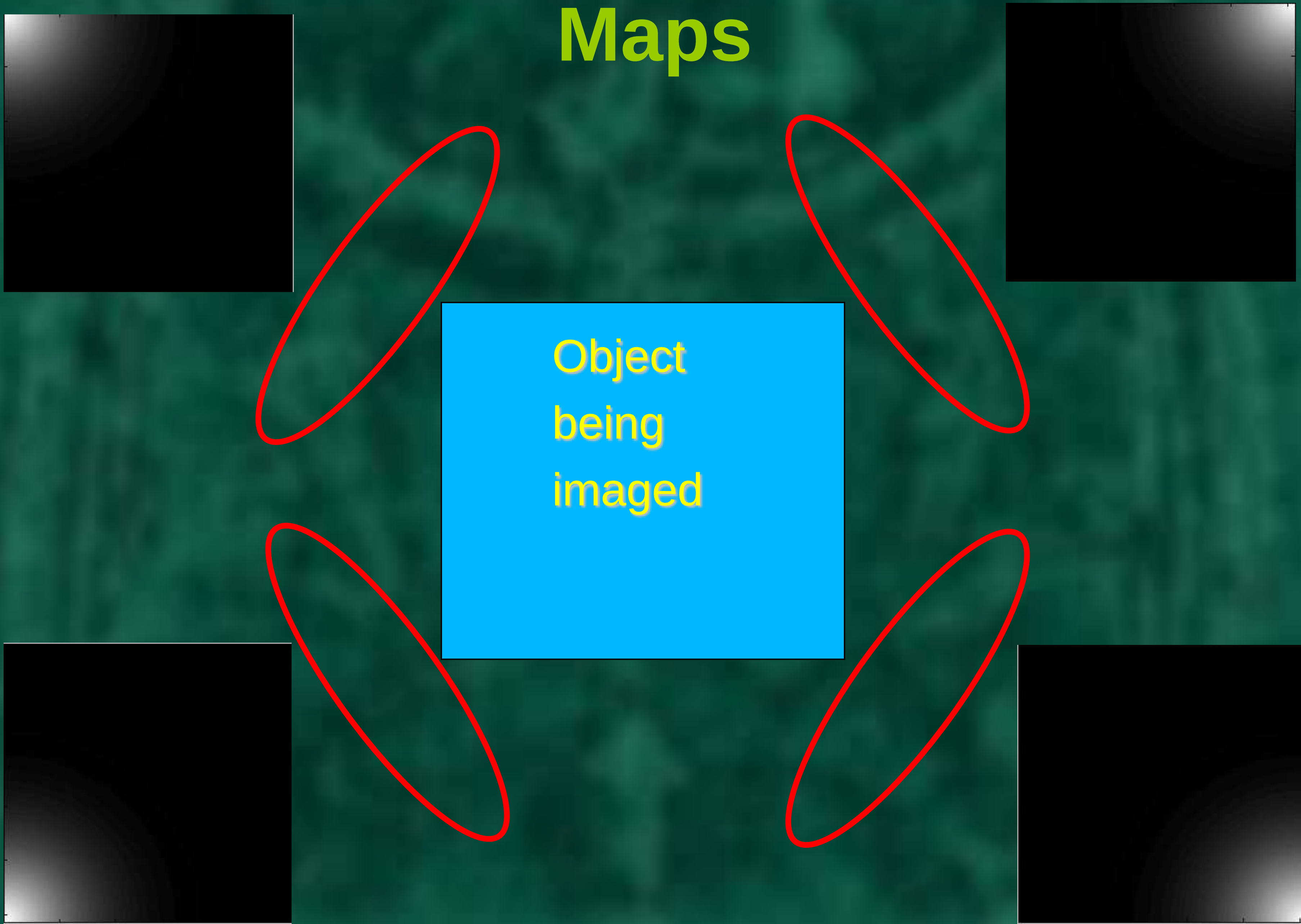


Using Coil Sensitivity to Un-alias an Image: An Example

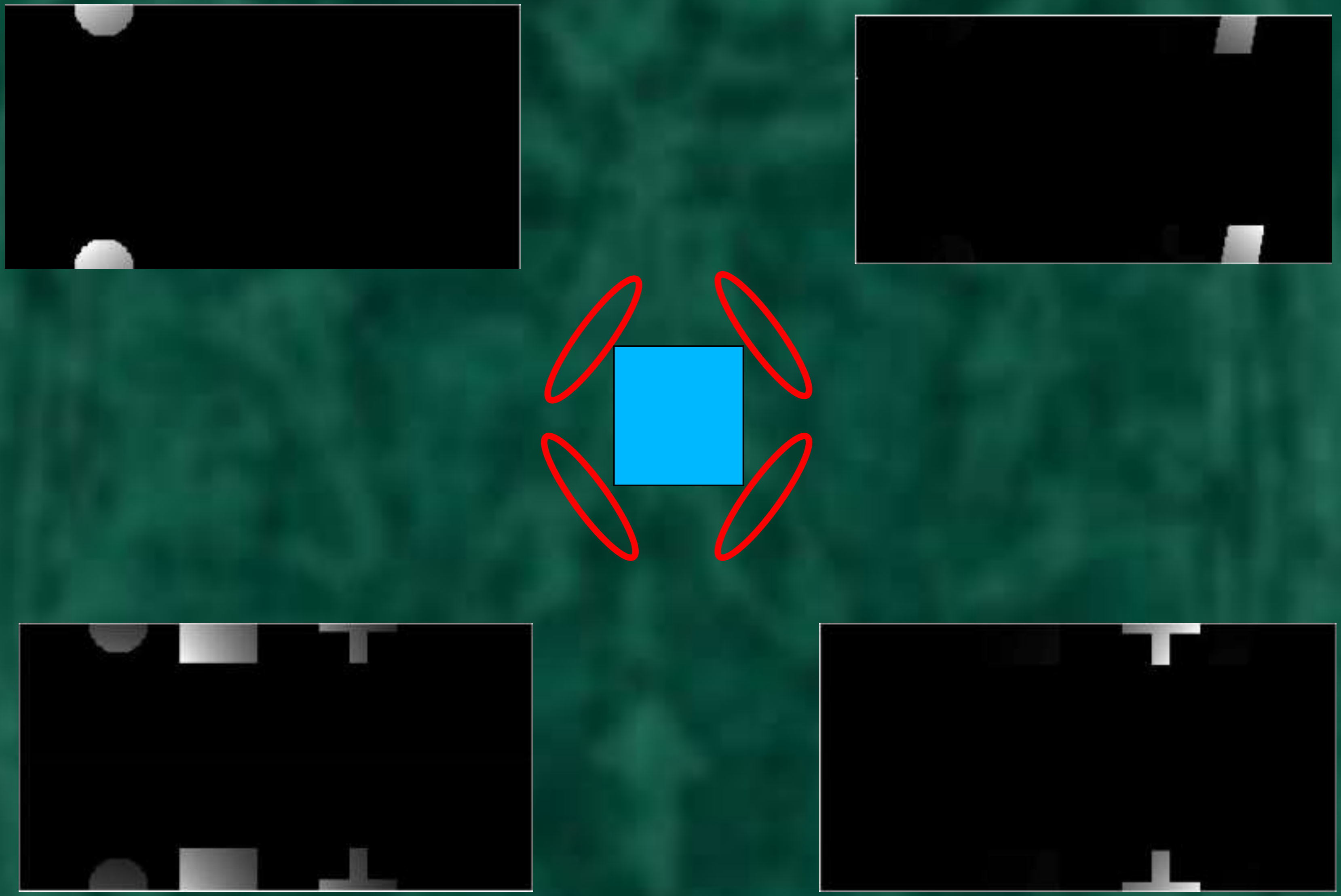


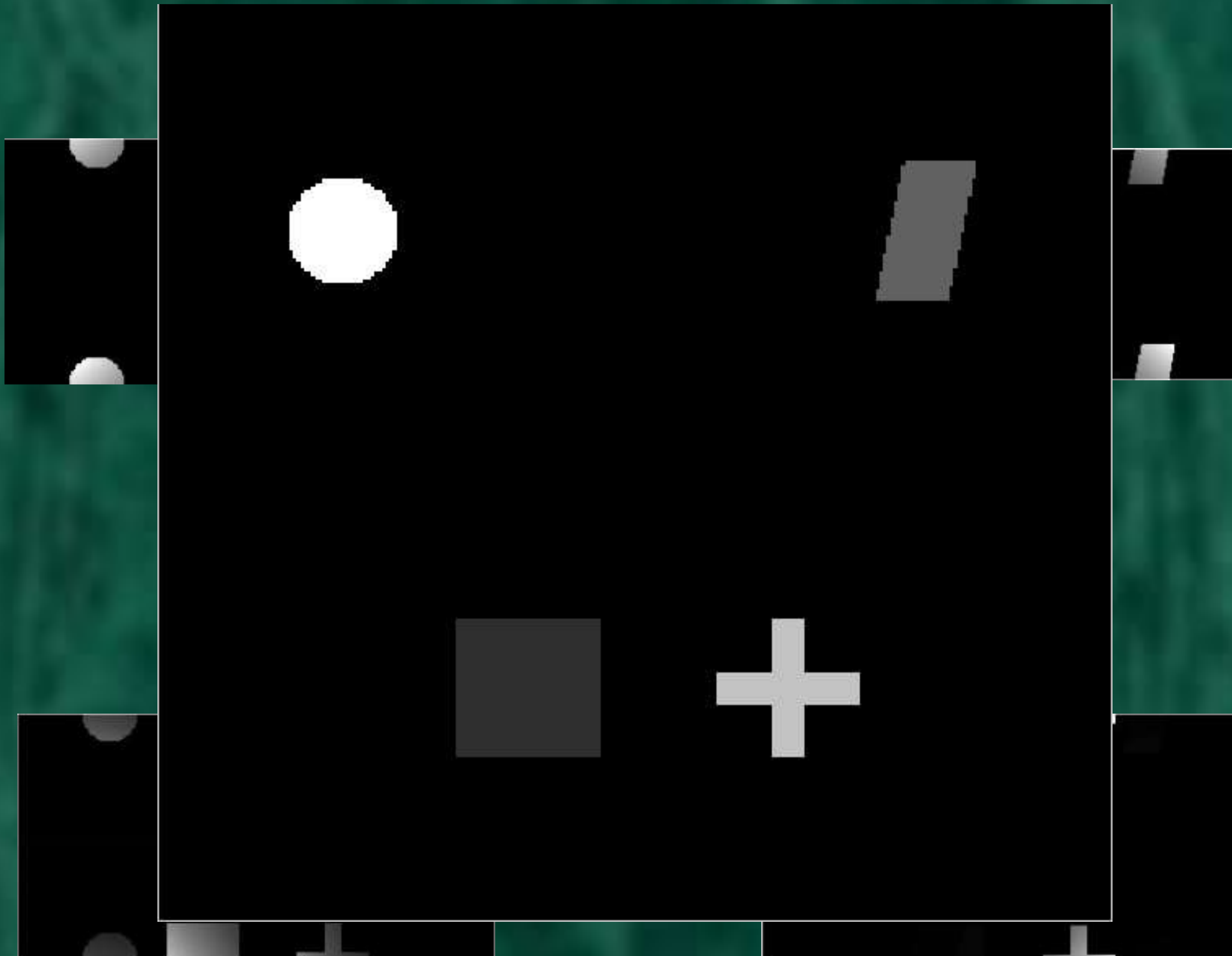


Coil Locations and Sensitivity Maps



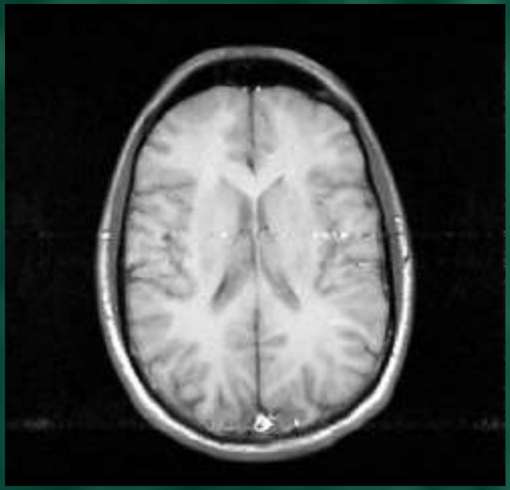
Using Coil Sensitivity to Un-alias an Image





Two Parallel Approaches

- Image based: Reconstruct images from each element, then untangle (SENSE, ASSET) (our demo)



- k-Space based: Untangle data to create fully-filled k-space(s), then reconstruct image (SMASH, GRAPPA)

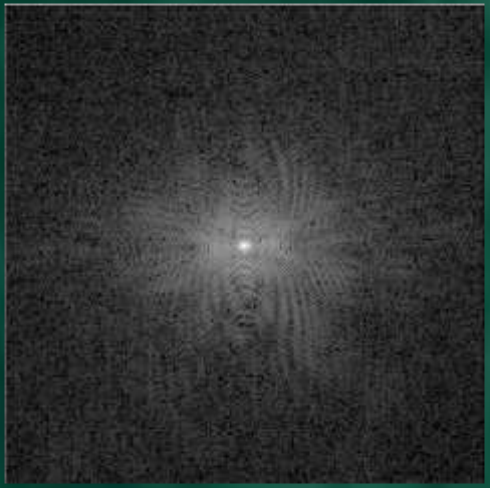


Image-based pMRI: The Encoding Matrix

$$S_p \approx \sum_j B_{pj} \rho_j$$

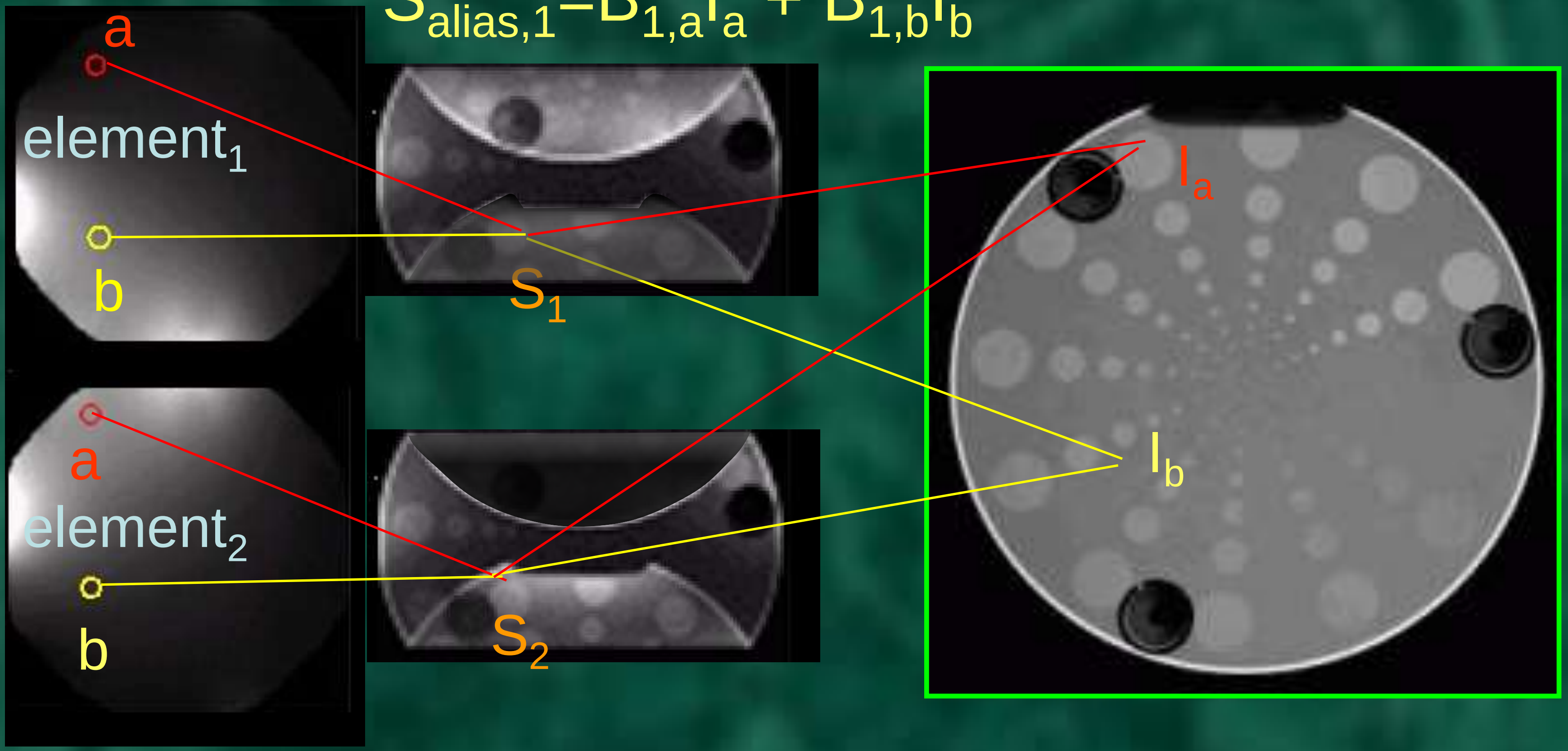
$S_{p:}$ signal received by the coil, p.
ρ_j: proton density at the pixel index, j
B_{pj}: encoding function that connects the coil response to the proton signal at a location.

In matrix notation: $S = B\rho$
or inverting: $\rho = B^{-1}S$

Thus if B^{-1} can be calculated, ρ can be determined.

A Simplistic SENSE Example

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

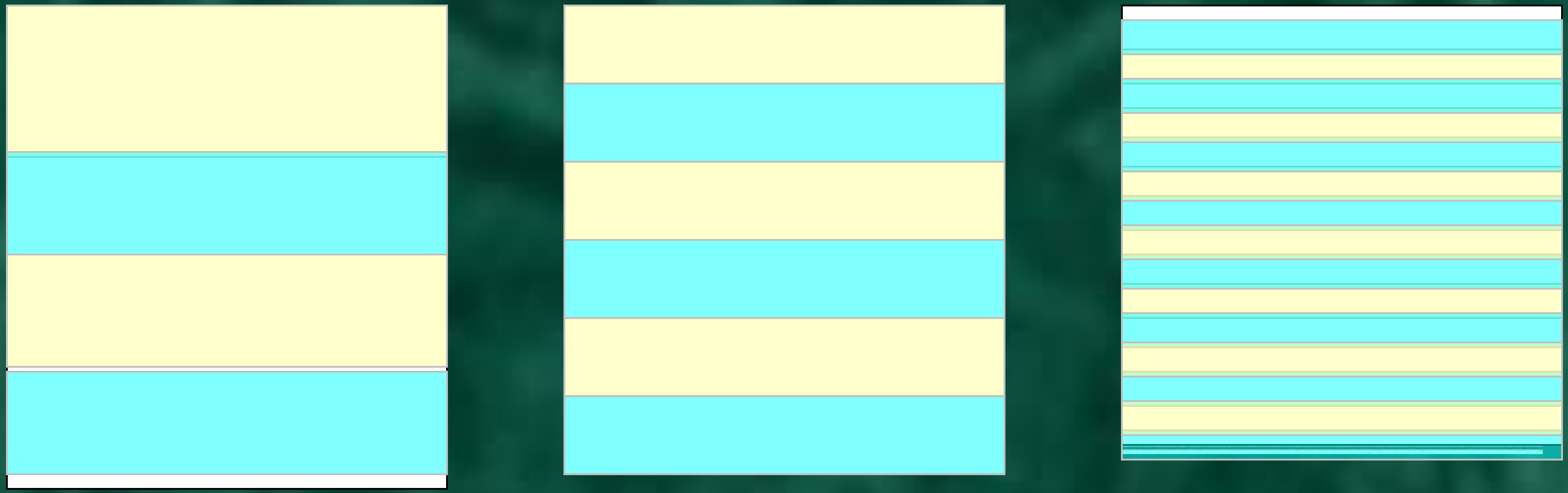


$S_{alias,2}=B_{2,a}I_a + B_{2,b}I_b$

SMASH – an Early k-Space Based pMRI Method

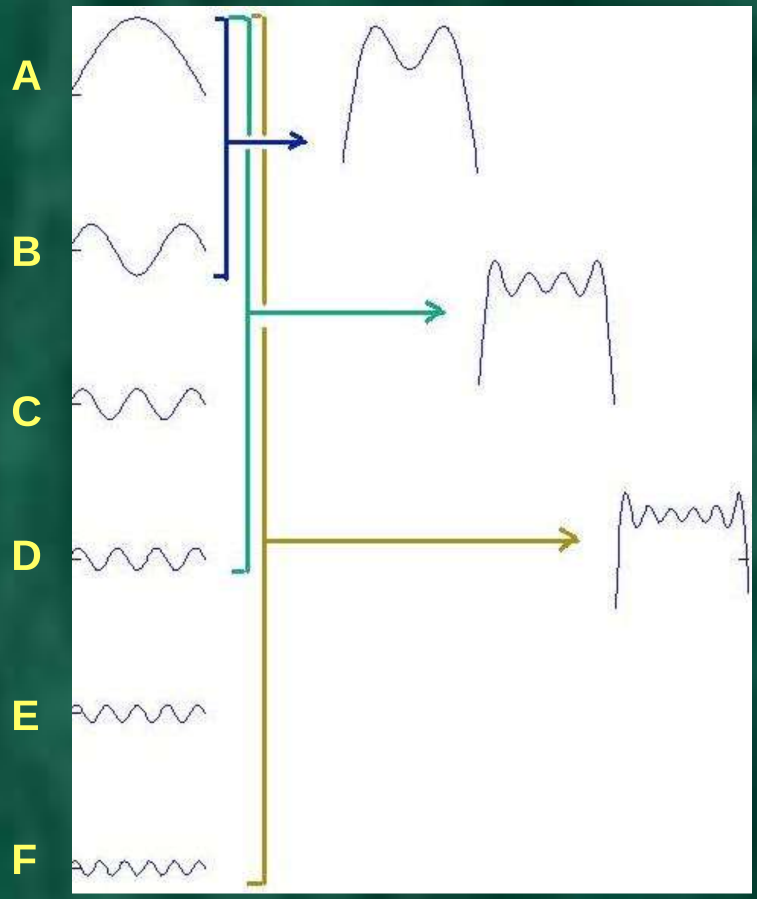
- Assumes spatial harmonics of phase-encoding gradients can be omitted and emulated by a linear combination of coil sensitivities
- Coil sensitivity still required (measured in some manner, and complex).

A Simplistic SMASH Example



- Phase encoding → modulation of phase as a function of position.

Frequency-Domain Basics



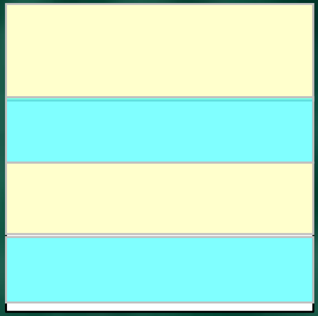
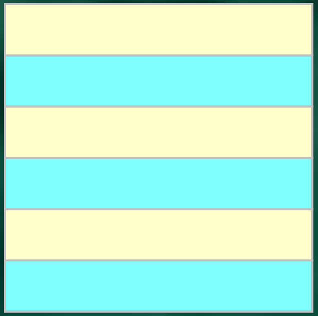
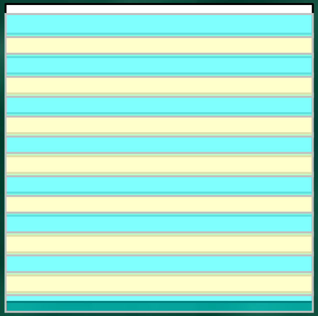
1D example: complicated wave = sum of simple waves.

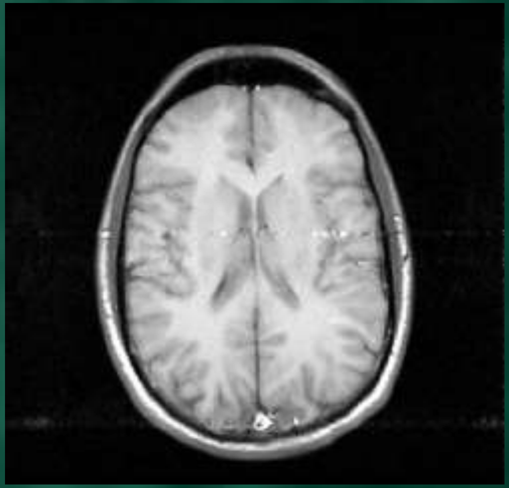
Need amplitudes/phases to perform the sum.

In this example, we could keep going to create a square wave.

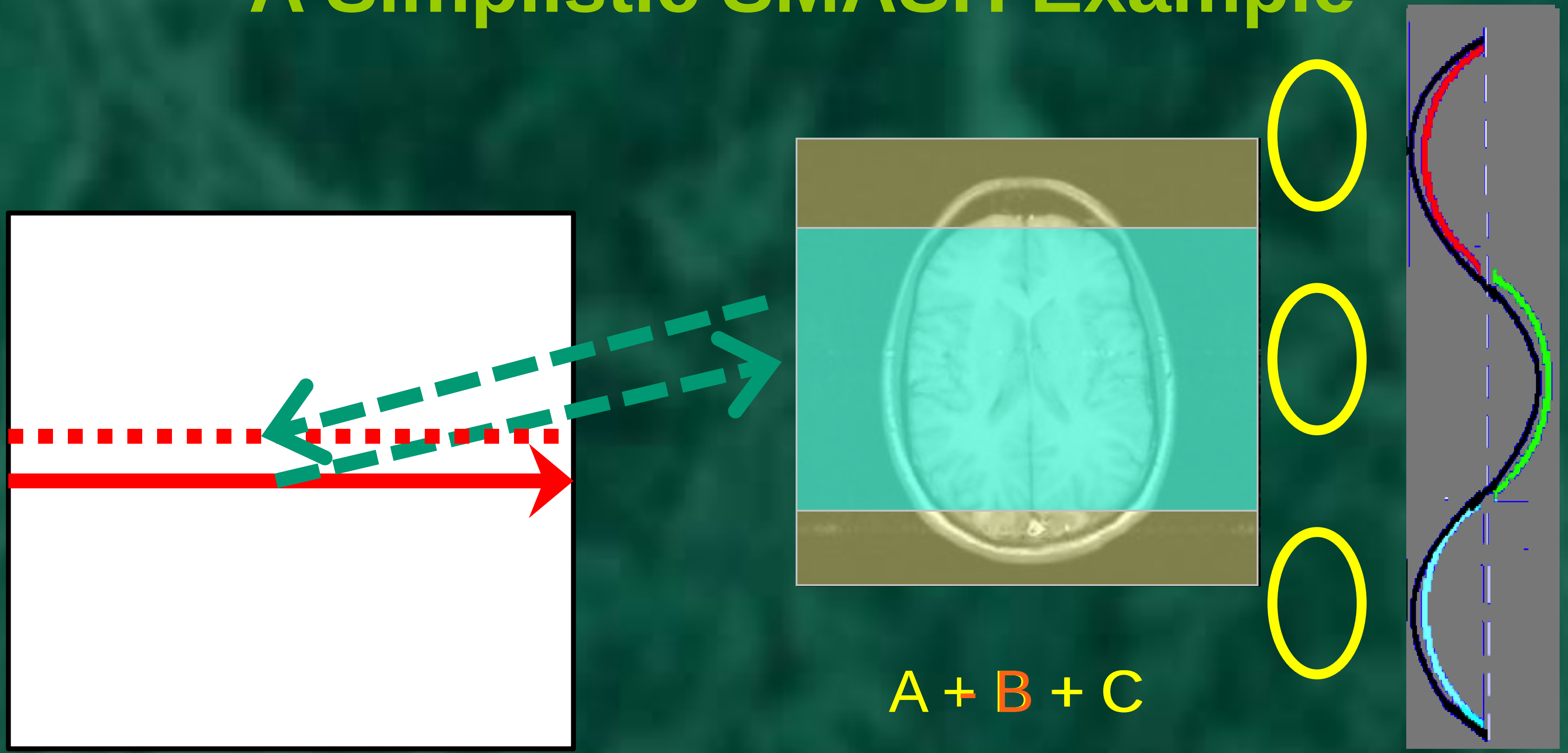
Same issue in 2D (here, image = “wave”).

A Simplistic SMASH Example

A_1*  $+A_2$*  $+A_3$*  + …

= 

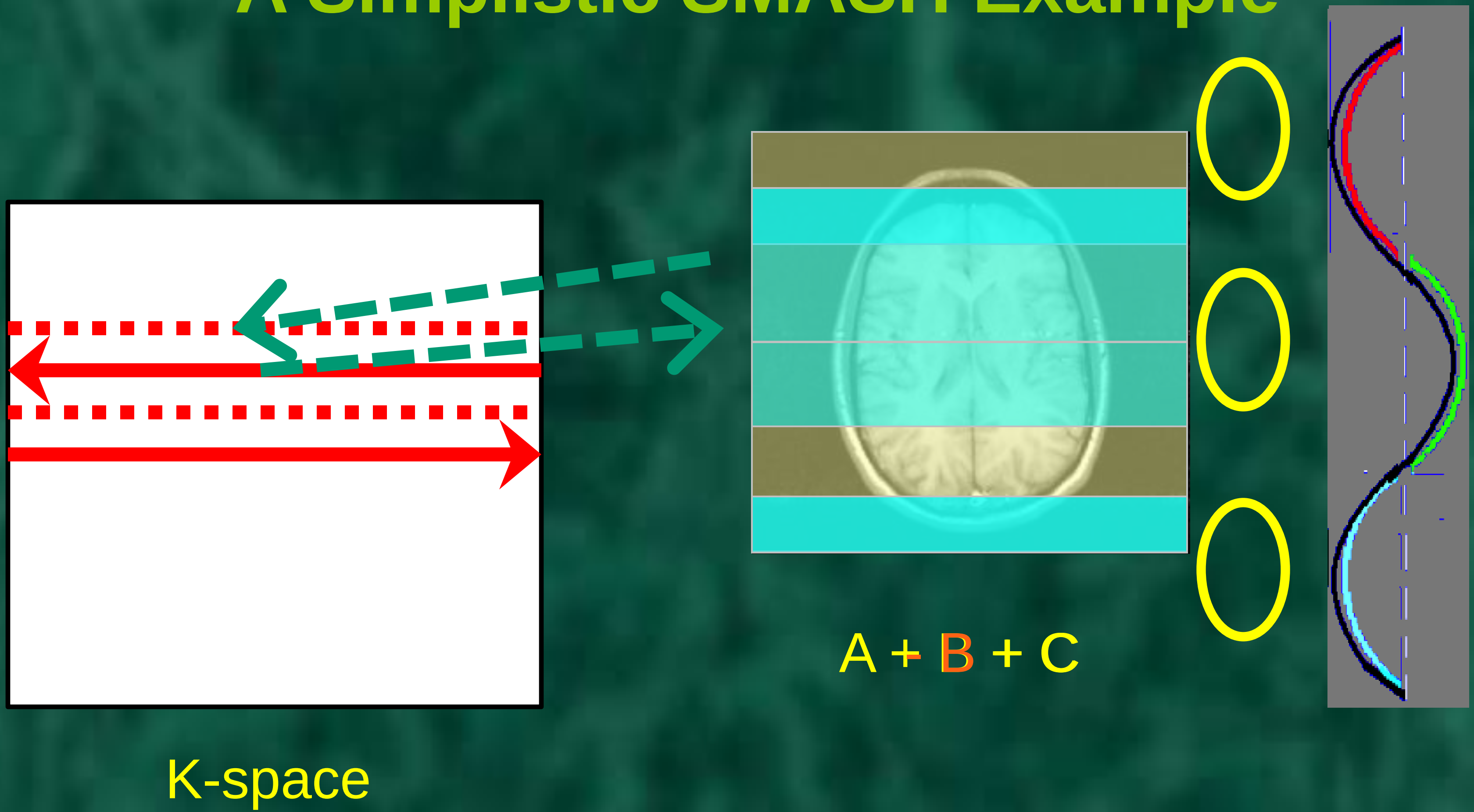
A Simplistic SMASH Example



K-space

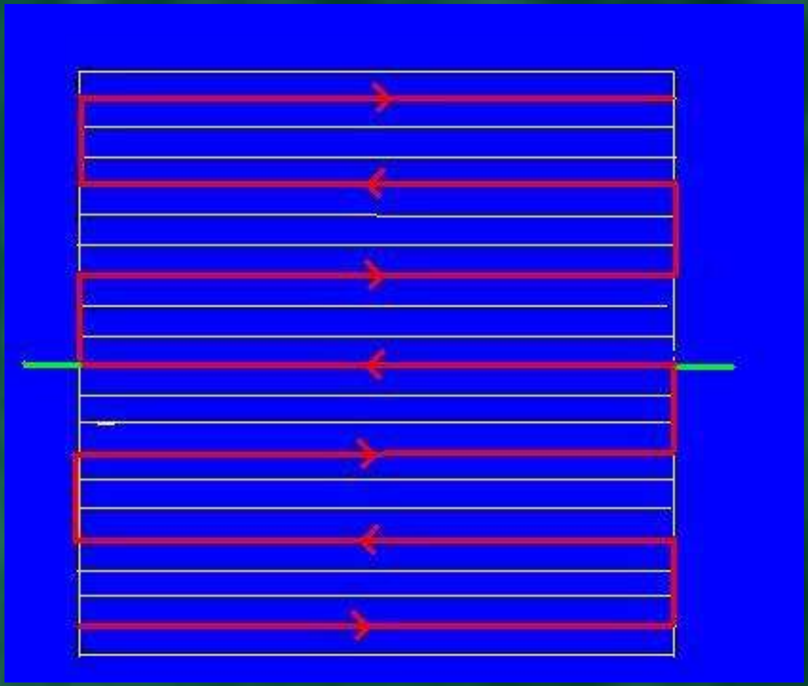
Rather than preparing all phase modulations, omit some for the sake of time, and use coils to emulate the modulations.

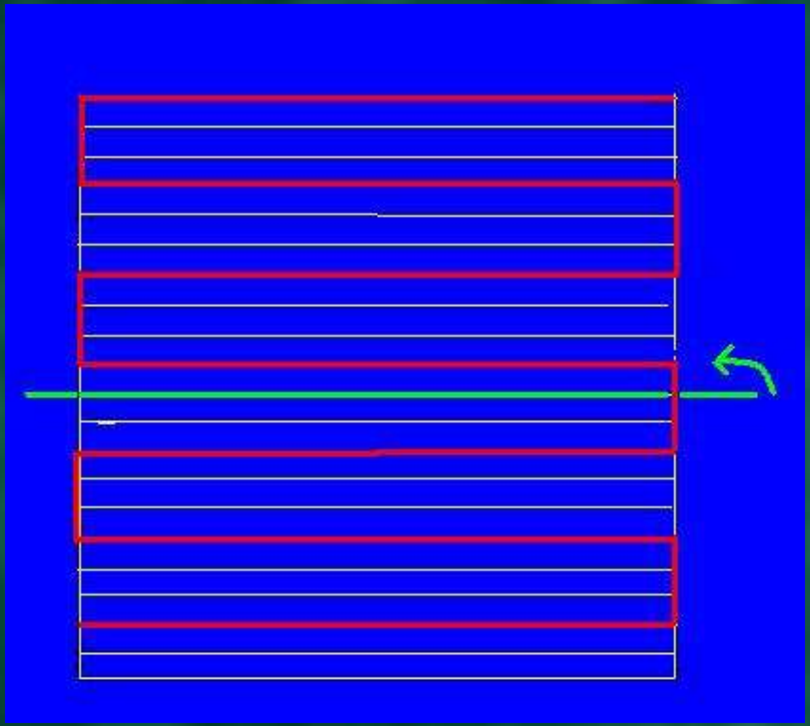
A Simplistic SMASH Example

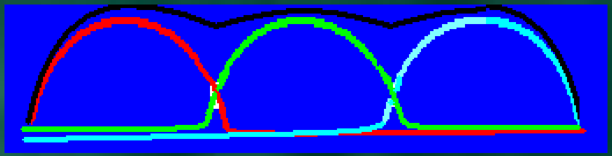


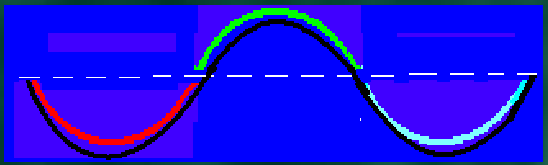
Rather than preparing all phase modulations, omit some for the sake of time, and use coils to emulate the modulations.

A Simplistic SMASH Example







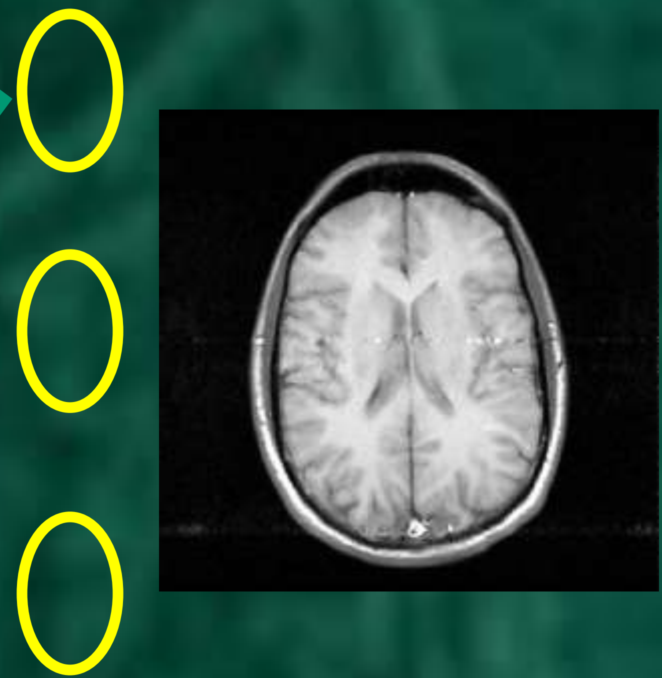


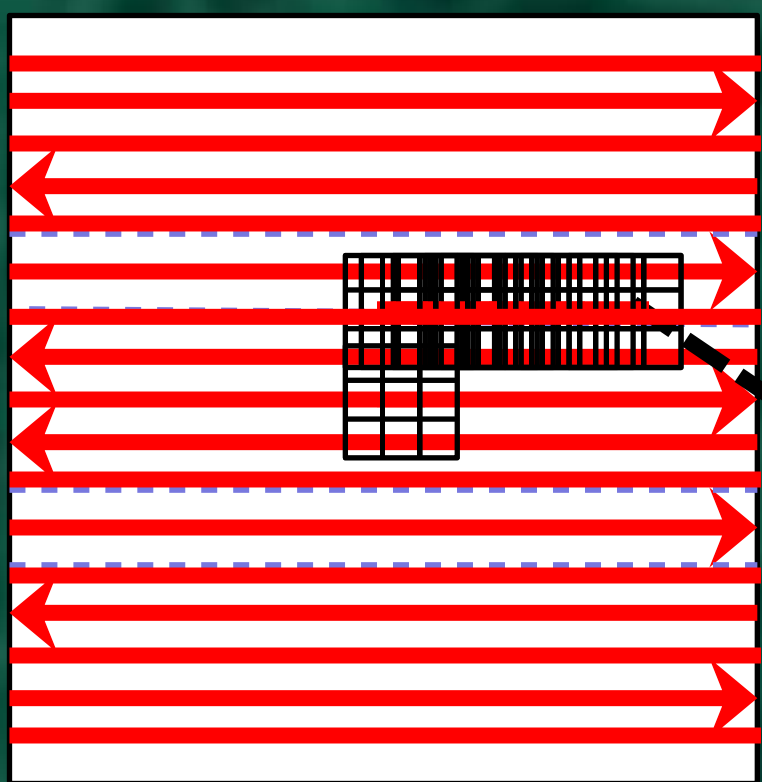
- Resultant combinations (spatial harmonics) allow for filling of all lines in a composite k-space.

GRAPPA (Griswold, et al. MRM 2002)

- More general application of SMASH principles.
- Generate extra lines of k-space via convolution process (similar to weighted sums in SMASH).
- K-spaces from each coil can be individually reconstructed.
- How to determine the weights? Use sensitivity information contained in image.
- ***Autocalibration***: Acquire reference lines (ACS lines) in k-space rather than whole coil sensitivity images (data from center of k-space acts like a sensitivity profile)

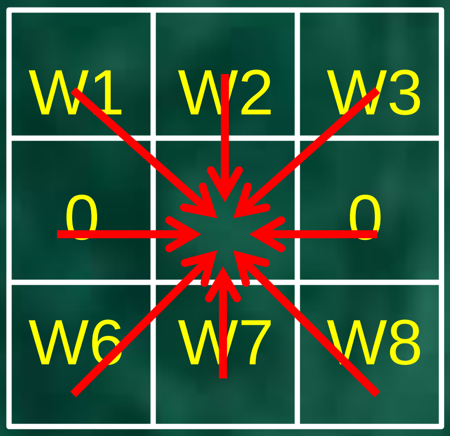
GRAPPA





K-space for each individual element.

Weights come from fits to calibration data.



Parallel Imaging (Technique Pros/Cons)

Image-based reconstruction: More artifacts, but easier to implement the sequence.

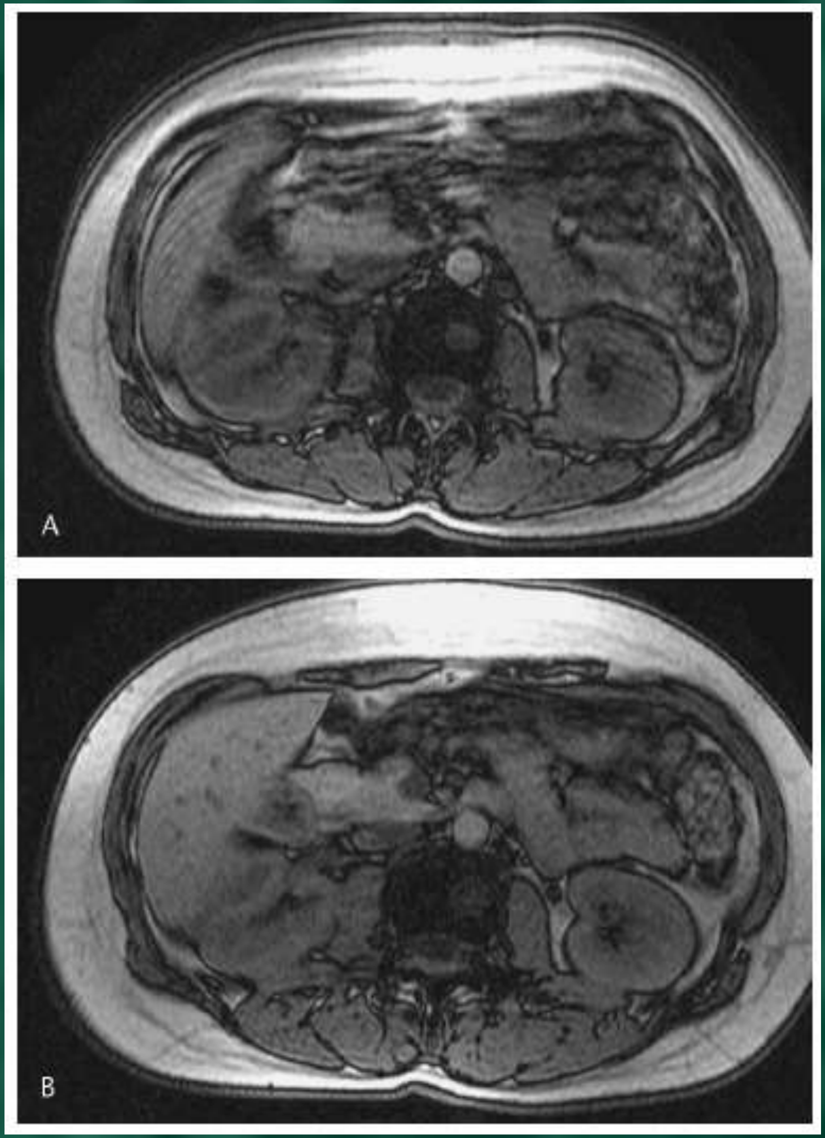
K-space based reconstruction: Depends more strongly on coil design, less artifacts, but longer to reconstruct.

Advantages/Uses of pMRI

When Should You Use Parallel MR Imaging?

- To reduce total scan time
- To speed up single-shot MRI methods
- To reduce TE on long echo-train methods
- To mitigate susceptibility, chemical shift and other artifacts (may cause others)
- To decrease RF heating (SAR) by minimizing number of RF pulses ($\propto B^2$)

Use #1: Body Imaging



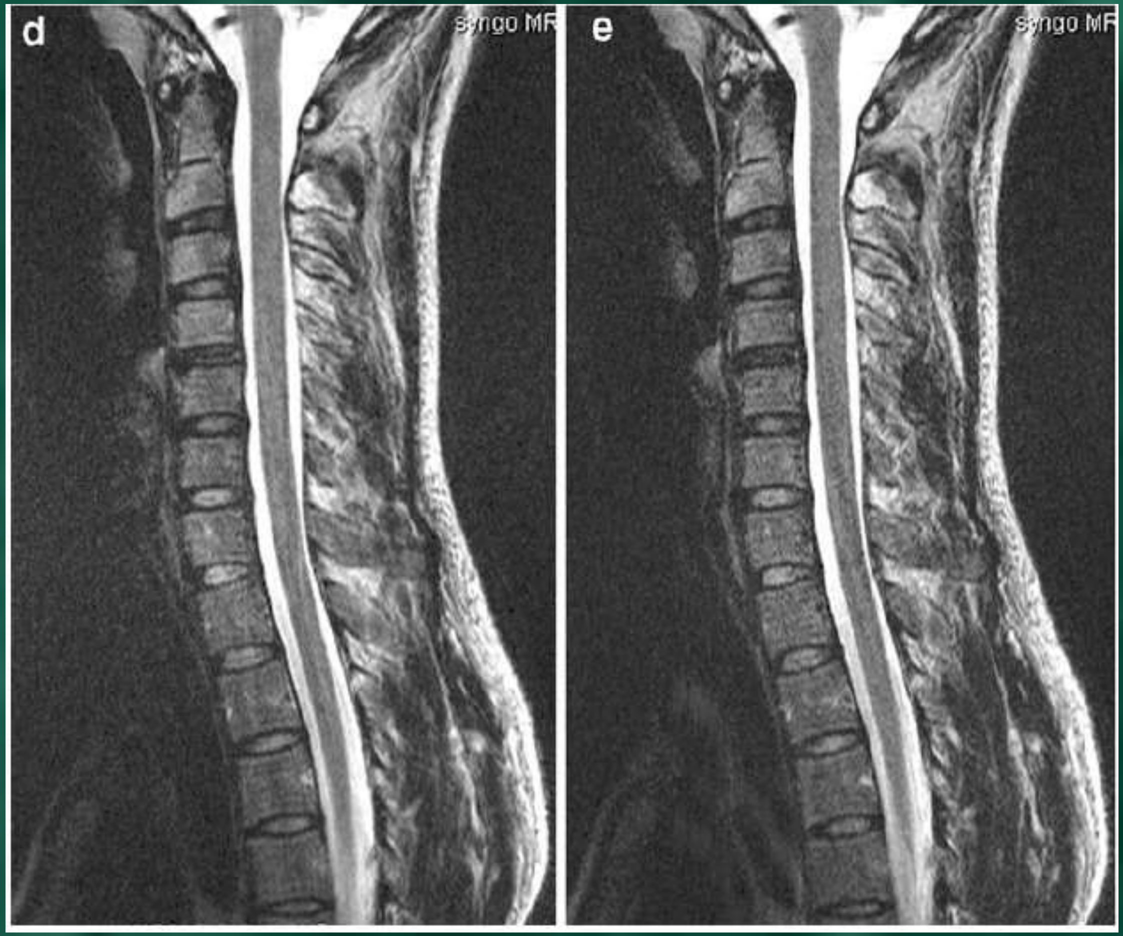
A: 22 sec acquisition w/ 15 sec breathhold

B: 11 sec acquisition w/ 11 sec breathhold + R=2

- To reduce total scan time (or eliminate breath holds)
- ***To decrease RF heating (SAR) by minimizing number of RF pulses***

Margolis D et al. Top Magn Reson Imag 2004; 15: 197-206

Use #2: Spinal Imaging



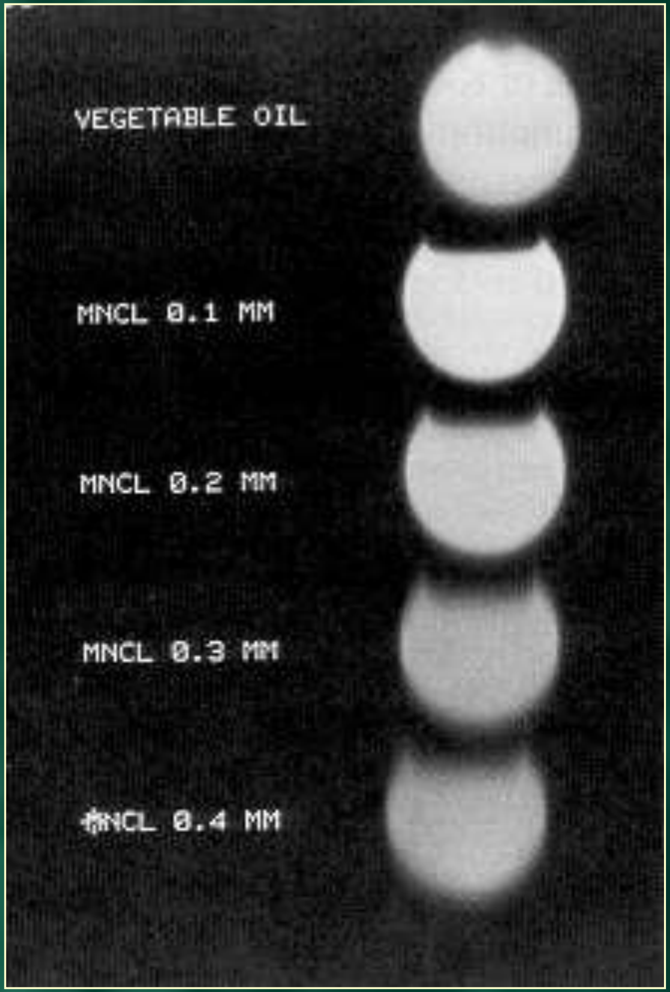
D: non-pMRI

E: R=2

- Image quality is of similar quality for ½ the scan time

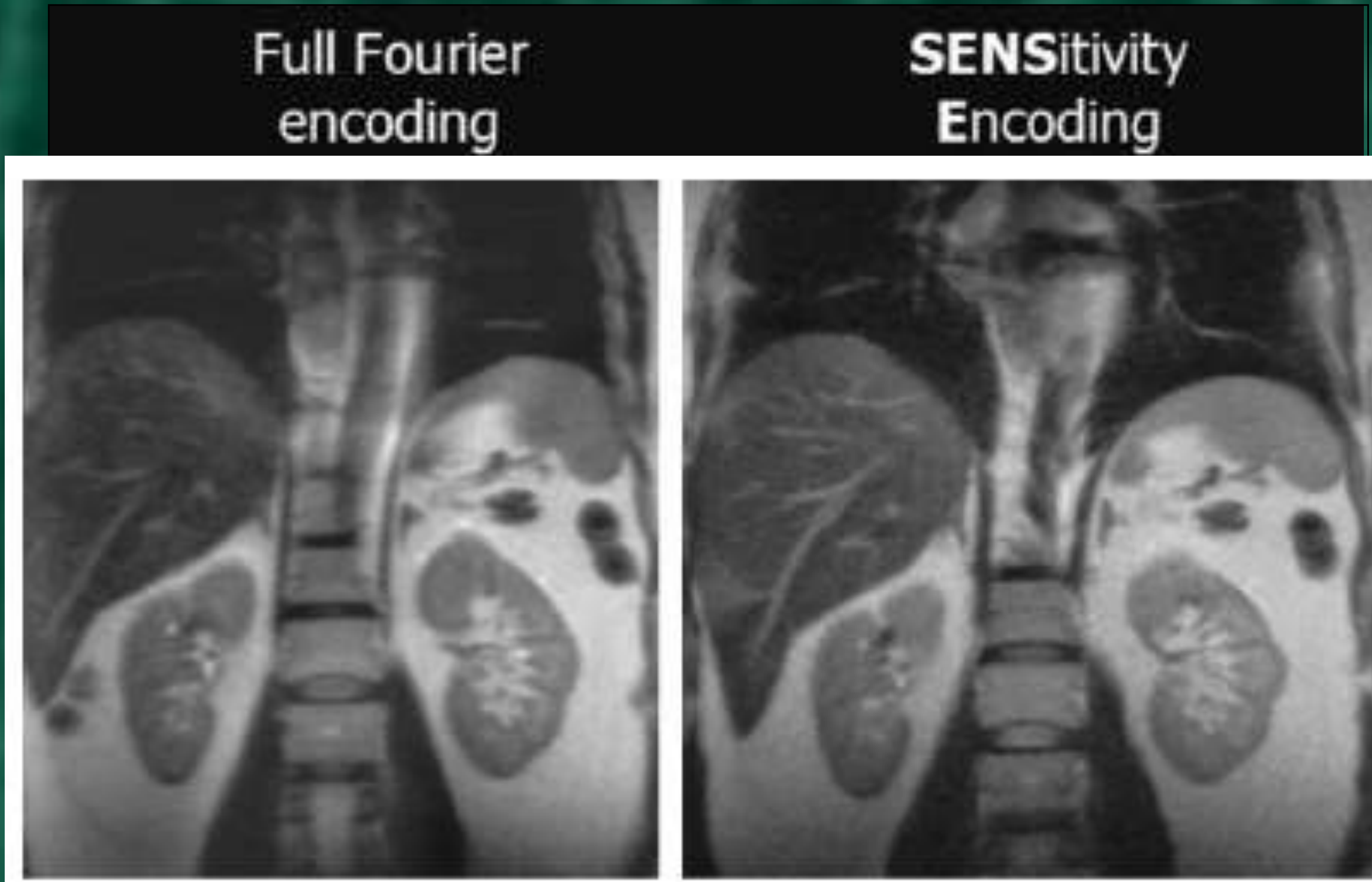
Noebauer-Huhmann et al. Eur Radiol 2007; 17: 1147-1155

Use #3: Reduce T2 Blurring (FSE)



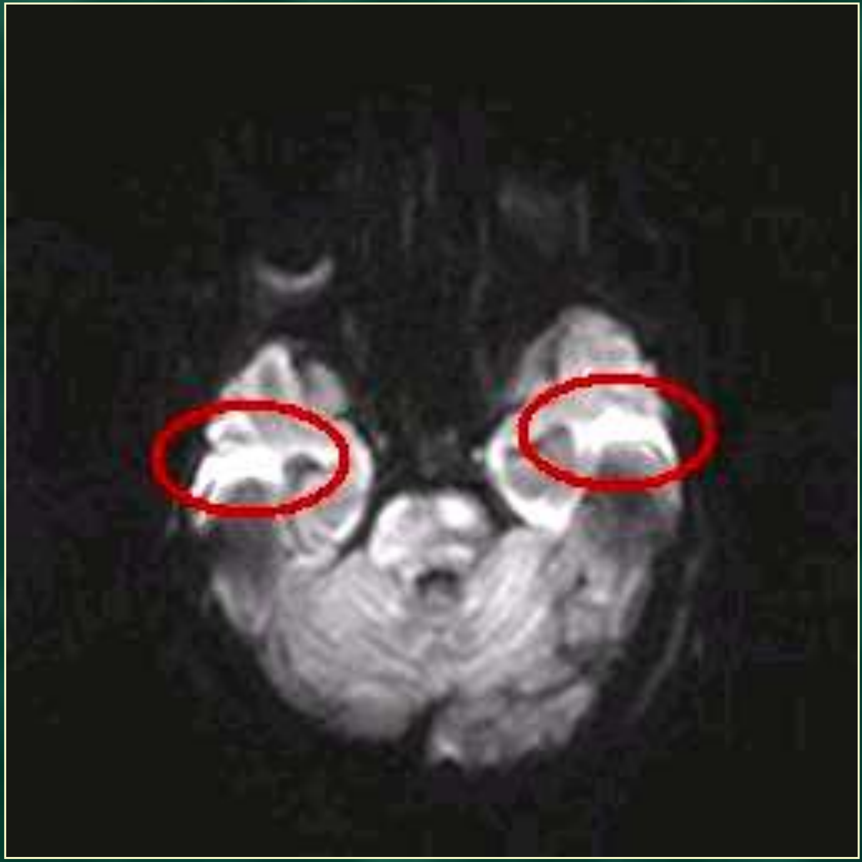
- Problem #1: Greater ETL → lower SNR
- Problem #2: T2 relaxation during acquisition of ETL results in “T2 blurring”.
- pMRI: reduce ETL.
  - facilitate reductions in TEeff.

Use #3: Reduce T2 Blurring



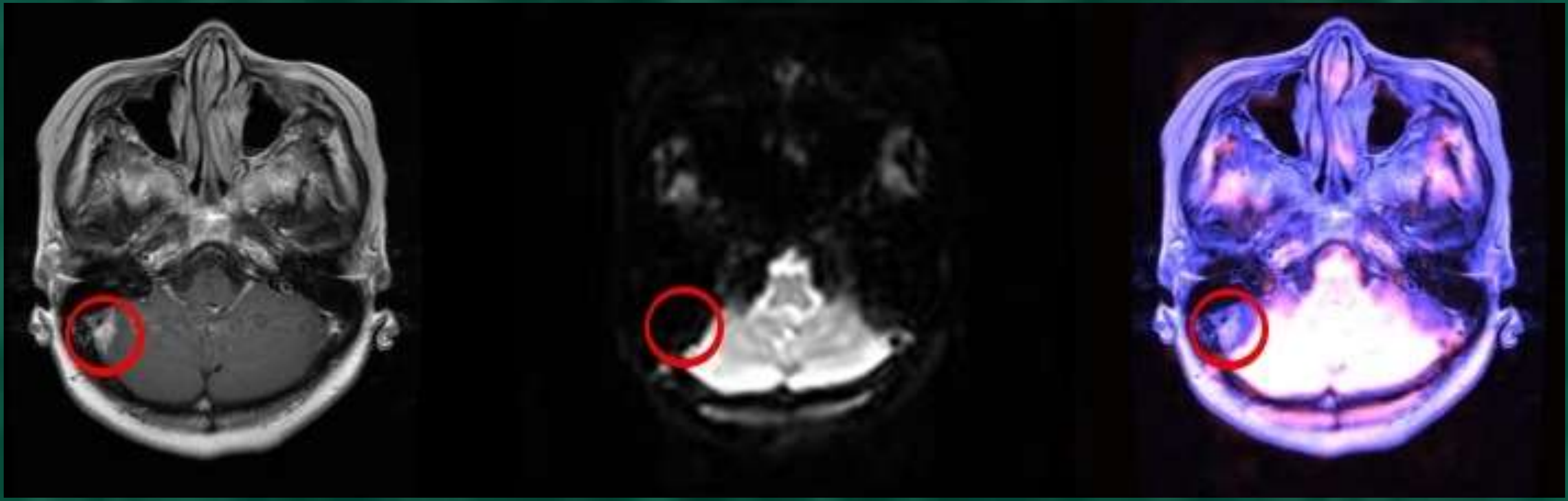
Augustine Me et al. Top Magn Reson Imag 2004; 15:207
Glockner et all. RadioGraphics 2005; 25: 1279-97

Use #4: Susceptibility Artifacts – Air Sinuses



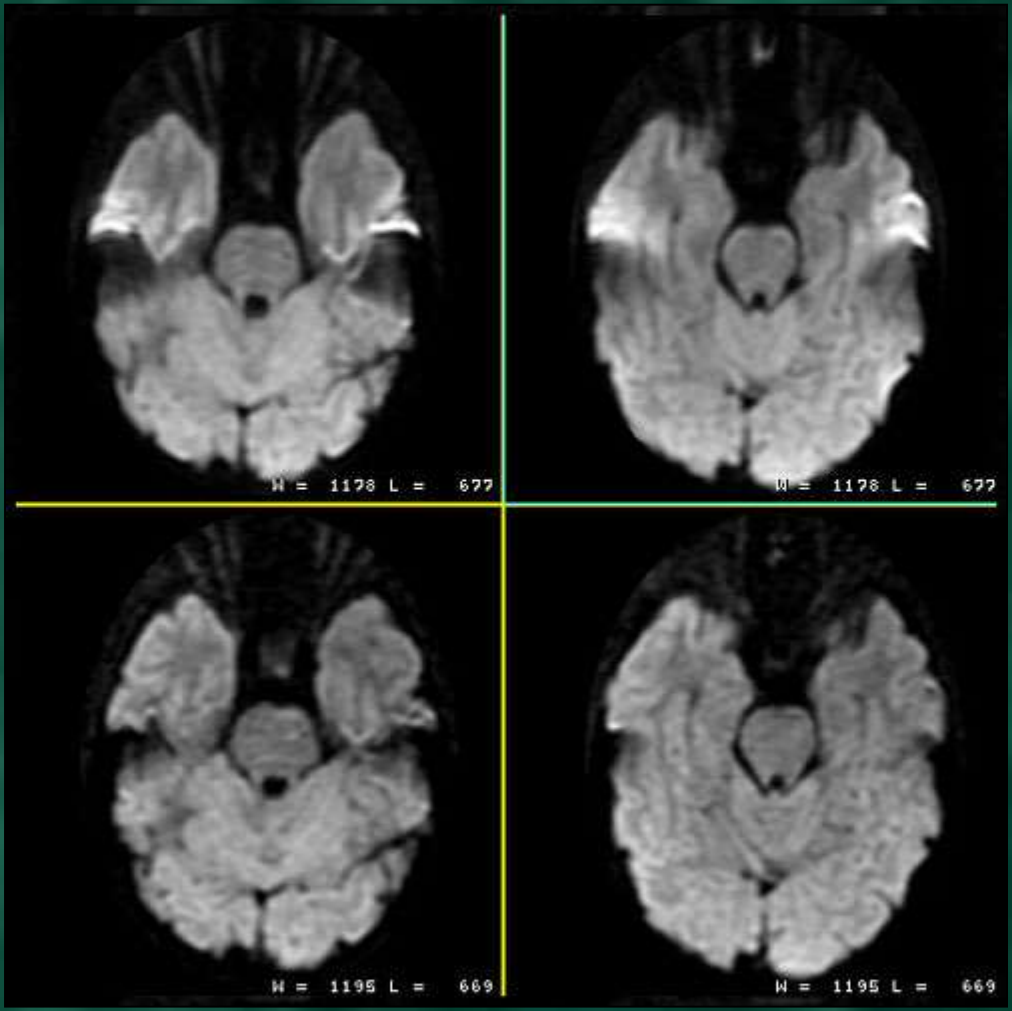
- Regions of air/bone/soft tissue causes local gradients due to differences in magnetic field susceptibility

Susceptibility Artifact Reduction with Parallel Imaging



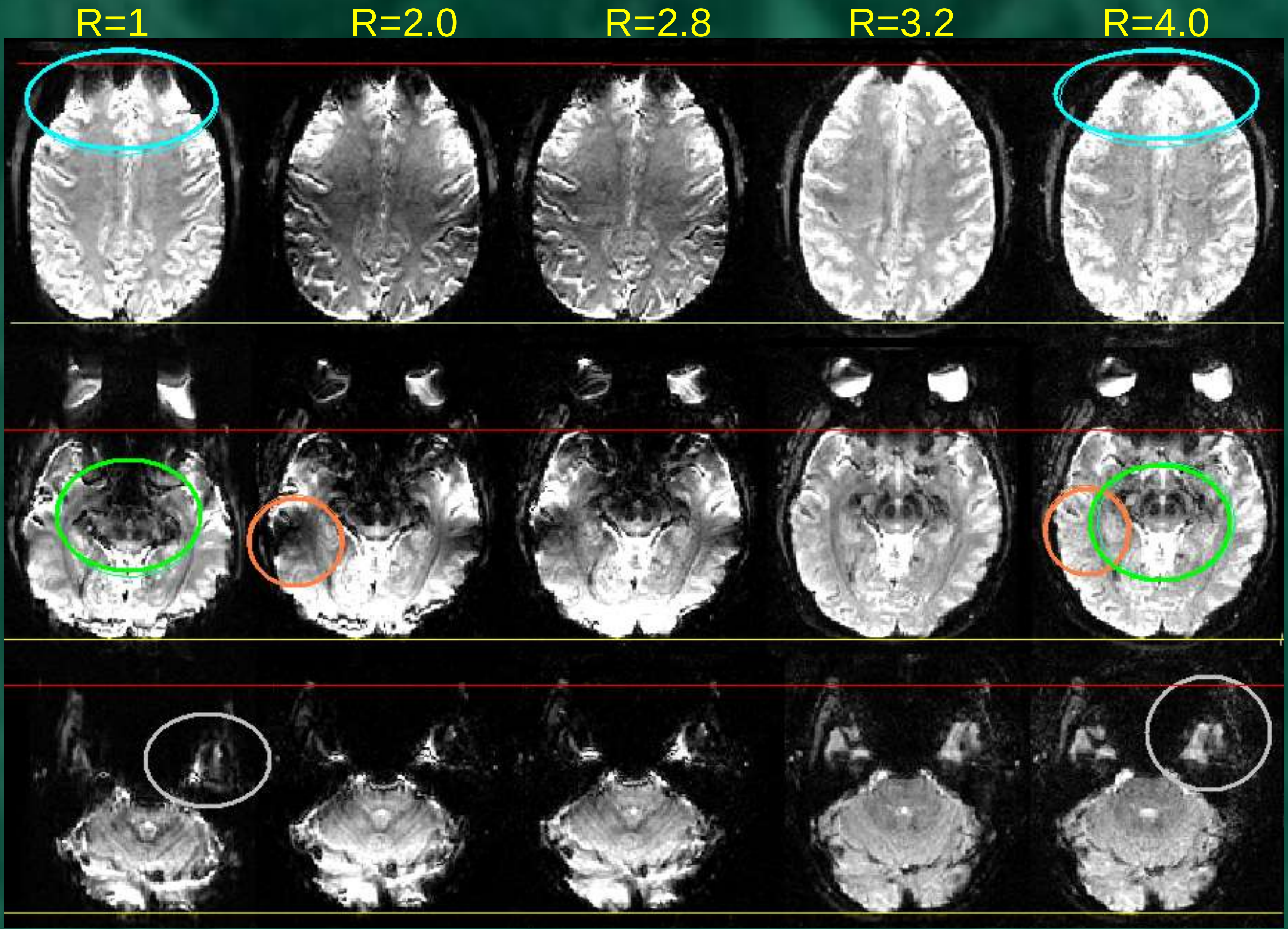
•Clinical example: remediation of distortion would have been nice in this circumstance.

Susceptibility Artifact Reduction with Parallel Imaging

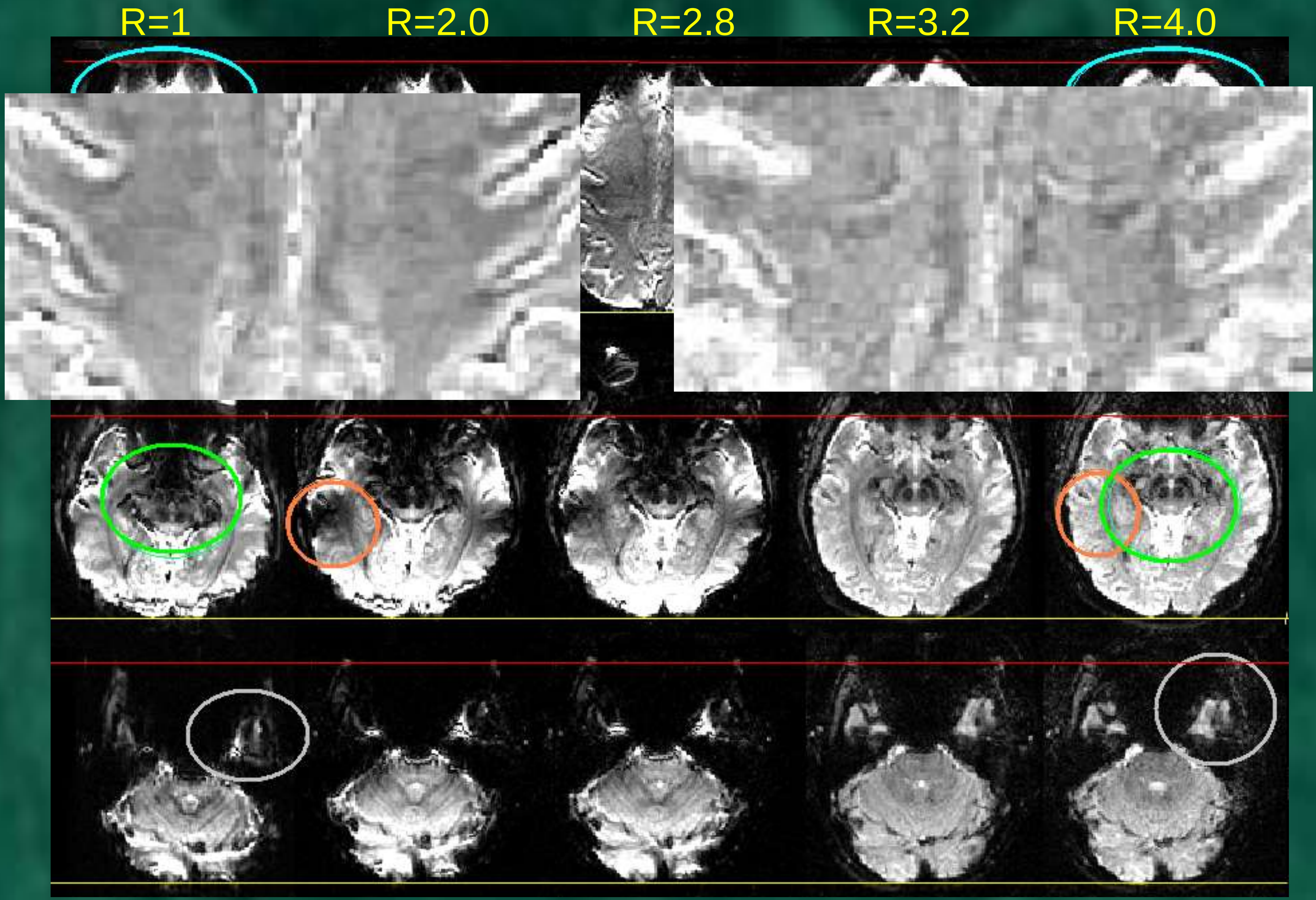


- Shortening readout window/TE helps (must have less phase encodes to do this).
- EPI-based sequences gain more in general (e.g., DWI, perfusion)
  - Top – normal acquisition,
  - Bottom – R=2 acceleration

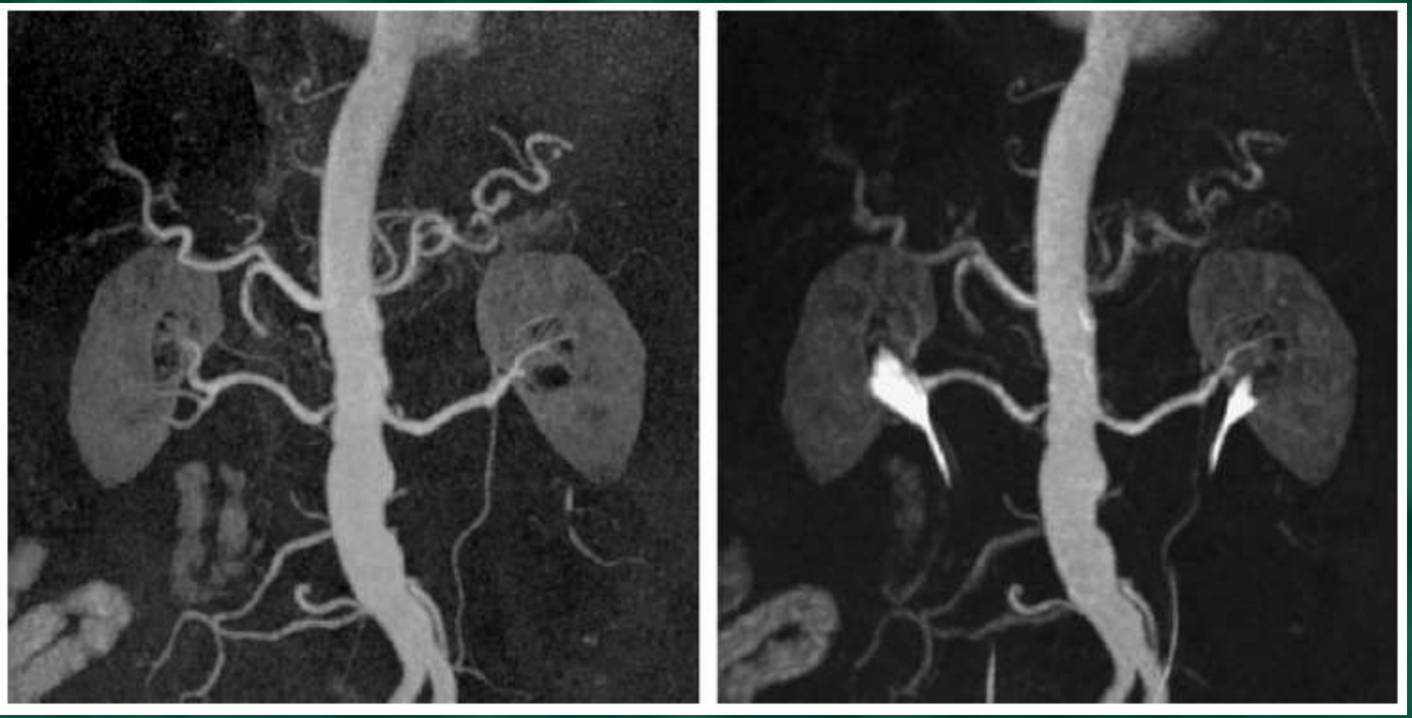
"Turn Key" Parallel Imaging ?



"Turn Key" Parallel Imaging ?



Use #5: Contrast-enhanced MR (MRA)

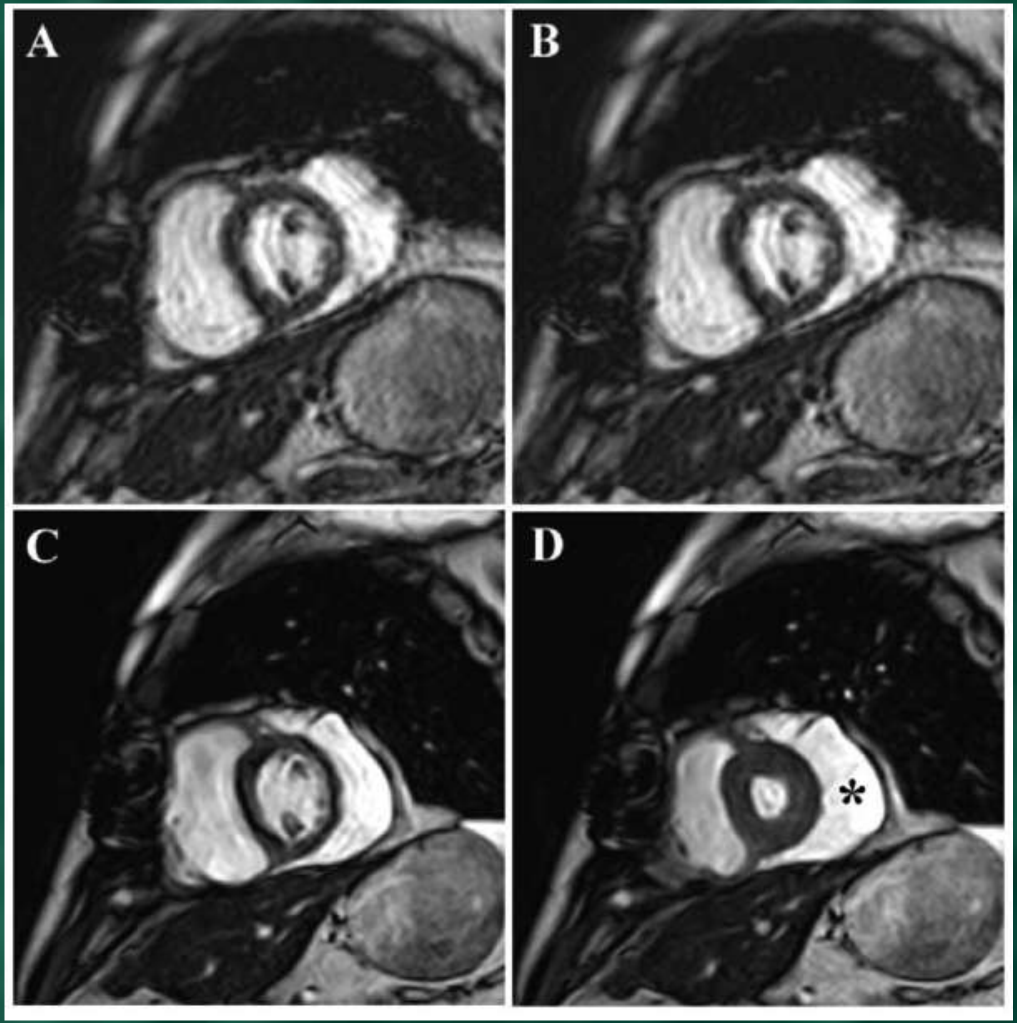


Left: R~ 1.5; Right: non-pMRI with reduced FOV

- Improved spatial resolution for a given scan time.

Wilson, et al. Top Magn Reson Imag. 2004; 15: 169-185

Use #6: Cardiac Imaging



Balanced FFE MRI

A&B: 11 sec breath holds

C&D: 5 sec breath holds + R=2

Van den Brink, et al. Eur. J. Rad. 2003; 46: 3-27.

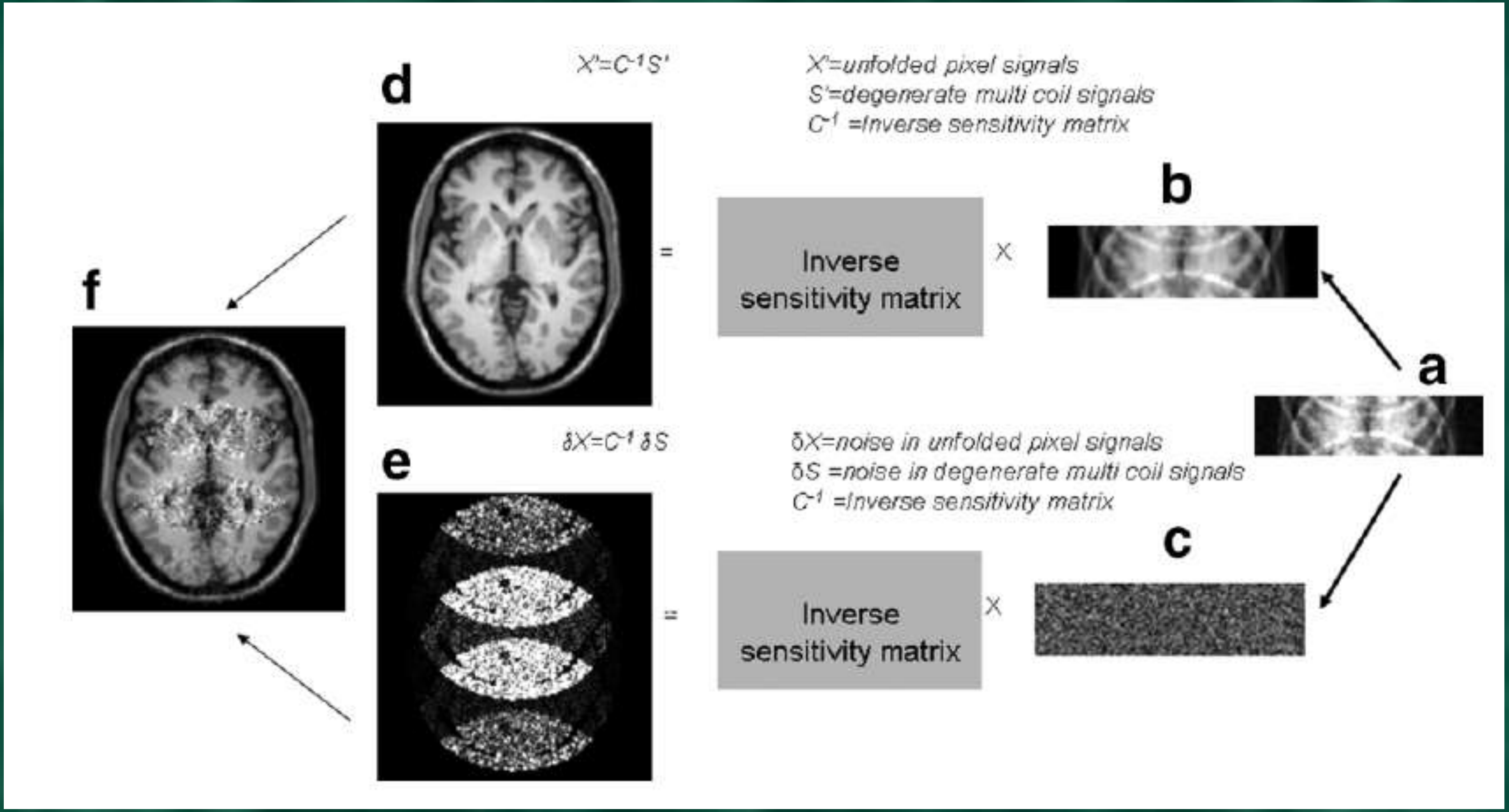
Drawbacks/Consideration of pMRI:
SNR Properties & Artifacts

SNR

SNR is a concern with pMRI for three reasons:

- Non-uniformity of signal (array coils)
- Non-uniformity of noise (pMRI)
- Lower signal from acceleration (pMRI)

Non-Uniformity of Noise



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

Key SNR Parameters in Parallel Imaging

- SNR depends on number, size and orientation of the coil elements

$$SNR_{i,j,k}^{PI} = \frac{SNR_{i,j,k}^{norm}}{g_{i,j,k}\sqrt{R}}$$

- R: acceleration factor
- g: coil-dependent noise amplification factor

(non-uniformity that we observed)

Key SNR Parameters in Parallel Imaging

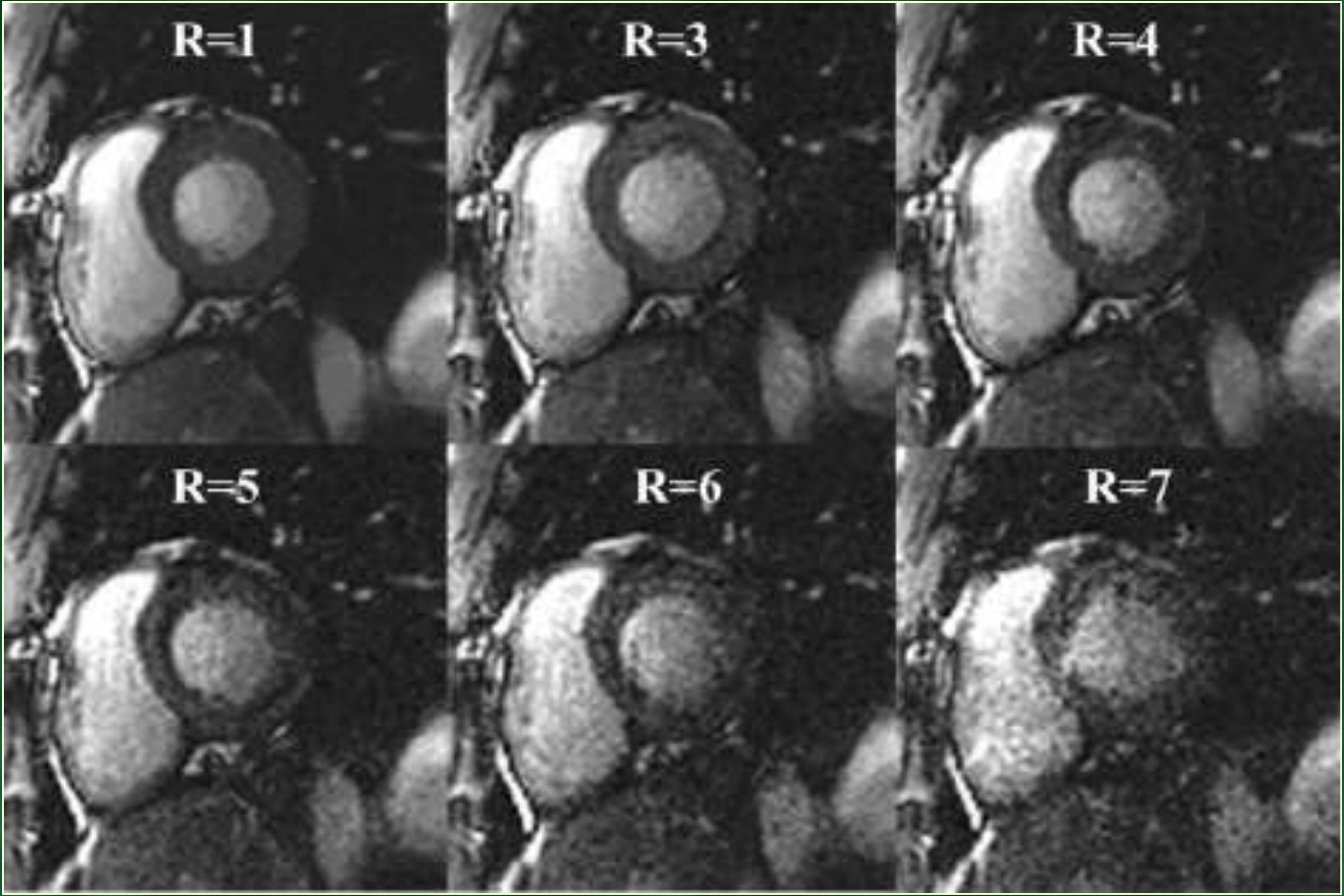
- SNR depends on number, size and orientation of the coil elements

$$g(\vec{r}, R) = R^{-1/2} \frac{SNR^{norm}}{SNR^{PI}(\vec{r})}$$

- R: acceleration factor
- g: coil-dependent noise amplification factor

(non-uniformity that we observed)

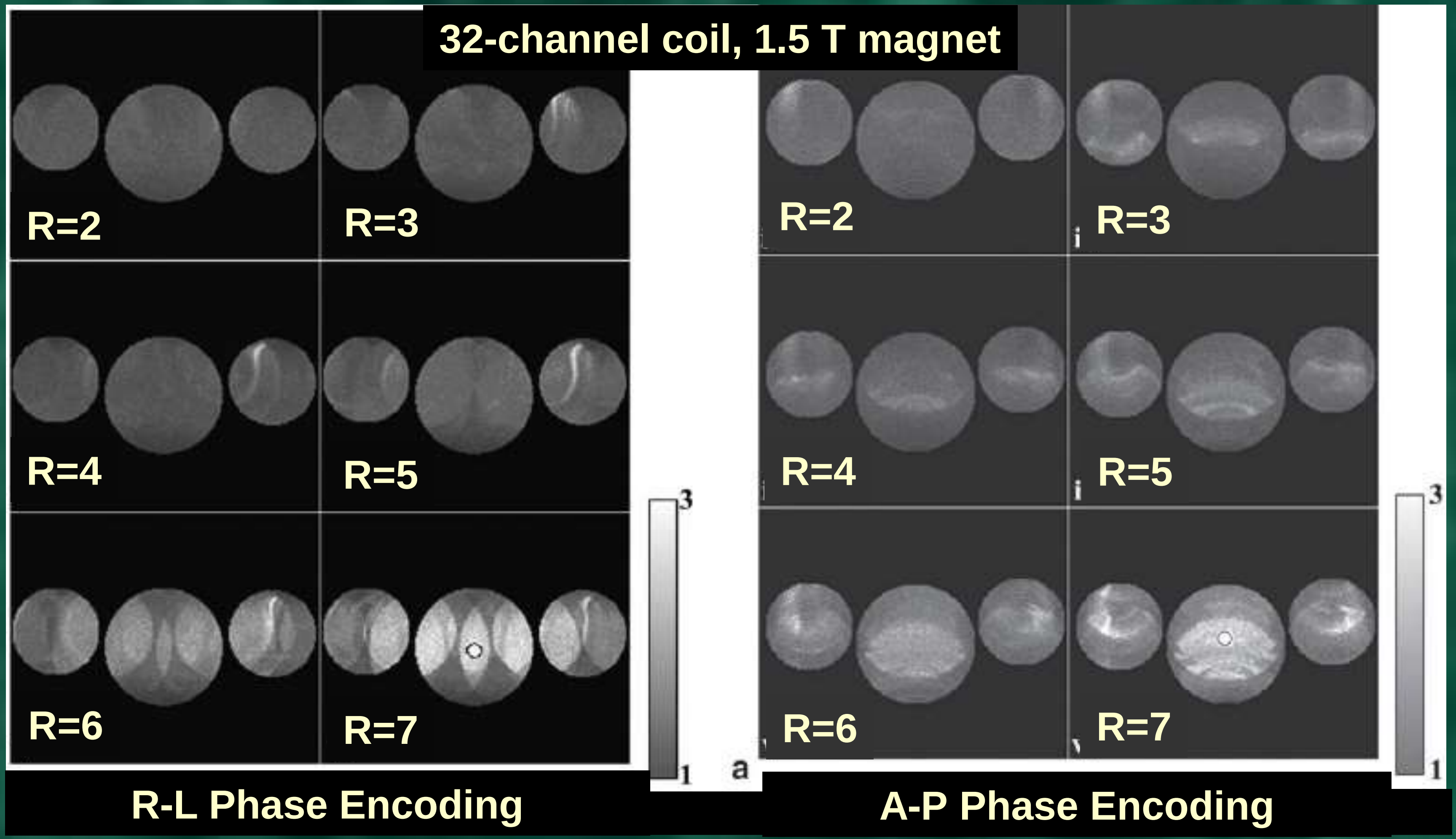
SNR vs. Acceleration



Short-axis cardiac images – 32-channel coil – 1.5 T magnet

Reeder SB et al. MRM 54:748, 2005

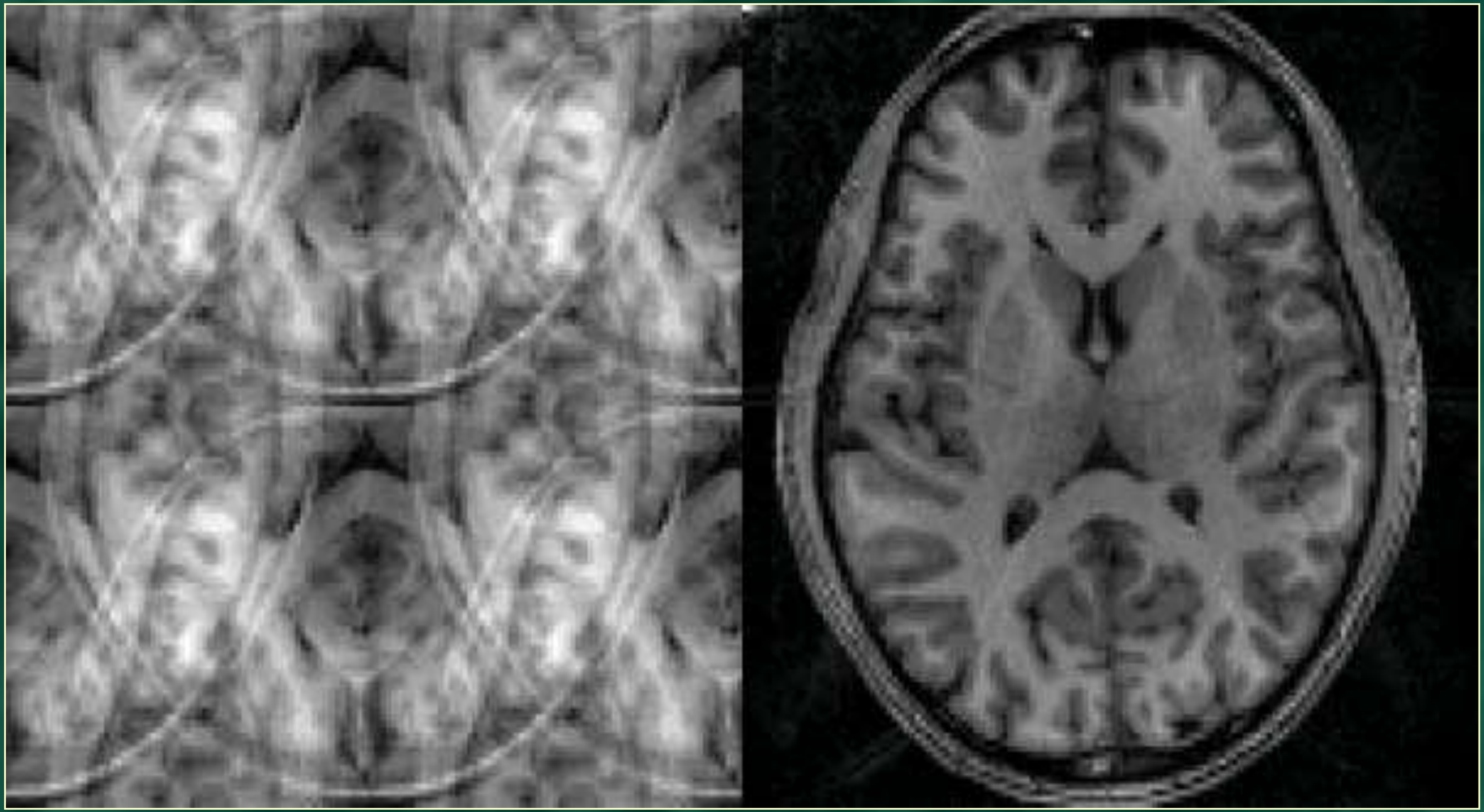
g-Factor Calculated Maps



- g-Factor changes with R

Reeder SB et al. MRM 54:748, 2005

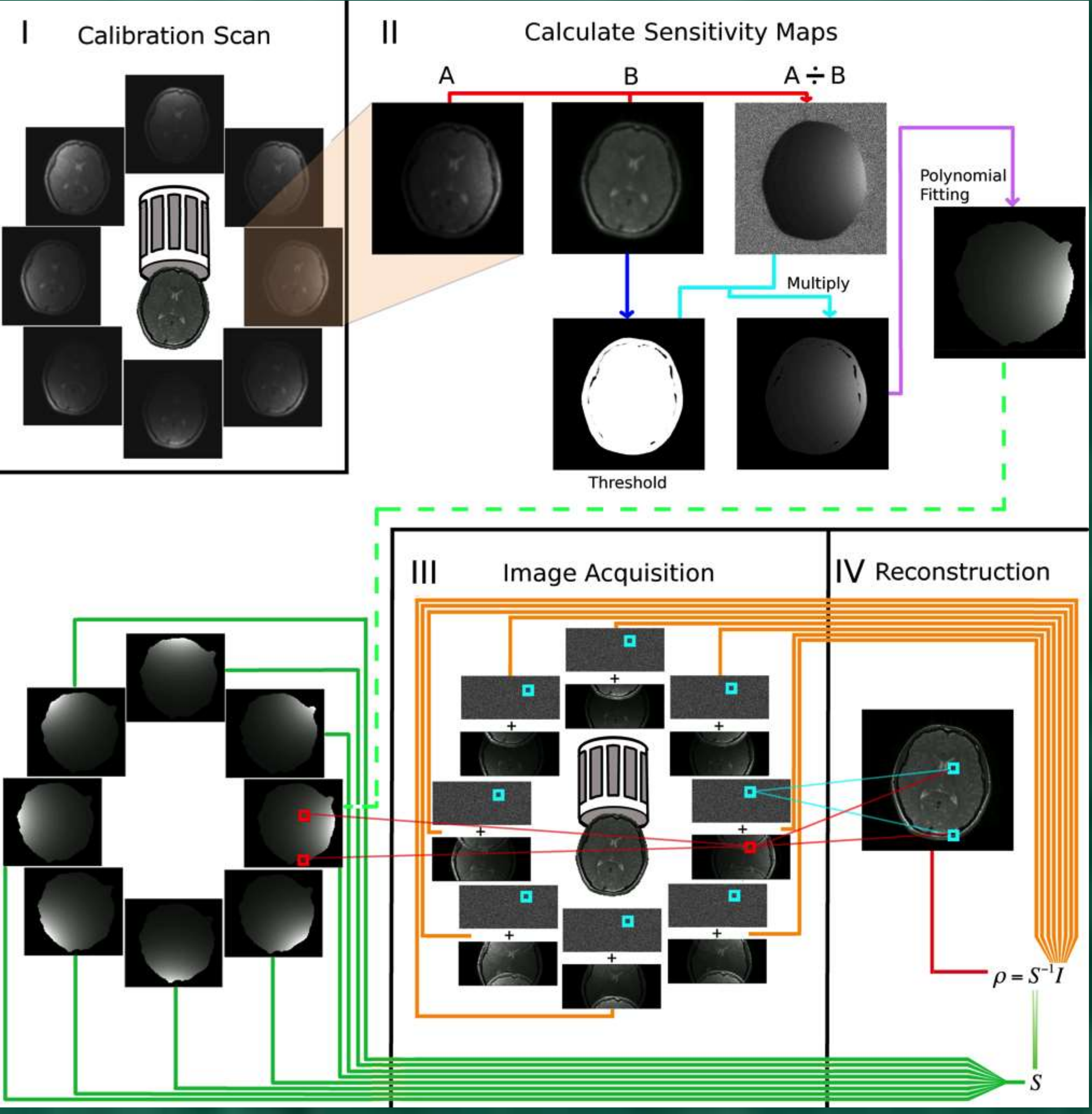
2D SENSE (with 3DFT MRI)



http://www.nmr.mgh.harvard.edu/~fhlin/tool_sense.htm

2D SENSE reconstruction (2X in L-R and 2X in A-P) from an 8-channel head array coil conjugated gradient iterative solver after 10 iterations.

Generally better g-factor with 2D acceleration compared with same acceleration in 1D.



Potential Sources of Artifacts

Yanasak and Kelly, Radiographics, 2014 (in press)

Artifacts

Artifacts associated with pMRI may or may not be subtle.

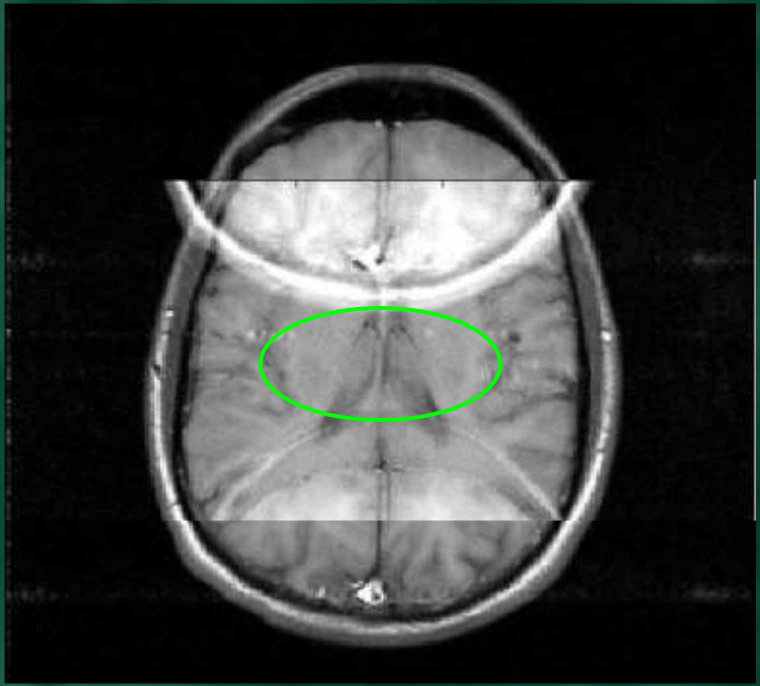
Similarities to conventional MRI artifacts (aliasing, ghosting).

Important to prescribe the acquisition properly, and to avoid movement.

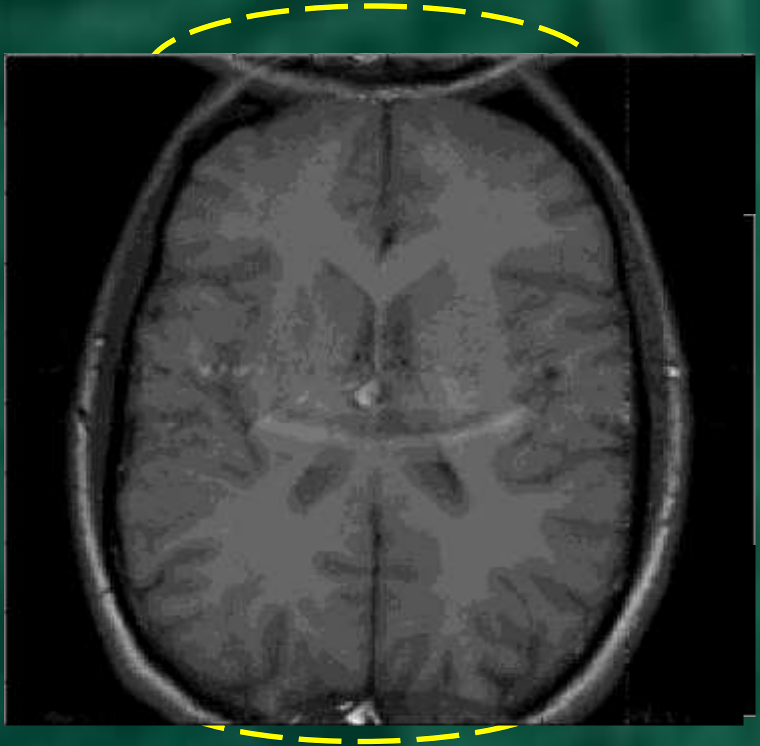
Artifact #1: Tissue Outside of FOV (SENSE)—Wrap-around artifact

Undersampling MRI

What happens when the FOV is too small?



Normal FOV



Smaller FOV

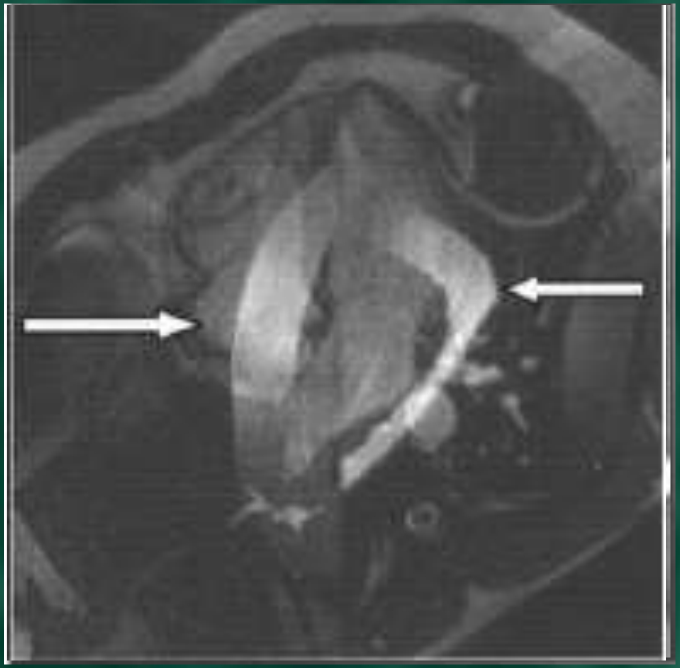
Center region in this example should be unaliased, for acceleration R=2.

Treated as non-aliased tissue during reconstruction.

Examples: Phantom and Patient

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

Goldfarb, JMagn Reson Imag. 2004

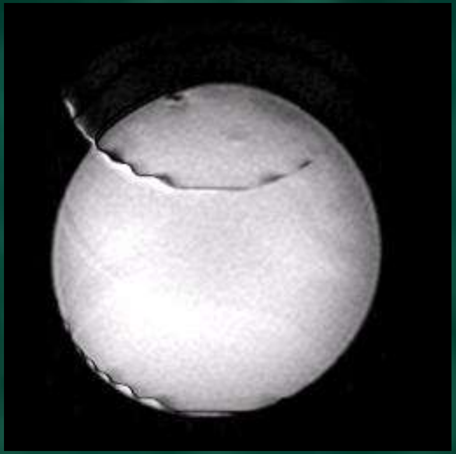


SENSE
Small FOV
Normal FOV

Artifact #2: Motion After Calibration Scan (any non-auto-calibrated sequence)

Calibration scan must accurately represent tissue position.

Small displacement



Medium displacement

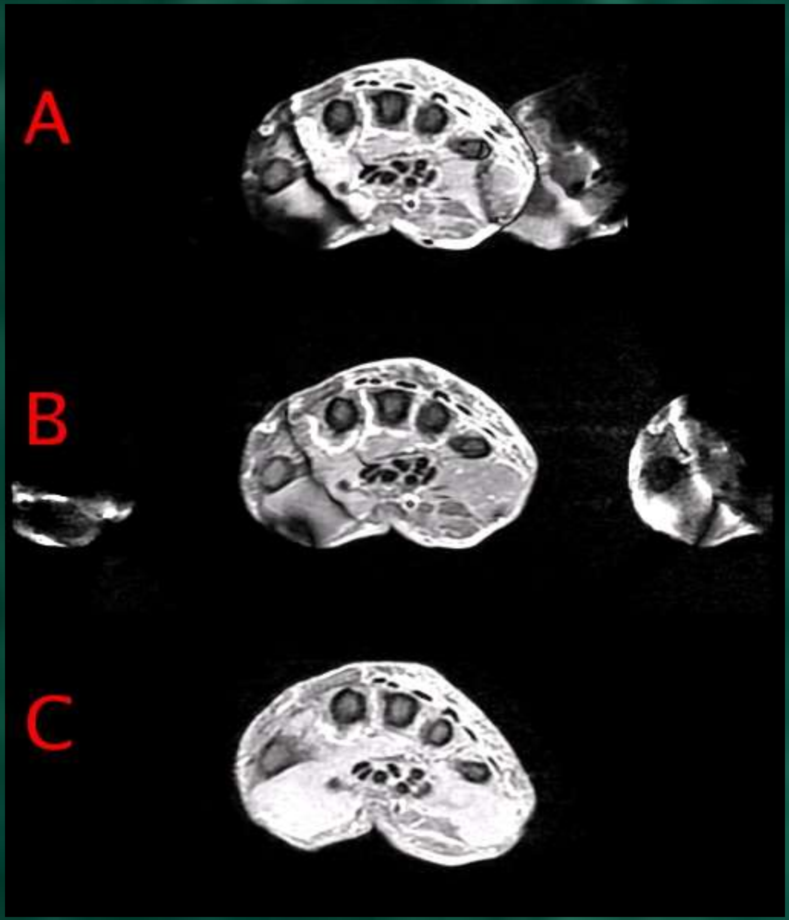
Large displacement

Artifact #2: Motion After Calibration Scan (any non-auto-calibrated sequence)

Affected by FOV choice as well.

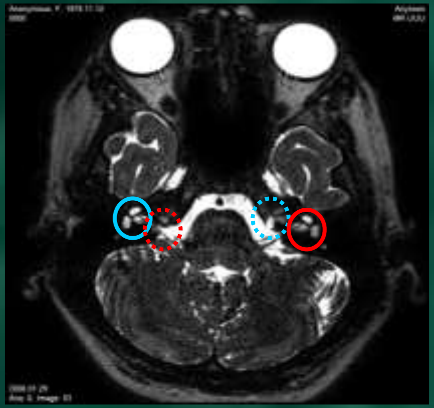
Small FOV

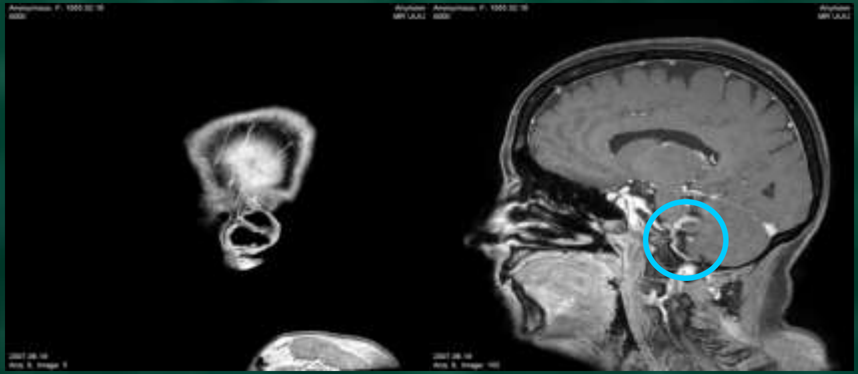
Large FOV



Not aliasing, folks!

Clinical Artifact Examples



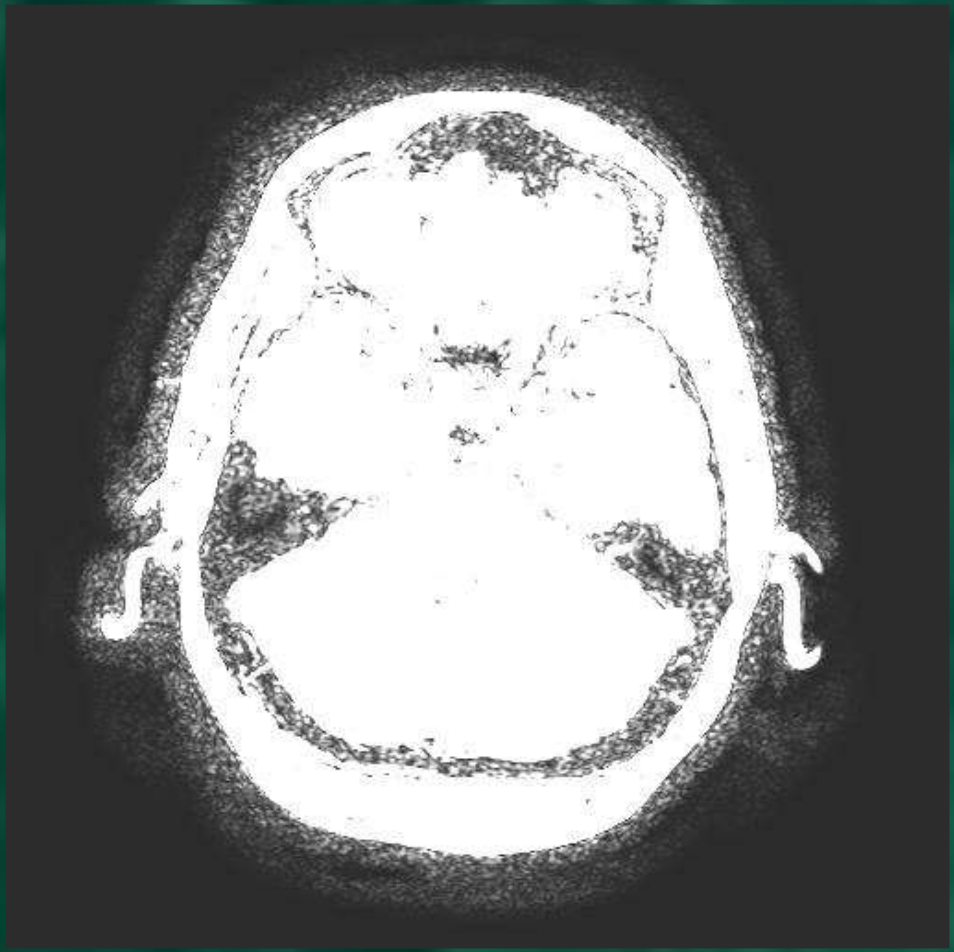


Pseudo-”failure” of fat sat: Patient moved between reference and SENSE scans

IAC structure ghosting

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

Clinical Artifact Examples



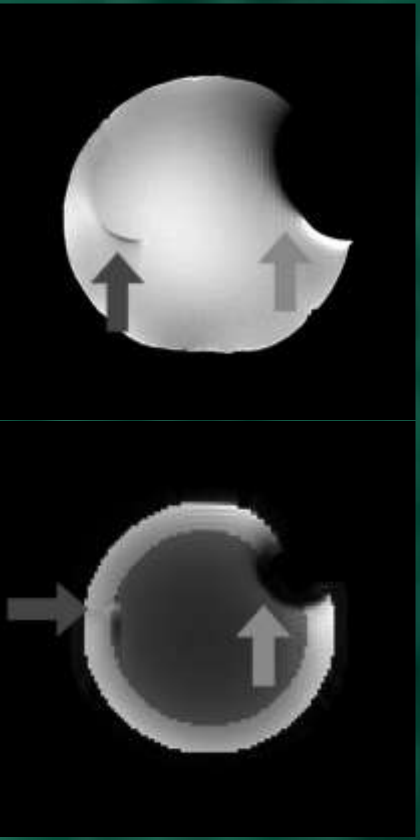
Thin, bright structures in the periphery of sensitivity map—mismatch between sensitivity and anatomy.

pMRI and Traditional Artifacts

Appearance of traditional artifacts may be modified by pMRI

Susceptibility (artifact not perfectly represented on sensitivity map)

phantom



simulation

Yanasak and Kelly, Radiographics, 2014 (in press)

When NOT to use pMRI?

- Regions near metal
- SNR-starved imaging
- Small FOV (non-auto-calibrated scans)
- Patients that move a lot
- Incapable of holding their breath.

Importance of pMRI

- Increases MR imaging speed
- Is applicable to all MRI sequences
- Is complimentary to all existing MRI acceleration methods
- Can often reduce artifacts
- Alters SNR in MR images

Application of pMRI

- pMRI offers the promise of high resolution MR imaging at speeds as fast as CT.
- Applications of parallel imaging include FSE, cardiac MR, diffusion and perfusion EPI brain imaging methods, 3D MRI (and MRA).
- Parallel imaging is tool for managing RF heating in the body at 3T and higher field strengths.
- Parallel imaging and dedicated RF coil design are enabling technologies for high B_o MRI.

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