Optimizing and Troubleshooting MRI Scanning for Radiation Therapy

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Washington University in St. Louis
School of Medicine

Disclosure

- Dr. Gach owns common shares in ViewRay Inc., the manufacturer of WashU's MRI Guided Radiotherapy System.

- WashU has Master Research Agreements with Siemens, ViewRay, and Philips and may receive research funding or support from these vendors.

Agenda

Introduction:
- Workflow
- Priorities

Optimization:
- Acquisition Tradeoffs
- Metal Artifact Reduction
- Low Field MRI for MRIgRT

Troubleshooting:
- Image RT-facts
- Diagnostics

Educational Goal: Introduce some issues and solutions for MRI-based RT.

WashU Clinical MRI Systems

Radiation Oncology:

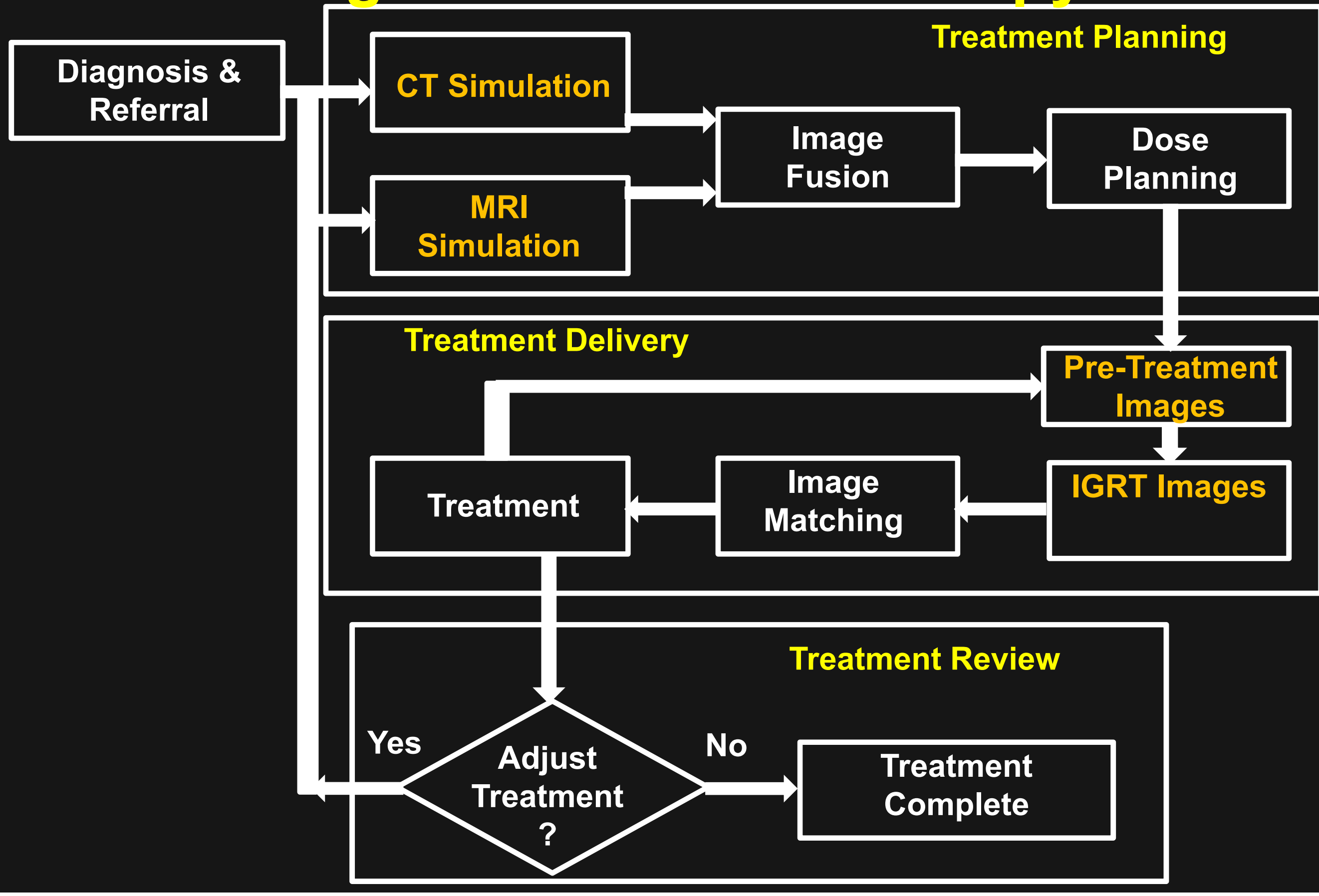
- MRI Sim: Philips 1.5 T Ingenia with HIFU (R5.1.7) Sonalleve
- MR-RT: ViewRay ^{60}Co MRIdian 0.35 T (VB19)→MRI Linac
  ViewRay MRI Linac 0.35 T (VB19)

Mallinckrodt Institute of Radiology:

- Diagnostic Radiology: Siemens 1.5 & 3 T MRIs
- Center for Clinical Imaging Research (CCIR):
  - Siemens mMR 3 T (PET/MRI, VB20→VE11)
  - Siemens 3 T Trio (VB17)→Prisma 3 T VE11
  - Siemens 1.5 T Avanto (VB17)→Vida 3 T VEA
- Neuroimaging & Human Connectome (East Building):
  - Siemens 3 T Prisma (VD13→VE11)

Takeaway: Every MRI is unique. Solutions must be customized.

WU Image-Guided Radiotherapy Workflow



MRI-based RT Priorities

1. Precise tumor and OAR delineation
2. Electron density determination
   A. Fusion with CT
   B. MRCAT
3. Motion management (Simulation and Treatment)
   A. Artifact suppression
   B. Motion characterization
   C. Motion compensation (gating, compression, treatment boundary)
4. Adaptation for changes in anatomical structural (e.g., bladder, bowel)
5. Patient comfort and safety
6. Determination of delivered "actual" dose
7. Tumor response assessment

What's Really Important?

Things that tend to be OK:

- Gradient nonlinearities.
- B_0 field shim.
- Eddy currents.

Things that tend to be problems:

- Patient compliance (e.g., motion) and size.
- Tissue interaction with fields: Shim and susceptibility.
- SNR, CNR, and RF coil performance.
- Patient Safety:
  - Specific absorption rate (SAR) and patient heating.
  - Metal.

What I want: *In vivo* measurement/correction of geometric distortions.*

*e.g., JC Lau et al., Neuroimage in press.

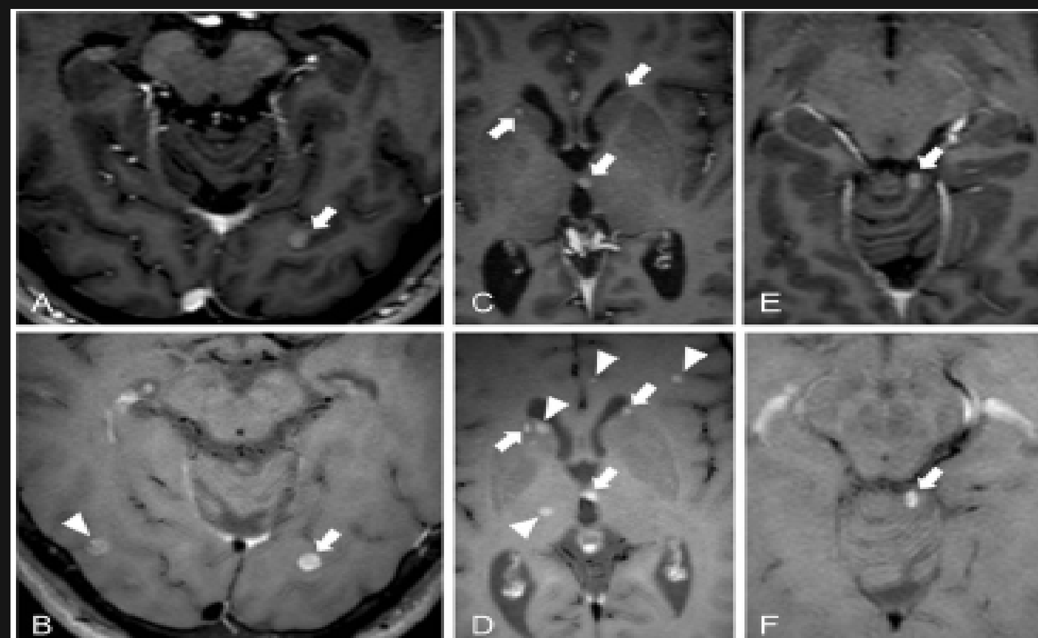
Optimization

Is 3D T1W TSE better than MPRAGE for detecting lesions?

After Gd Administration

3D T1W MPRAGE
(TE/TR: 6.7/12 ms
0.8x0.8x0.8 mm, 8^0)

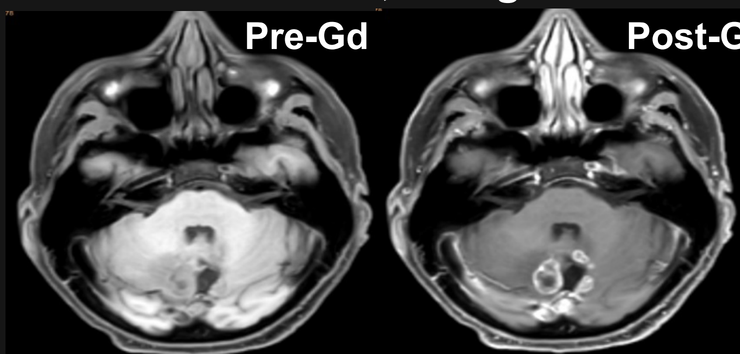
3D T1W TSE+SPIR
(mVISTA)
(TE/TR: 24/700 ms
0.8x0.8x0.8 mm)



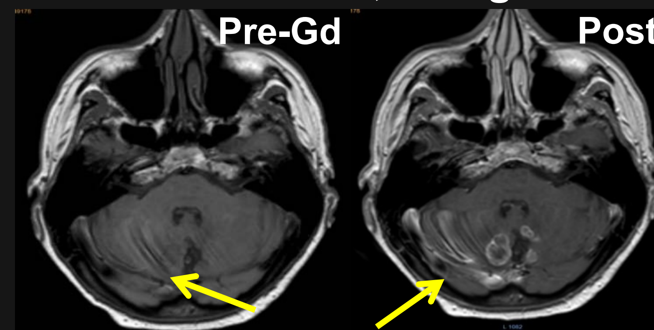
NN Kammer et al., Eur Radiol 26:1818-1825 (2016)

3D vs. 2D T1Ws (1.5 T)

3D TSE
TE/TR: 10/500 ms
1x1x1.2 mm, 819 Hz/Pixel
TA: 318 s, 2 Avgs

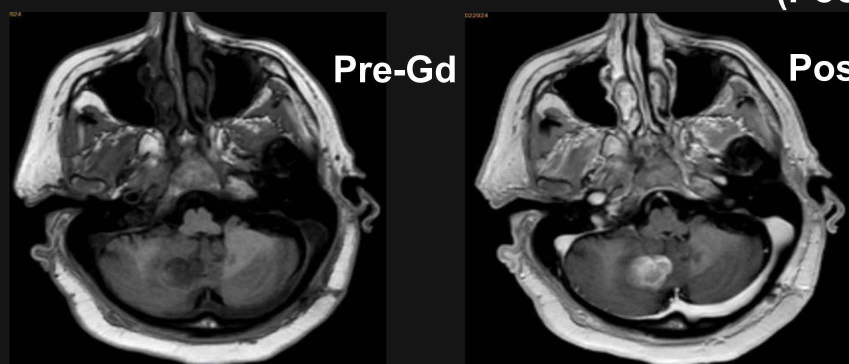


2D TSE
TE/TR: 15/732 ms
1x1x3 mm, 115 Hz/Pixel
TA: 274 s, 1 Avg



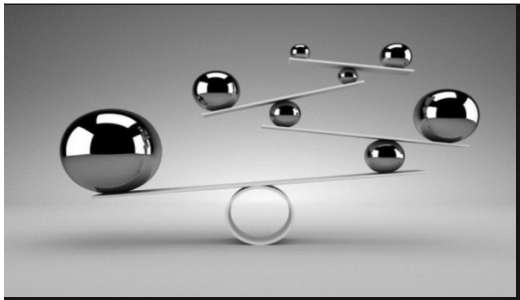
(Poor Flow Comp)

3D MPRAGE
TE/TR: 4/8 ms, 8^0
1x1x1.2 mm, 190 Hz/Pixel
TA: 429 s, 1 Avg



Different Patient

Takeaway: Benefit of 3D TSE appears small.



Tradeoffs: Receiver Bandwidth

Benefits of increasing receiver bandwidth:

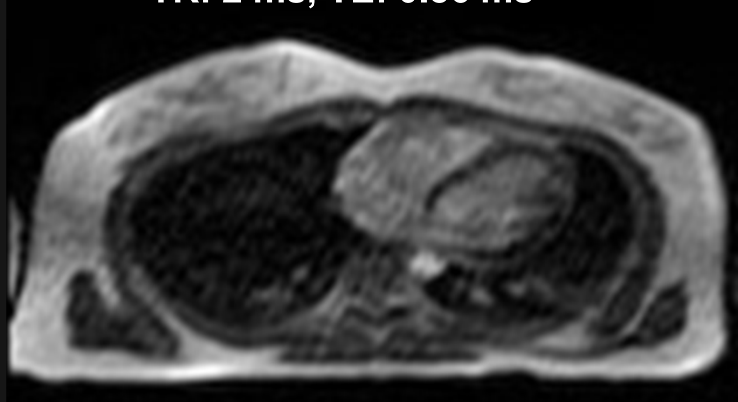
1. Minimizes chemical shift artifacts
   - Ideally rBW >3.5 ppm/pixel.
2. Minimizes geometric distortion
3. Reduces acquisition time

Disadvantages of increasing receiver bandwidth:

1. SNR drops.
2. Stress on hardware.
3. Echo interference?

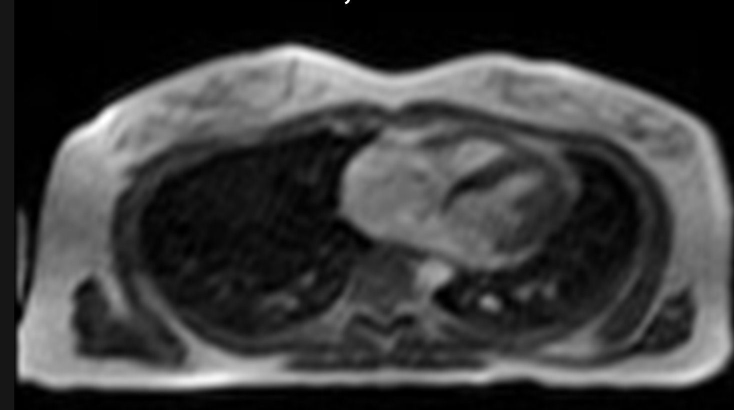
ViewRay (0.35 T):
Cardiac Imaging
TrueFISP

1502 Hz/pixel, 5/8 Fourier, GRAPPA 2,
TR: 2 ms, TE: 0.86 ms



103 ms/image

501 Hz/pixel, 5/8 Fourier, GRAPPA 2,
TR: 2 ms, TE: 0.86 ms



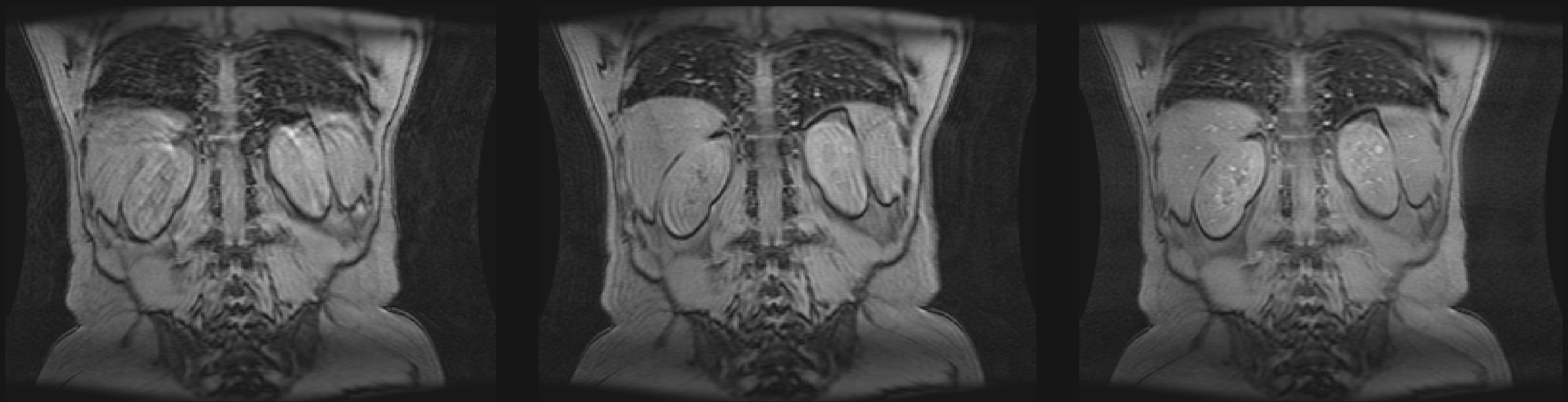
160 ms/image

MUTROG044

Takeaway: Slowing down may improve image quality.

Respiratory Motion (1.5 T)

Coronal 3D Fast Gradient Recalled Echo (T_1 weighted)



Free-Breathing

Breathhold

Navigator-Echo Gating

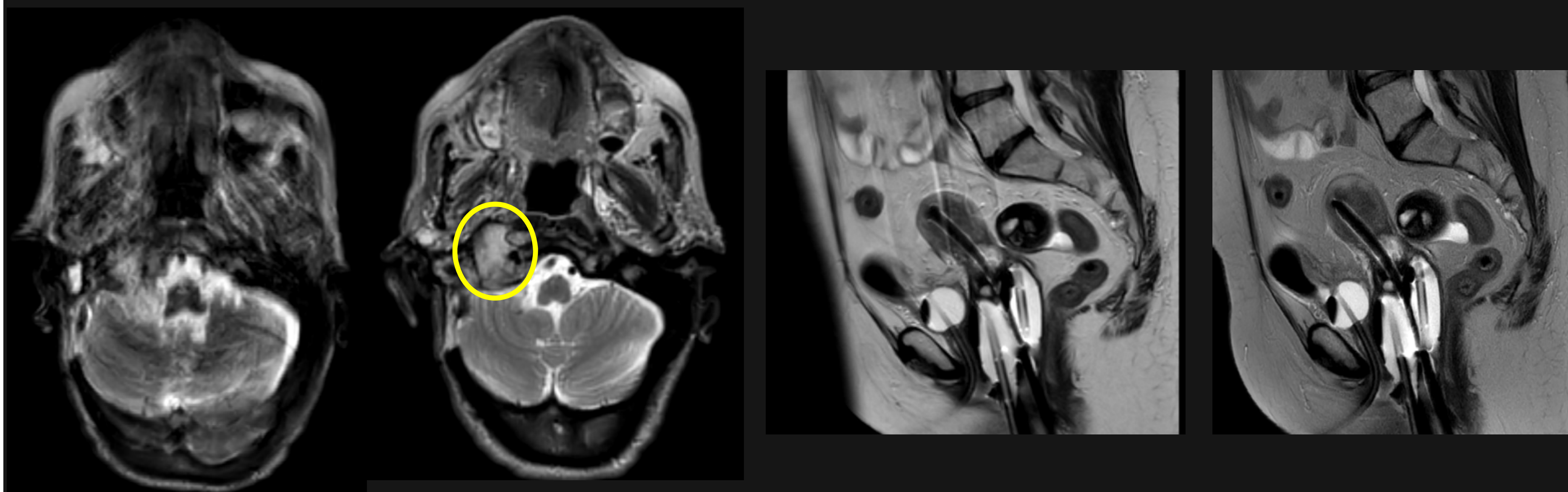
Motion: 2D vs. 3D

2D: Displacements between slices.
- Even with respiratory gating/triggering.
- Not good for treatment planning.

3D: Motion gets averaged into volume.
- Artifacts may affect all slices.

Motion Compensation - Philips MultiVane (1.5 T)

2D TSE T2W	2D MultiVane T2W	2D TSE T2W	2D MultiVane T2W
TE/TR: 0.1/12 s	TE/TR: 0.11/4 s	TE/TR: 0.1/1.9 s	TE/TR: 0.11/4 s

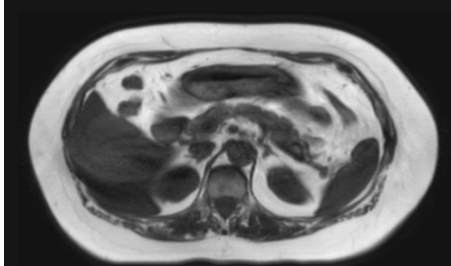


7-18-2017: First day after MV installation

Single-Breathhold 3D Acquisitions
Can We Simulate 0.35 T at 1.5 T?

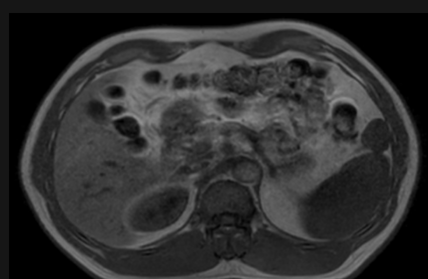
The Target:
VR 3D Sim
T2/T1 TrueFISP
0.35 T
1.5x1.5x5 mm

3D T2W ViewTSE
(1.6x1.6x3 mm resolution)
rBW: 285 Hz/pixel
TE/TR: 71/326 ms
60 Slices/Slab
TA: 21 s/image



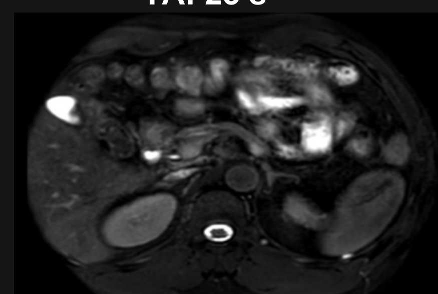
MUTROG073

3D T1W Dixon VIBE
(1.6x1.6x5 mm resolution)
TE1/TE2/TR: 3/5/6 ms
rBW: 677 Hz/Pixel
70 Slices/Slab
TA: 17 s

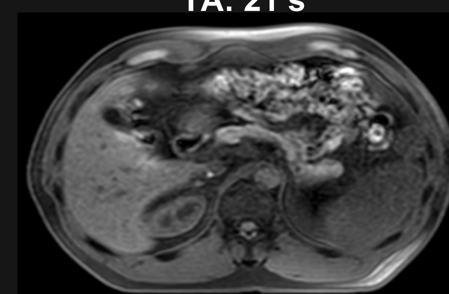


Gachtest08222016

3D bTFE Fat Suppressed
(1.6x1.6x6 mm resolution)
TE/TR: 2/4 ms
rBW: 1603 Hz/Pixel
50 Slices/Slab
TA: 23 s



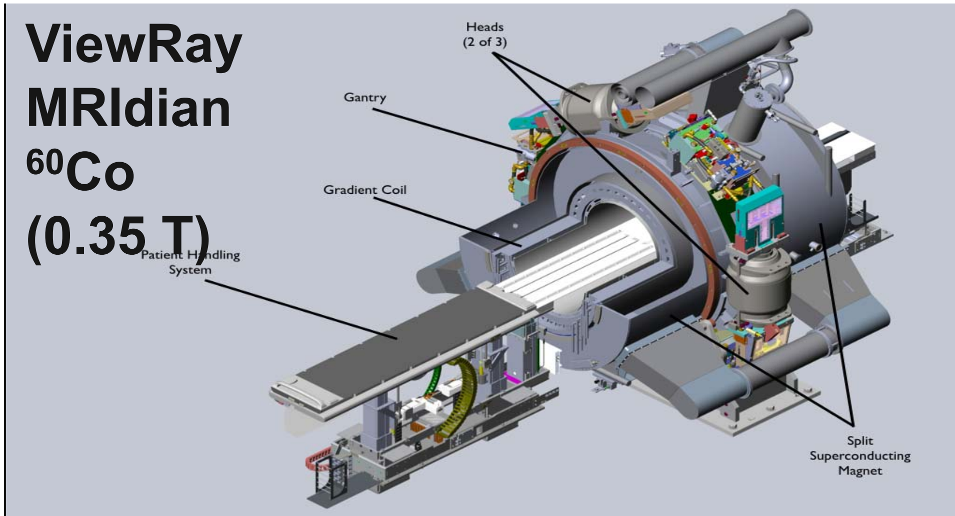
3D T1W WAVE (MagPrep)
(1.6x1.6x4 mm resolution)
TE/TR: 4/8 ms
rBW: 722 Hz/Pixel
60 Slices/Slab
TA: 21 s

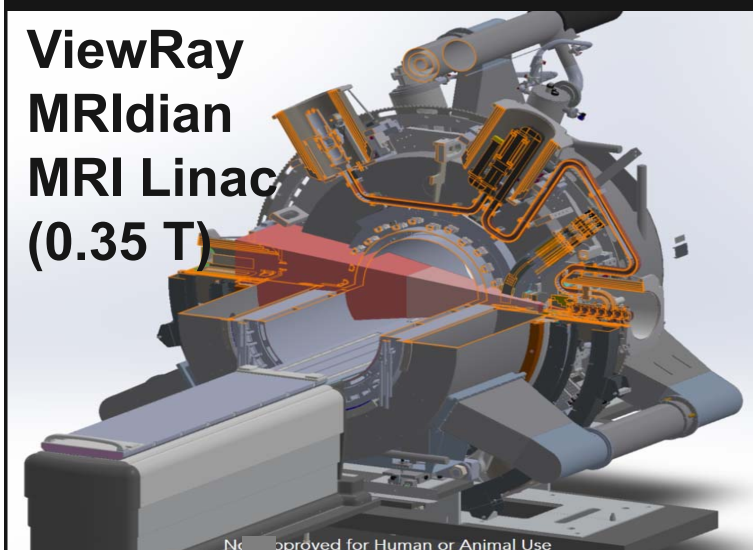


Gachtest08222016

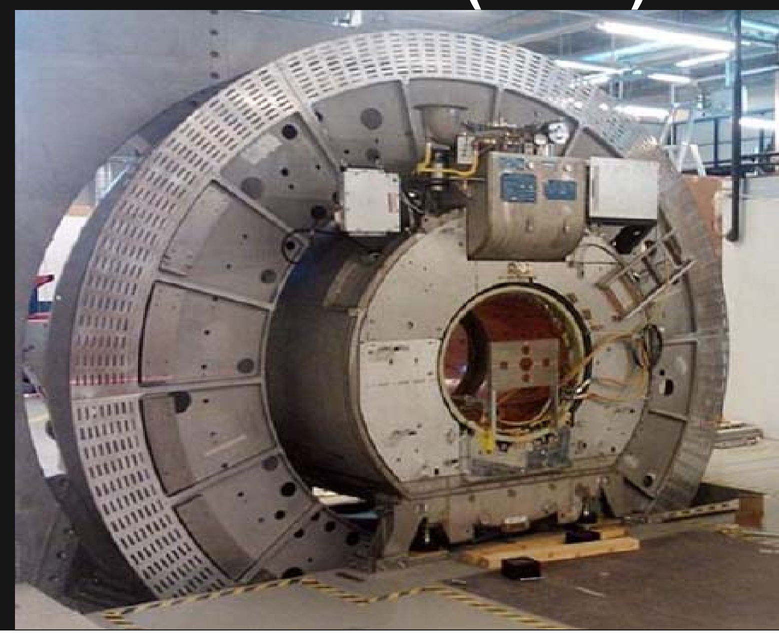
Takeaway: Need T_1 and T_2 values to optimize sequences.

Commercial MRI-Guided Radiotherapy



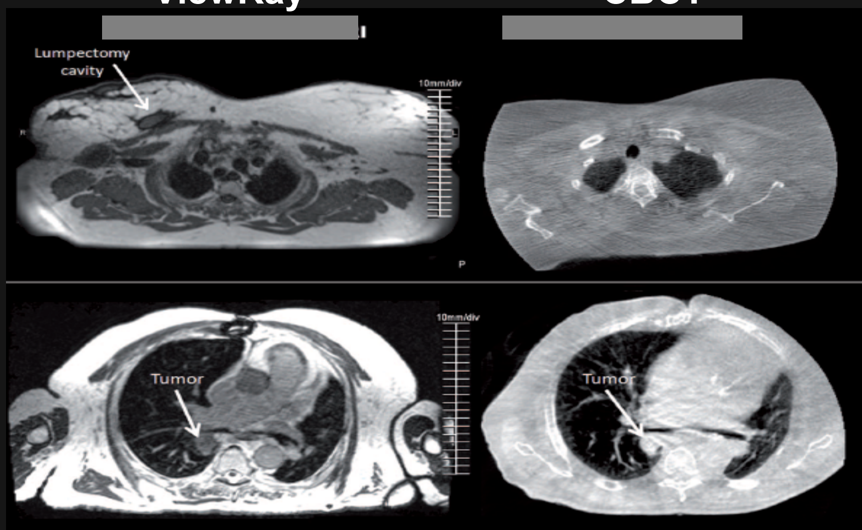


Elekta Unity
MRI-Linac (1.5 T)

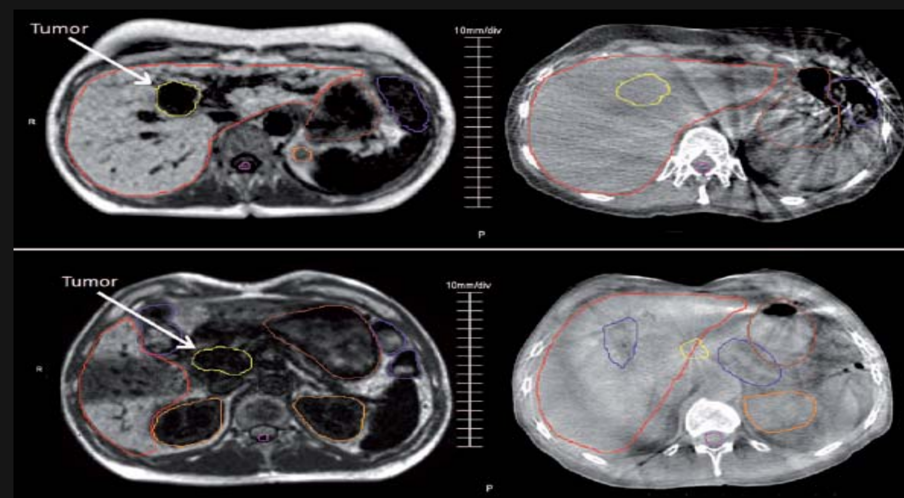


Why MRIgRT?

ViewRay | CBCT



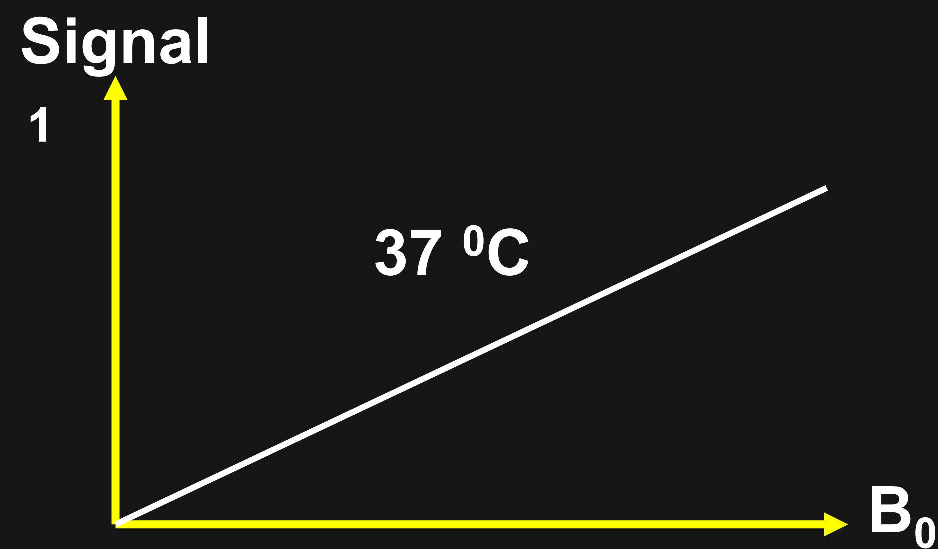
ViewRay | CBCT



C. Noel et al., Acta Oncologica 54(9):1474-1482 (2015)

Why High Field? More Signal

The NMR Signal is proportional to the net magnetization:



The NMR signal is very small:
a net of 10 out of 1 million protons will be in the ground state (3 T, 310 K).

Why Low Field?

Pros:

- Electron return effect minimally impacted by magnetic field.
- Reduced inhomogeneities, susceptibilities, and geometric distortion.
- SAR does not restrict duty cycle & pulse amplitudes.
- Shorter T_1 can lead to shorter TRs and faster acquisitions.
- High CNR in TrueFisp.
- Reduced safety concerns (Lorentz/Lenz) for implants.
- Negligible chemical shift.

Cons:

- SNR and image resolution are constrained.
- Cannot saturate fat signal.

1) F. G. Shellock, Ed. Magnetic Resonance Procedures: Health Effects and Safety. CRC Press. 2000.
2) R. W. Brown et al., Magnetic Resonance Imaging: Physical Principles and Sequence Design. Wiley-Blackwell 2014.

ViewRay

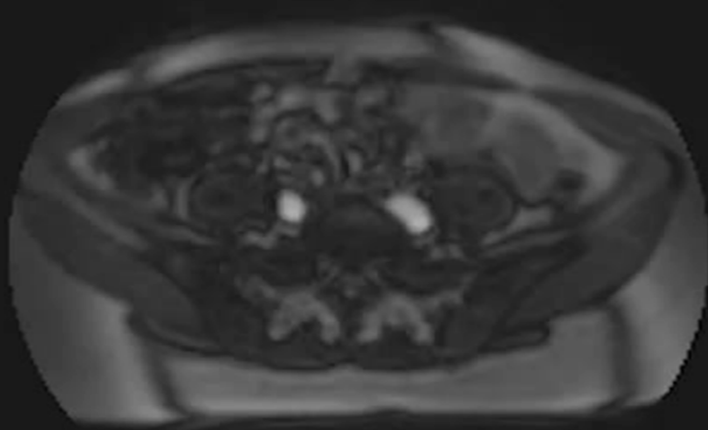
- 3D Simulation and 2D real-time imaging use TrueFISP
  - Balanced steady-state free precession (bSSFP)
  - T_2/T_1 weighted contrast. High CNR at low field.
  - Popular for cardiac MRI
  - Short TE and TR
  - Lower SAR than TSE
  - Vulnerable to field inhomogeneities
- Other sequences can be run in MRI-only mode.
- MRI uses Siemens hardware and software (IDEA/ICE).

1) R. W. Brown et al., Magnetic Resonance Imaging: Physical Principles and Sequence Design. Wiley-Blackwell 2014.
2) K. Scheffler and J. Henning. MRM 40:395-397 (2003).
3) B. Hargreaves. JMRI 36(6):1300-1313 (2012).

ViewRay (0.35 T)

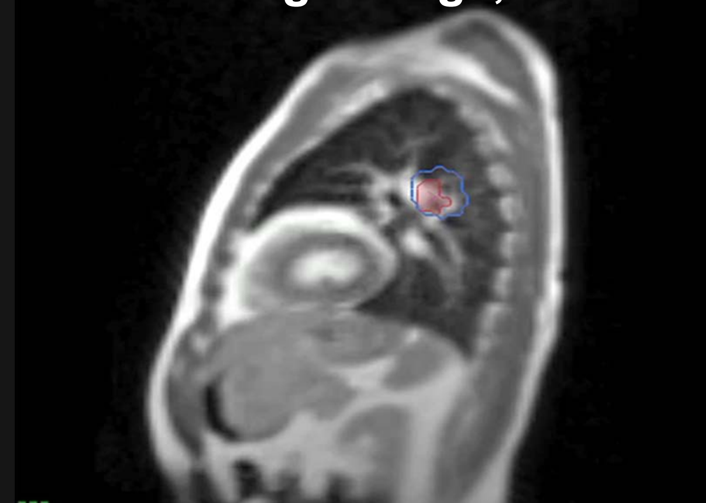
3D Simulation

TE/TR: 1.6/3.8 ms, 1.5 mm resolution
>500 Hz/pixel, > 17 s
6/8 Fourier, GRAPPA 2, FA: 60^0



2D Cine

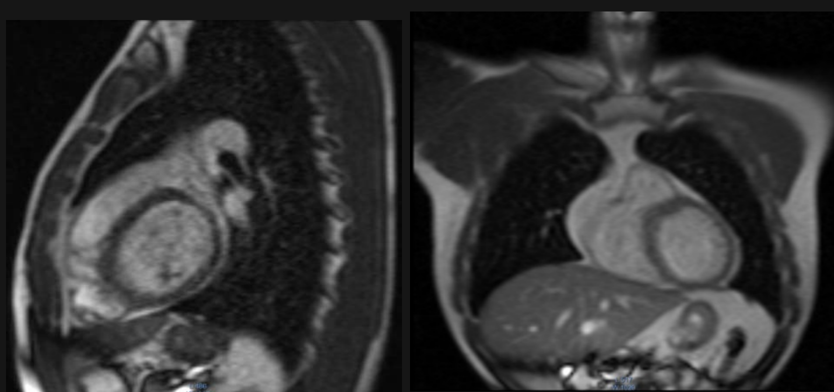
TE/TR: 1/2 ms
6/8 Fourier, GRAPPA 2,
3.5 mm resolution
2 Avgs, >1000 Hz/pixel
0.25 s/avgd image, FA: 60^0



2D TrueFISP vs. Field Strength

0.35 T

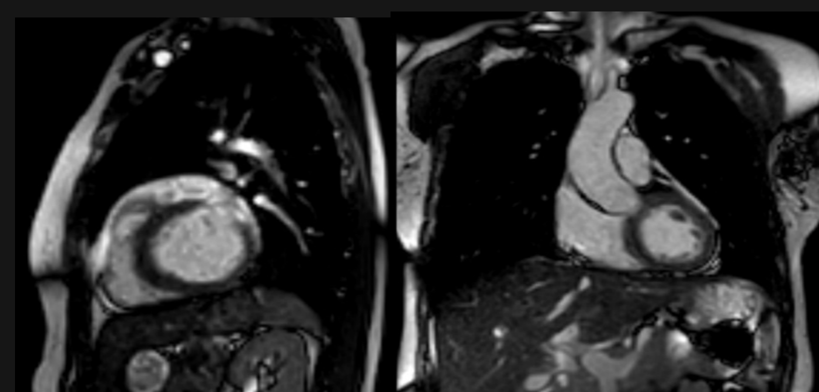
2D TrueFISP
(2.5x2.5x5 mm resolution)
rBW: 300 Hz/pixel
TE/TR: 2/4 ms
TA: 0.4 s/image



MUTROG050
(No Distortion Correction)

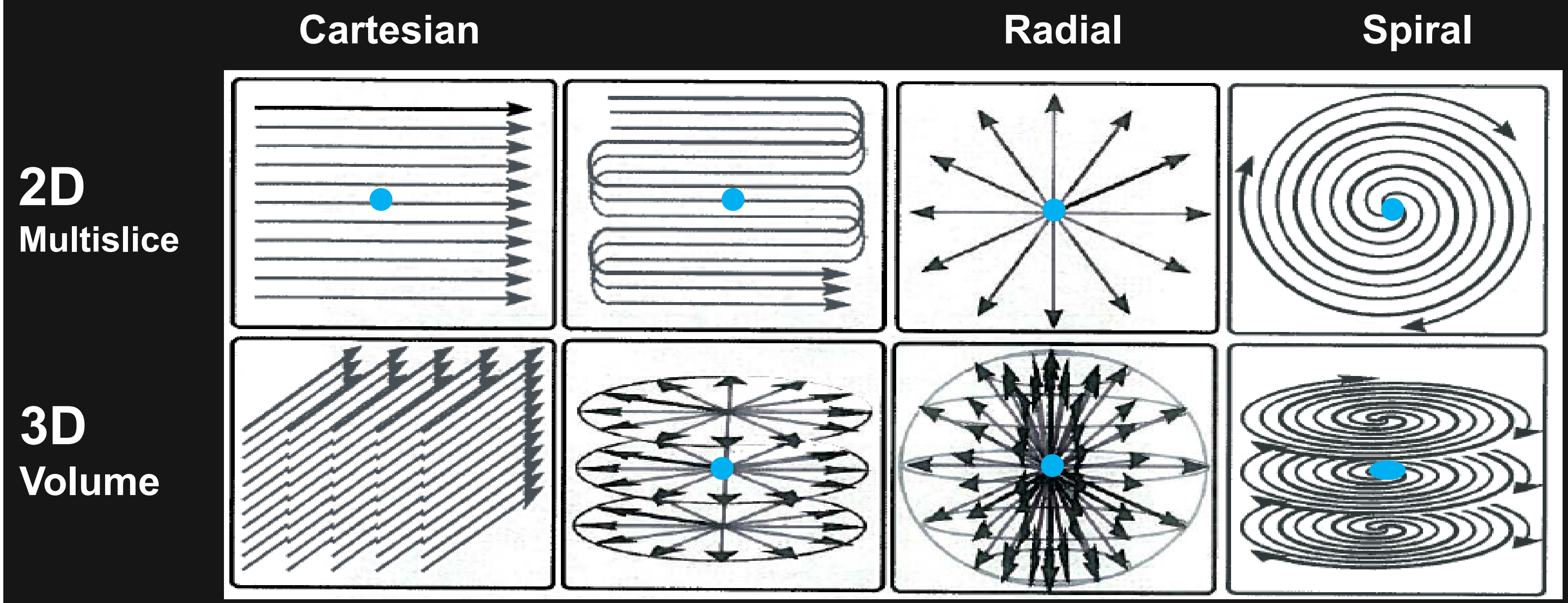
1.5 T

2D bTFE
(2.5x2.5x5 mm resolution)
rBW: 1417 Hz/pixel
TE/TR: 1/3 ms
TA: 0.3 s/image



MUTROG080

k-Space Trajectories



Center of k-space

M. Lustig et al., Technical Report No. 2007-3. Stanford University

Why Radial Trajectory for Fast Imaging?

Pros:

- Can optimize temporal resolution by updating k-space using moving window.
- Can get quality images despite undersampling.
- Less sensitive to motion than Cartesian.

Cons:

- Reconstruction is more complicated than Cartesian.
- Reconstruction time may preclude real-time reconstruction.
- Need $\pi/2$ times higher number of k-space samples vs. Cartesian to avoid undersampling.
- Parallel imaging may be more challenging.
- Vulnerable to field inhomogeneities and gradient errors.

ViewRay (0.35 T) Radial TrueFISP

Healthy Volunteer
(3 mm Resolution)

Arrhythmia Patient
(2.5 mm Resolution)

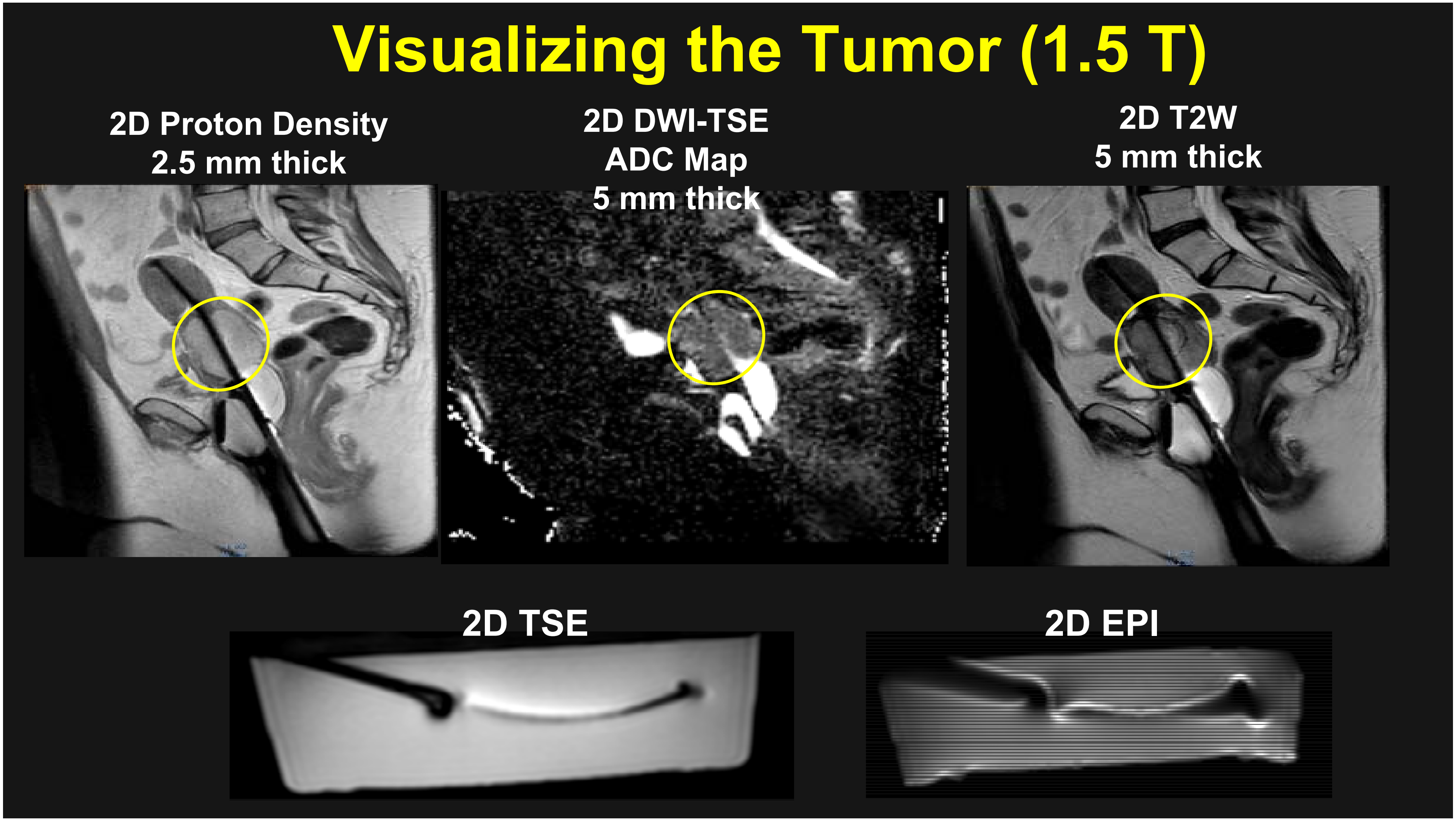
0.17 s/image, 112 Radial lines, Flip angle: 110^0

MRI-Based Brachytherapy
1.5 T

Brachytherapy MRI Priorities

1. Tumor delineation
2. Implant delineation
3. Fiducial marker delineation

Per Perry Grigsby MD



Visualizing the Tumor (1.5 T)
2D Proton Density
2.5 mm thick
2D DWI-TSE
ADC Map
5 mm thick
2D T2W
5 mm thick
2D TSE
2D EPI

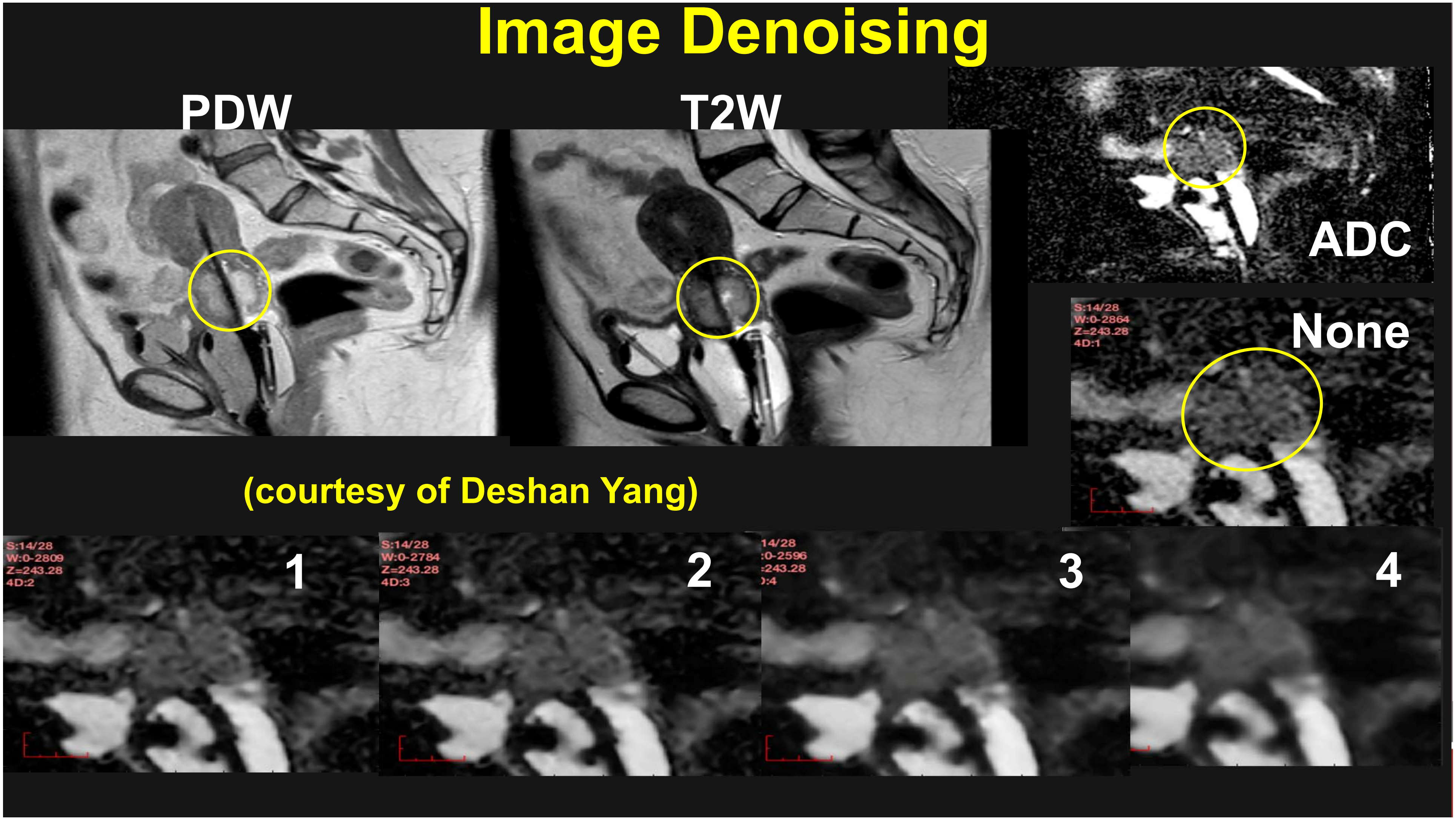


Image Denoising
PDW
T2W
ADC
S:14/28
W:0-2864
Z=243.28
4D:1
None
(courtesy of Deshan Yang)
S:14/28
W:0-2809
Z=243.28
4D:2
1
S:14/28
W:0-2784
Z=243.28
4D:3
2
14/28
:0-2596
:243.28
):4
3
4

Suppressing Metal Artifacts

- Use spin echo acquisitions
- Increase receiver bandwidth
- Use wide bandwidth RF excitations
- Use metal artifact reduction sequences
  - View angle tilting
  - Z-shimming
- Change readout axis
- Avoid high-field systems (e.g., 3 T)

1) W. Lu et al., MRM 62:66-76 (2009).
2) B. Hargreaves et al., AJR 197:547-555 (2011).
3) R. V. Olsen et al., Radiographics 20: 699-712 (2000).

Philips O-MAR

- New product.

- Comes in slice encoding for metal artifact correction (SEMAC) or metal artifact reduction sequence (MARS) versions.
  - SEMAC addresses in-plane and through-plane artifact.
  - MARS addresses in-plane artifact.

- Can be selected with most weightings (PD, T_1, T_2, and STIR).

- Requires additional acquisition time.

- May reduce SNR unless acquisition time is increased.

- Image contrast may differ from conventional images.

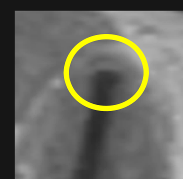
Lu et al., MRM 62(1):66-76 (2009). Kolind et al., JMRI 20:487-495 (2004). Cho et al., Med Phys 15:7-11 (1988).

Susceptibility & Conductivity

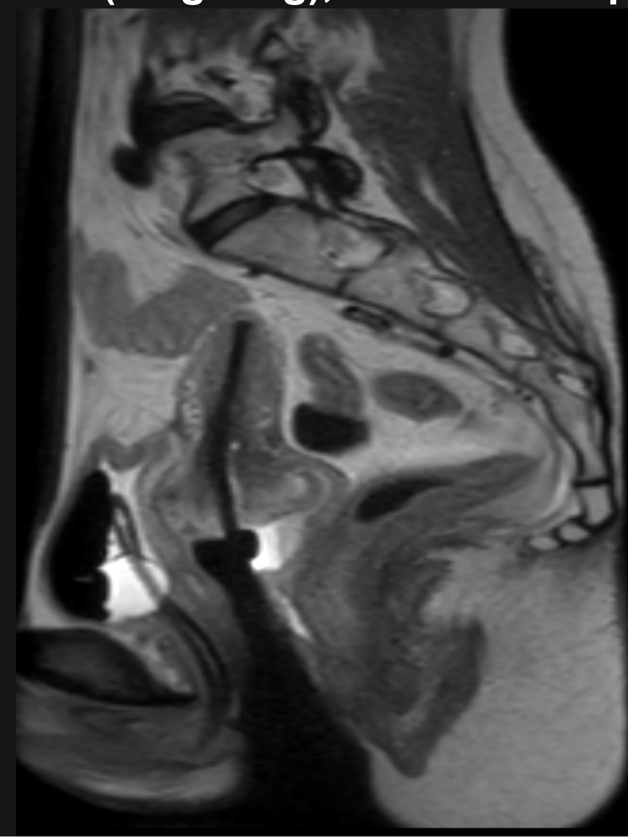
Material	Magnetic Susceptibility (ppm) X	Electrical Conductivity (S/m)
Gold	-34	44.2E6
Silver	-23.1	62.1E6
Iodine	-22.2	1E-7
Bone	-11.3	0.15
Copper	-9.63	58.5E6
Soft Tissue or Distilled Water	-9.05	0.6-1.0
Fat	-8.44	0.5
Air	0.36	0
Aluminum	22	36.9E6
Platinum	26	9.43E6
Tantalum	178	7.63E6
Titanium	182	2.38E6
Niobium	237	6.7E6
Nitinol	245	1.22E6
Cobalt-chromium	900	2.5E6
Cobalt-chromium-molybdenum	1300	1E6
Stainless Steel	3000-5000	1.5E6
Iron	2E5 - 2E11	10E6

O-MAR Proton Density

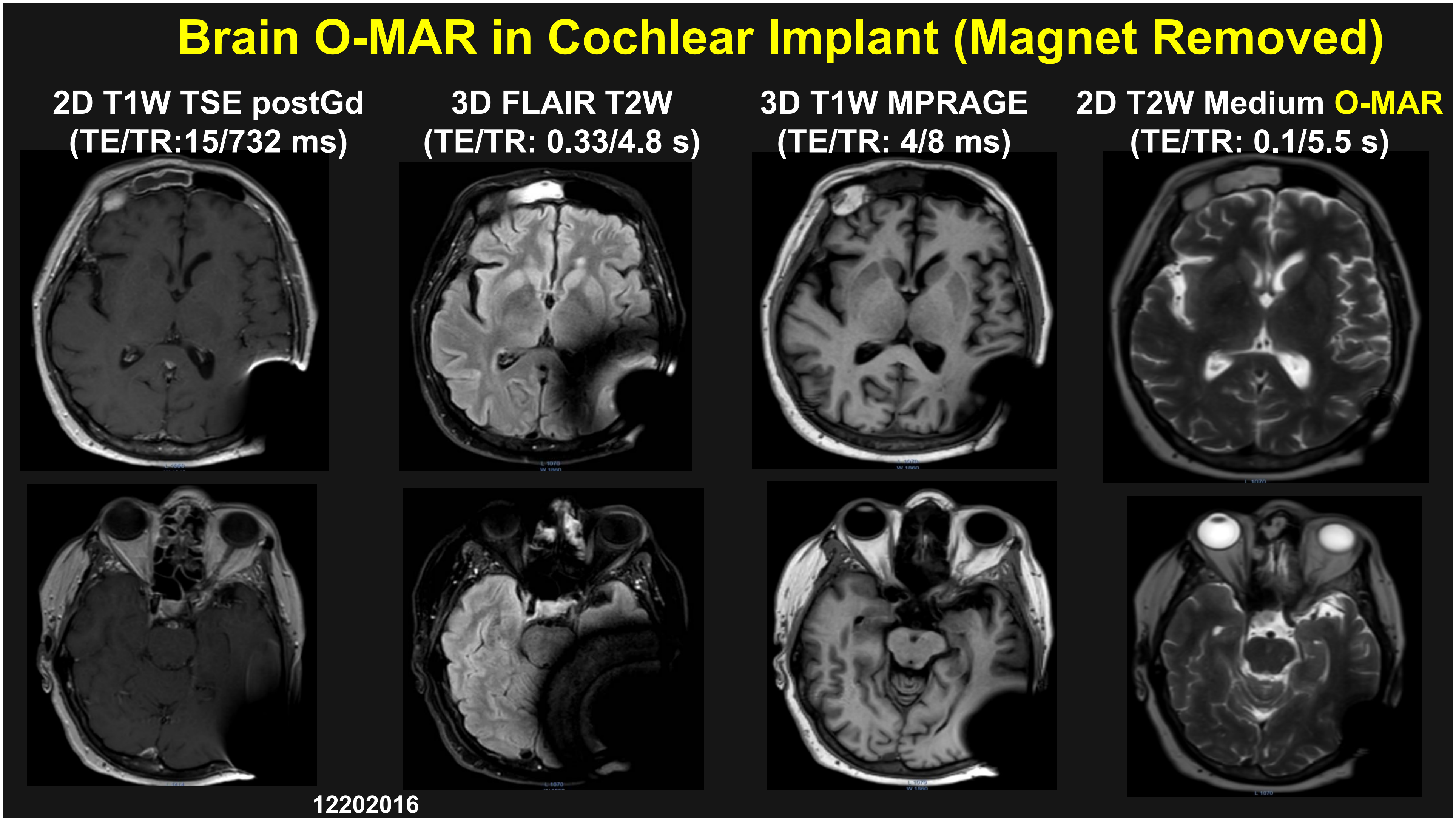
Nominal
2 Avgs, 2.5 mm thick, TE: 5 ms
TA: 336 s (with resp. gating)
rBW: 449 Hz/pixel



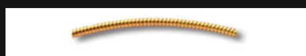
SEMAC (Medium)
1 Avg ,2.5 mm thick, TE: 30 ms
TA: 463 s (no gating), rBW: 943 Hz/pixel



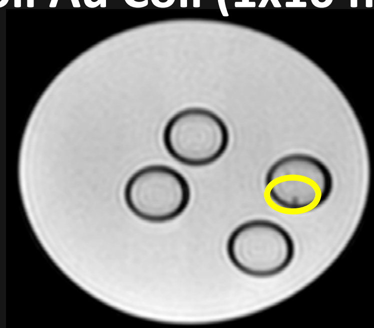
Rao Y. et al.
Physics Med
Biol,
62(8): 3011-3024
(2017).


Brain O-MAR in Cochlear Implant (Magnet Removed)
2D T1W TSE postGd
(TE/TR:15/732 ms)
3D FLAIR T2W
(TE/TR: 0.33/4.8 s)
3D T1W MPRAGE
(TE/TR: 4/8 ms)
2D T2W Medium O-MAR
(TE/TR: 0.1/5.5 s)
12202016

Proton Density MRIs of Fiducials
Goal: Conspicuous with minimal susceptibility

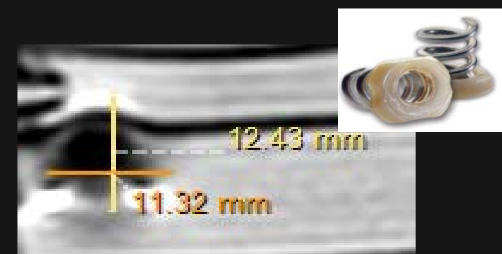


Visicoil Au Coil (1x10 mm)

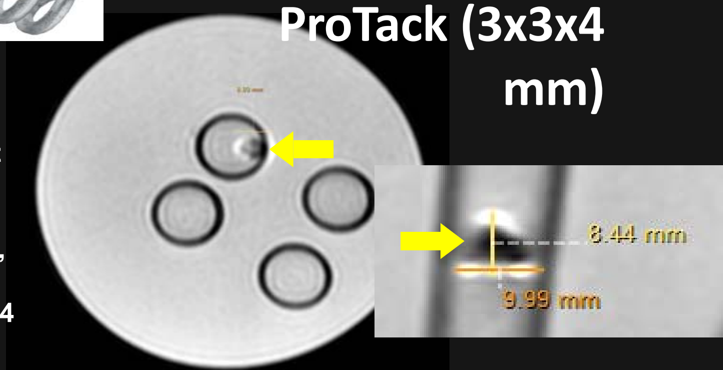


Civco Ti-Au Coil (1x10 mm)

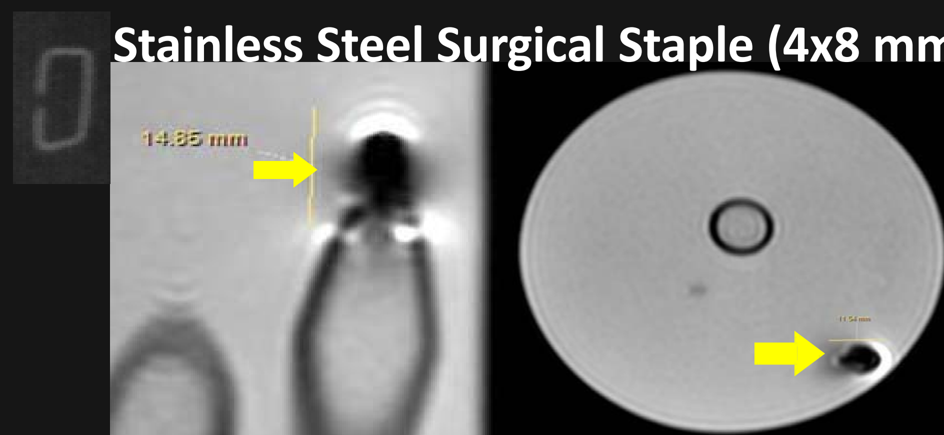
Bard CapSure Stainless Steel Tack (3x3x4 mm)



Medtronic Ti ProTack (3x3x4 mm)



Stainless Steel Surgical Staple (4x8 mm)



Rao Y. et al. Physics Med Biol, 62(8): 3011-3024 (2017).

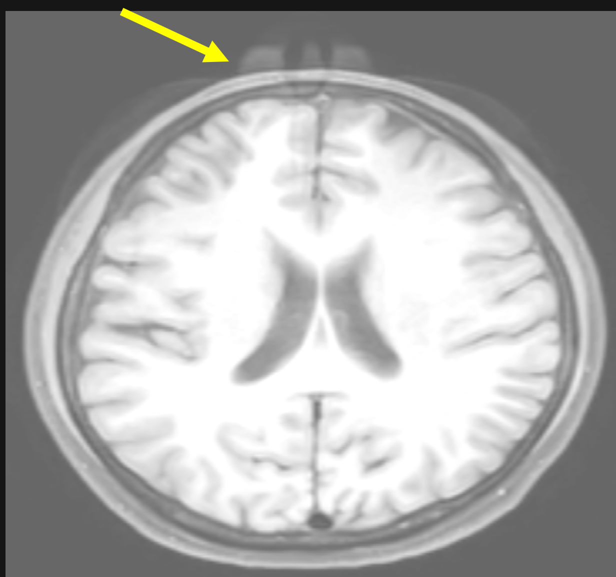
Troubleshooting

MR RT-Facts

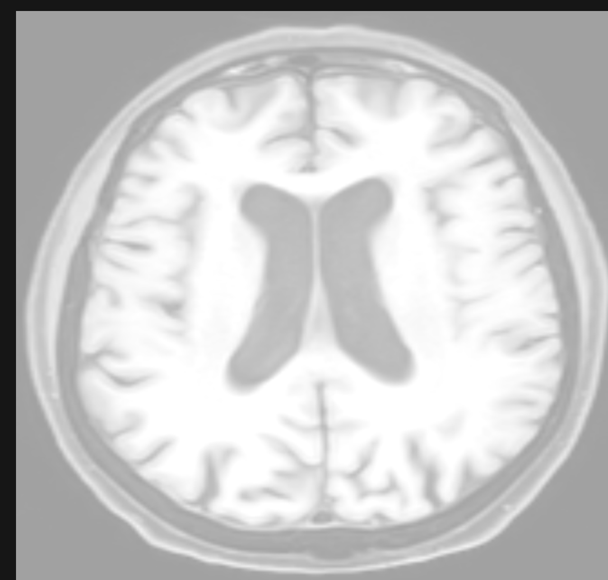
Aliasing (1.5 T)

3D TSE: TE/TR: 10/500 ms
1x1x1.2 mm, 819 Hz/Pixel, 2 Avgs

SENSE Factor 1.8 in both phase and slice directions

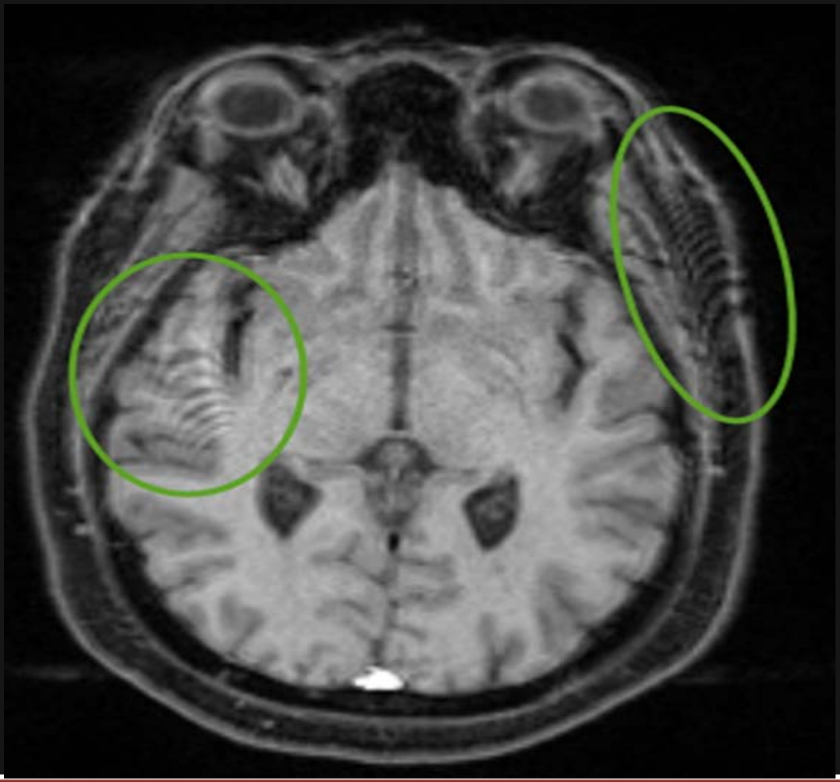


SENSE Factor 1.8 in phase dir. and off in slice direction



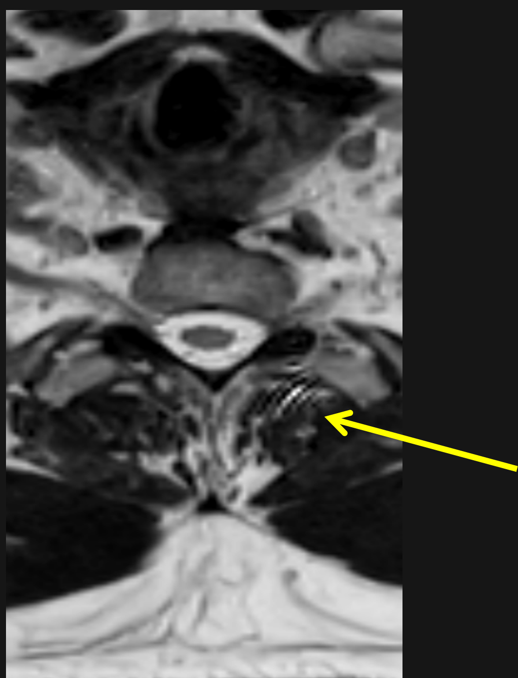
Moire Fringe Artifacts
(1.5 T Siemens Espree)

FL3D: TE/TR: 7.7/38 ms
BW: 90 Hz/pixel

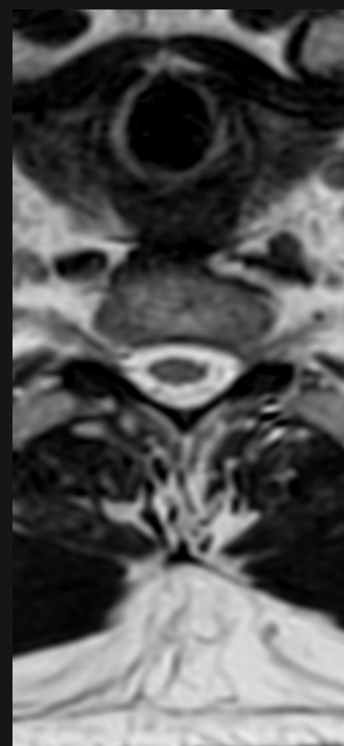


Moire Fringe Artifacts
(1.5 T Philips Ingenia)

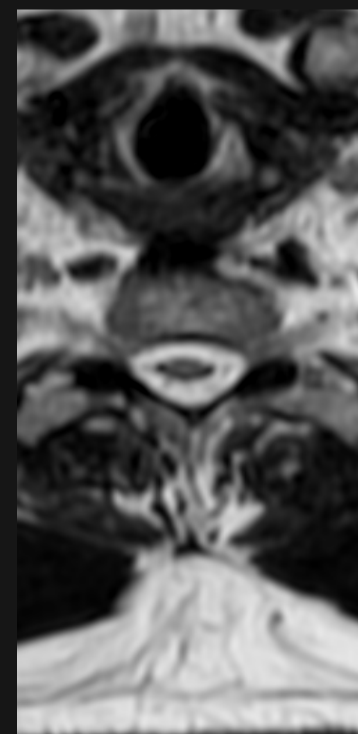
3D T2W Drive
TE/TR: 75/1400 ms



Strong Image Filter



FID Reduction
(Stronger crusher gradients)



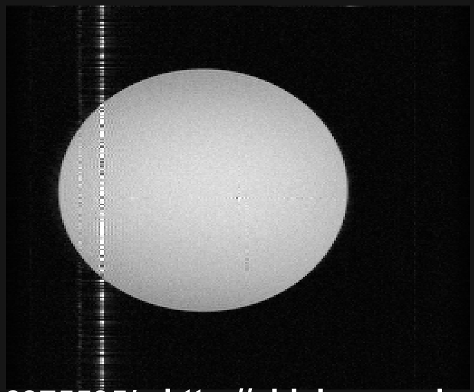
RF Spikes –
Searching for the needle in the haystack

● Manifests as white pixels, corduroy (herringbone) artifacts, or increased noise.

● Cause: metal-metal contact or RF source inside Faraday cage.

Examples:

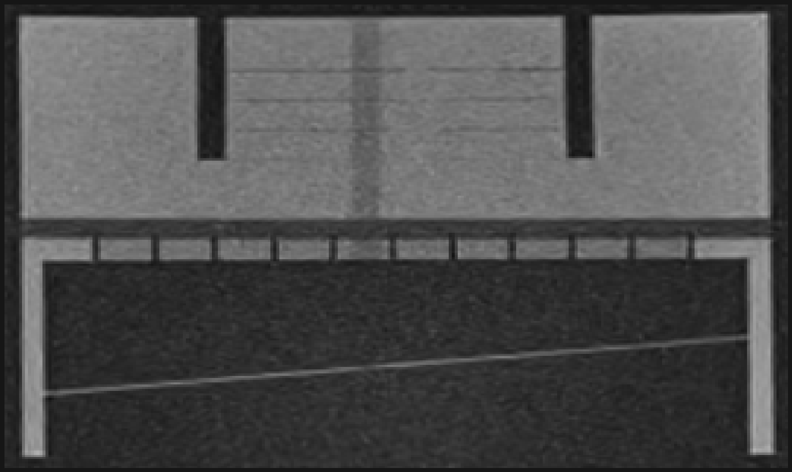
- Loose cables or broken conductors\components
- Improper lighting or electrical sources
- Failed line filters or Faraday cage seals
- (Gradient) resonant excitation of components



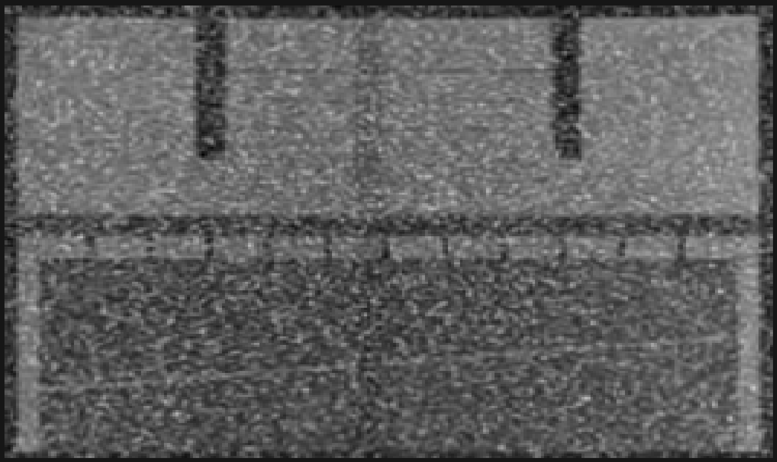
https://www.pinterest.com/pin/534309943266975595/ http://chickscope.beckman.uiuc.edu/roosts/carl/artifacts.html

RF Coil Troubleshooting
ViewRay (0.35 T)

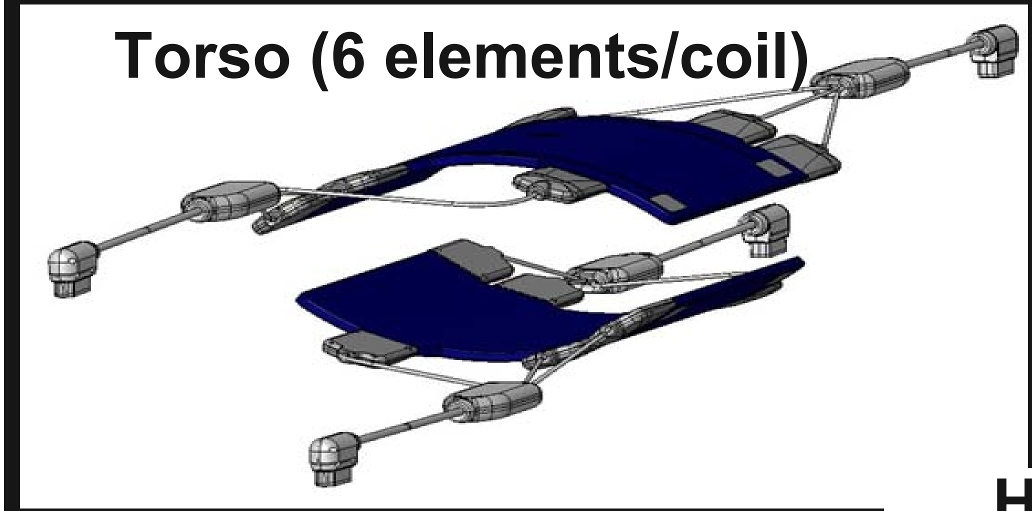
Expected Result



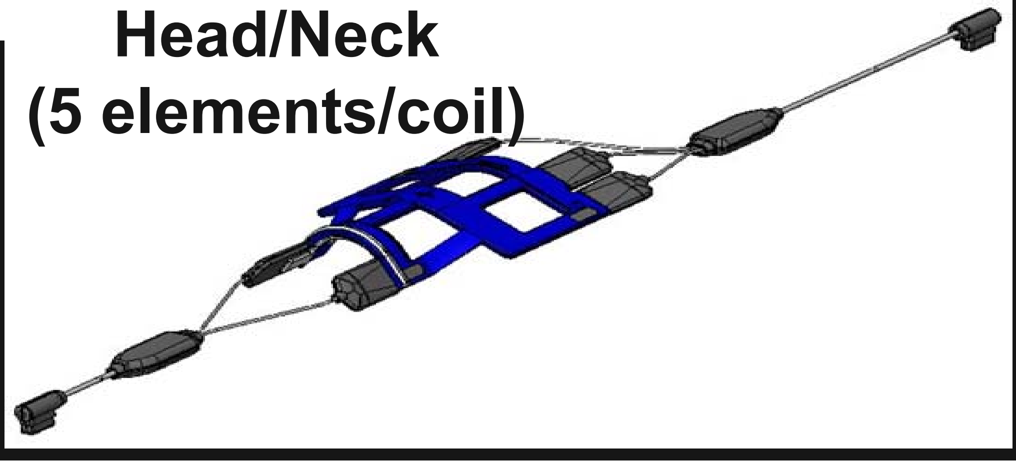
Bad Coil Element



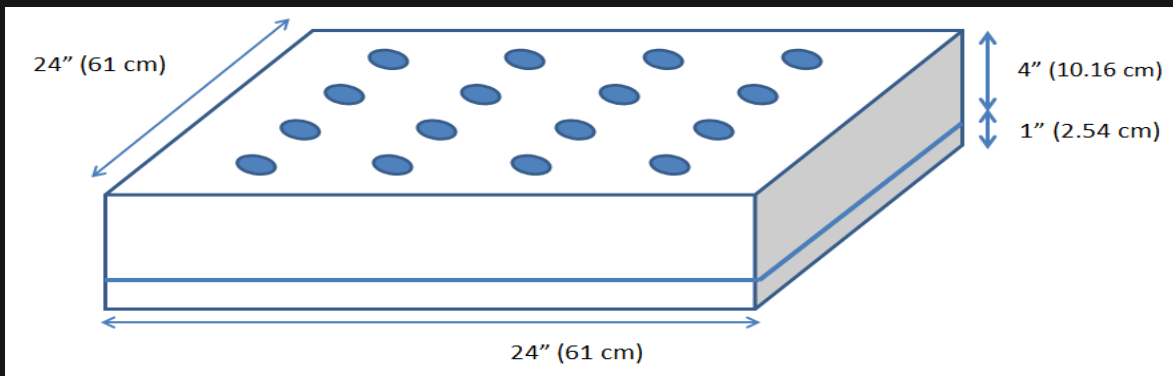
ViewRay Receive Coils



Coils are thin and flexible to minimize photon attenuation.



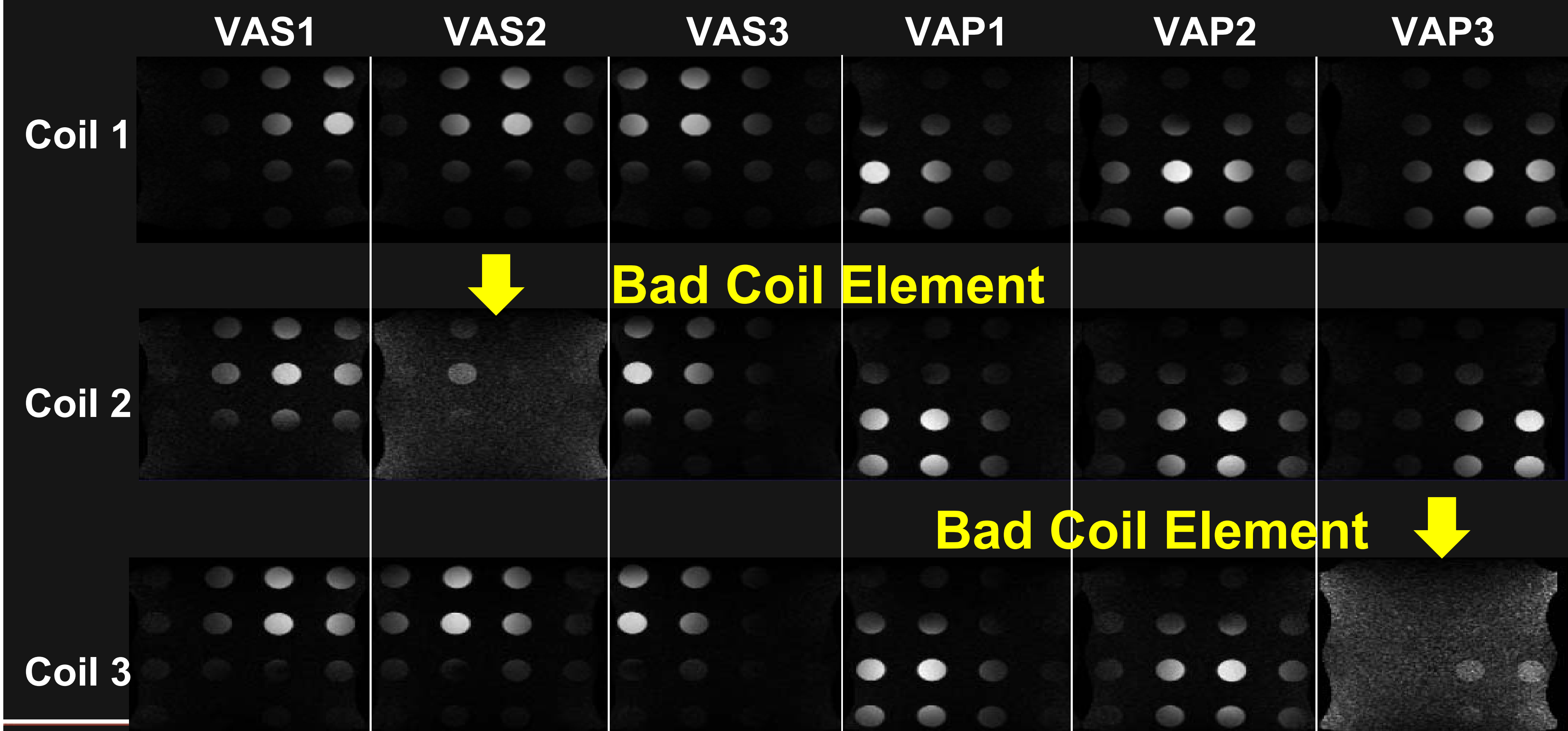
Phased Array Coil Test Phantom Holder



Add Load (e.g., Saline)

Bottles filled with $NiCl \cdot 6H_2O$ doped water

VR RF Phased Array Coil QA (6 Element Coil)

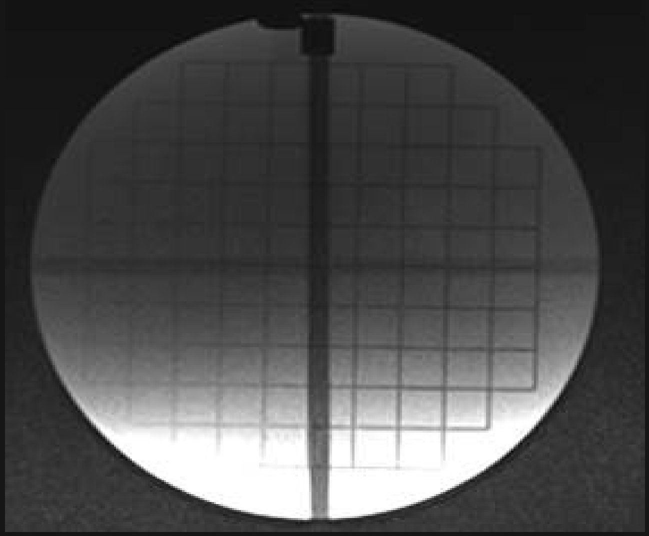


For more details see ePOSTER: MO-RPM-GePD-IT-5

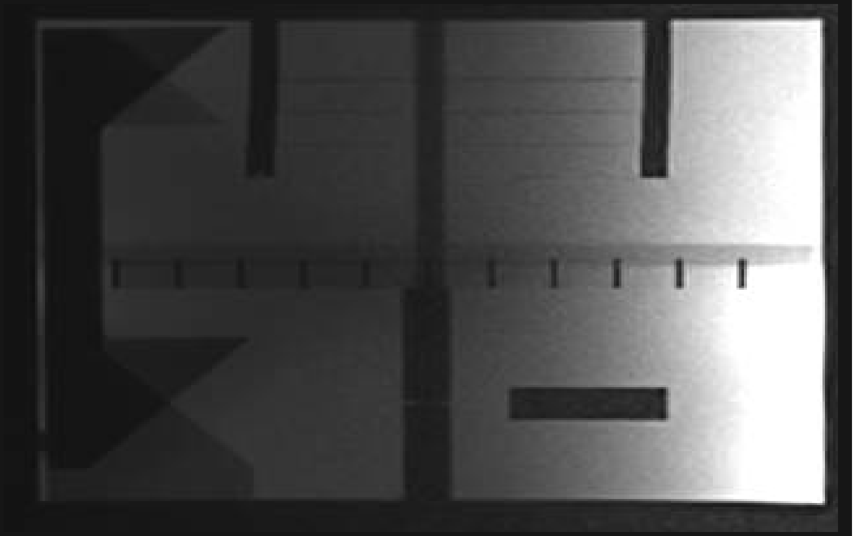
Oops!

Anterior coil has weak signal but passed phased array coil QA.

Anterior



Anterior



Solution: Add signal intensity uniformity test

Phased Array Coil Test Findings

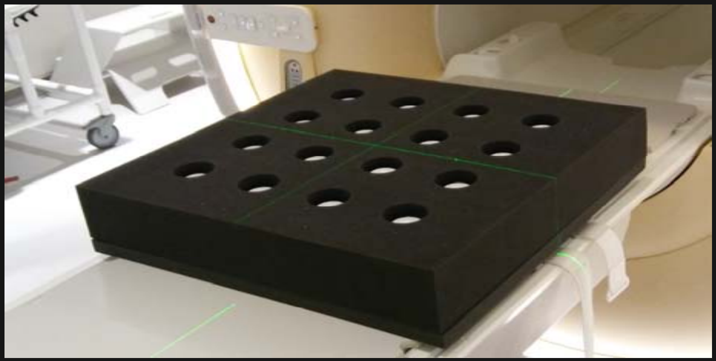
- VR coils fail frequently (e.g., every 1-2 months).

- The phased array coil QA test detects failed elements with coils laying flat.

- However, coils often fail only when flexed.

- Better troubleshooting solutions are needed.

Philips Ingenia 1.5 T MRI



Torso coil is more rigid and robust.

Stability Tests

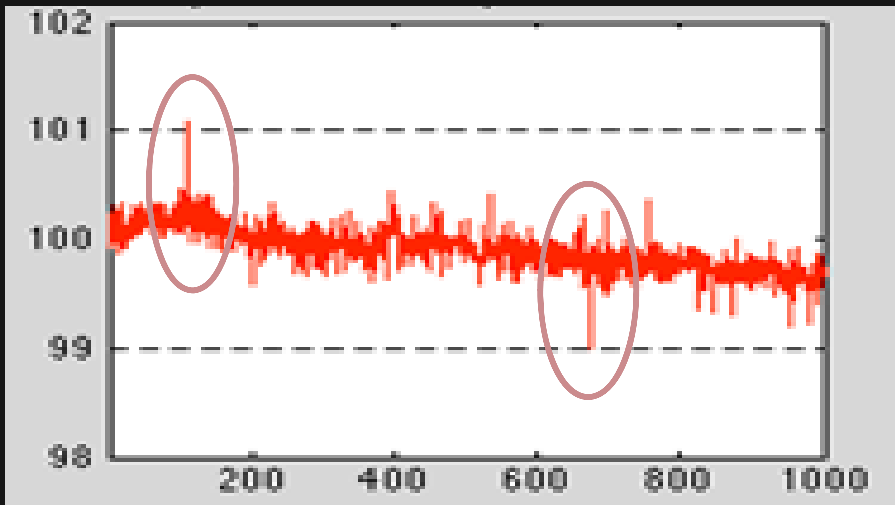
- Assess the stability of RF and gradient components (drivers and coils).
- Acquire longitudinal data during repeated scans.
- Stress the system and components, similar to actual operations.
- Can detect loose fittings and components (e.g., metal-to-metal contact) that can produce spike noise.
- Can detect issues that may not show up in a standard QA test (e.g., ACR).
- Spec will be based on manufacturer specs and baseline measurements.

1) L. Friedman and G. H. Glover. JMRI 23:827-839 (2006).
2) A. E. Campbell-Washburn et al., MRM 75(6):2517-2525 (2016).

3T EPI Stability Tests
(Siemens 3 T Trio)

BAD

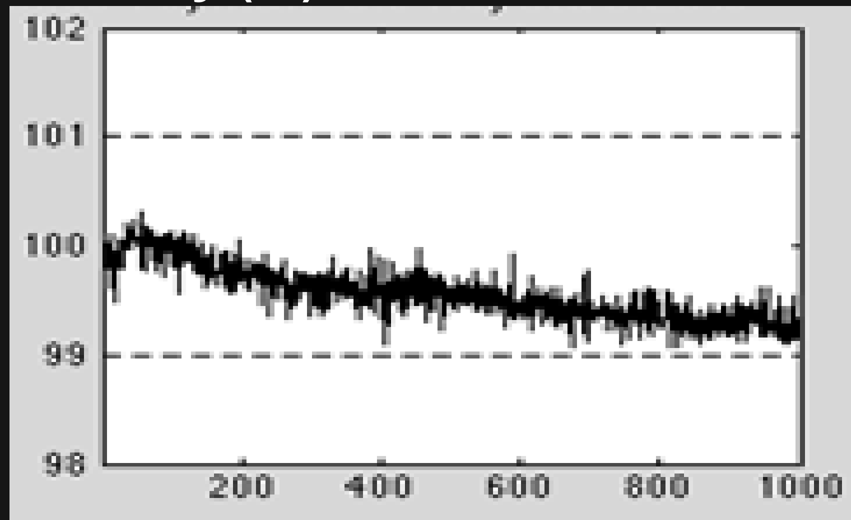
Arbitrary (%)



Repetition

GOOD

Arbitrary (%)



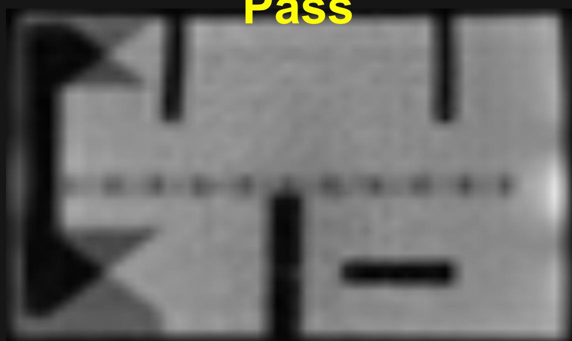
Repetition

EPI stability spec typically: +/- 0.25-0.5%

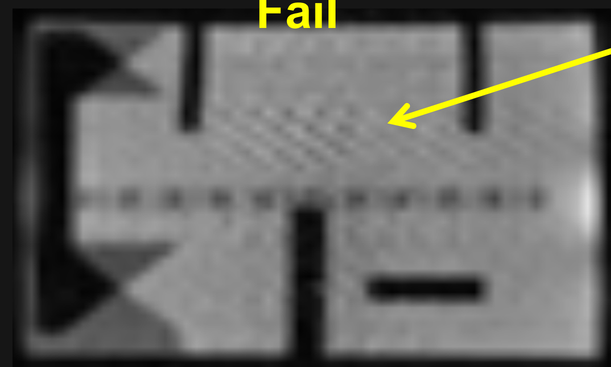
ViewRay (0.35 T) Stability

TrueFISP 3 Slices TE/TR: 1/2 ms

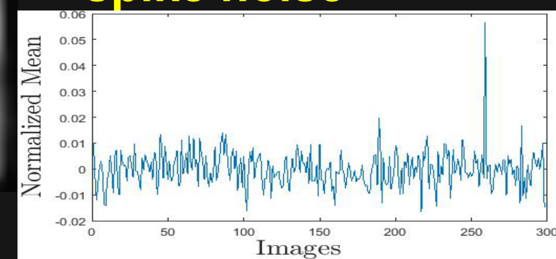
Pass



Fail



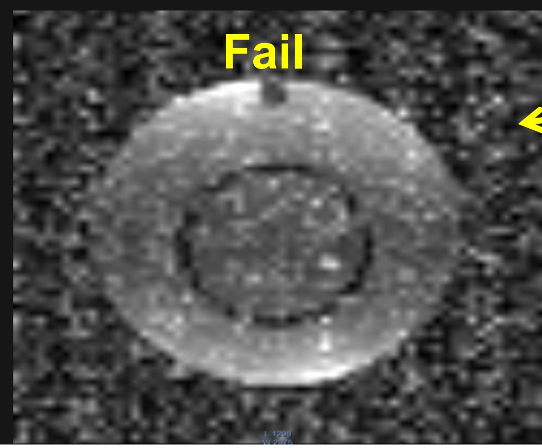
Herringbone pattern typical of RF spike noise



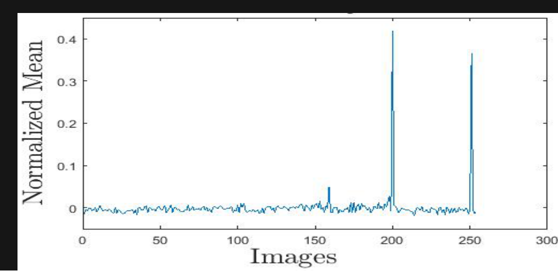
EPI 9 Slices TE/TR: 22/367 ms

Pass

Fail



White pixels



Summary

● MRI-based and MRI-guided RT is growing. More MRI-Sim and MRIgRT systems will be sited.

Optimization

● RT priorities may differ from diagnostic radiology priorities.

● MRI physicists are needed to help optimize protocols to meet the needs of RT.

Troubleshooting:

● RT demands high MRI performance for treatment accuracy.

● Lessons learned from diagnostic and research MRI should be applied to MRI in RT.

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- Olga Green
- Sasa Mutic
- Perry Grigsby
- Parag Parikh
- Cliff Robinson
- Deshan Yang

Questions?

This talk is dedicated to:

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Father of Pulsed NMR
June 9, 1921 –
Sept. 20, 2016

Peter Mansfield
Co-Inventor of MRI
Oct. 9, 1933 –
Feb. 8, 2017

Josef Dadok **Aksel**

Aksel Bothner-By
High-Field NMR Pioneer
April 29, 1921 –
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