Parallel Magnetic Resonance Imaging (pMRI): Implementations, Problems and Future

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Overview

- Quick Review
- Implementations of Parallel Imaging
- QA problems in Parallel Imaging
- QA solutions in Parallel Imaging
- Advanced Parallel Imaging and other reconstruction techniques

Parallel Imaging: What is it good for?

Faster acquisition time

Can be added to a majority of MR Protocols

Complementary to other acceleration methods

Cardiac Imaging

Perfusion and Diffusion Imaging

Parallel Imaging: How does it work?

Coil sensitivity profile found before or during acquisition

Multiple phased array coils acquire pieces of k-space

Pieces put together like a puzzle

Aliasing occurs

Coil sensitivity profile used to un-alias image

Parallel Imaging

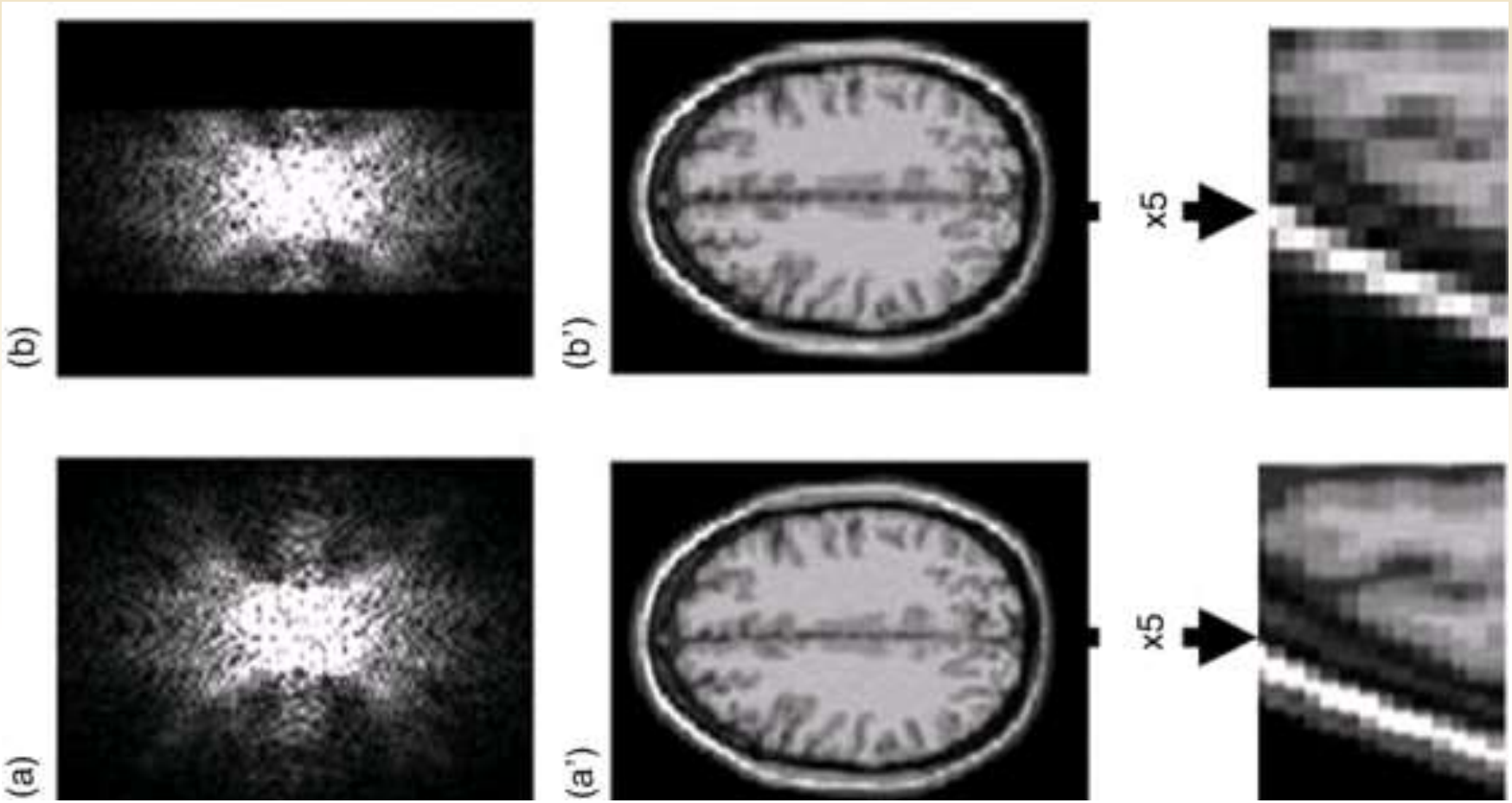
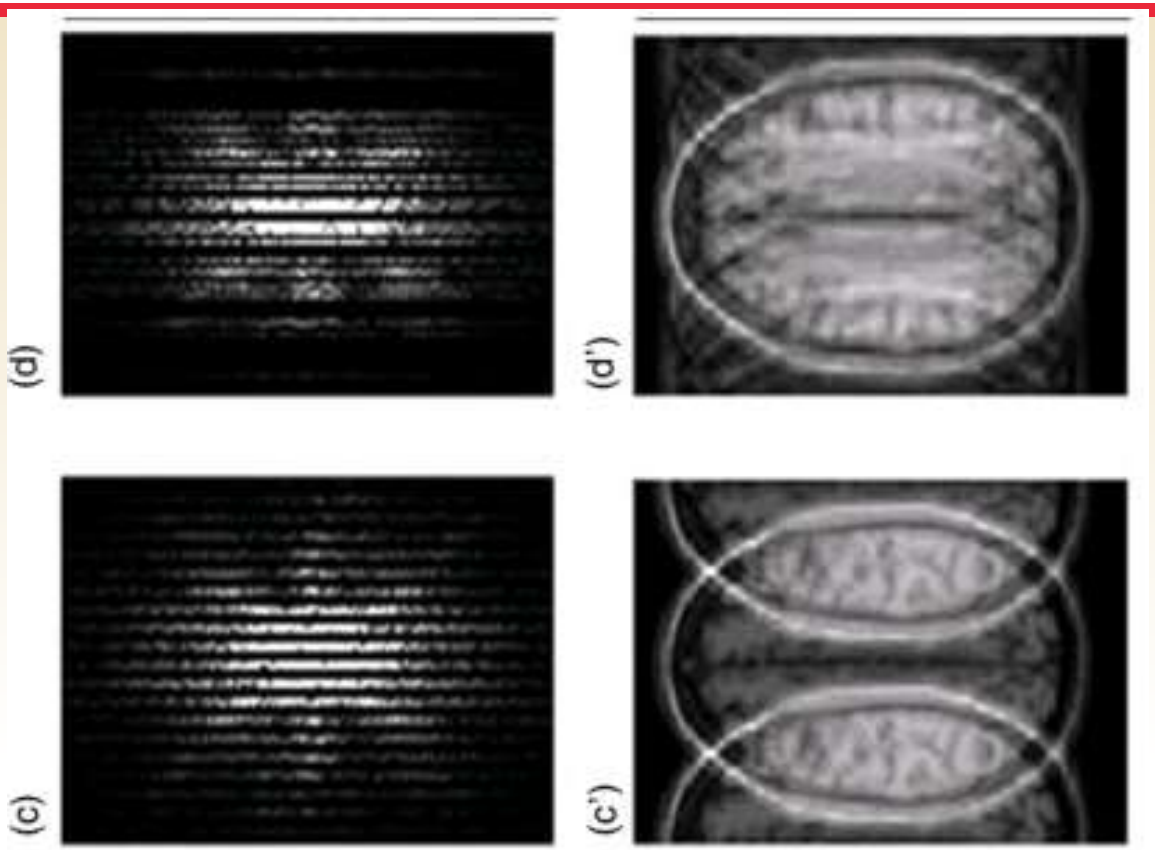


Image taken from: Larkman DJ, Nunes RG. Parallel magnetic resonance imaging. Phys Med Biol 2007 Apr;52(7):R15-55.

Parallel Imaging



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Parallel Imaging

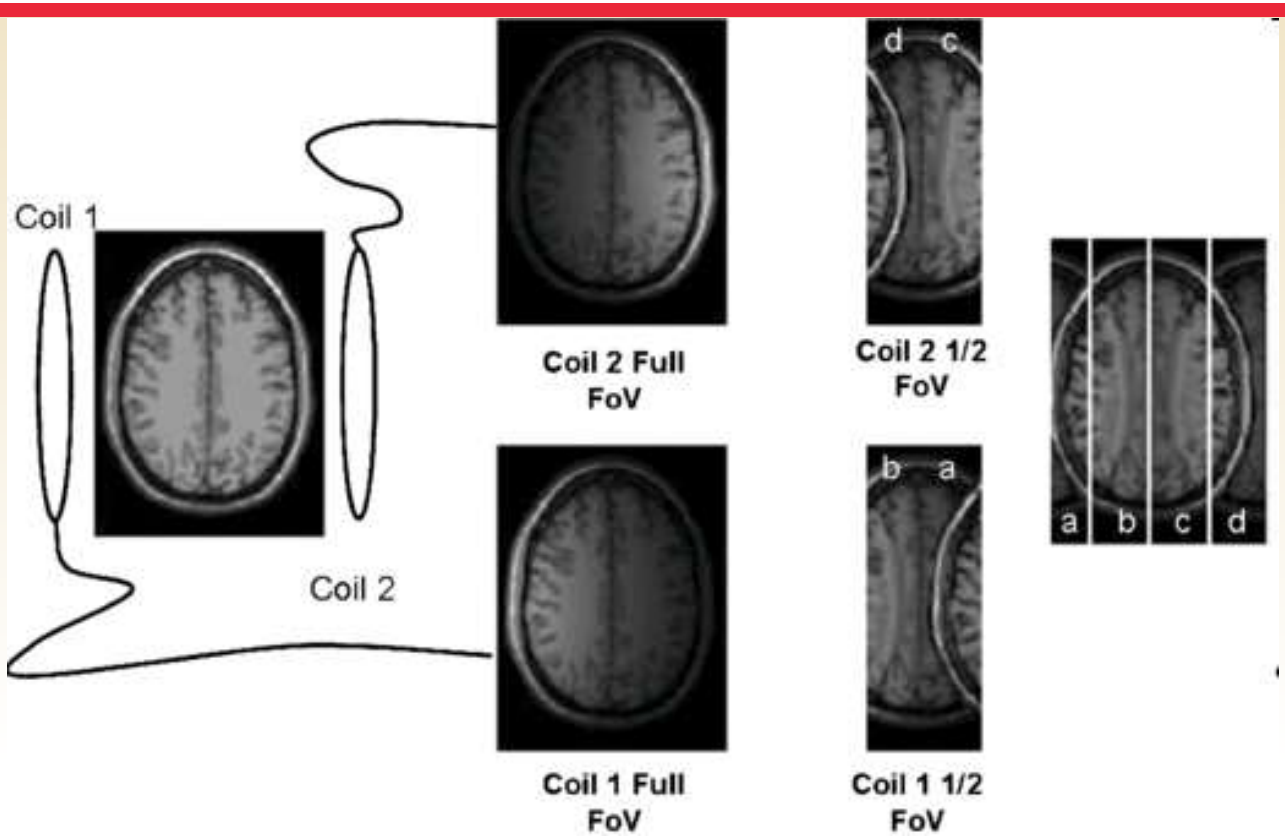


Image taken from: Larkman DJ, Nunes RG. Parallel magnetic resonance imaging. Phys Med Biol 2007 Apr;52(7):R15-55.

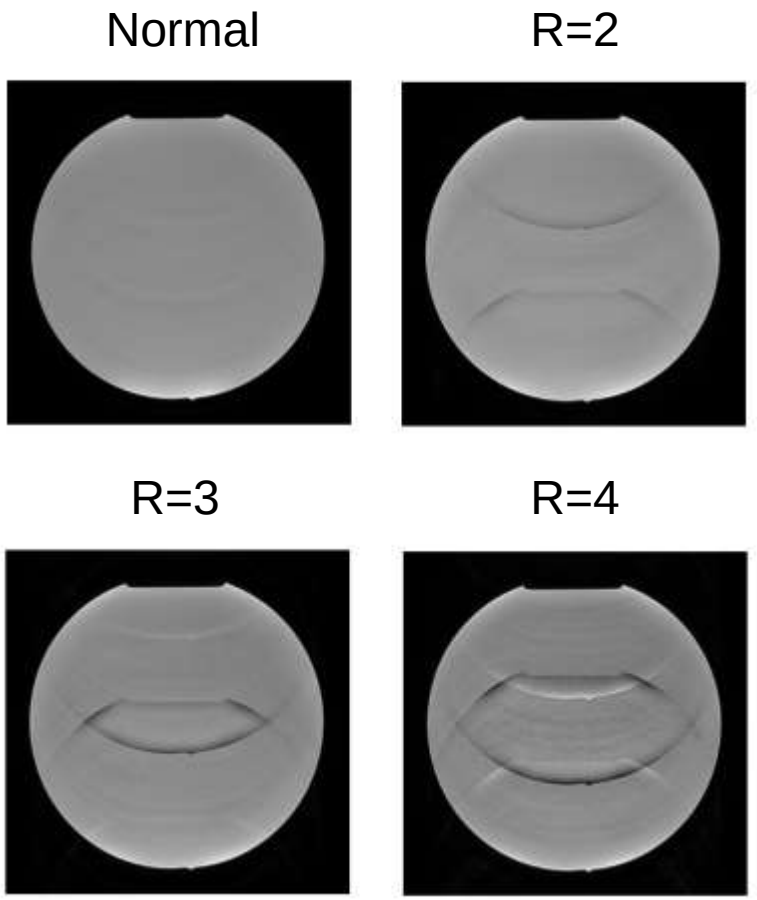
Parallel Imaging

Can provide faster acquisition times

R- the **reduction factor** is the factor that the acquisition time is reduced by

Trade-off is **reduced** signal to noise ratio **(SNR)** and an increase in residual aliasing artifacts

Typical R values are 2, 3, or 4



Artifacts with increased R for an FSE sequence with Parallel Imaging

pMRI Acronyms by manufacturer

Acronym	Manufacturer	Reconstruction Method	Calibration Method
GRAPPA	Siemens	k-space	Auto
mSENSE	Siemens	image space	Auto
SENSE	Philips	image space	Pre-scan
ASSET	GE	image space	Pre-scan
ARC	GE	k-space	Pre-scan
SPEEDER	Toshiba	image space	Pre-scan

g-factor

Introduced by Pruessman as a metric to indicate the decrease in SNR

Reduction achieved with coil sensitivity information

- Results in spatially varying noise and thus SNR
- g-factor accounts for this variation

g-factor varies with spatial position

- Useful images typically have a g between 1 and 2
- Difficult for clinical diagnostic physicist to obtain
- Requires knowledge of coil sensitivities

$$g = \frac{SNR_{R=1}}{SNR_R \sqrt{R}} \geq 1$$

Problem

Accurate SNR measurements difficult to obtain with Parallel Imaging implemented

Difficult to compare image quality across protocols and platforms

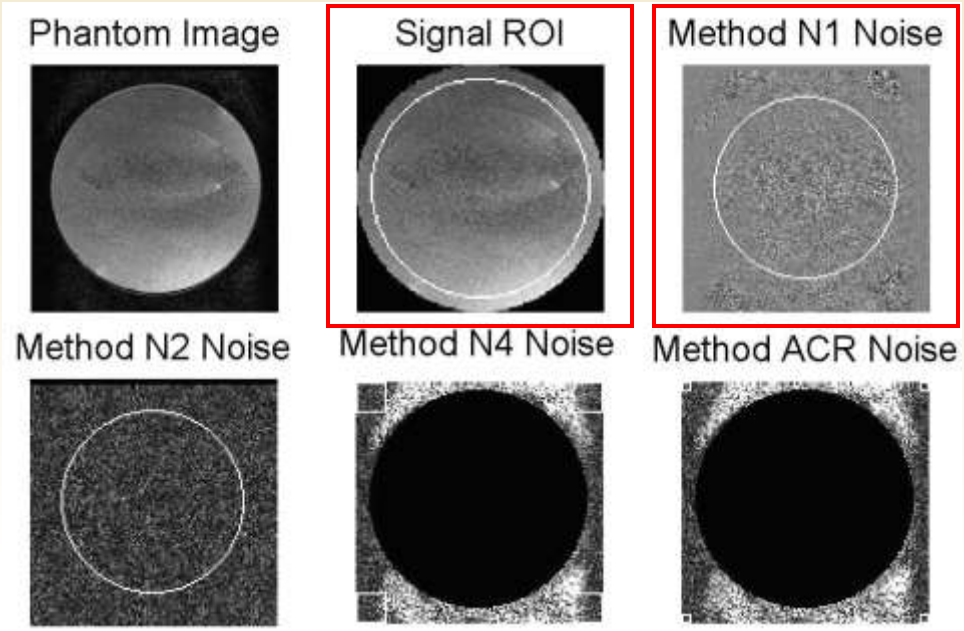
Most difficult to measure noise because it varies from pixel to pixel

$$SNR_R = \frac{SNR_{R=1}}{g\sqrt{R}}$$

SNR measurement Methods

NEMA method 1: Image subtraction

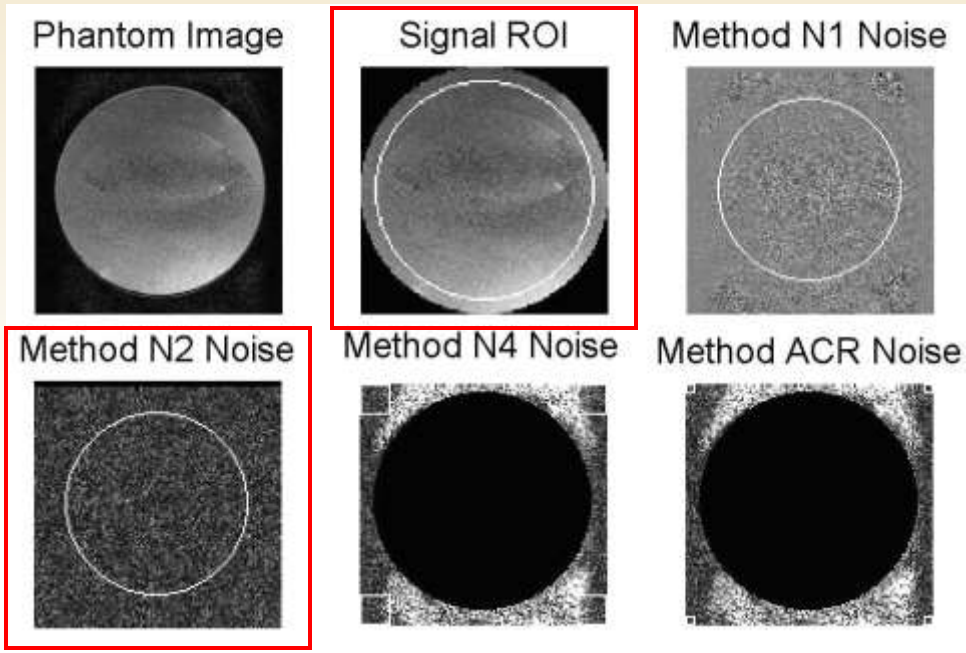
- Signal: 80% average signal ROI
- Noise: 80% SD ROI of subtracted images



SNR measurement Methods

NEMA method 2: No signal image

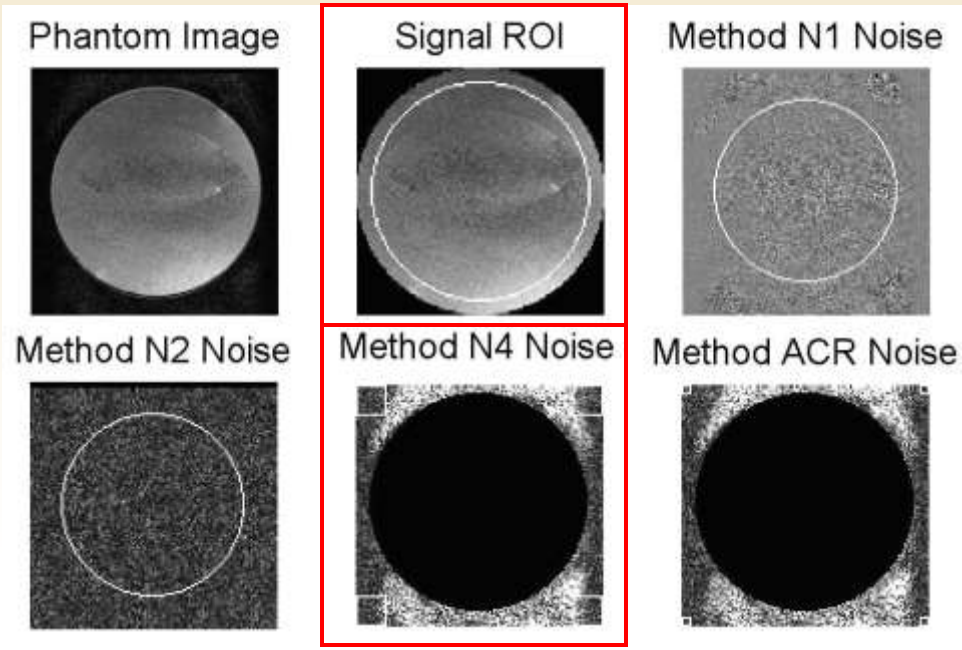
- Signal: 80% ROI
- Noise: 80% SD ROI of no signal image



SNR measurement Methods

NEMA method 4: SD of background

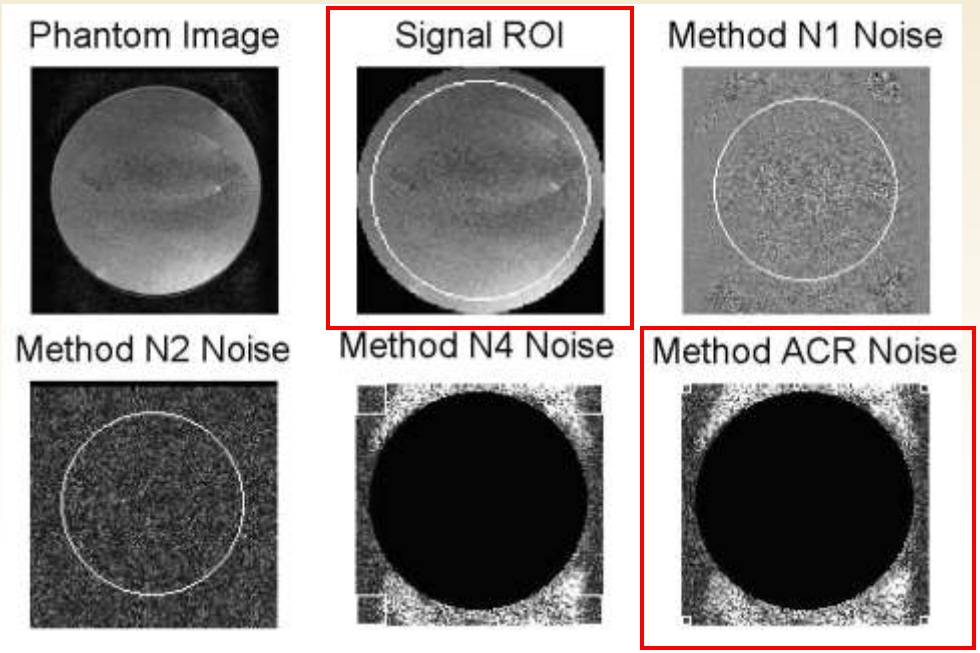
- Signal: 80% ROI
- Noise: SD of 1000 pixels from background/0.66



SNR measurement Methods

ACR method: SD of smaller background portion

- Signal: 80% ROI
- Noise: SD of 50 pixels from background portion of image



Sequences Compared

Turbo Spin Echo (TSE)

- T_2 weighted images

Echo Planar Imaging (EPI)

- Functional MRI studies

Balanced Steady State Free Precession (TruFISP)

- Cardiac imaging

Data Collection & Analysis

Each sequence was taken with two methods of auto calibrated parallel imaging at R=2,3 and 4

- mSENSE: image based recon
- GRAPPA: k-space based recon

Three acquisitions per protocol

$$g = \frac{SNR_{R=1}}{SNR_R \sqrt{R}} \geq 1$$

- 2 for image subtraction
- 1with RF voltage set to 0 V, for no signal method

Each SNR method implemented

- g-factor calculated for each method
- Best method should maintain g-factor>1 for R=2,3 and 4

Results

g-factor ≥ 1

Average of all sequences

- NEMA 1: **2.01** ± 0.70
- NEMA 2: 0.64 ± 0.22
- NEMA 4: 0.81 ± 0.31
- ACR: 0.64 ± 0.22

GRAPPA					
R	M100	N1	N2	N4	ACR
2	0.99 ± 0.01	1.08 ± 0.02	0.58 ± 0	0.59 ± 0.02	0.58 ± 0.04
3	1.15 ± 0.01	1.31 ± 0.02	0.44 ± 0	0.4 ± 0.01	0.38 ± 0.03
4	1.76 ± 0.03	2.06 ± 0.03	0.35 ± 0	0.38 ± 0.01	0.35 ± 0.02

mSENSE					
R	M100	N1	N2	N4	ACR
2	1.04 ± 0.12	1.13 ± 0.19	0.81 ± 0.05	0.9 ± 0.09	0.89 ± 0.07
3	1.24 ± 0.03	1.4 ± 0.13	0.83 ± 0.06	0.9 ± 0.08	0.9 ± 0.08
4	1.92 ± 0.04	2.28 ± 0.35	0.88 ± 0.11	0.93 ± 0.13	0.92 ± 0.09

Data taken from: Goerner FL, et al. Signal-to-noise ratio in parallel imaging MRI**. Med Phys 2011 Sept;38(9)**

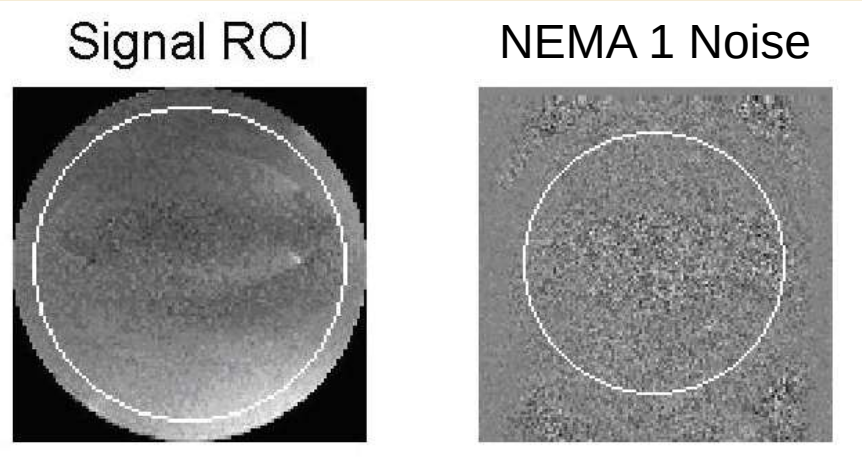
Conclusions

NEMA 1: is the only method maintaining g>1

- g=1.61 ± 0.62

The ACR method consistently results in g<1

- g=0.44 ± 0.31



- Recommendation: To compare SNR protocols using parallel imaging, the image subtraction method should be used

Uniformity

NEMA method 1 (UN1):

- Peak deviation non-uniformity

NEMA method 2 (UN2):

- Gray Scale Uniformity Map

NEMA method 3 (UTTT):

- Tic Tac Toe Method

ACR Method (UACR):

- Percent Image Uniformity

NAAD (UNAAD):

- Normalized Absolute Average Deviation

Uniformity: UACR

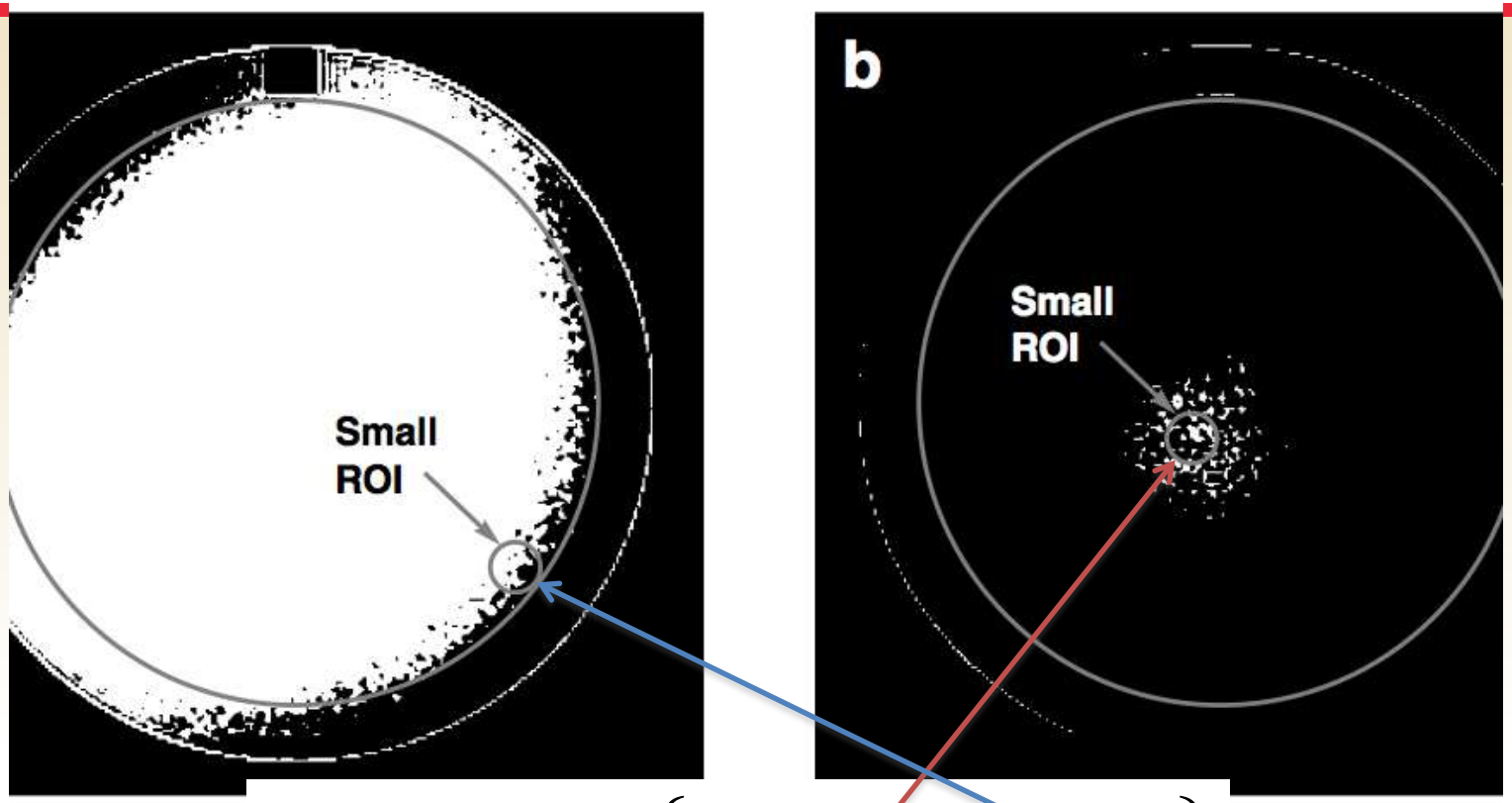
UACR: Percent Image Uniformity

- Two ROI's encompassing 0.15% of the phantom volume (S_{max} & S_{min})
- S_{max}- area of greatest signal intensity
- S_{min}- area of lowest signal intensity

$$UACR = 100\left\{1 - \frac{(S_{\max} - S_{\min})}{(S_{\max} + S_{\min})}\right\}$$

- Higher number indicates greater uniformity

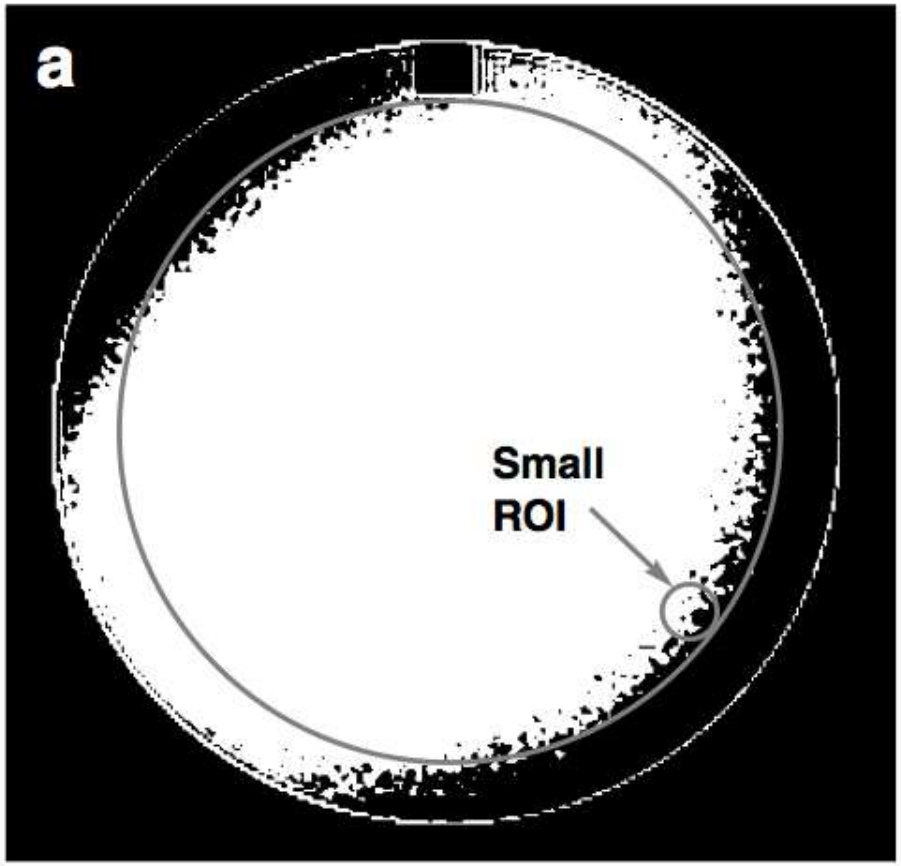
Uniformity: UACR



$$UACR = 100\left\{1 - \frac{(S_{max} - S_{min})}{(S_{max} + S_{min})}\right\}$$

Image taken from: ACR MRI Quality Control Manual 2004

Uniformity: UN1



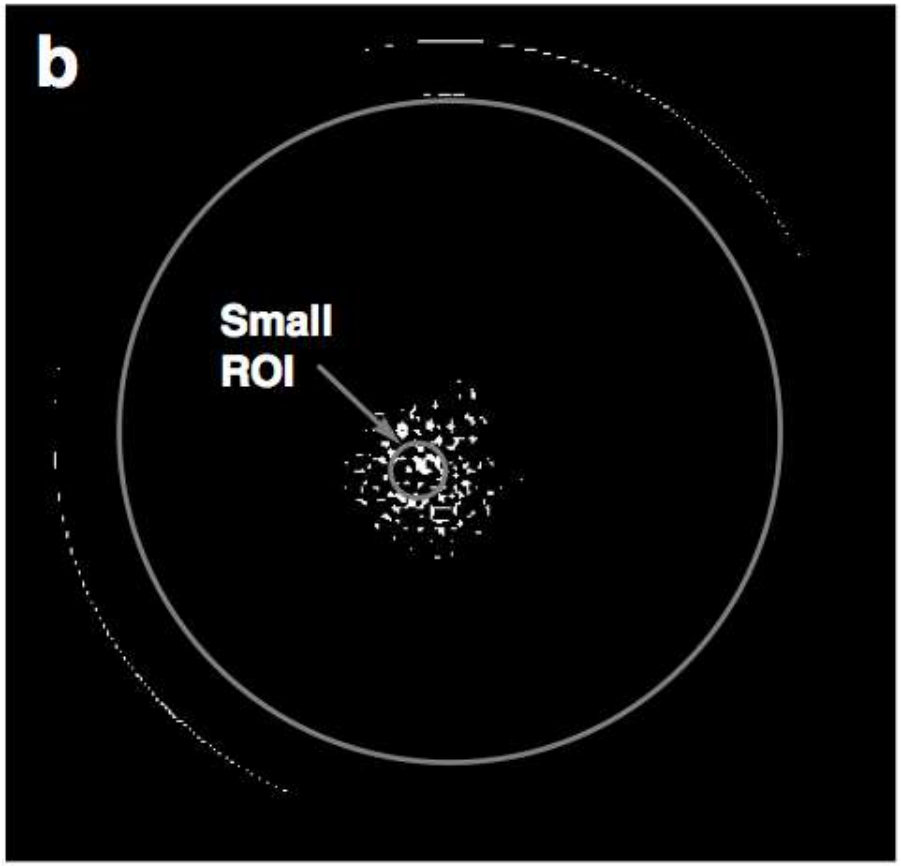


Image taken from: ACR MRI Quality Control Manual 2004

Uniformity

UN2: Gray Scale Uniformity

- Take the mean (m) from a 75% ROI
- Reassign pixel values (pv) according to difference from mean
  i. -10%<pv<10% neutral
  ii. 10%<pv<20% next brighter grey level
  iii. -20%<pv<-10% next darker grey level
  iv. pv>20% white
  v. pv<-20% black

Uniformity: UN2

- Provides visual uniformity map
- For numerical comparison
- Group number found by taking total number of pixels in that group and dividing by total number of pixels

Group 1

i. 10%<pv<20%

ii. -20%<pv<-10%

Group 2

iii. pv>20%

iv. pv<-20%

$$UN2 = 100(1 - (0.5 \cdot Group_1 + Group_2))$$

Uniformity

UNAAD

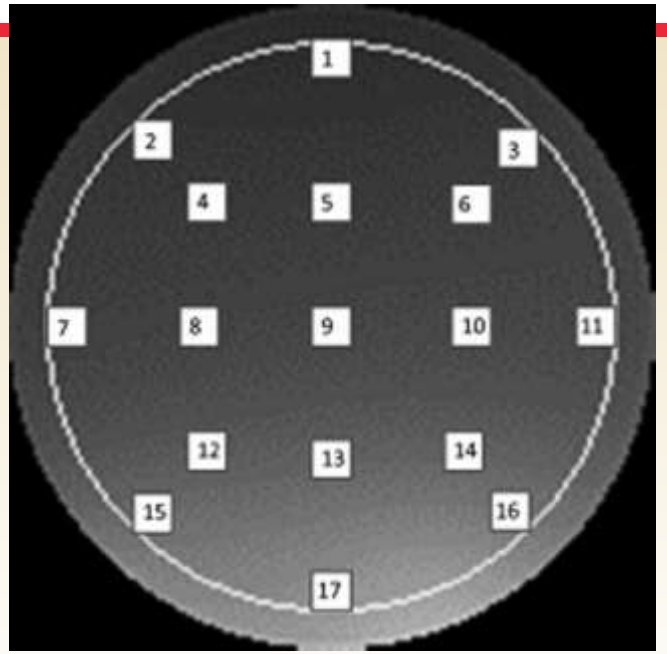
- Take a 75% ROI and find the average pixel value $(\overline{Y})$

$$UNAAD = 100\left(1 - \frac{1}{N \cdot \overline{Y}} \sum_{i=1}^{N} \left| Y_i - \overline{Y} \right|\right)$$

- Where Y_i is individual pixel value and N is the total number of pixels

Uniformity

UTTT: Tic Tac Toe Method



- S_{18}- mean of 75% ROI
- 17 small 7x7 pixel ROI's
  - 9 in a tic-tac-toe pattern
  - 4 in the corners of the image
  - 4 in the middle edge of each side
- S_n- mean of small ROI
- n- ROI number

$$UTTT = 100 \times \left(1 - \frac{\sum_{n=1}^{17} \frac{|S_n - S_{18}|}{|S_n + S_{18}|}}{17 - 1}\right)$$

Image taken from: Goerner FL, et al. A comparison of five standard methods for evaluating image intensity uniformity in partially parallel imaging MRI**. Med Phys 2013 Aug;40(8)**

MRI Phantom

Phantom: Soccer ball provided by AAPM TG#118

- 19 cm outer diameter, 16.6 cm inner diameter
- filled with 5.45 g NaCl (99.99% pure) and 5.29 mL of Magnevist per 1 L distilled water
- Total volume: 2415 mL

Materials and Methods

Pulse Sequences

- Echo planar imaging (EPI)
- Fast Low Angle SHot (FLASH)
- True Fast Imaging with Steady-state Precession (Tru-FISP)
- Turbo Spin Echo (TSE)

Variables

Two methods of reconstruction

- GRAPPA- k-space based
- mSENSE- image space based

Varied R-values: 2,3,4

Varied phase encode:

Axial: AP and RL

MRI Protocols

FOV=220 mm

1 mm slice gap

5 mm slice thickness

256x256 matrix size

5 slices

Sequence	TR (ms)	TE (ms)	BW Hz/pixel
EPI	1840	187	752
FLASH	175	4	240
Tru-FISP	6.88	3.44	244
TSE	1200	76	122

Analysis

Linear fits for R-value vs. Uniformity

- Average slopes

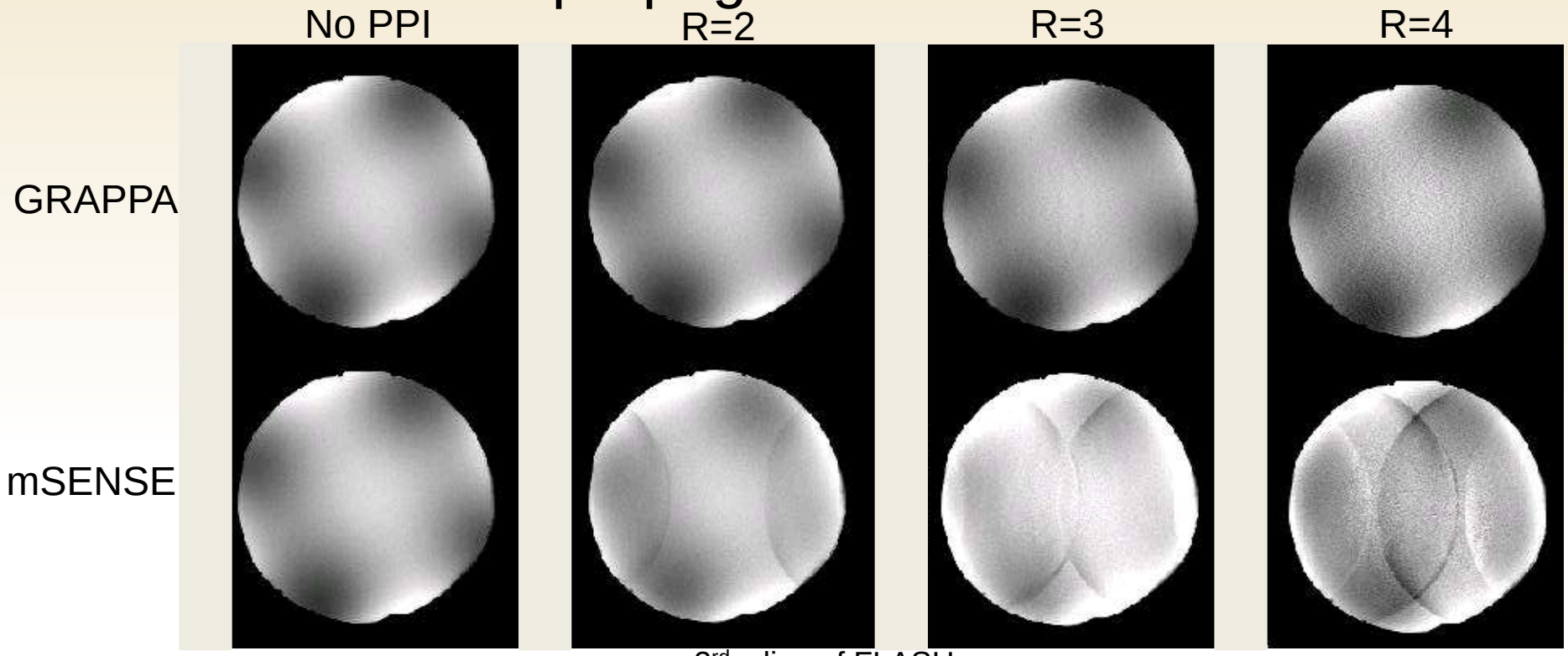
Two way ANOVA- R-value vs.

- Reconstruction method
- Pulse sequence
- PE direction

Noise Propagation Artifact

Decrease in uniformity with increasing R-value

Increase in noise propagation with mSENSE

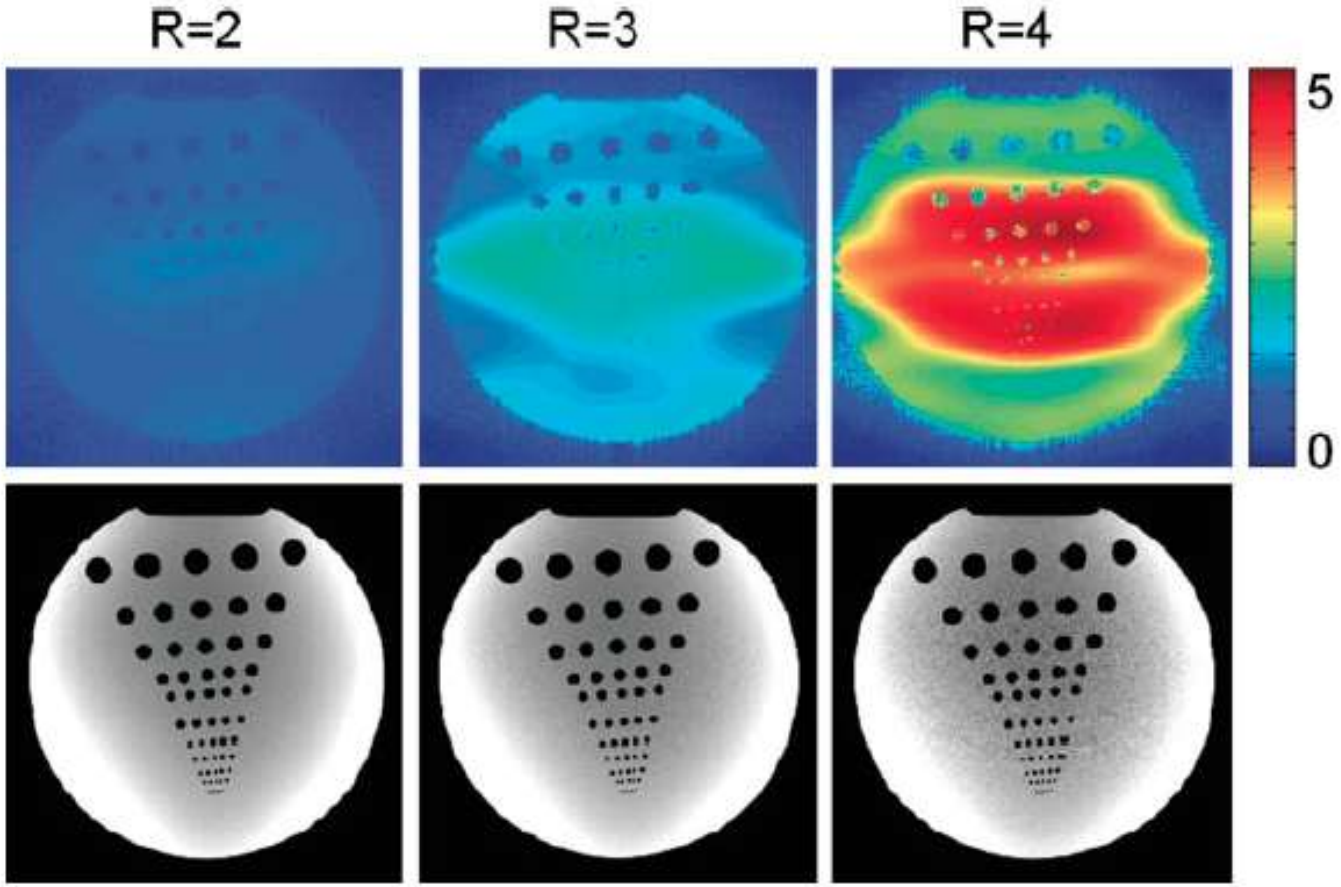


3rd slice of FLASH sequence

Image taken from: Goerner FL, et al. A comparison of five standard methods for evaluating image intensity uniformity in partially parallel imaging MRI**. Med Phys 2013 Aug;40(8)**

g-factor map changes

With increase in R
Decrease in uniformity



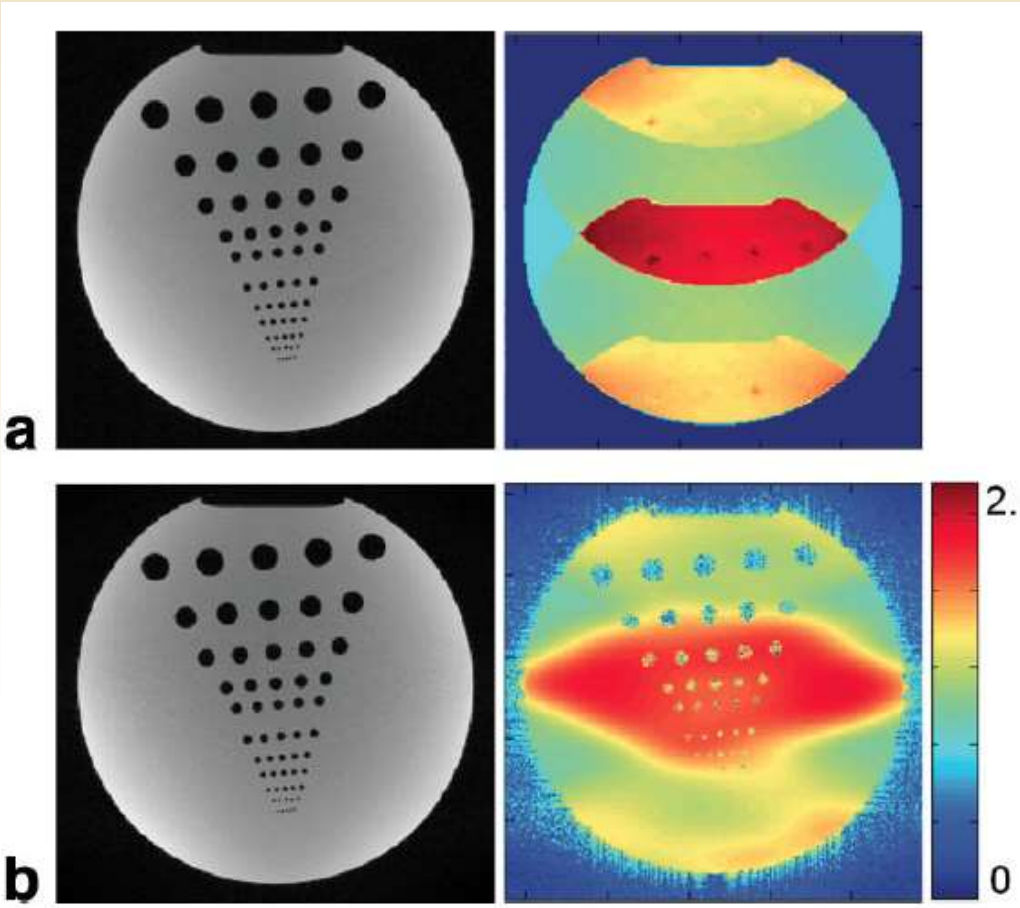
Images from: Breuer FA, et. al. “General Formulation for Quantitative G-factor Calculation in GRAPPA Reconstructions” MRM (2009) 62:739-746

g-Factor maps

a- mSENSE (image space)

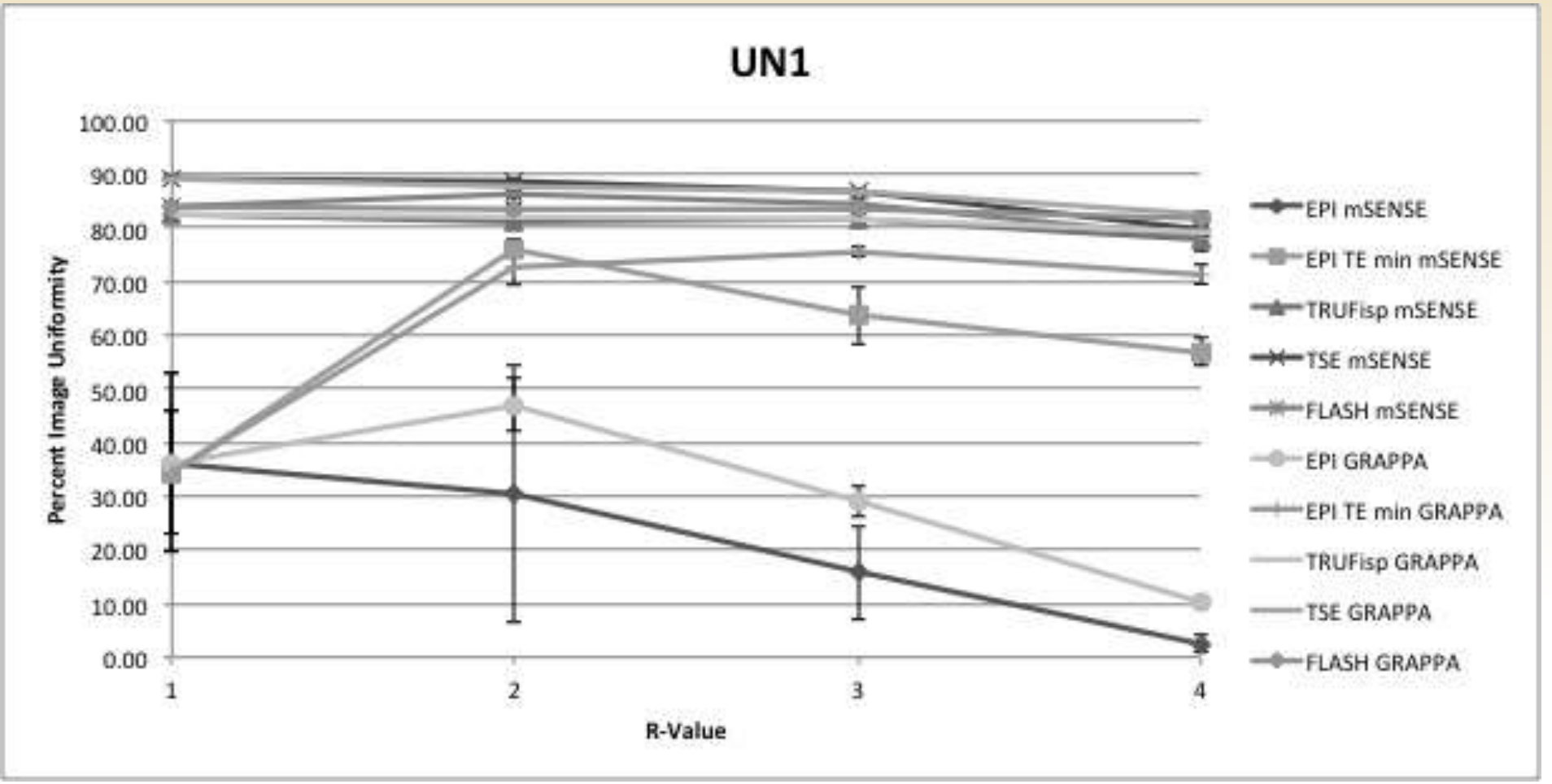
b- GRAPPA (k-space)

Arguably worse uniformity with mSENSE



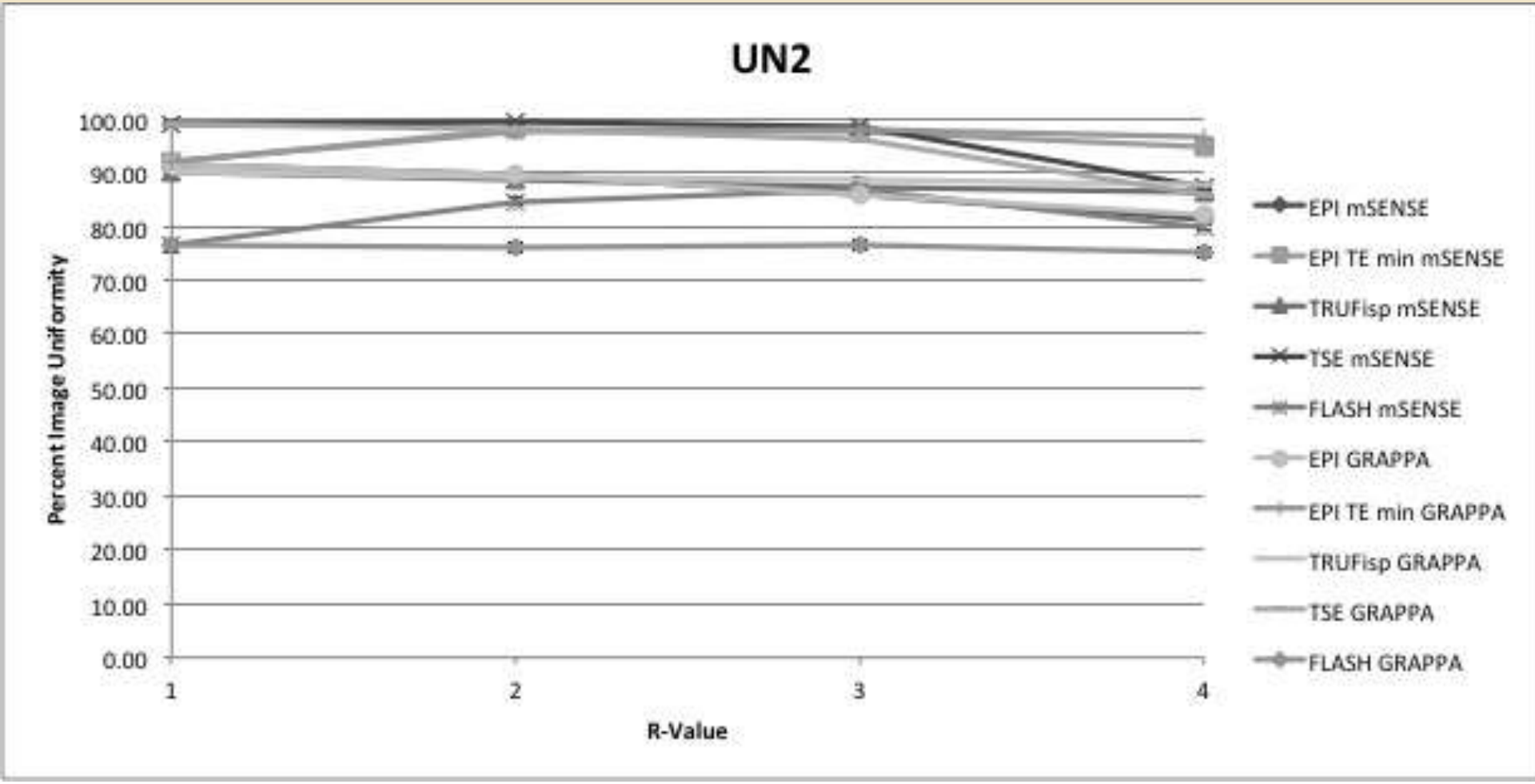
Images from: Breuer FA, et. al. “General Formulation for Quantitative G-factor Calculation in GRAPPA Reconstructions” MRM (2009) 62:739-746

UN1: Average Slope -4.0±4.2



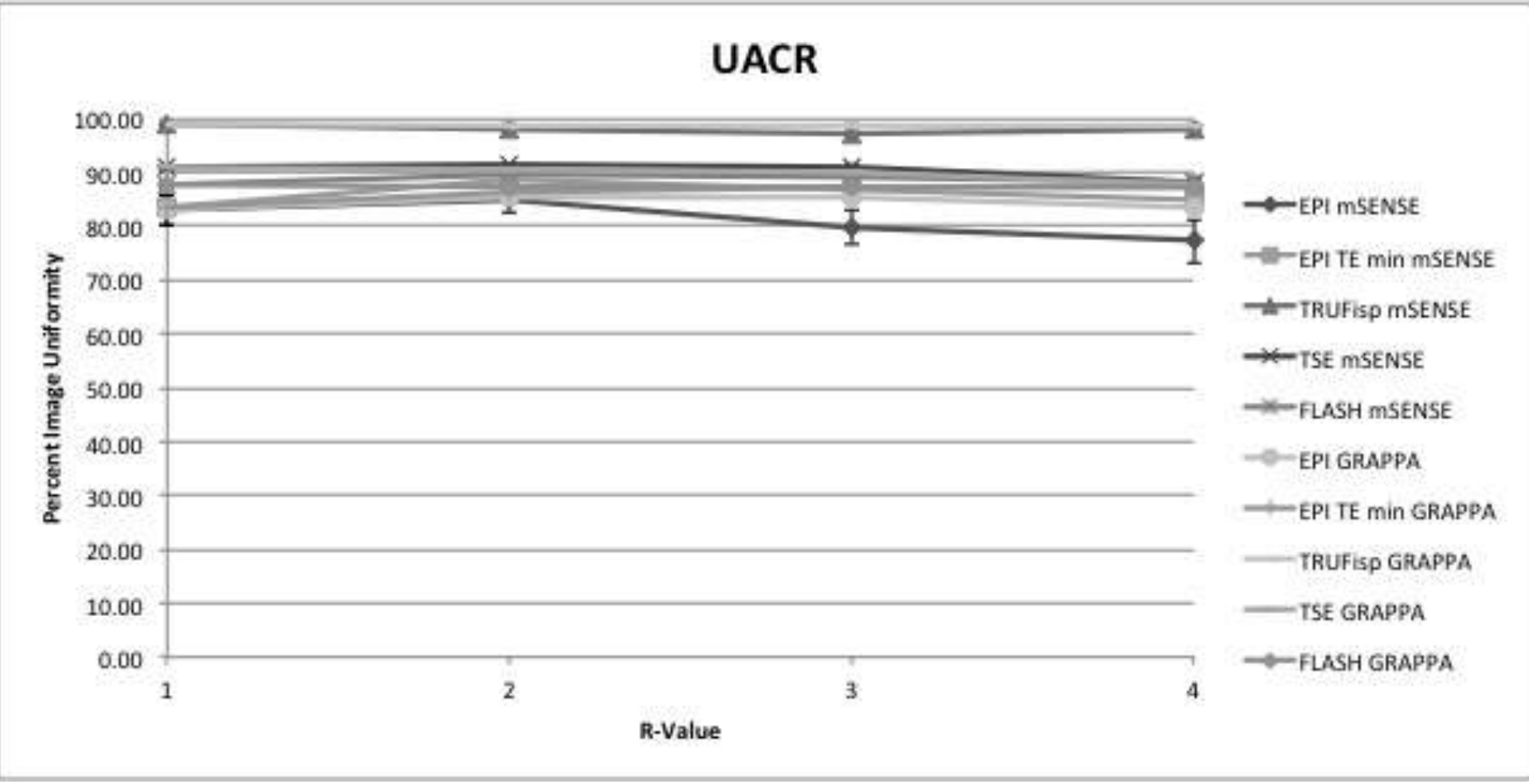
Graph taken from: Goerner FL, et al. A comparison of five standard methods for evaluating image intensity uniformity in partially parallel imaging MRI**. Med Phys 2013 Aug;40(8)**

UN2: Average Slope -1.03±1.4



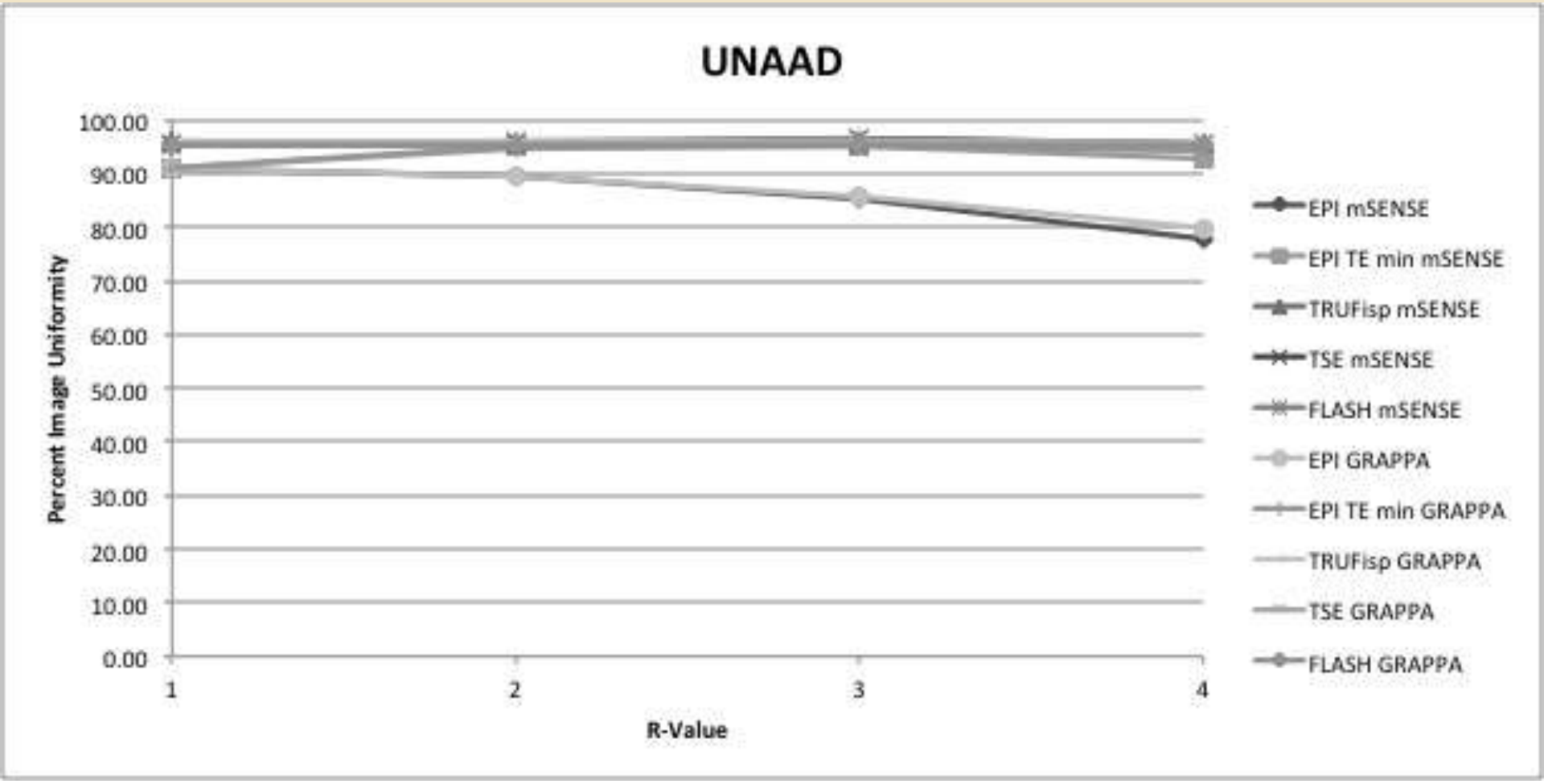
Graph taken from: Goerner FL, et al. A comparison of five standard methods for evaluating image intensity uniformity in partially parallel imaging MRI**. Med Phys 2013 Aug;40(8)**

UACR: Average Slope -0.50±0.82



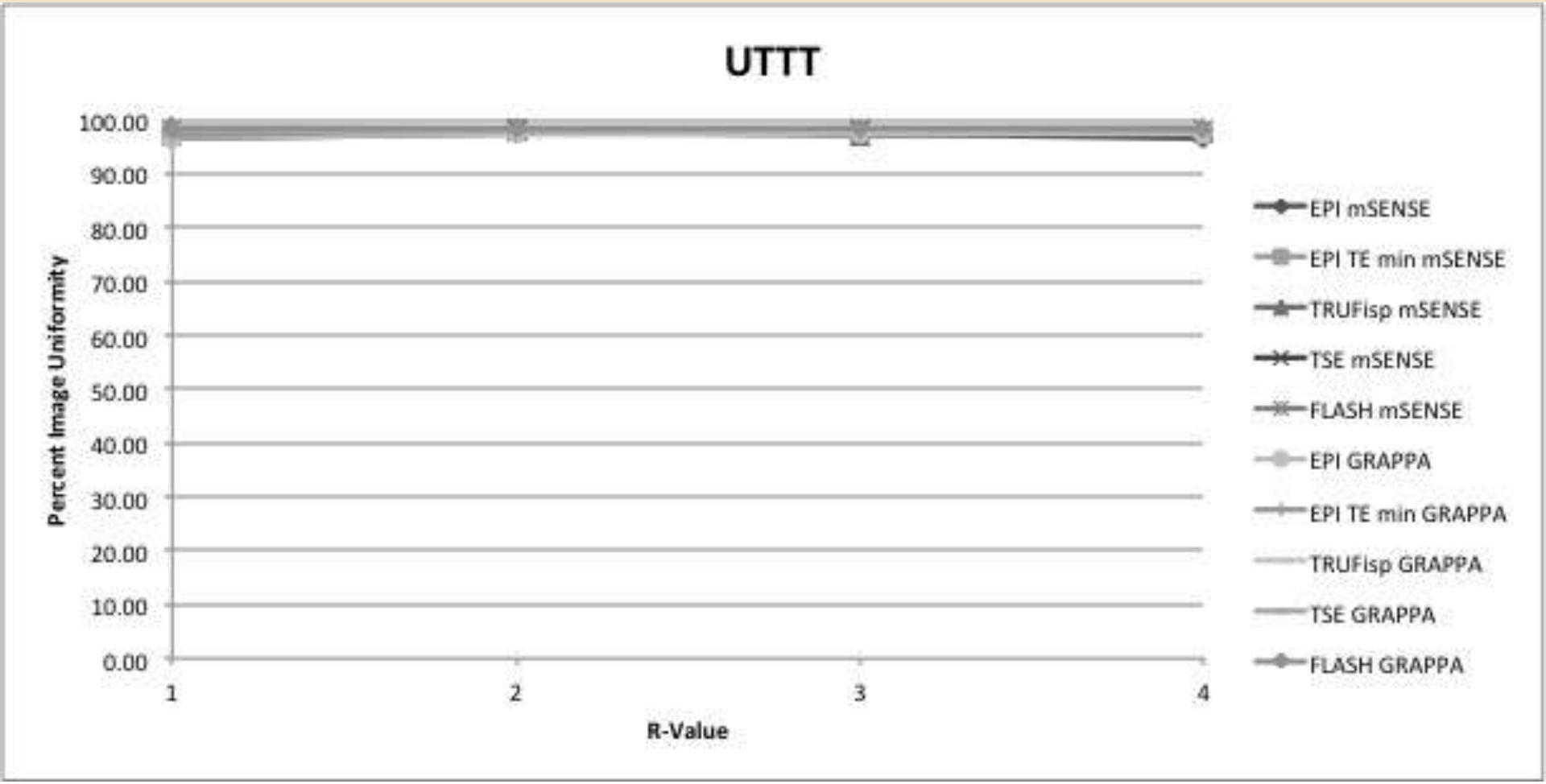
Graph taken from: Goerner FL, et al. A comparison of five standard methods for evaluating image intensity uniformity in partially parallel imaging MRI**. Med Phys 2013 Aug;40(8)**

UNAAD: Average Slope 1.02±1.8



Graph taken from: Goerner FL, et al. A comparison of five standard methods for evaluating image intensity uniformity in partially parallel imaging MRI**. Med Phys 2013 Aug;40(8)**

UTT: Average Slope: 0.004±0.2



Graph taken from: Goerner FL, et al. A comparison of five standard methods for evaluating image intensity uniformity in partially parallel imaging MRI**. Med Phys 2013 Aug;40(8)**

Conclusions

UN1 and UN2 were more likely to have negative slopes (-4.0 and -1.2)

UN1 only uses two pixels and is sensitive to SNR

UN2 is difficult to measure clinically

There isn't really a good Uniformity measurement to characterize multi-channel coils and parallel imaging protocols.

Advanced/Upcoming Techniques

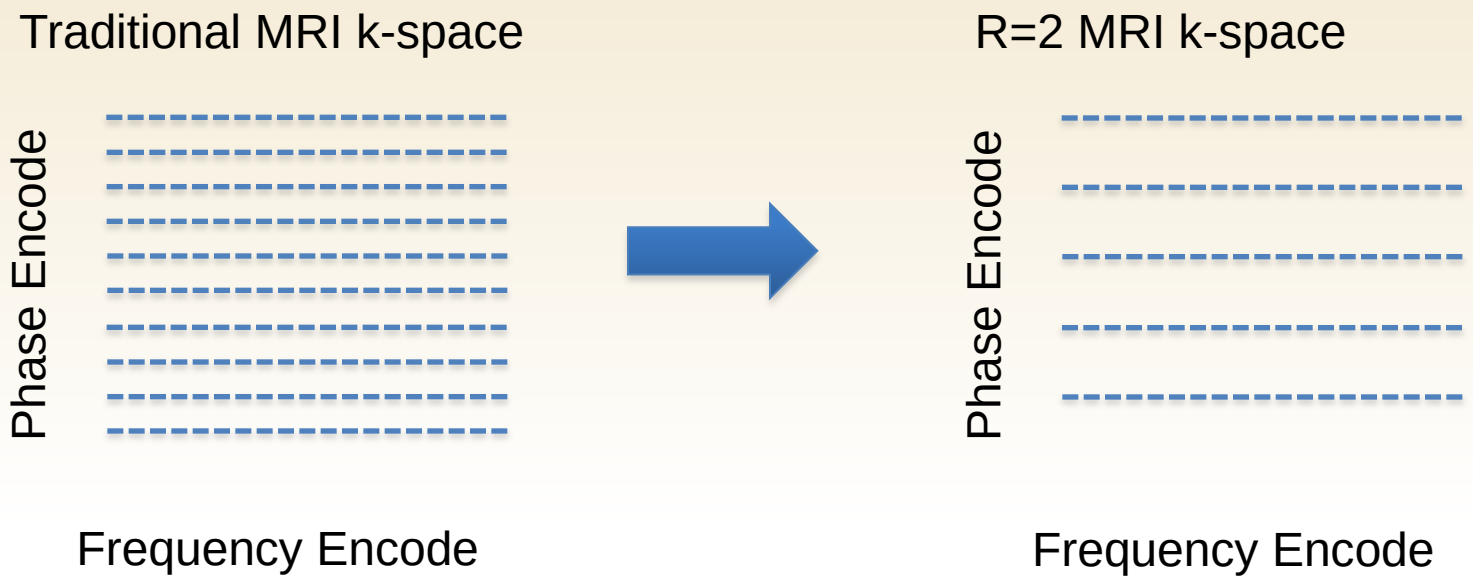
Parallel imaging in 2 directions

CAIPIRINHA

Compressed Sensing

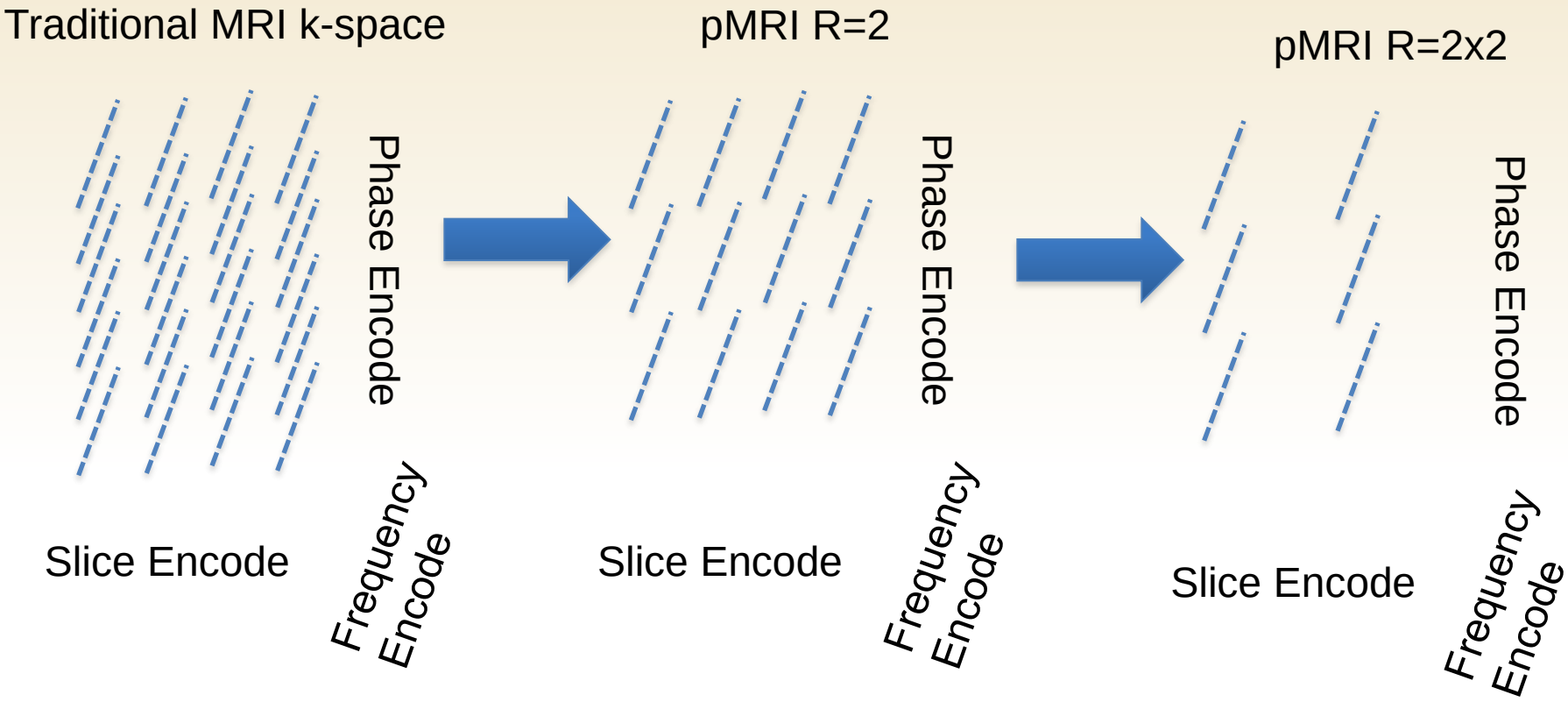
Parallel imaging 2 Directions

Current method- Reduce number of PE steps



Parallel imaging 2 Directions

Current method- Reduce number of PE steps



2 direction Parallel imaging

If R=2x2

Every other Phase Encode line is eliminated

Every other Slice Encode line is eliminated

Acquisition time reduced by 4x

Experimental techniques involve other trajectories not parallel to Phase or Slice encoding directions.

CAIPIRINHA

First seen in 1918 in Sao Paulo Brazil

Now the National Drink of Brazil

Ingredients:

50 ml Cachaca

½ Lime (cut into four wedges)

2 teaspoons refined sugar

Short for: Controlled aliasing in parallel imaging results in higher acceleration

CAIPIRINHA: The Quest

CAIPIRINHA

Controlled aliasing in parallel imaging results in higher acceleration

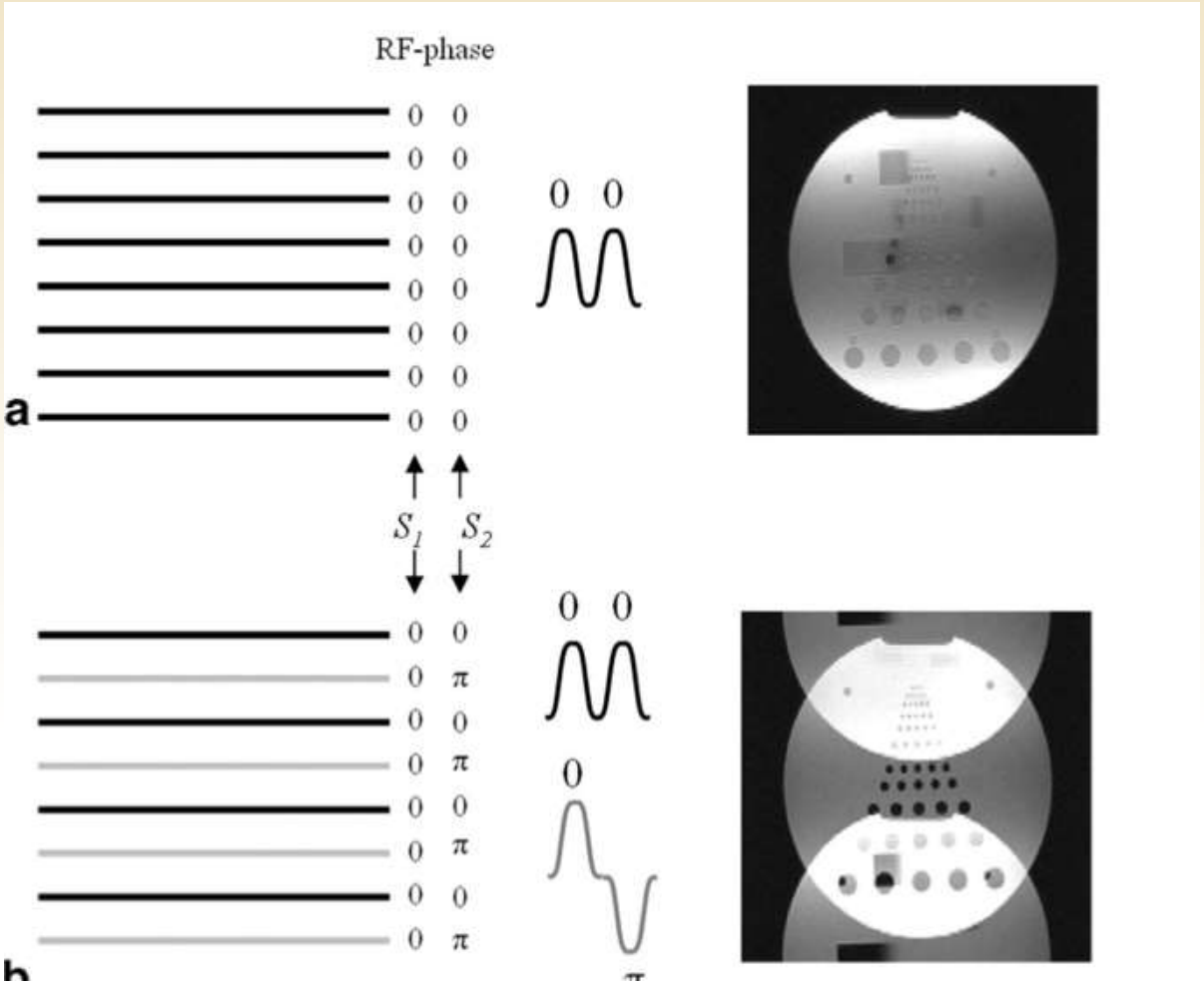
Multiple slices excited at once

Phase encode is shifted with respect to other slices

Creates a shift in aliasing artifact

Potentially results in increased SNR, more R-values, fewer artifacts

Multiple Slice Excitation



Clinical Example

3D VIBE Liver

Without pMRI

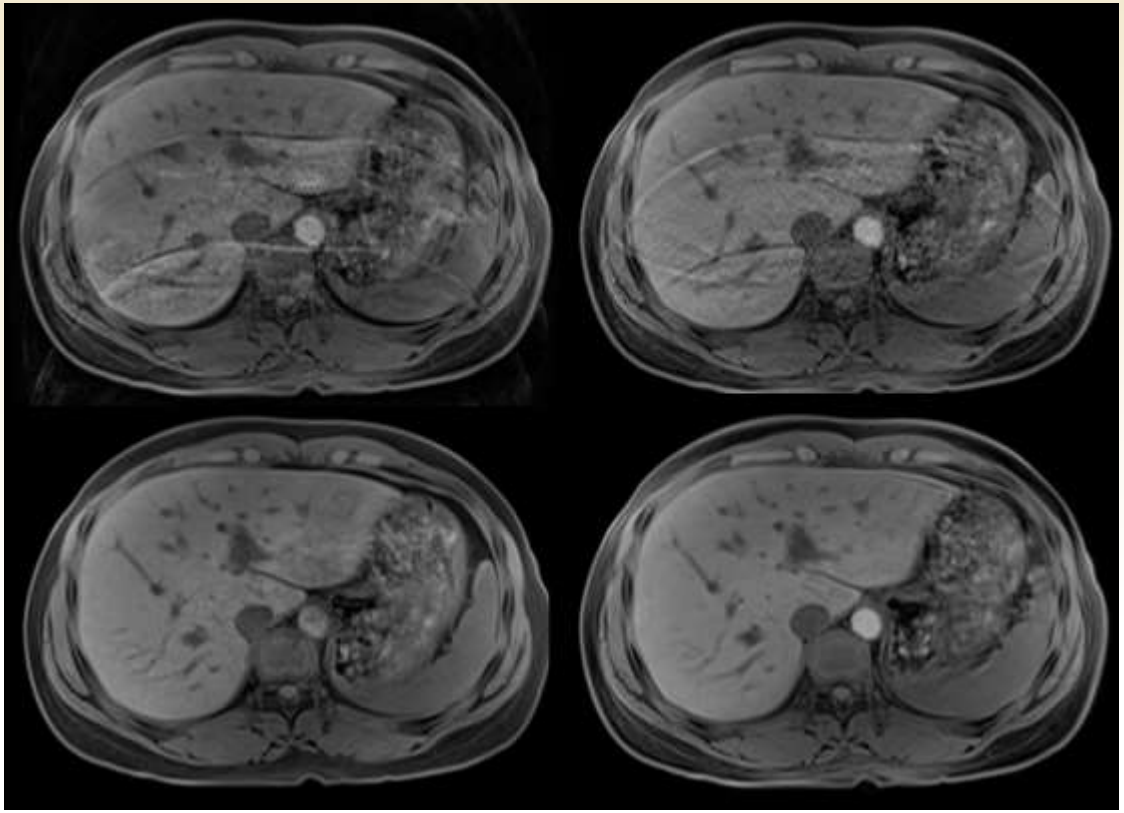
Acq Time= 43 seconds

With R=4

Acq Time = 17 seconds

With R=2x2

Acq Time = 11.4 seconds



Compressed Sensing

Similar concept to Parallel Imaging

- Take less data

Different from Parallel imaging

- Try to figure out what data you don't need and don't acquire it

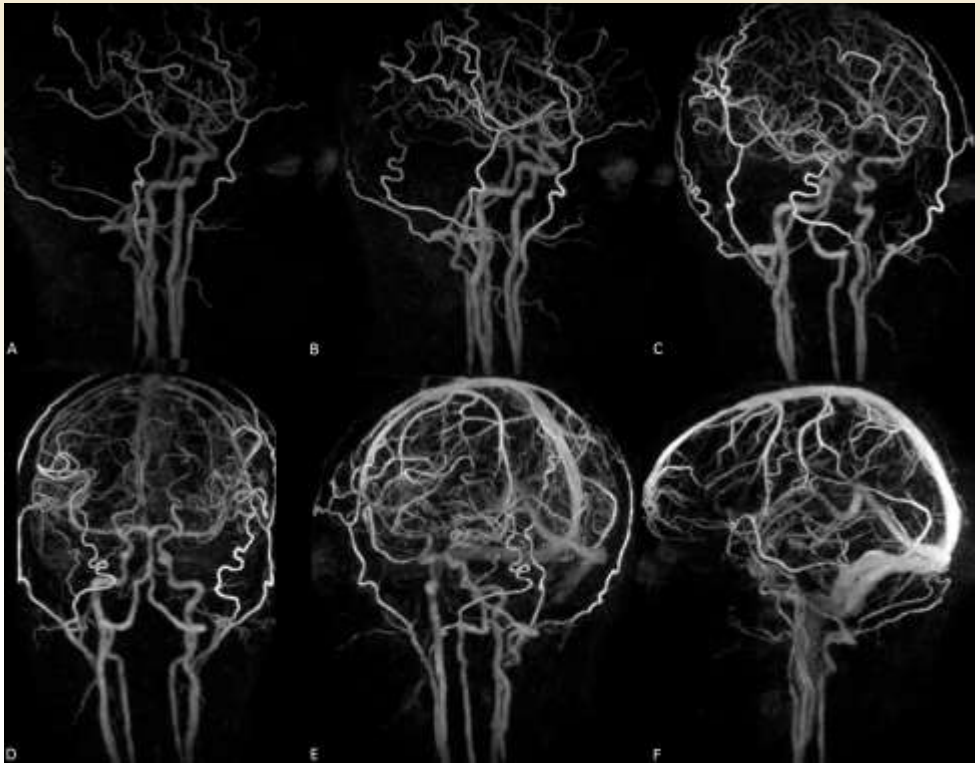
JPEG images are compressed around 14x because of a lot of the information is similar. Compressed sensing works similarly.

Requires a lot of processing power!

Compressed Sensing

illustrates 6 sequential, time-resolved MIP acquisitions during a contrast enhanced MR angiogram also acquired at 3T using a 32-channel head coil.

Courtesy of Mark Griswold, Cleveland, OH



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