REDUCING SEDATION & ANESTHESIA IN PEDIATRIC MRI

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Conflicts of Interest: none

Acknowledgment

The Compressed Sense images were acquired and shared with me by Jean Tkach, Ph.D. clinical MR scientist at Cincinnati Children’s Hospital

Background

- Acute risks from sedation & general anesthesia (S/GA) in pediatrics*
  - Cardiorespiratory depression
  - Upper-airway obstruction
  - Hypoventilation
  - Hypoxia (most common side effect**)
  - Hypotension
  - Post-sedation nausea, vomiting, disorientation, sleep disturbance and nightmares

**Arlachov BJR 2012 85(1019): e1018-31*
***Horton US Pharm 2008 33(3):HS2-HS8*

Background

- Long term effects (mixed results)
  - Intelligence quotient and attention/executive functioning deficits*
  - No long term effect (5 yr follow up) found for S/GA in preemies**
  - FDA warning (12-14-2016): negative effects on developing brain
- Removing the discussion of side effects
  - S/GA incurred the greatest cost and had the longest visit duration***
  - Most MR schedules have substantial backlog
  - Quicker imaging is generally results in better imaging

**Zellem et al. pediatr crit care med 2014 15(3):189-96*
***Roze et al JAMA 2018 162(8): 728-33*
****Vanderby et al. Radiology 256(1):229-237*

Patient Preparation

- Child life coaching patients
  - Preparation videos
    - Patients/parents see the department and the MR experience before beginning screen process
    - Minimize nervousness
  - Mock scanner
    - Simulates sounds
    - Simulate claustrophobic scenario
    - Review patients ability to lie still

Courtesy: Nathan Artz, PhD St Jude Children's Res. Hosp.

Approaches to Reduce Sedation/GA

- Distractions-videos, music, light shows, parents involvement, etc.
- Noise-reduction
- Feed-and-bundle techniques
- Free-breathing acquisitions
- Sparse imaging algorithms
- Motion compensation algorithms
  - Gross motion
  - Cardiac
  - Respiratory
- Protocol brevity-eliminate unnecessary sequences/steps
- Use alternative imaging methods: e.g., CT or US

Ahmad et al. Pediatr Radiol 2018 48:37-49

Sequence Options

- Latest technological breakthroughs changing how we acquire MR
  – Synthetic MR: simultaneous multi contrast acquisition
  – Fast acquisition
  – Quiet sequences
  – Free breathing imaging

Simultaneous Multi-Contrast Acquisition

- Synthetic MR: allows retrospective manipulation of image
  - Proposed in 1984, but computational power was lacking
  - GE (MAGiC); Philips (SyntAc, QMap); Siemens (SyntheticMR); independent vendors (SyMRI)

Courtesy GE

Simultaneous Multi-Contrast Acquisition

- Measure parametric properties of tissue
  - T1 (R1), T2 (R2), proton density (ρ_H), and B_1 values
  - E.g., single acquisition (e.g., QRAPMASTER-SyMRI; 6 min)
    - TR = 4000 ms, TE = 22 & 90 ms ETL = 12
  - Change the "signal" by manipulating ETL, ESP,
  - Create synthetic images by manipulating TI, TR, and TE

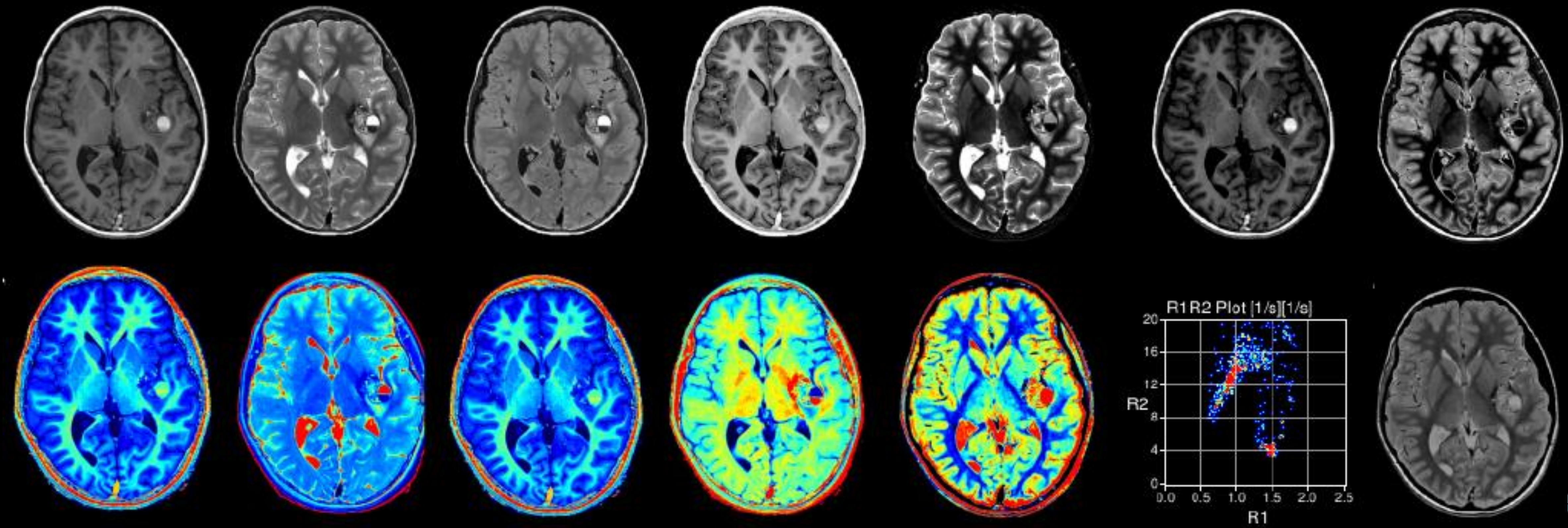
$$signal \cong \rho_H\left(e^{-\frac{TE}{T2}}\right)\left(1-2e^{-\frac{TI}{T1}}\right)\left(1-e^{-\frac{TR-TI}{T1}}\right)$$

$$signal \cong \rho_H\left(e^{-\frac{TE}{T2}}\right)\left(1-e^{-\frac{TR-(ETL*ESP)}{T1}}\right)$$

Ahmad et al. Pediatr Radiol 2018 48:37-49
Andica et al. J of neuroradiology 2019 46(4): 268-275

Simultaneous Multi-Contrast Acquisition

- Contrasts: T1, T2, STIR, T1 FLAIR, T2 FLAIR, dual IR, phase sensitive IR, and PDW

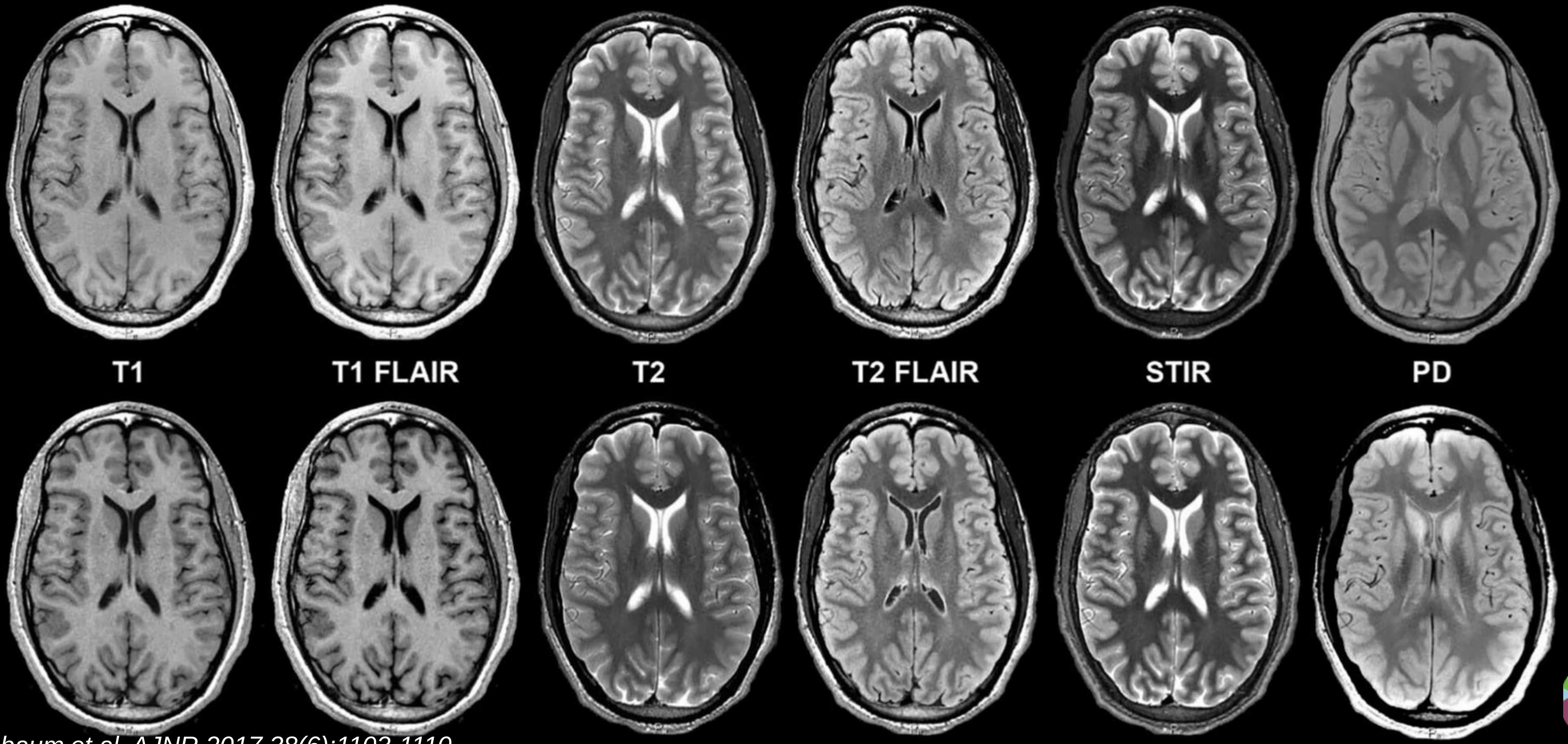


Courtesy GE

Simultaneous Multi-Contrast Acquisition

- How accurate is synthetic MR?
  - *Tanenbaum et al. AJNR 2017 http://dx.doi.org/10.3174/ajnr.A5227*
  - N = 109 (45 M; 64 F)
  - Conventional images acquired first
    - 2D T1W, T2W, T1W & T2W FLAIR & STIR, and PD
  - Multiple dynamic multiple echo MDME (many TE samples) synthetic MR sequence
    - MDME data reconstructed using MAGiC (GE)
    - Randomized blinded review by 7 neuroradiologsts (> 10 yr experience)
      - Intra observer test after 4 week memory washout period
  - Image quality: 5 point Likert scale, artifact analysis, clinical findings recorded (Osborn classification)

Simultaneous Multi-Contrast Acquisition

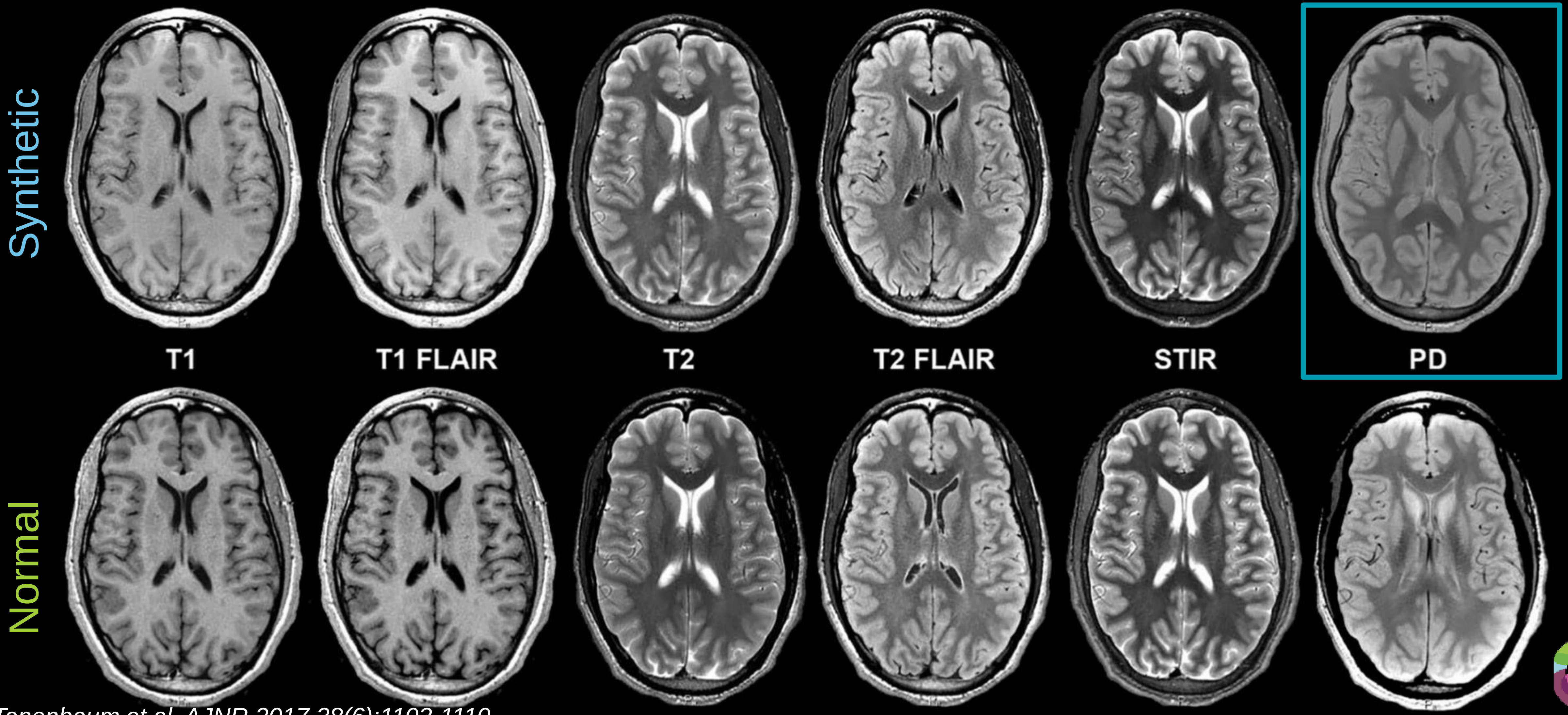


Tanenbaum et al. AJNR 2017 38(6):1103-1110

Simultaneous Multi-Contrast Acquisition

- How accurate is synthetic MR?
- Positives:
  - Diagnostic performance of synthetic imaging was similar to that of conventional MR imaging
  - Conventional morphology agreed > 95%
  - Suggested with shorter scan times less motion artifacts
- Negatives:
  - Except in the posterior limb of the internal capsule for T1, T1 FLAIR, and PDW (> 80%)

Simultaneous Multi-Contrast Acquisition



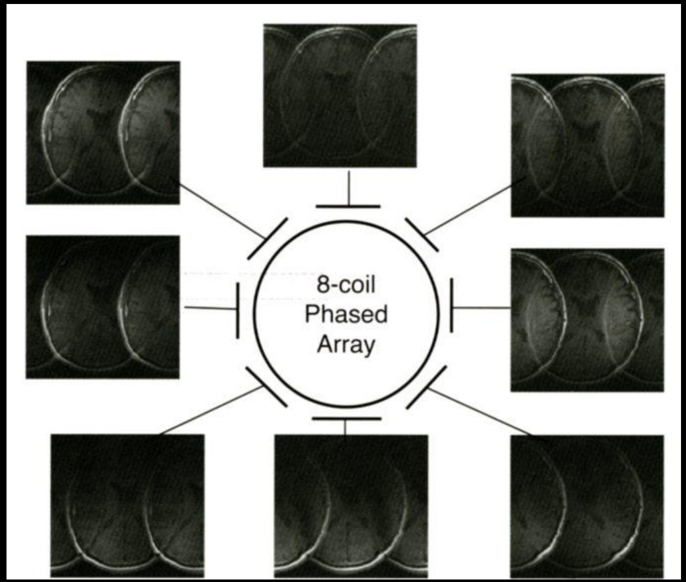
Tanenbaum et al. AJNR 2017 38(6):1103-1110

Simultaneous Multi-Contrast Acquisition

- Continued…How accurate is synthetic MR?
  - Synthetic MR did not improve sensitivity and specificity of diagnostic read
  - MR imaging in neuroradiology
    - Sensitivity: 39% to 98%
    - Specificity: 33% to 100%
    - Still depends on training/reader experience
  - Fewer artifacts (all characterizations) were identified in synthetic
- Synthetic MR is mostly used for quantitative purpose, but may offer the opportunity to reduce scan time in the future

Fast Acquisition

- Compressed Sensing (CS)
  - 1999: SENSE [parallel imaging (PI)]
    - Parallel imaging
      - Fills k-space using multiple RF coils coupled together w/ independent channels
  - 2016: multiband SENSE
  - 2017: compressed SENSE (CS; Philips)
    - CS + PI = complementary
      - PI produces more incoherent samples for CS
        - » Reduces incoherent aliasing artifacts
      - CS prevents high g-factors due to irregular sampling



Bushberg 3rd ed.

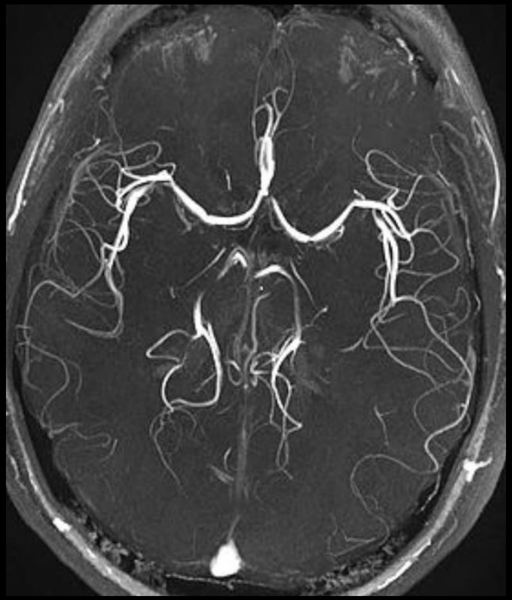
Fast Acquisition

- How does compressed sensing (CS) work?
  1. MR data is redundant, i.e., MR imaging can be compressed
  2. MR scanners naturally acquire encoded samples, NOT direct pixel sampling
     - E.g., CT reconstruction matrix directly correlates with a spatial domain location (x,y)
     - E.g., MR reconstruction the received signal at time (t) is the Fourier transform of the object (O) sampled at spatial frequency (*w*)

$$s(t) = \int_R O(\vec{r}) e^{-i2\pi\vec{\omega}(t)\vec{r}} dr$$

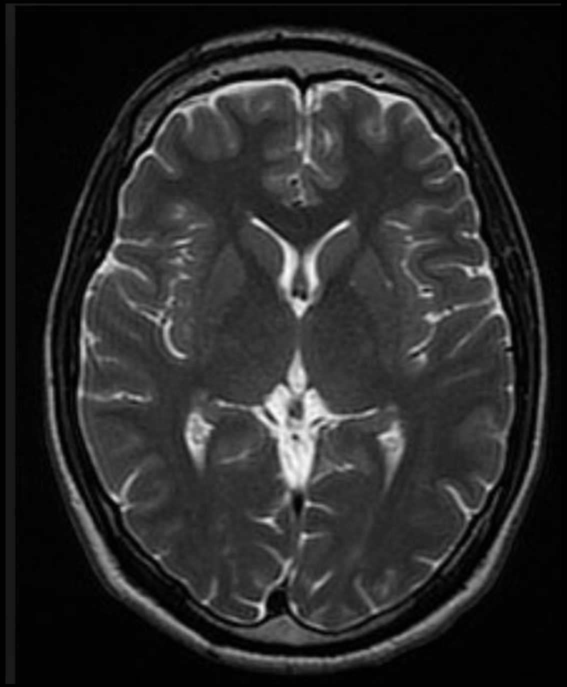
Fast Acquisition

- “Simple” images
- Some MR exams, such as angiograms, are inherently sparse
  - i.e., filled with very little pixel information
  - Sparse image data: Not acquiring some of this information will not affect image reconstruction
    - Thus allowing speeding up of the acquisition



Fast Acquisition

- Complex images, such as brains, are not inherently sparse
  - Must be made to be sparse
  - Using a sparsifying transform (e.g., Wavelet domain)

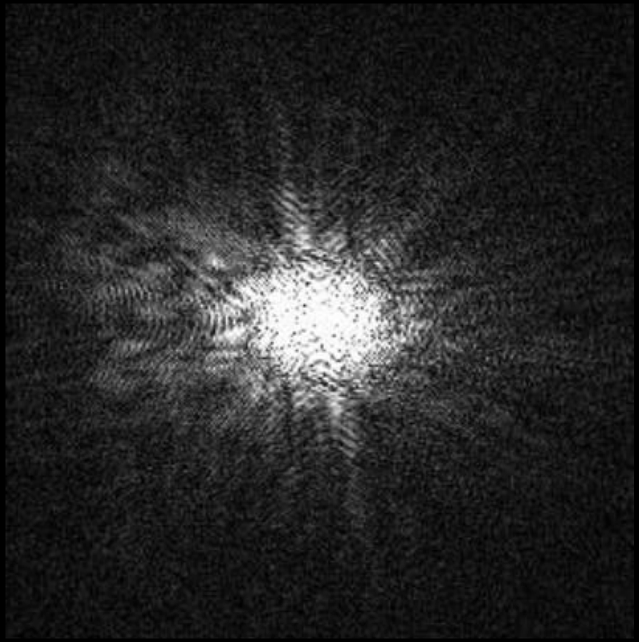


Fast Acquisition

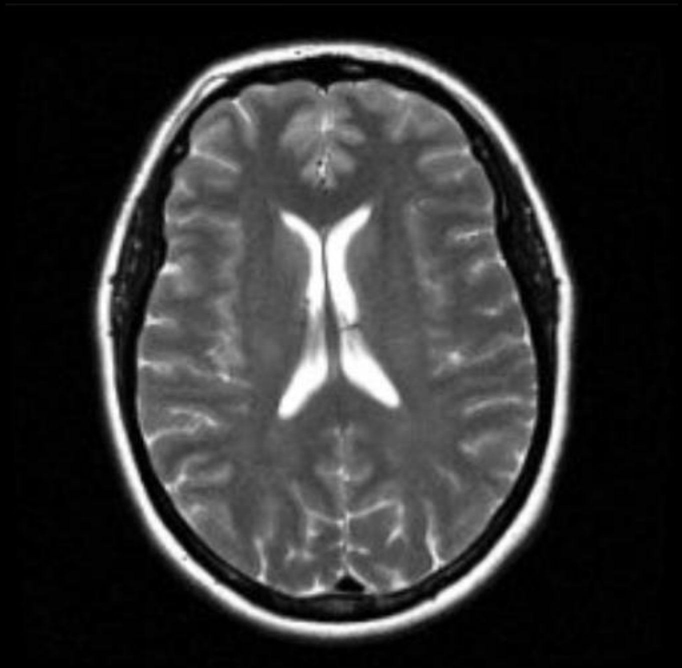
k-space

Fourier Transform

image-space



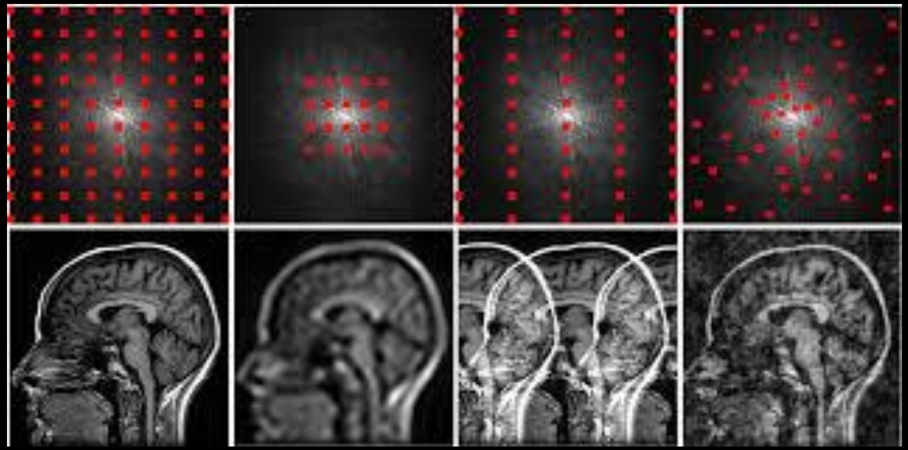
$$s(t) = \int_R O(\vec{r}) e^{-i2\pi\vec{\omega}(t)\vec{r}} dr$$



Fully sampled k-space takes time

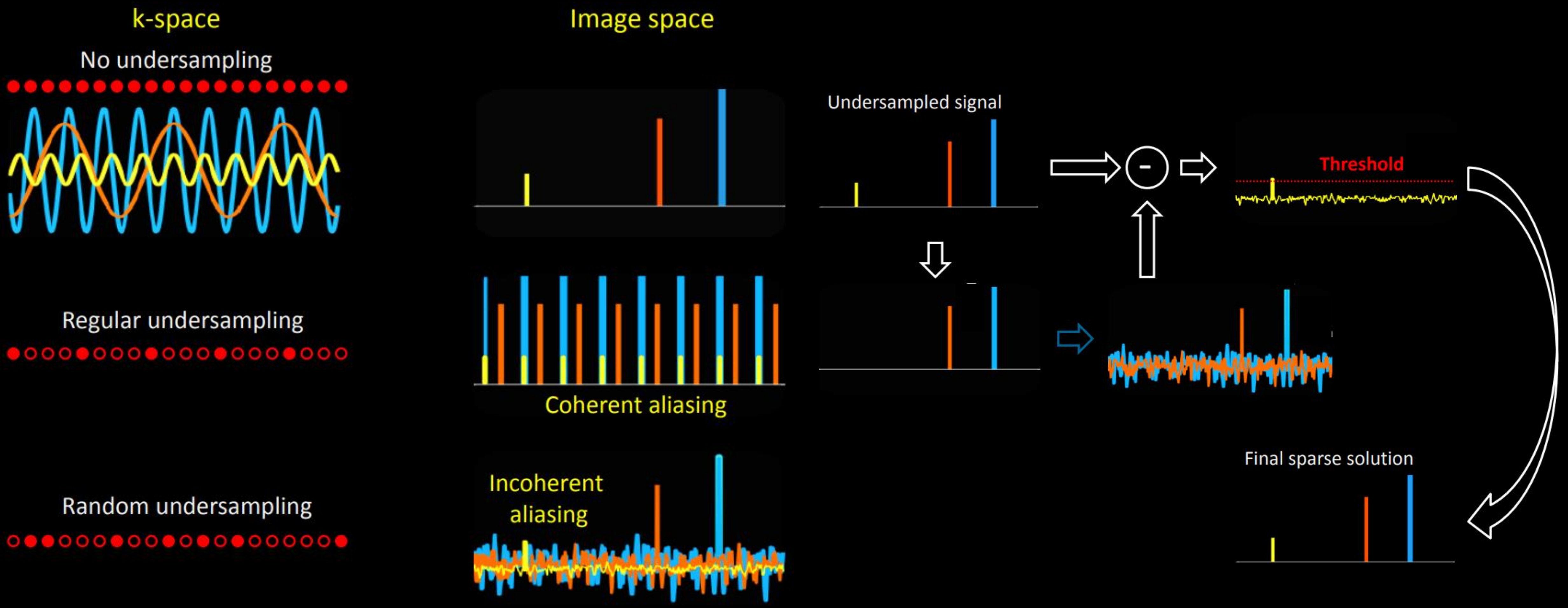
Fast Acquisition

- Must properly under sample k-space
- Coherent vs. incoherent k-space sampling
  - Coherent sampling leads to aliasing artifacts
  - Incoherent sampling leads to noise image



Dspace.library.uu.nl

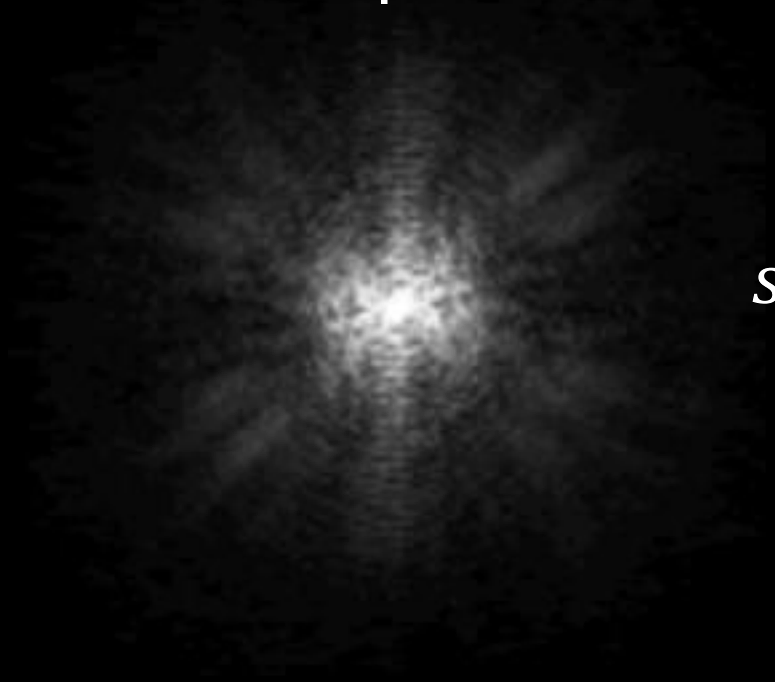
Fast Acquisition



Lustig et al. IEEE signal processing mag march 2008 72

Fast Acquisition

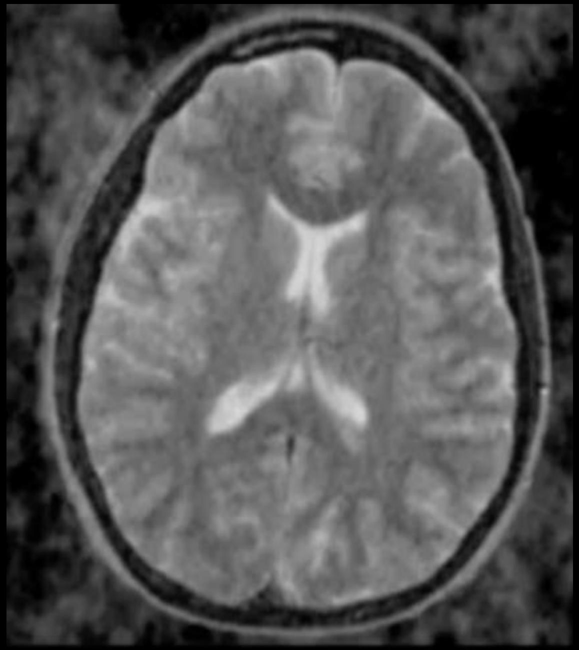
Incoherent sampled k-space



Fourier Transform

$$s(t) = \int_R O(\vec{r}) e^{-i2\pi\vec{\omega}(t)\vec{r}} dr$$

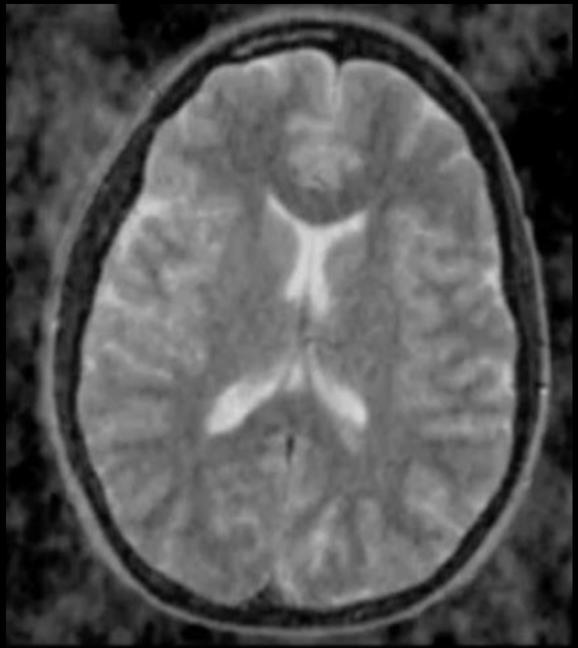
image-space



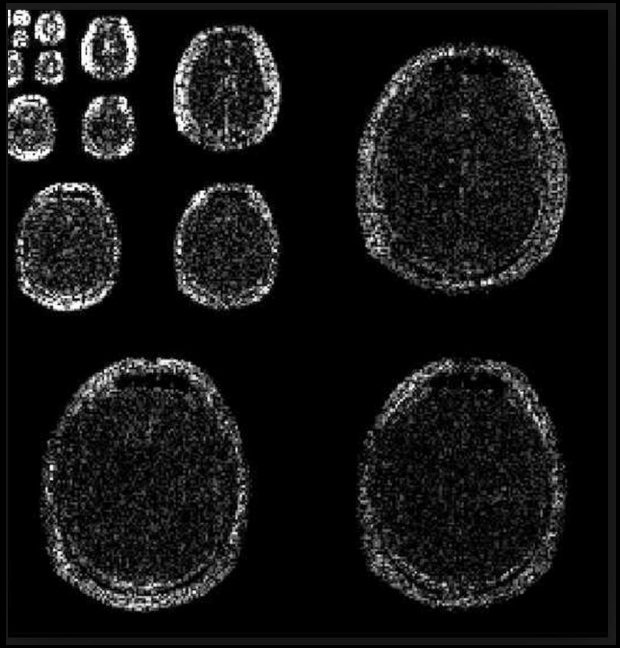
Sparse sampled k-space → noisy image

Fast Acquisition

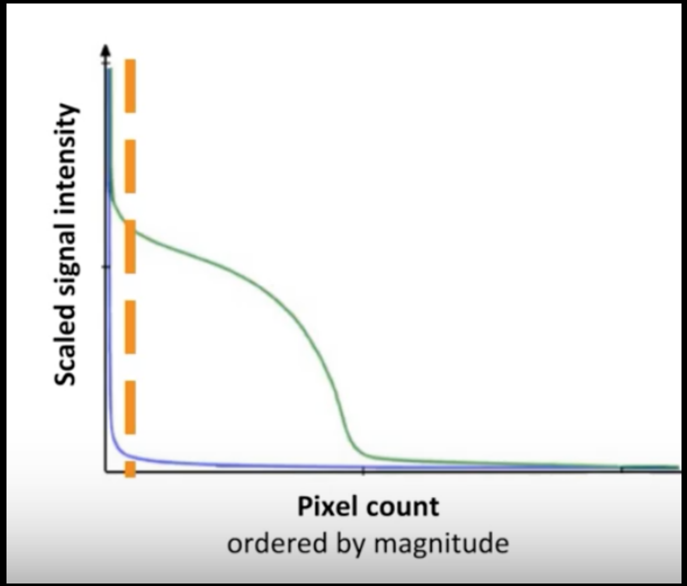
image-space



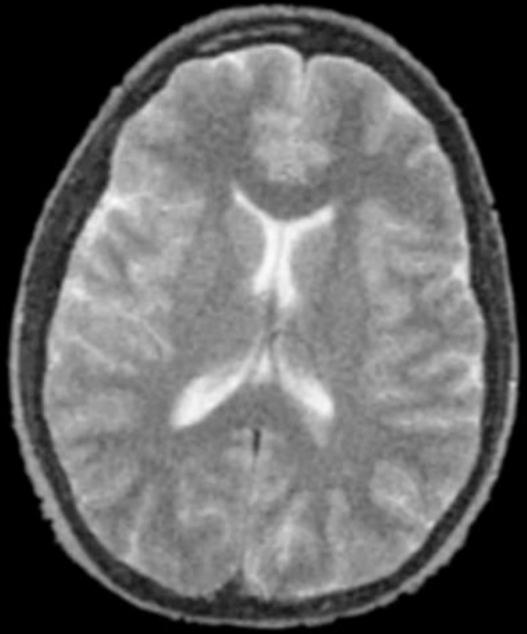
Wavelet Transform



Denoising

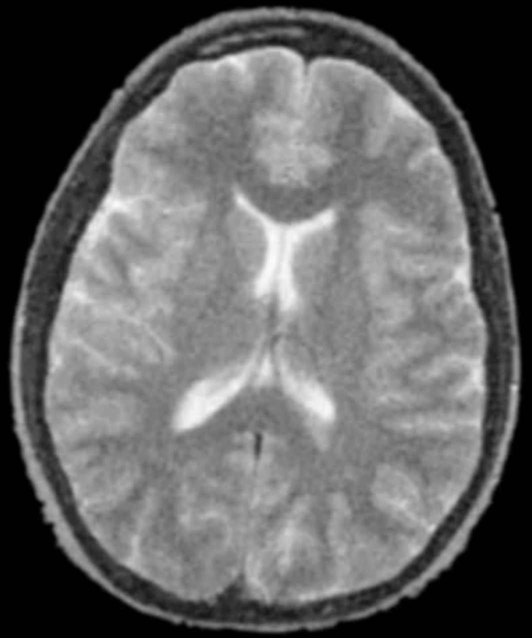


Denoised image



Fast Acquisition

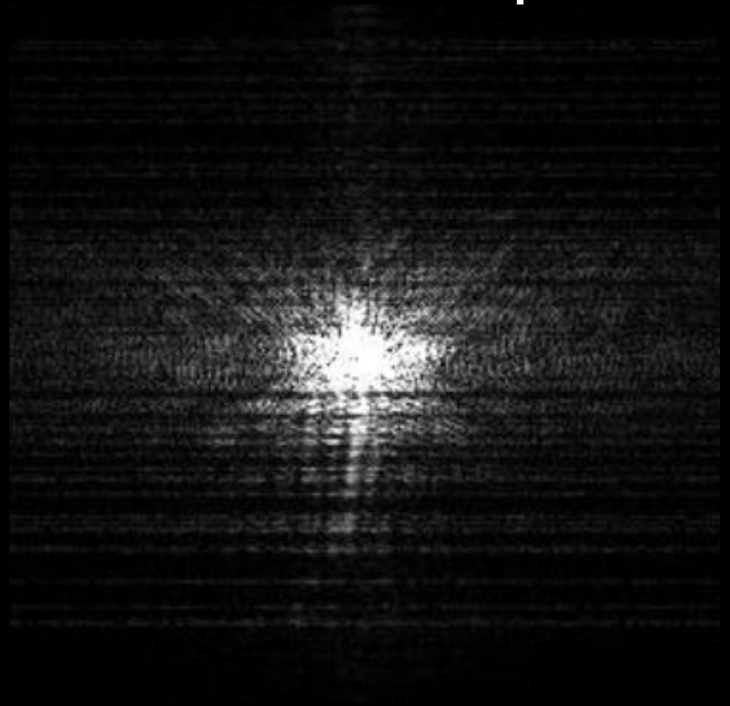
Denoised image



Inverse Fourier Transform

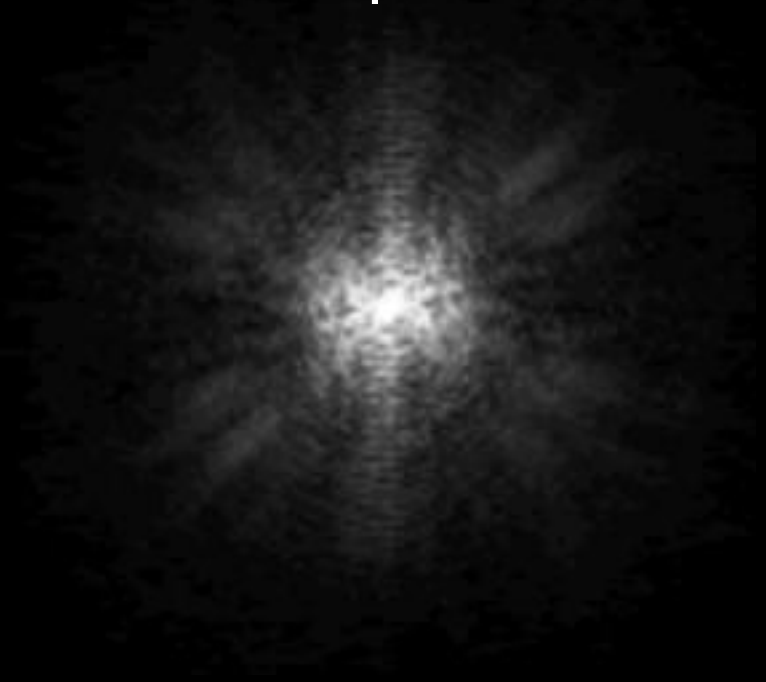
$$\mathfrak{I}^{-1}\{s(t)\}$$

Denoised k-space



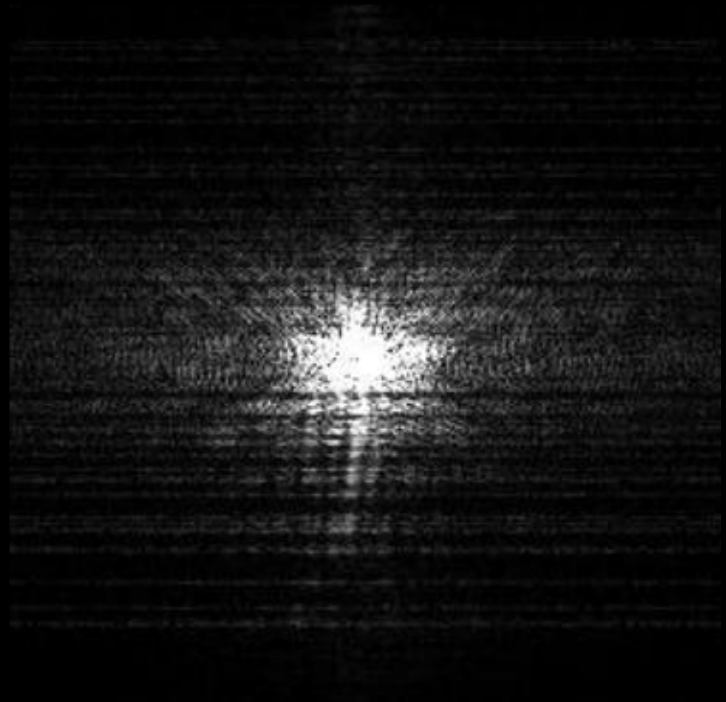
Fast Acquisition

Incoherent sampled
k-space



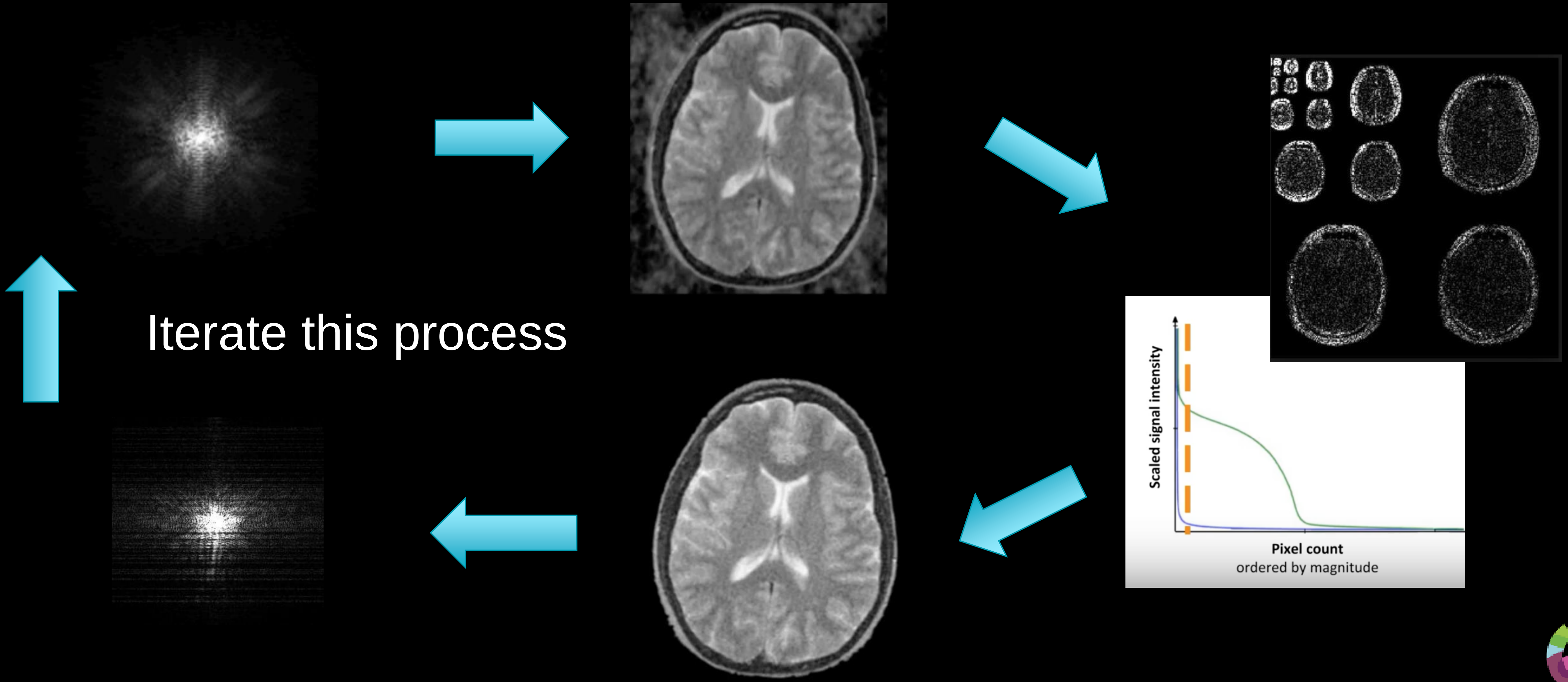
Subtract k-spaces

Denoised k-space

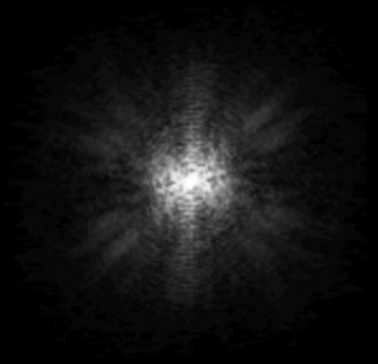


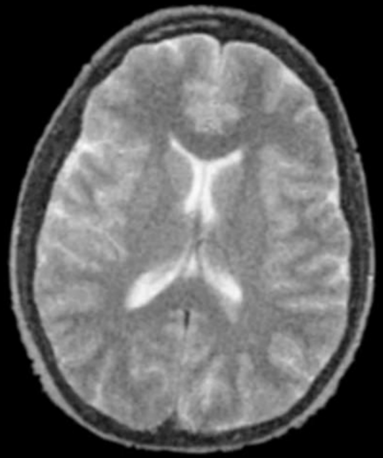
Common points = patient data
Uncommon points = noise

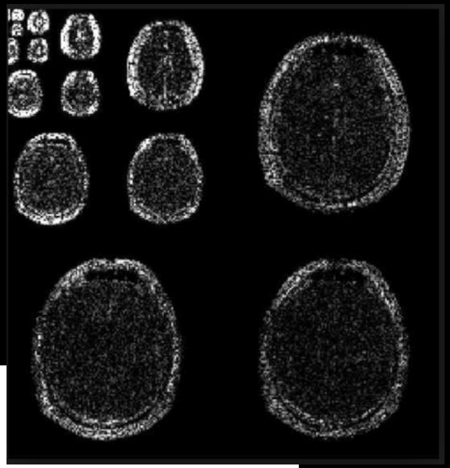
Fast Acquisition



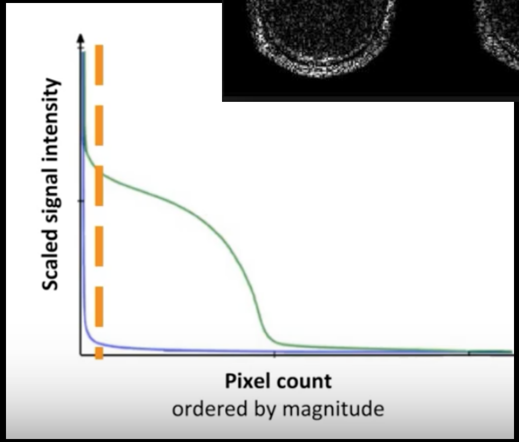
Fast Acquisition

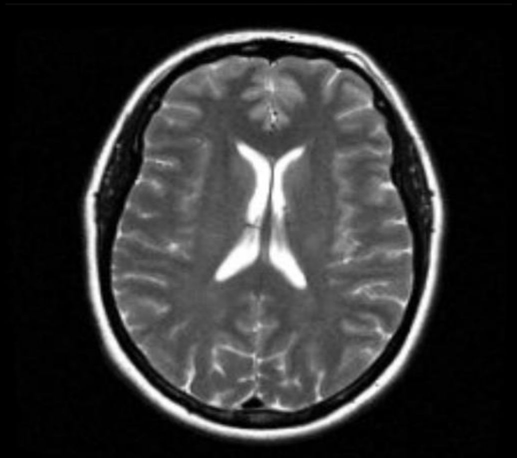




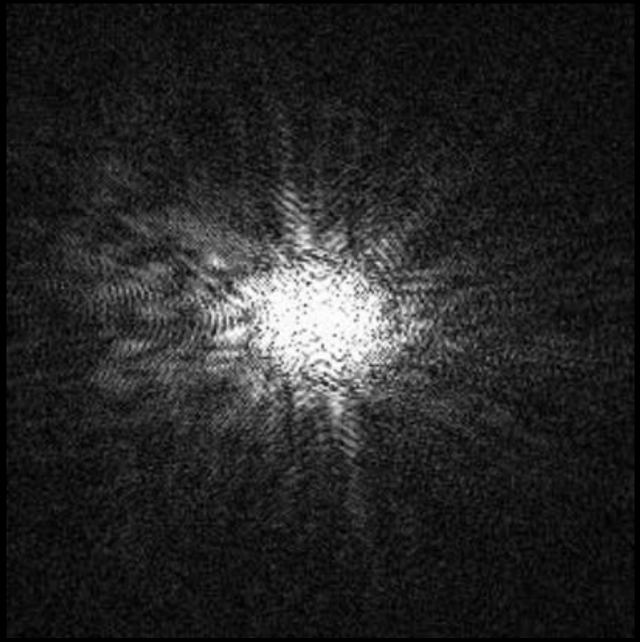


Iterate this process

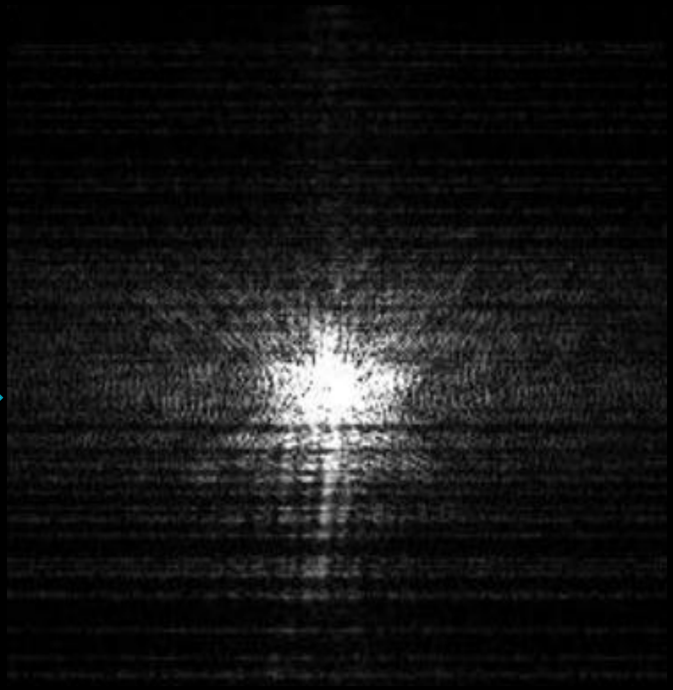




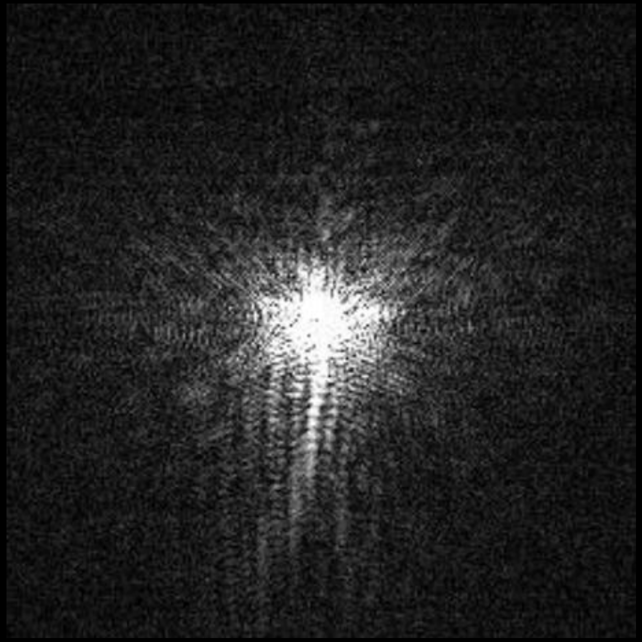
Fast Acquisition



Fully Sampled



Incoherently sampled



30 iterations

Fast Acquisition

- Compressed Sensing (CS)
  - Cannot use with EPI, MultiVane (PROPELLER), partial NSA, MRS, OMAR (MARS/VAT/SEMAC), etc.
  - CS does best for sparse data sets, e.g. TOF MRA, REACT, MRCP
  - Aggressively apply CS: 3T and 3D
  - Less sensitive to coil geometry (number of coil elements and arrangement) vs SENSE
  - Does not do well with gross motion (worse than SENSE)
    - But minimizes patient breathing/cardiac motion because faster

Fast Acquisition

- Initial examination average time reduction

	Original Time (min)	New Time (min)	Reduction (min)	Reduction (%)
Ankle	22:03	13:20	8:43	40%
Trauma Knee	19:07	19:07	4:08	18%
Elbow	31:47	26:21	5:26	17%
Whole Body (6 stations)	35:28	29:30	5:58	17%
Routine Brain (> 2yr old)	18:27	17:09	1:18	7%

3D PDW View

16yo male with ridged planovalgus with bilateral chronic foot pain

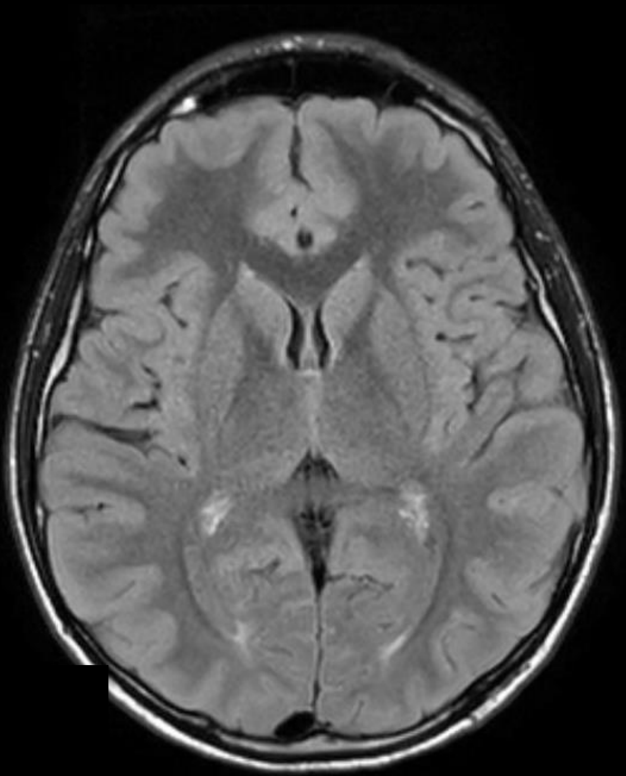
Ingenia 1.5T

4:24 min

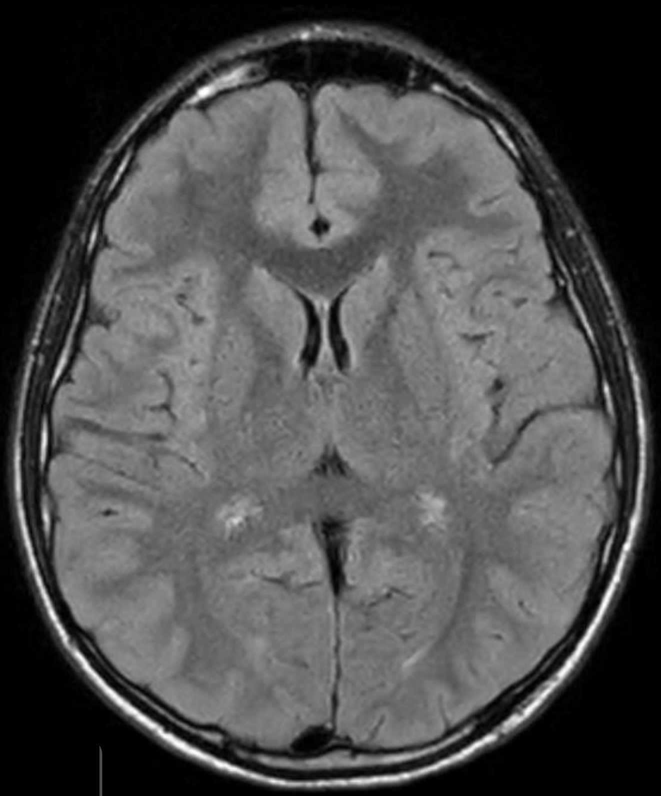
3:51 min
CS = 6

Brain 2D FLAIR

14yo male with headache, low body temp and reported episodes of LOC



4:00 min

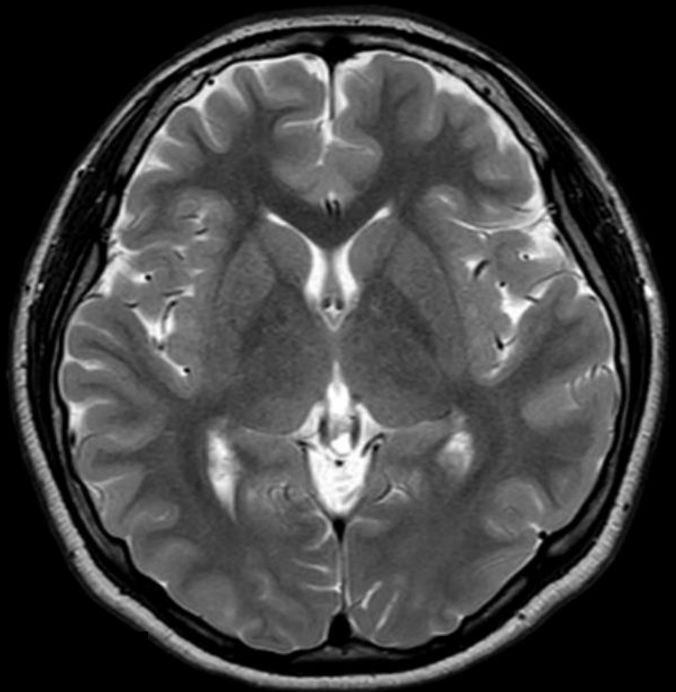


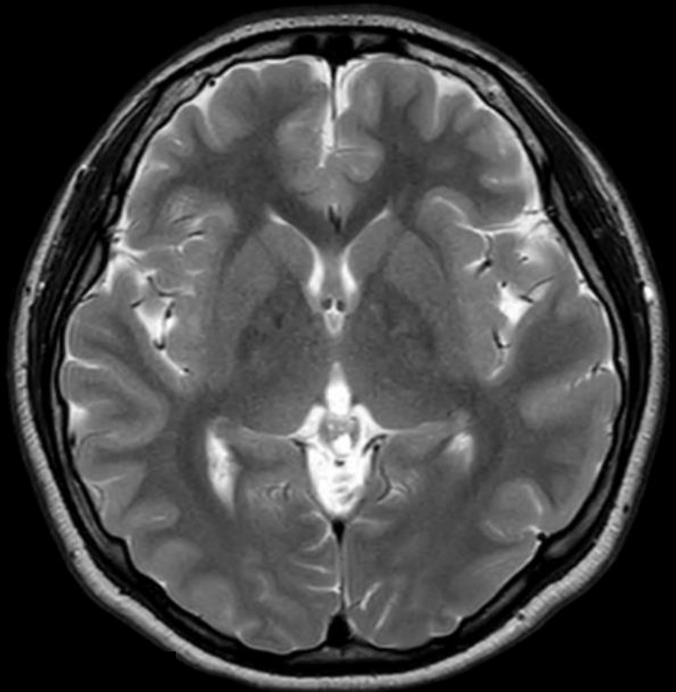
2:56 min
CS = 1.8

Ingenia 1.5T

Brain T2

13yo female, new onset hallucinations (visual and auditory)





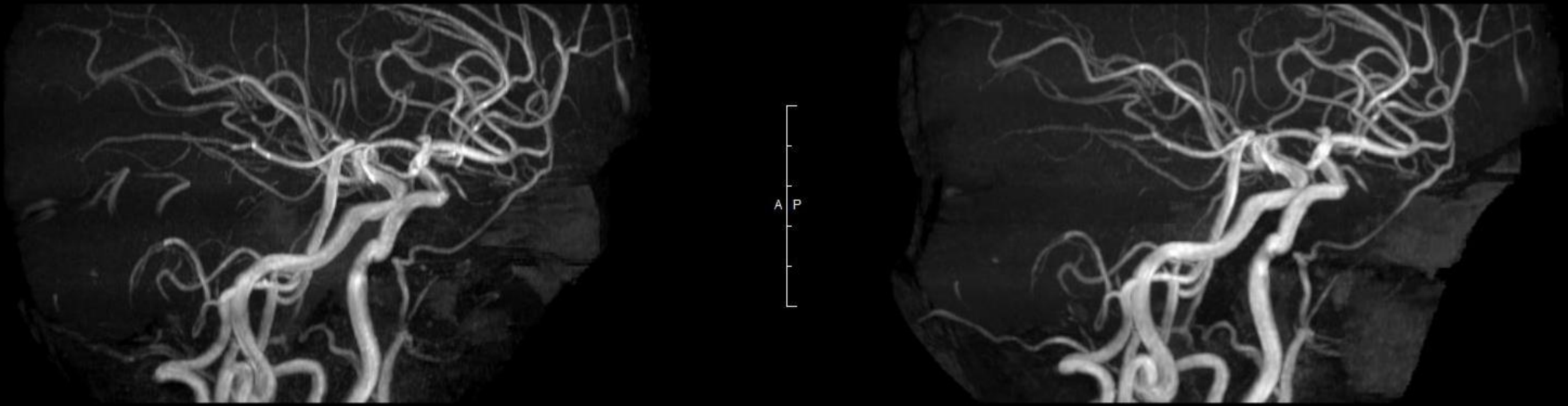
Ingenia 1.5T

4:11 min

3:43 min
CS = 2

3D TOF MRA

12yo male, new onset dystonia, facial droop lasting 30min 3x a week



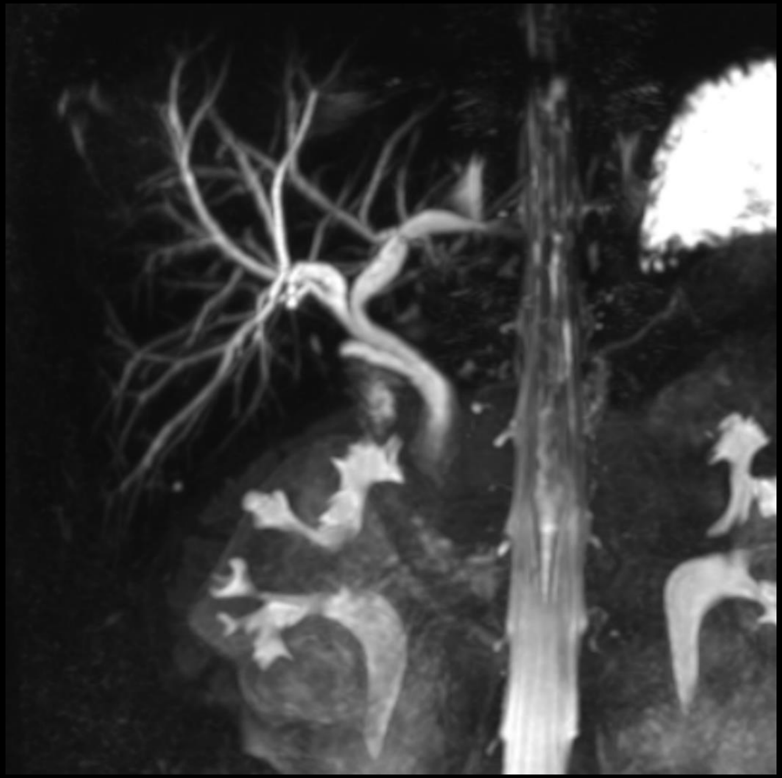
6:33 min

4:27 min
CS = 3

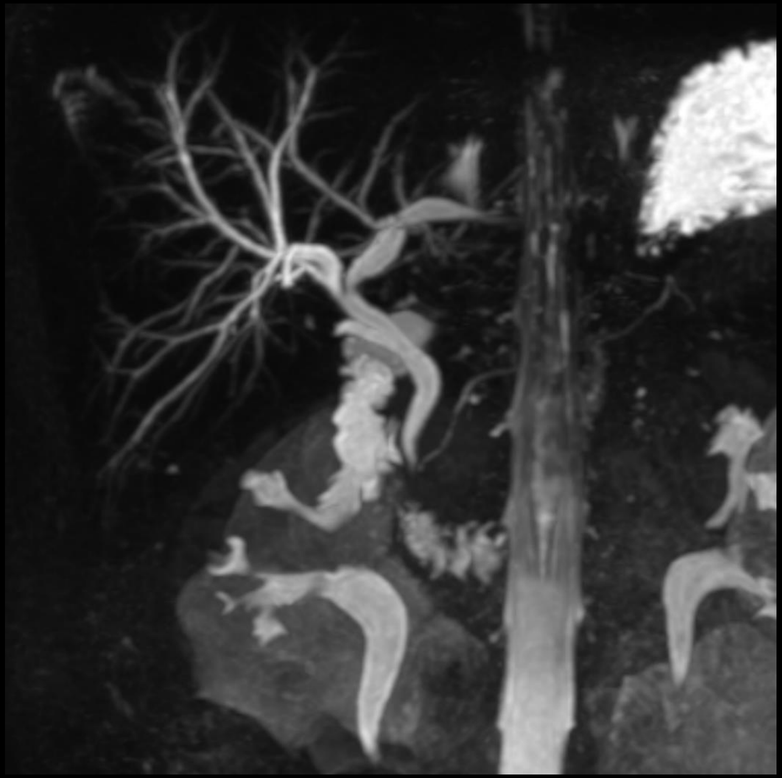
Ingenia 1.5T

Abdomen FSE

20 yo woman with right upper quadrant pain following cholecystectomy



3:54 min

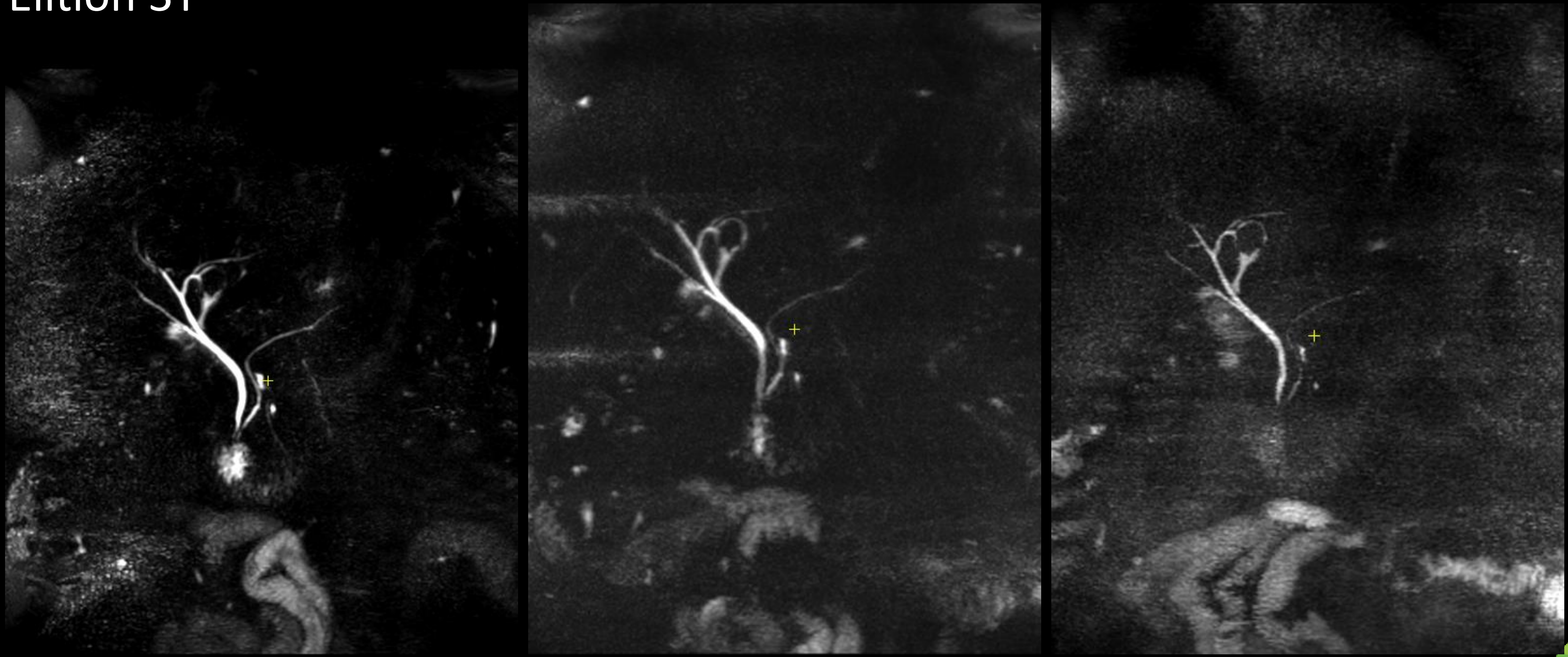


1:54 min CS = 6

Elition 3T

136 kg (300 lb) Adult

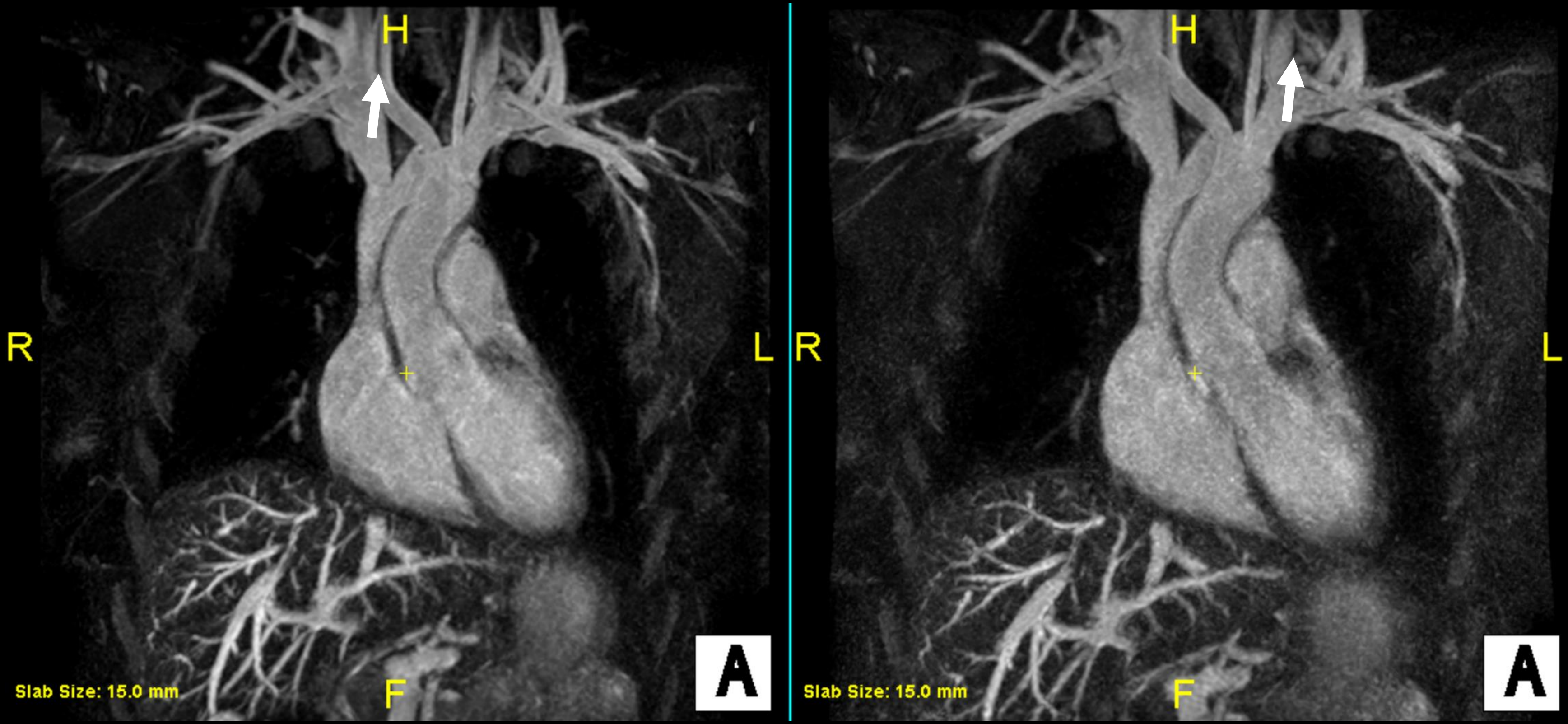
Elition 3T



No CS (4:33 + RespTr) | CS=4 (1:08 + RespTr) | CS=24 (0:15 BH)

Cardiac REACT

Young adult with left subclavian vein stenosis (with respiratory triggering)

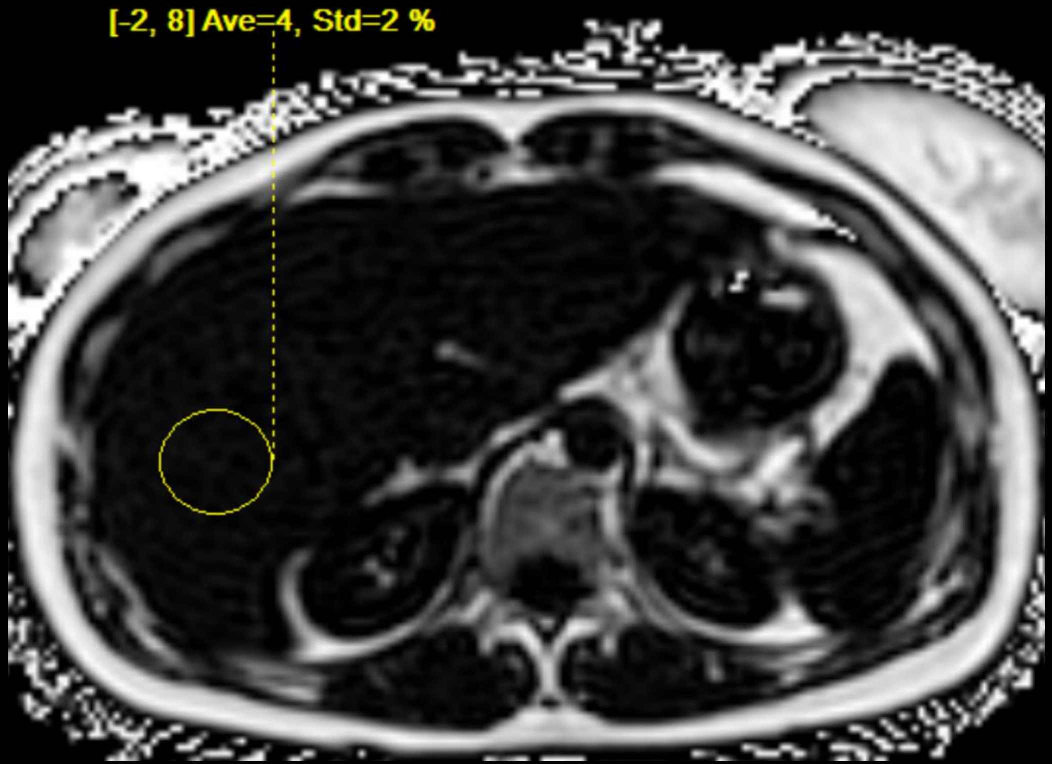


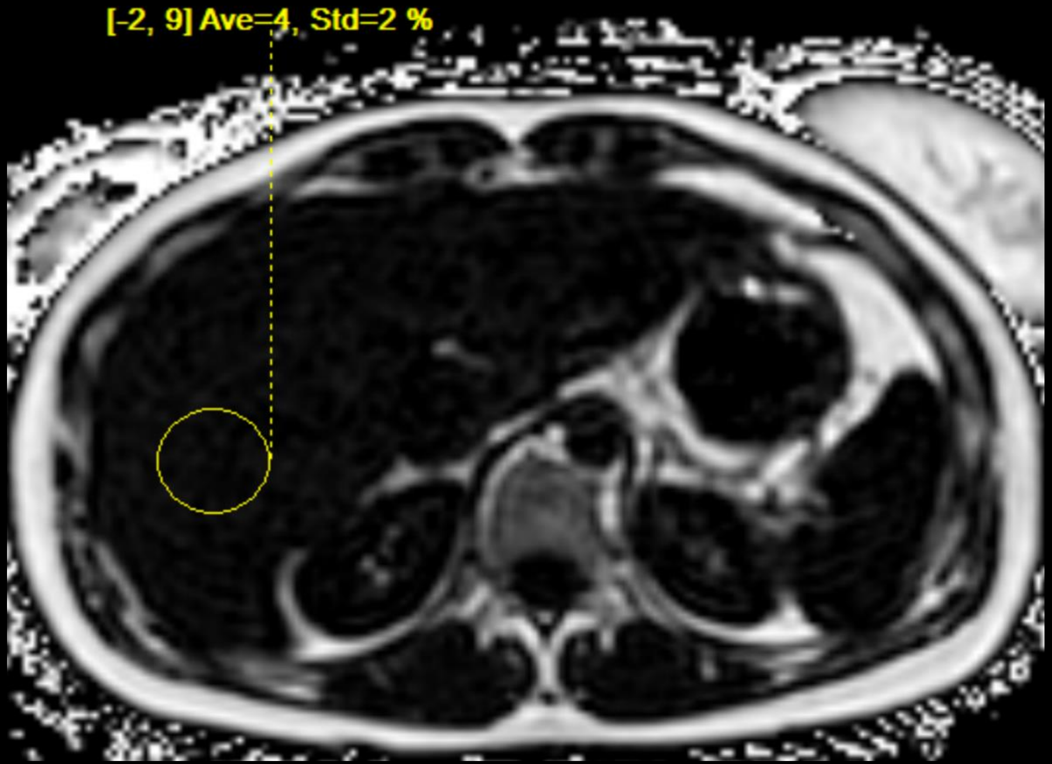
Ingenia 1.5T

5:27 min

3:04 min CS = 3

mDixon Quant





Ingenia 1.5T 10.1 sec

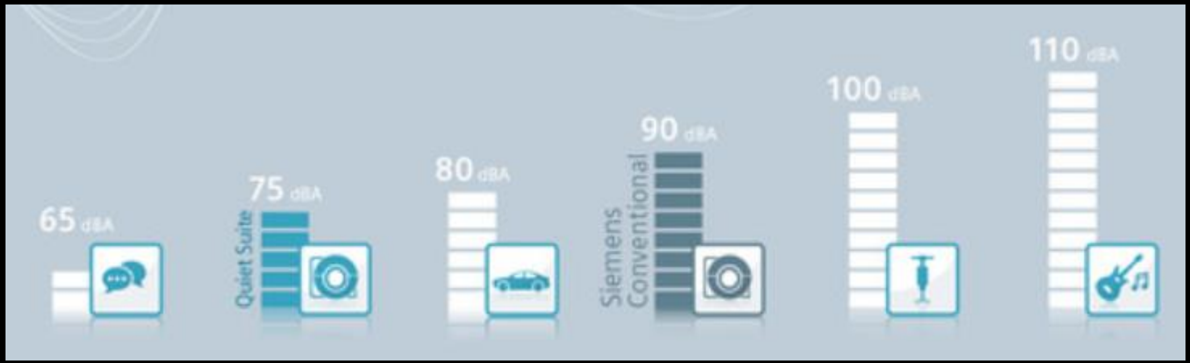
4.7 sec CS = 5

Fast Acquisition

- Quantitative accuracy
  - Need to determine how CS affects quantitative MR metrics, e.g.:
    - Elasto: kPa
    - T2*
    - PDFF
    - mDixon Quant

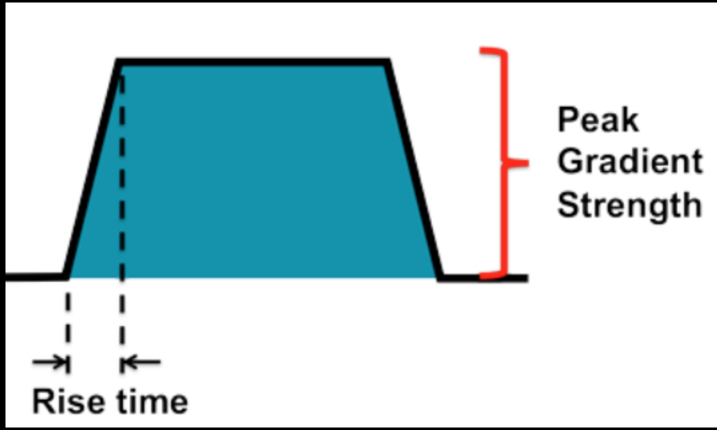
Quiet Sequences

- Current techniques to reduce MRI noise:
  - Gradient insulation
  - Force compensation
- Neither directly address the root cause:
  - Rapid directional gradient switching
- Siemens' QuietX & GE's Silenz are software solutions



Quiet Sequences

- Characteristics of a quiet sequence (per TR):
  - – Gradients are on during the whole TR
  - – But with very small TE (TE = 0.016 ms)
  - – Acquired in radial k-space instead of Cartesian
  - – Smaller tip angles
  - – Reduces slew rates



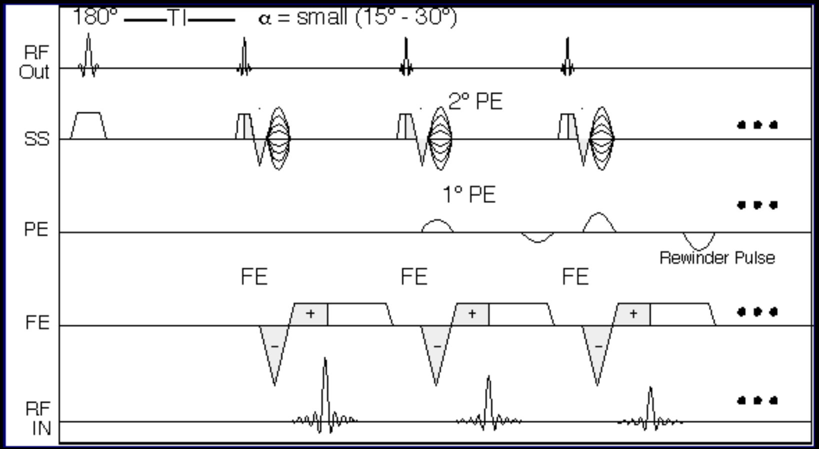
Quiet Sequences

GE BRAVO sequence

Siemens

GE

Fig. 1: Sequence diagram of the PETRA sequence.



Grodzki, M & Heismann, B. Quiet T1-weighted head scanning using PETRA. Proc. Intl. Soc. Mag. Reson. Med. 21 (2013)

Quiet Sequences

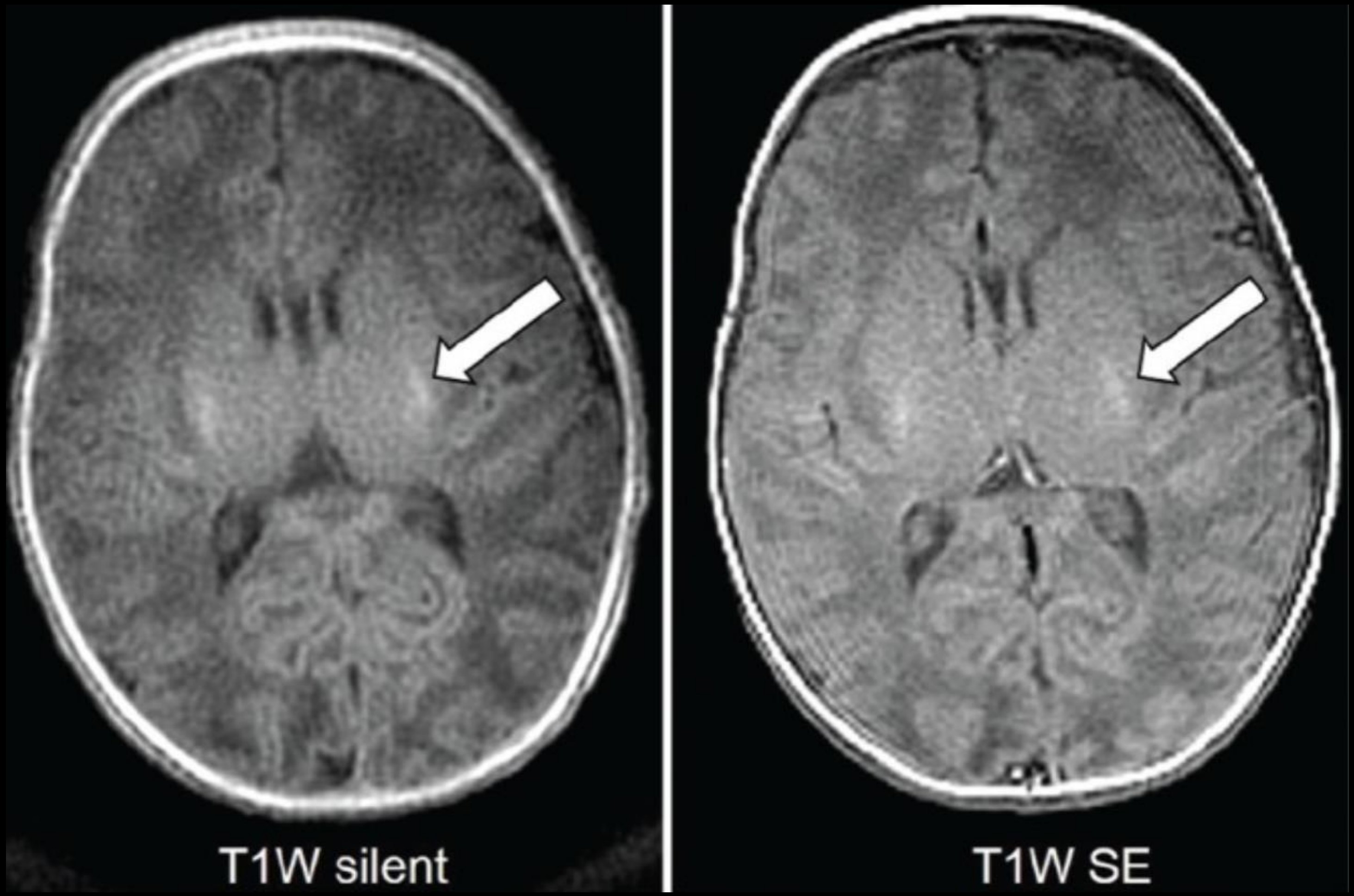
- Advantages:
  - Kids: reduced sedation
  - Patients can hear the movies used for distraction
  - FMRI: no auditory stimulation
  - Image Quality: Less vibrations from gradient banging equals less image artifacts
  - Bioeffects: No peripheral nerve stimulations
  - Intraoperative surgery: MD's can communicate easier

Quiet Sequences

- Quantitative contrast comparison
  - Myelination assessment in children w/ conventional SE
  - Compared using GE 750w 3T
    - 24 channel head coil
  - T1W: 3D GRE short TE and small flip angle and radial k-space
  - T2W: 2D SE w/ PROPELLER

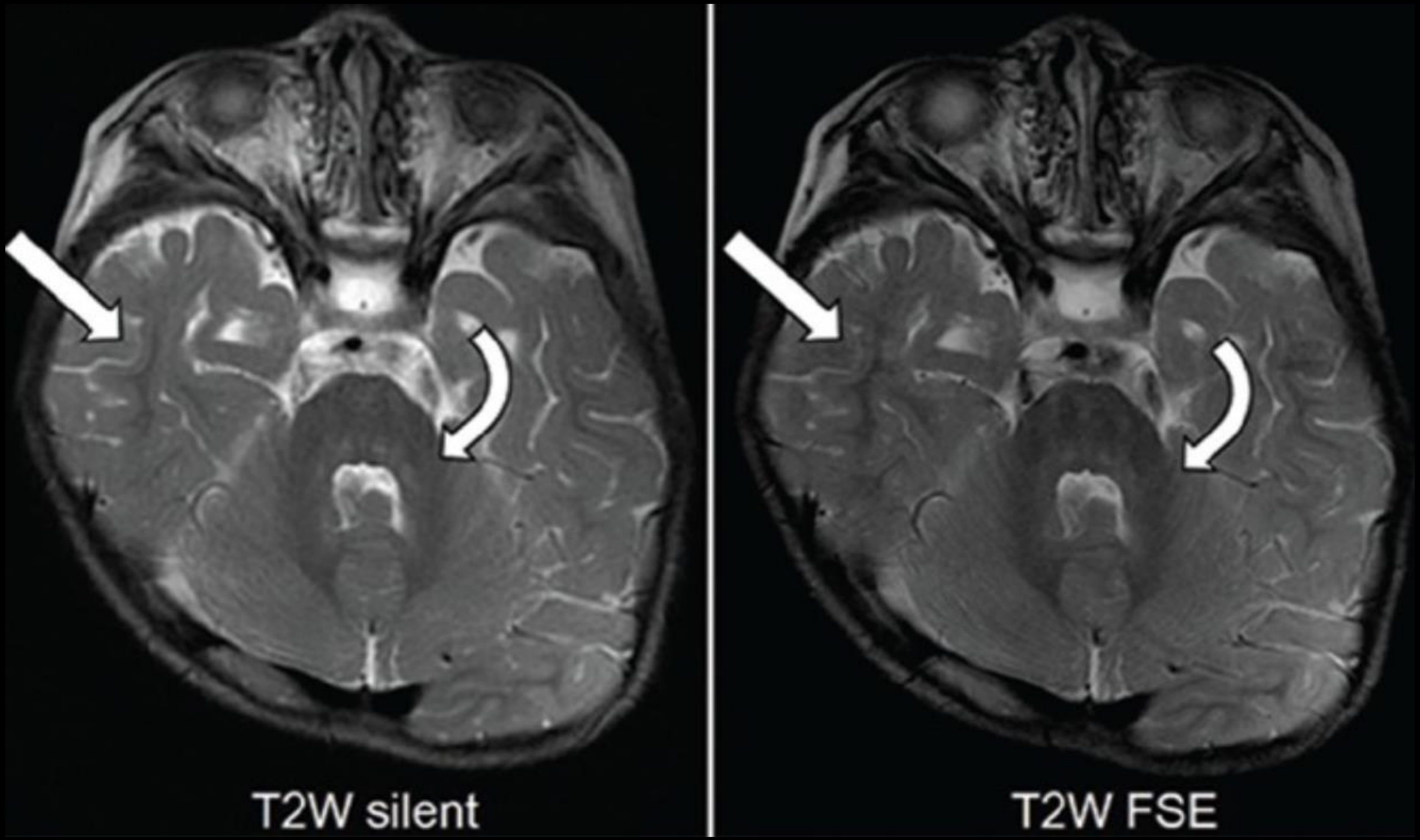
Matsuo-Hagiyama *et al.* *Magn Reson Med Sci*. *2017; 16(3): 209–216.*

Quiet Sequences



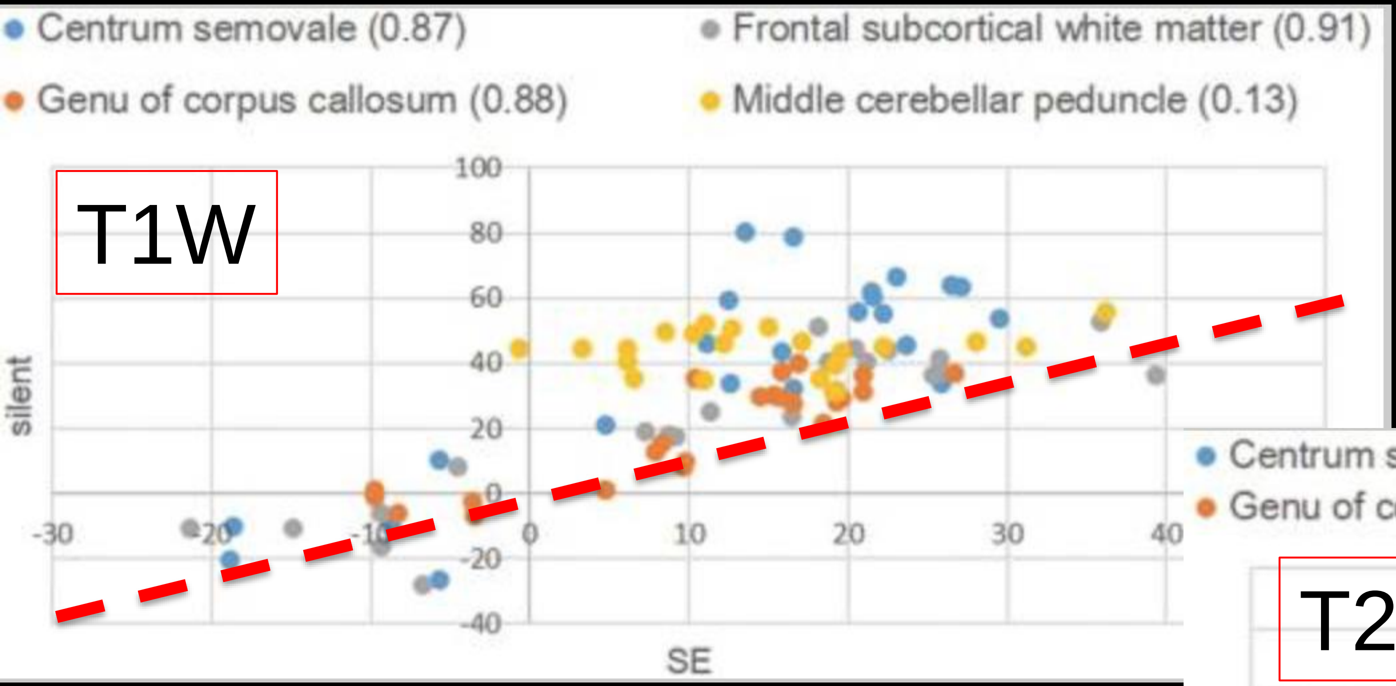
[Matsuo-Hagiyama](#) et al. [Magn Reson Med Sci](#). 2017; 16(3): 209–216.

Quiet Sequences

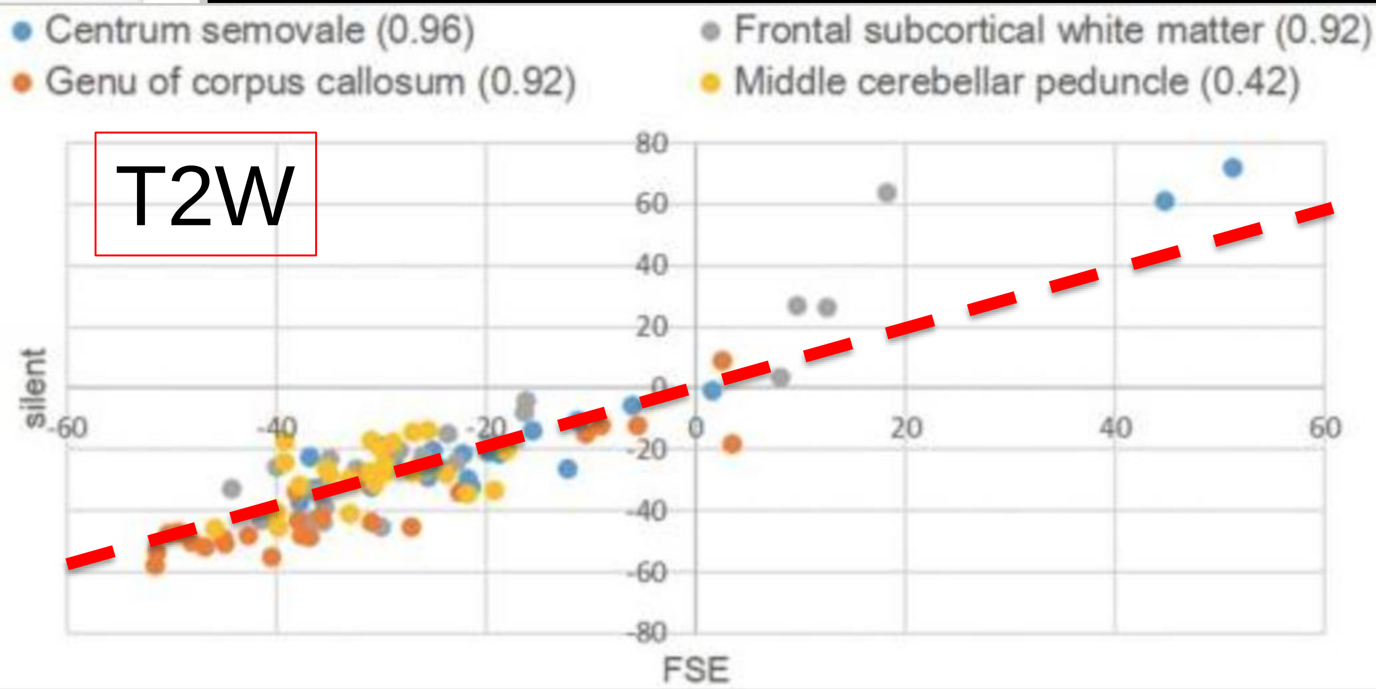


Matsuo-Hagiyama et al. Magn Reson Med Sci. 2017; 16(3): 209–216.

Quiet Sequences

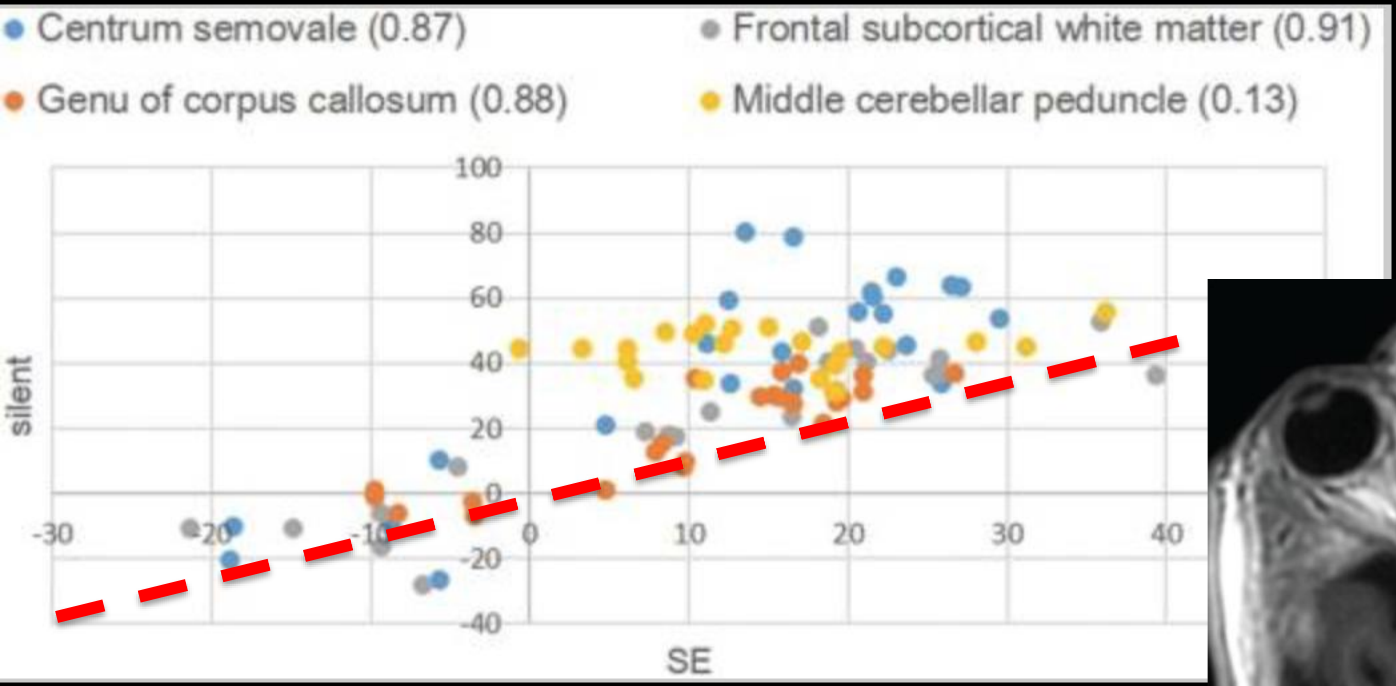


- Gross anatomical comparison agreed w/ κ ~ 0.8

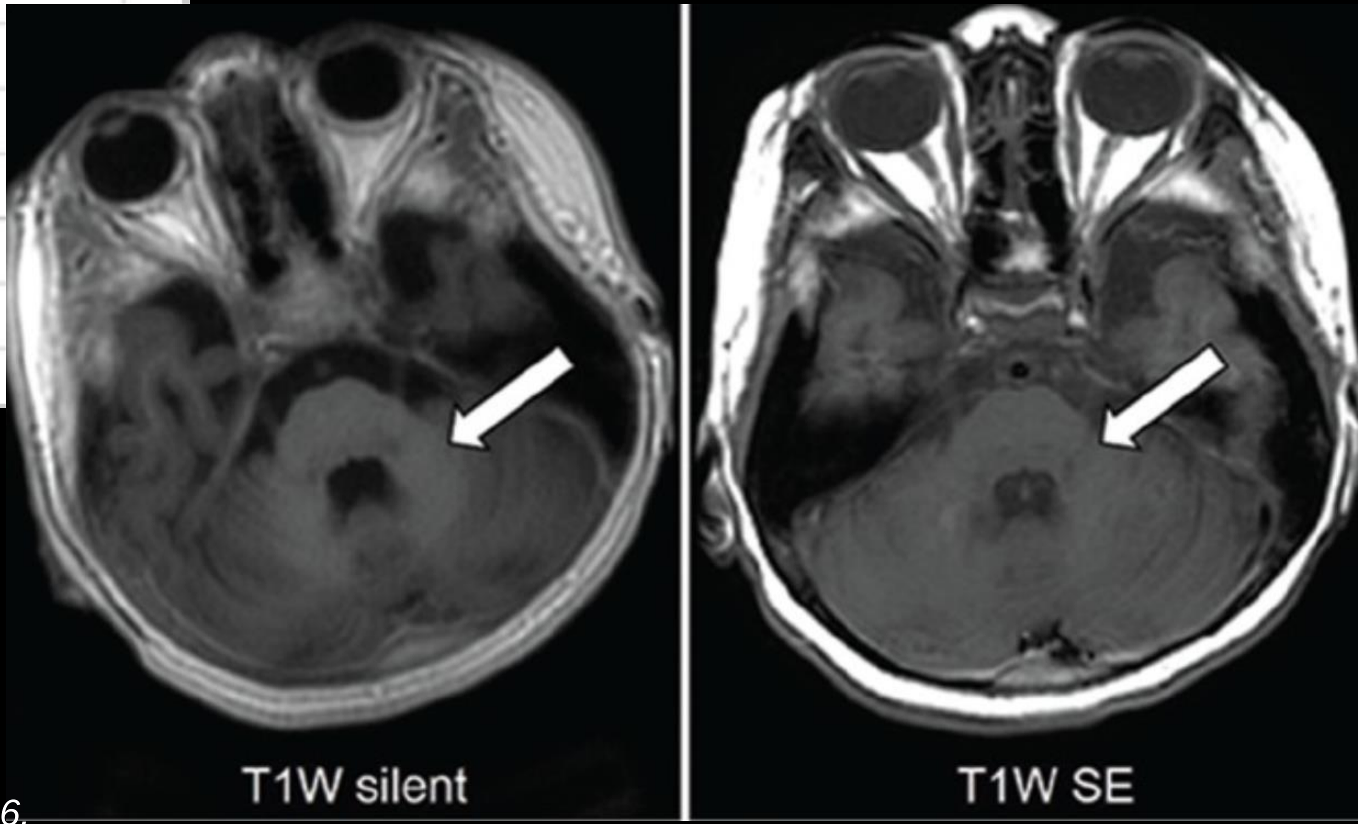


Matsuo-Hagiyama et al. Magn Reson Med Sci. 2017; 16(3): 209–216.

Quiet Sequences



- Cerebellar myelination poor agreement κ ~ 0.14



Matsuo-Hagiyama et al. Magn Reson Med Sci. 2017; 16(3): 209–216.

Quiet Sequences

- Noise reduction:
  - T1W: 82dB → 53 dB (~ 30 dB)
  - T2W: 85 dB → 59 dB (~26 dB)
- How does that compare with ear plug noise reduction?
  - NRR rating of 33
    - $NRR = \frac{33-7}{2} = 13\ dB$
  - NRR rating of 22
    - $NRR = \frac{22-7}{2} = 7.5\ dB$

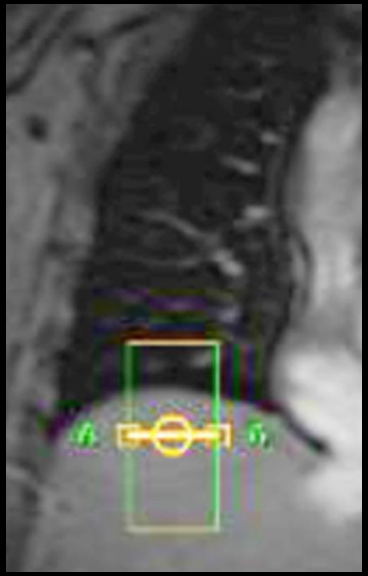
Matsuo-Hagiyama et al. Magn Reson Med Sci. 2017; 16(3): 209–216.

Free Breathing Imaging

- Major challenges in cardiovascular MRI:
- Image quality degradation due to respiratory motion
- Long scan times need
  - Breath hold (BH) acquisition
  - BH can be difficult for sick patients and pediatrics

Free Breathing Imaging

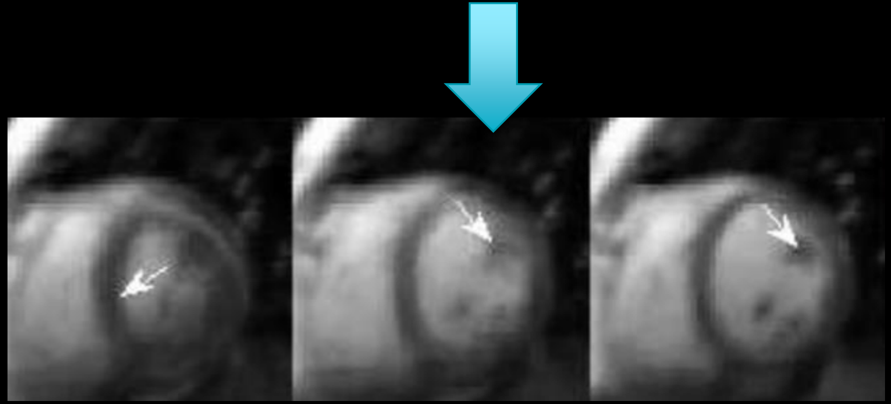
- Long scan times using diaphragmatic navigator gating
  - Predefined acceptance window of breathing cycle (e.g., end expiration)
    - All other data rejected for image reconstruction
  - Small gating window 3-5 mm
    - Prolonged acquisition times
  - Irregular breathing may require scan abortion

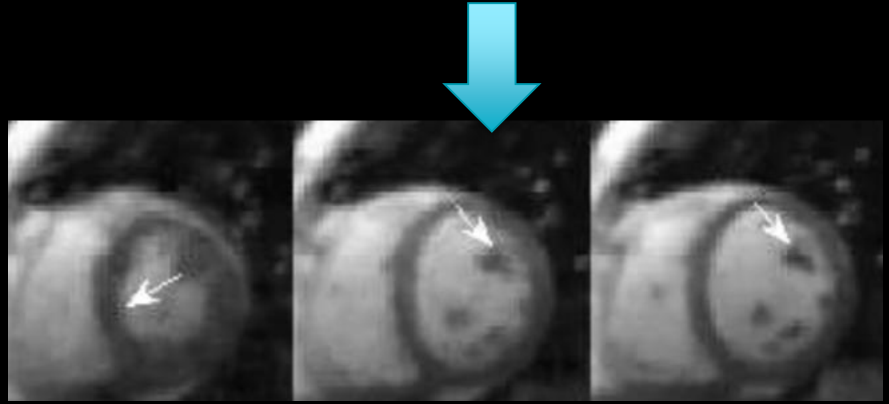


Free Breathing Imaging

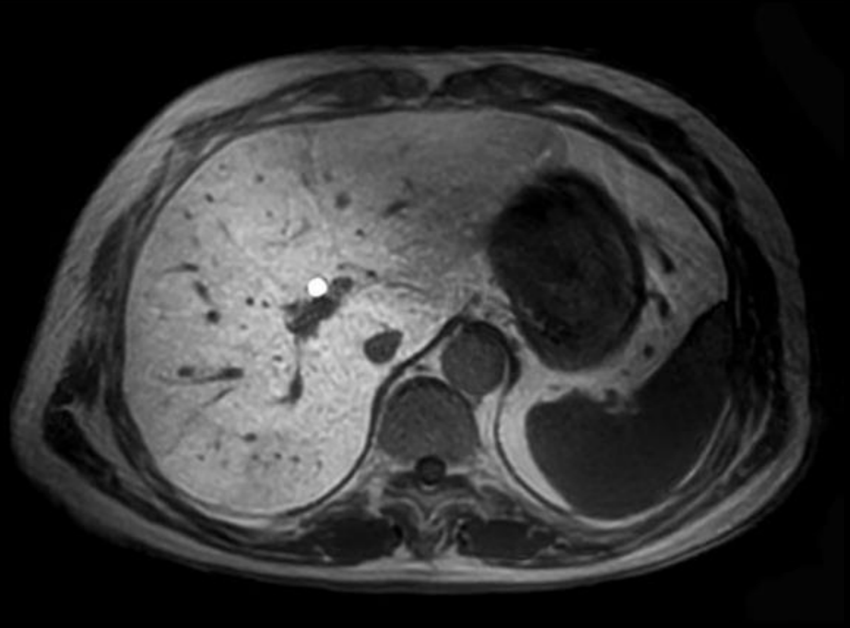
Failed Breath Hold

- Free breathing acquisition requires:
  - Shorter scan time
  - 3D CINE acquisition
  - Novel data sampling schemes
    - Binning data WRT respiratory cycle
  - Under sampling reconstruction (e.g. CS) + motion correction

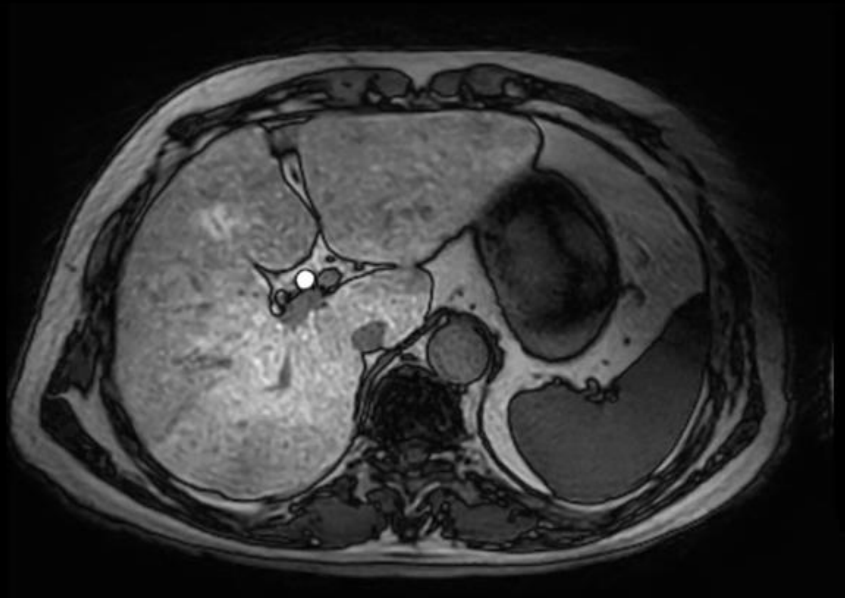




Free Breathing Imaging



mDIXON IP



mDIXON OP

Conclusion

- MRI is a rapidly evolving field
- New technologies are largely software-based
  - Used to speed up MR
  - Fast & accurate MR = better MR
- Some software technologies require new scanner platforms
  - $$$
  - Usually with time, manufacturers will make software available for older (legacy) scanners

Conclusion

- Staying current with new technologies
  - Will require additional training
    - Radiologists
    - Technologists
    - Medical physicists
  - Team work will aid in enable proper technology implementation
  - Goal: improved patient care

Thank you

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