MR Basics II: MR imaging for treatment planning

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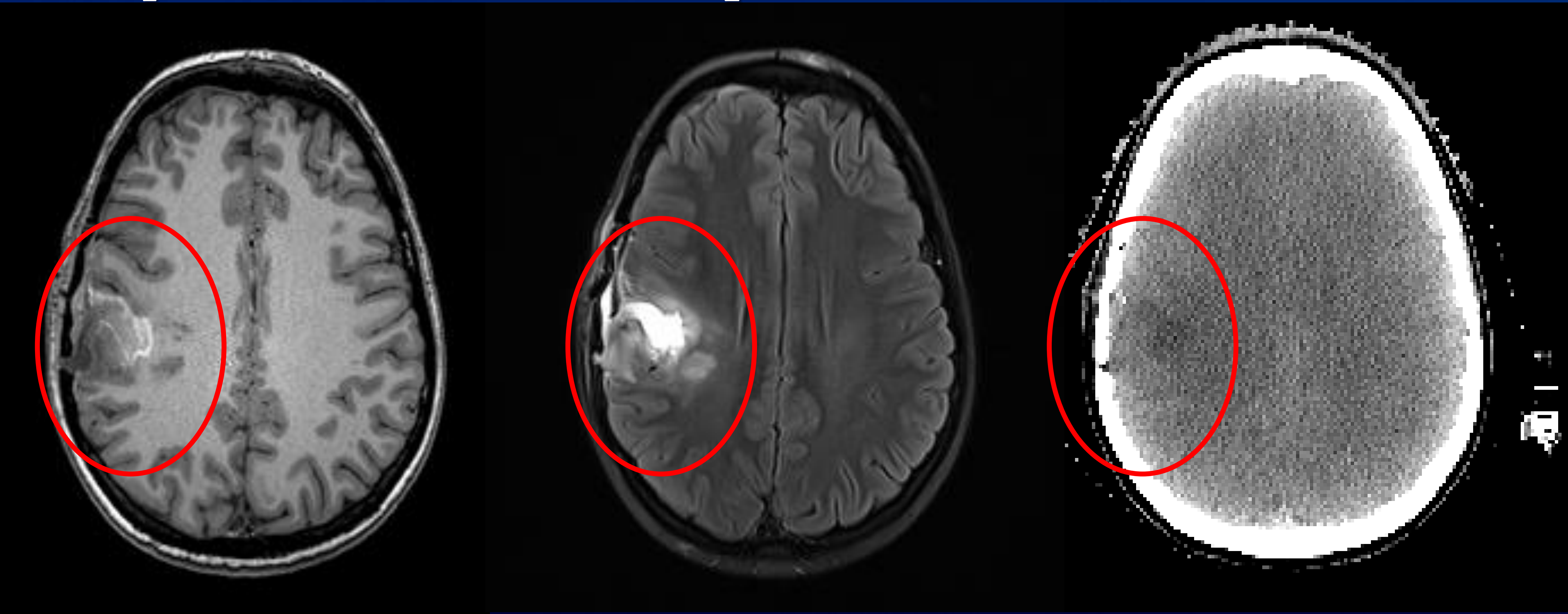
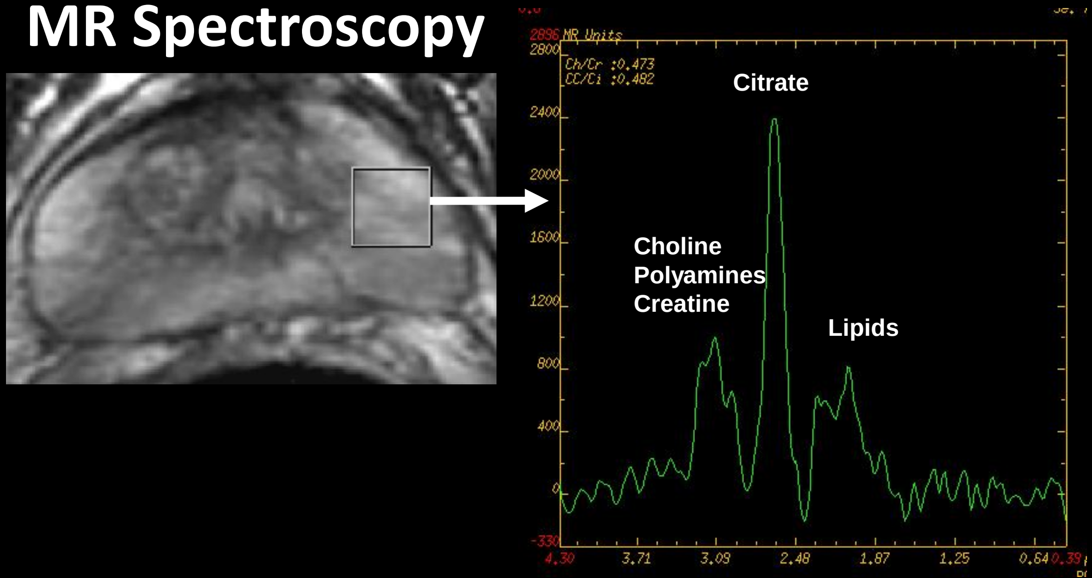
Imaging in Radiation Therapy: MR or CT?

T_1-Weighted T_2 FLAIR In Treatment Position CT

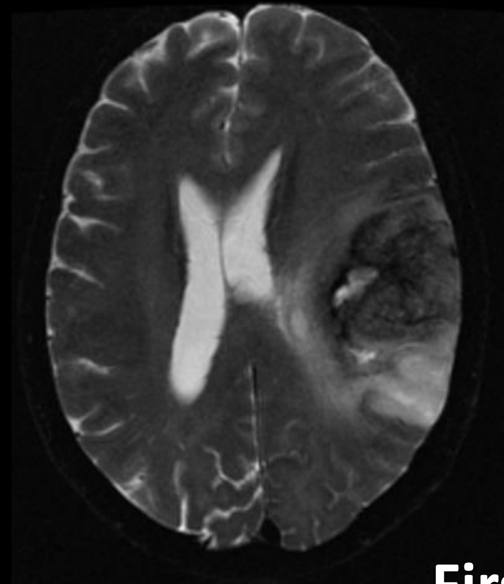


MR Imaging: Structure, Morphology and Function

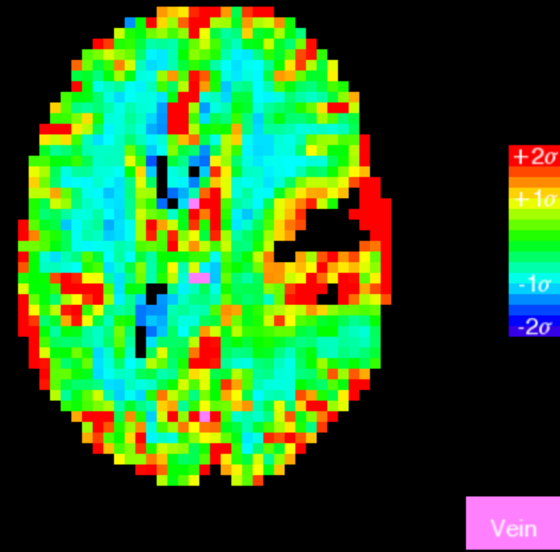
MR Spectroscopy



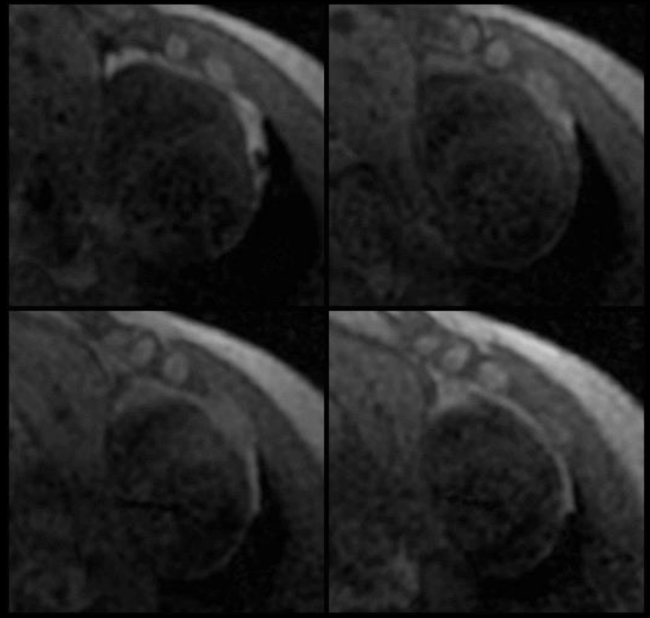
Morphology



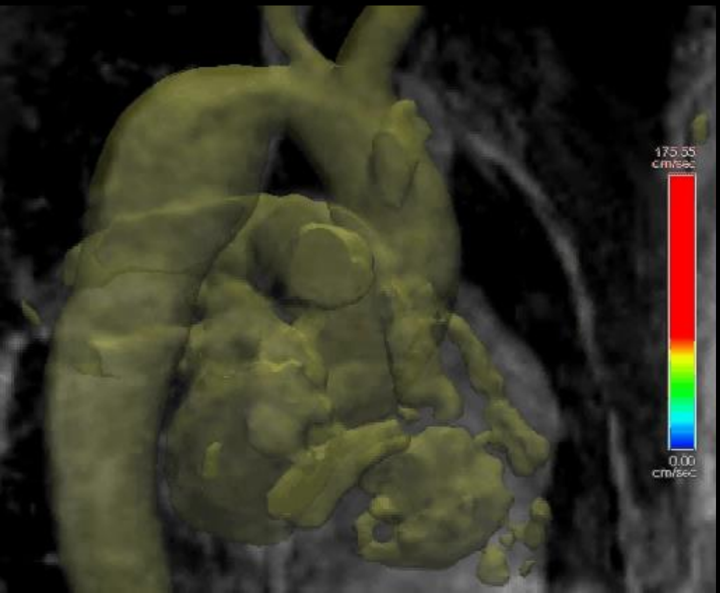
Relative cerebral blood volume



First Pass Perfusion Imaging



4D Flow Quantification



DTI Tractography

Objective

To answer the question:

How do I start, develop, and maintain a program for MR imaging in radiation therapy?

Outline

- Choosing an MR scanner
- MR Imaging techniques and pulse sequences
- Diagnostic vs. radiation planning MR Imaging
- Radiation therapy MR planning protocols
- MR imaging in the treatment position
- Sources of error in MR and corrective methods
- QA & QC
- Conclusions

Choosing an MR Scanner

Choosing an MR Scanner




- Field strength
- RF coils
- Bore Diameter
- Software
  - 2D vs. 3D pulse sequences
  - Advanced imaging (diffusion, perfusion, MRE…)
  - Post processing tools
- Vendor relationships

Choosing an MR Scanner: Field Strength

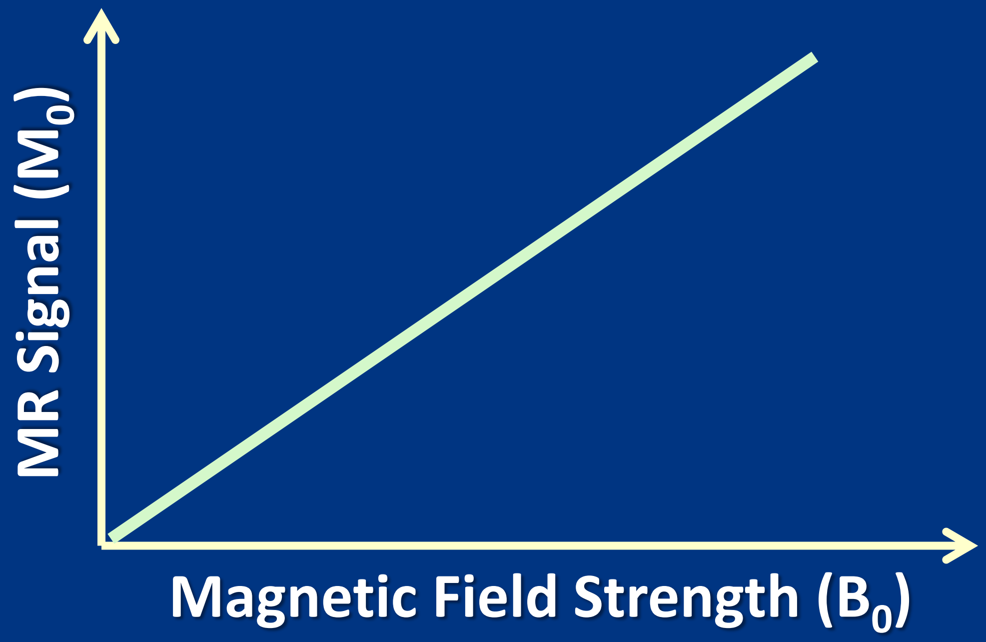
1.5T vs. 3.0T

- 3.0T Pros:
  - MR signal scales with field strength (B_0)
  - Potentially faster or higher resolution imaging
- 3.0T Cons:
  - Cost: $\$ \cong B_0$
  - Artifacts are worse at 3T
  - RF power deposition (SAR) scales with B_0^2

Field Strength Considerations

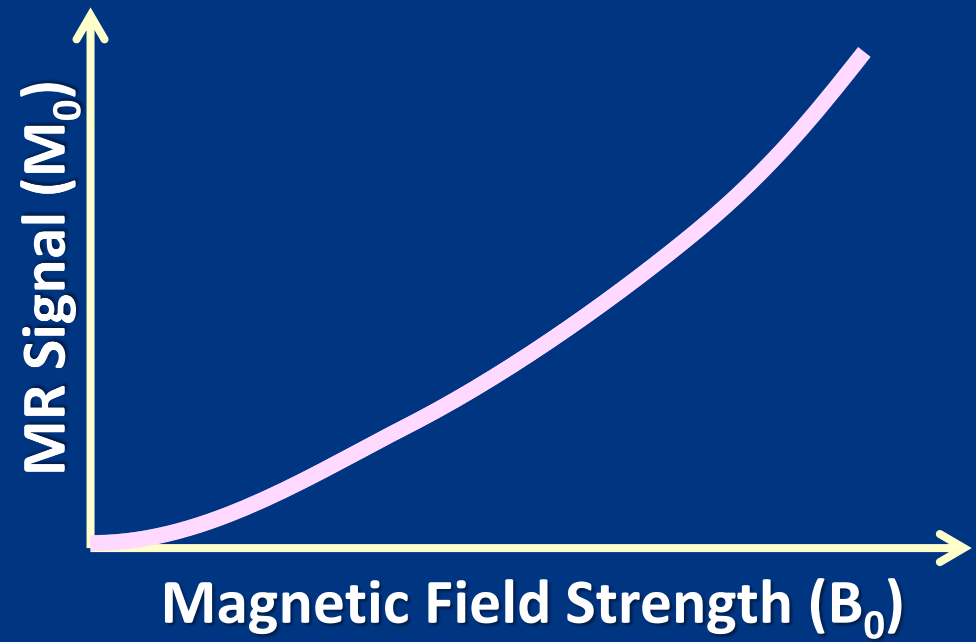
Magnetic Field Strength

$$P = \frac{1-e^{\left(-\mu B/k_B T\right)}}{1+e^{\left(-\mu B/k_B T\right)}} \approx \frac{\mu B}{2k_B T}$$



RF Heating (Specific Absorption Rate - SAR)

$$\text{SAR} \;\alpha\; B_0^2\, \theta^2\, \Delta f$$

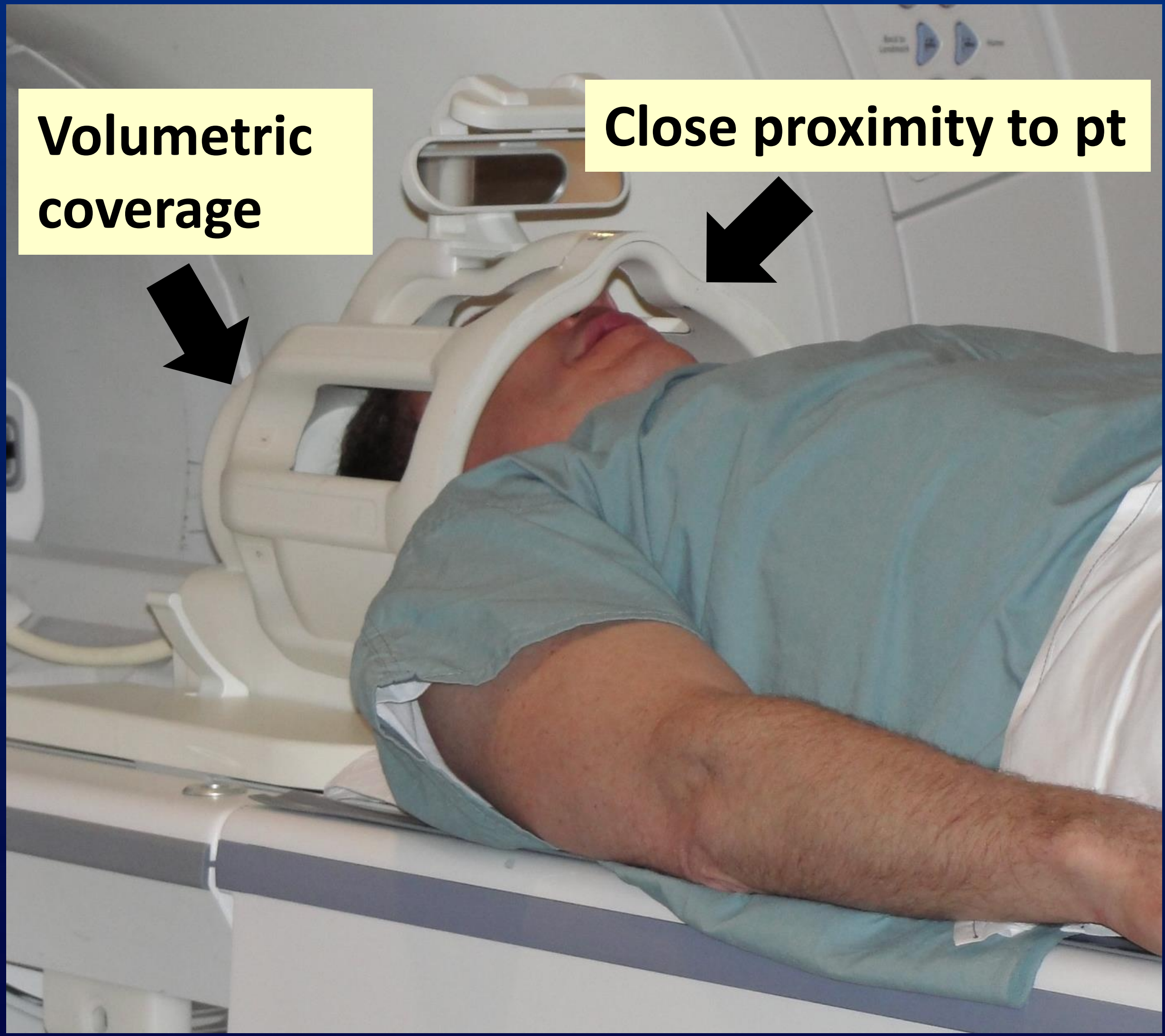


Choosing an MR Scanner: RF Coils

- Consider how the scanner will be used clinically:
  - Will it be used for both diagnostic and therapy MR imaging or therapy only?
- What coils are provided for diagnostic imaging?
- What suite of surface/flexible coils are available and what is their interconnectivity?

Choosing an MR Scanner: RF Coils

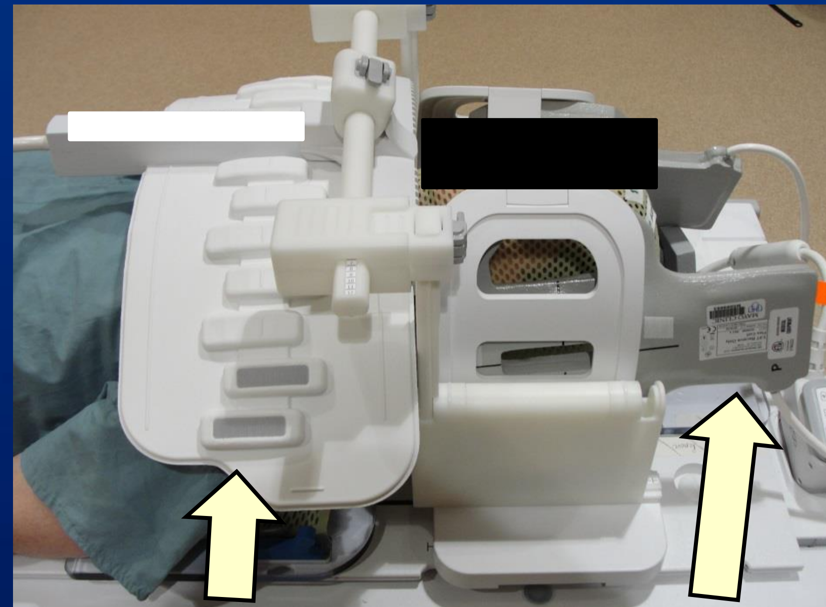
- Diagnostic RF coils:
  - Uniform sensitivity within imaging volume
  - Form factors tailored to specific anatomic sites
  - Close proximity to patient
  - Assumes patients are in neutral position



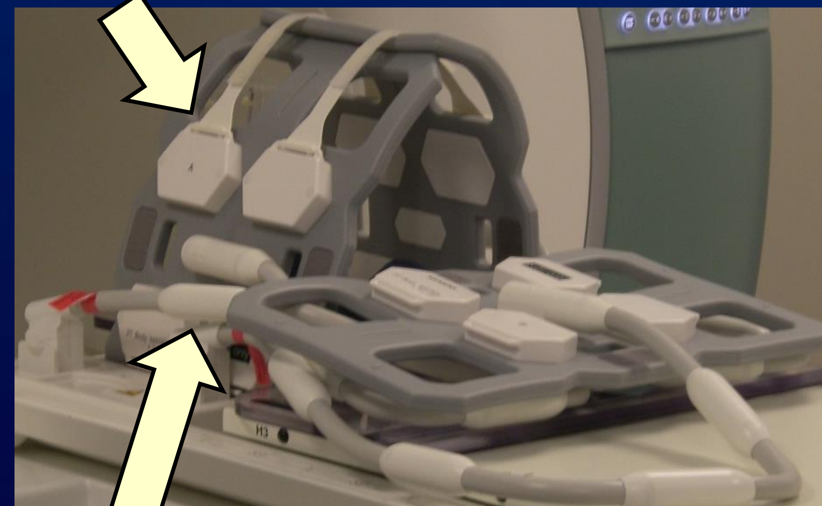
Choosing an MR Scanner: RF Coils

Therapy planning RF coils:

- Generic surface array coils
- Incomplete coverage of imaging volume
- Challenging to place coils close to patient due to immobilization devices



Flexible surface array coils



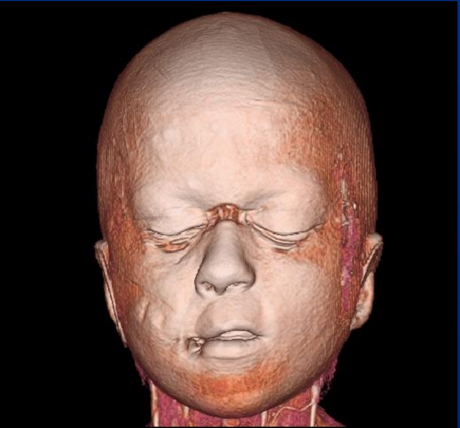
Non uniform volumetric coverage

Choosing an MR Scanner: Bore Diameter & Gradient Performance

	60 cm Bore	70 cm Bore
Max. gradient amplitude	50 mT/m	44 mT/m
Max. slew rate	200 T/m/s	200 T/m/s
Echo Planar Imaging		
Min. Echo Spacing - 25 cm FOV (64x64)	0.376 msec	0.456 msec
Min. Echo Spacing - 48 cm FOV (64x64)	0.256 msec	0.328 msec
Minimum TR (256 x 256)	5.0 ms	6.0 ms
Minimum TE (256 x 256)	1.5 ms	1.6 ms

Choosing an MR Scanner: MR Software & Vendor

- Software:
  - Does the vendor have the pulse sequences needed for radiation planning?
  - What are the post processing options available?
    - Reformatting
    - Advanced post processing
- Vendor:
  - What type of relationship do you expect with your vendor
  - What is the vendor's long term product roadmap



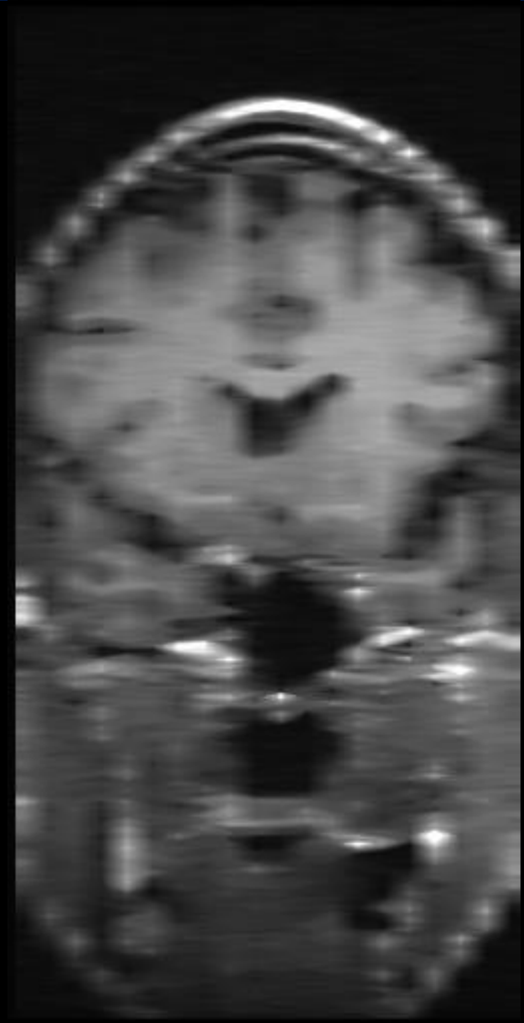
2D vs. 3D Imaging

- 3D Imaging
  - Pros:
    - Increase in SNR $\alpha \sqrt{\text{Slices}}$
    - Potential for isotropic resolution (improved reformatted data)
  - Cons:
    - More susceptible to motion corruption
    - Insufficient tissue contrasts
    - Artifacts
- Does the vendor provide sufficient range of pulse sequence types for 2D and 3D imaging?

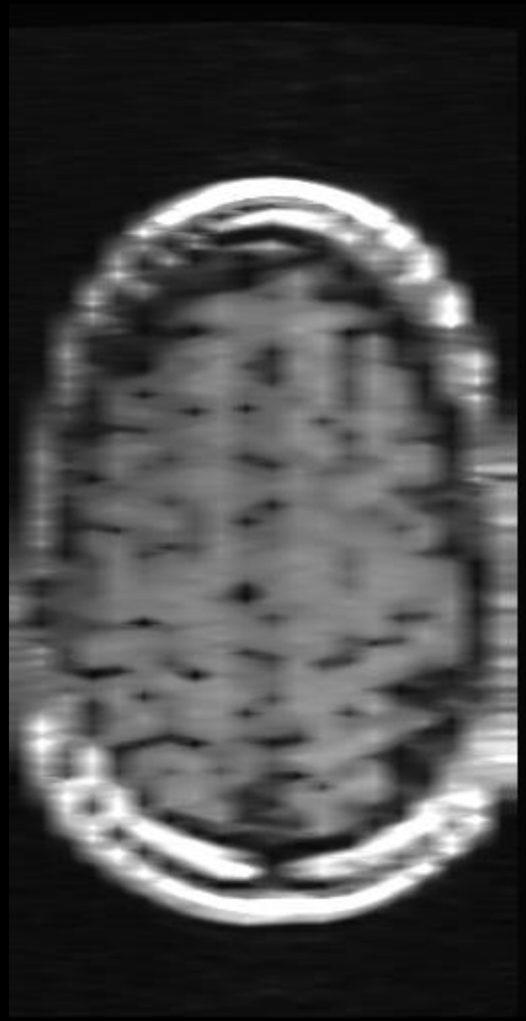
2D vs. 3D Data

2D Sagittal T_1 FLAIR (5 mm)

Coronal Reformat

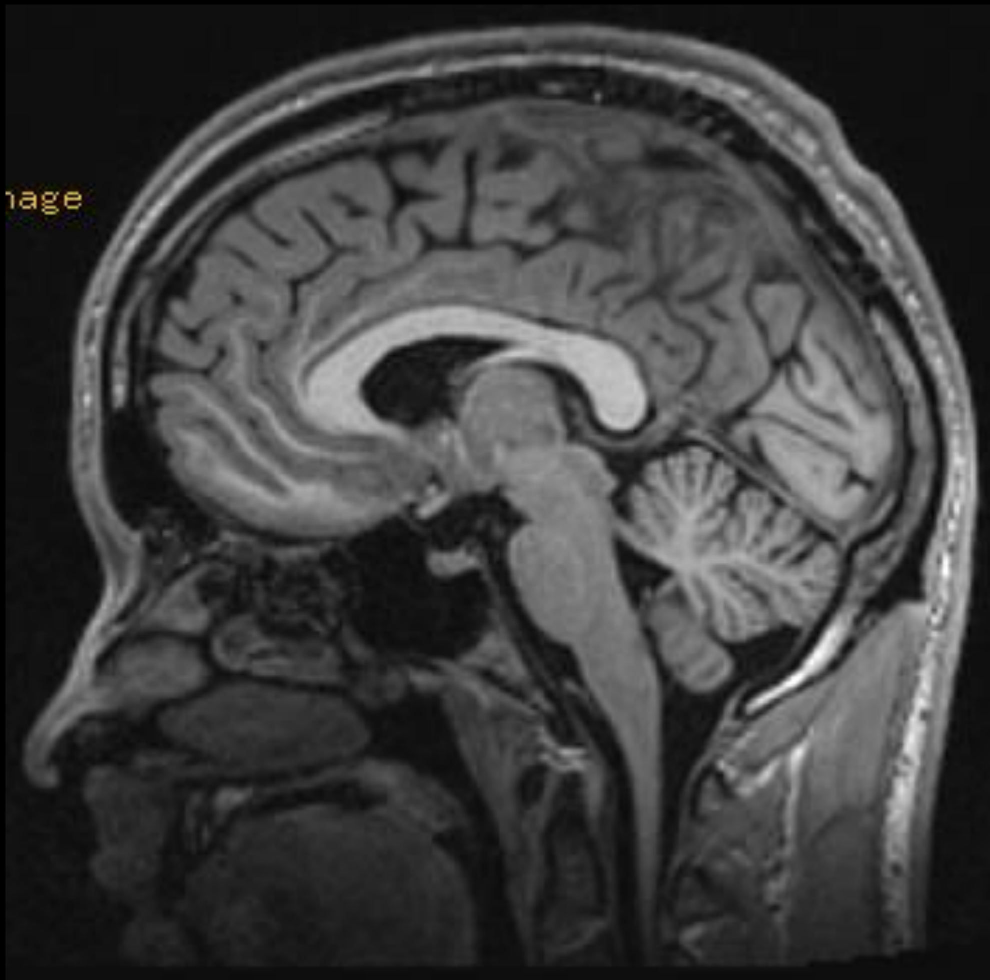


Axial Reformat

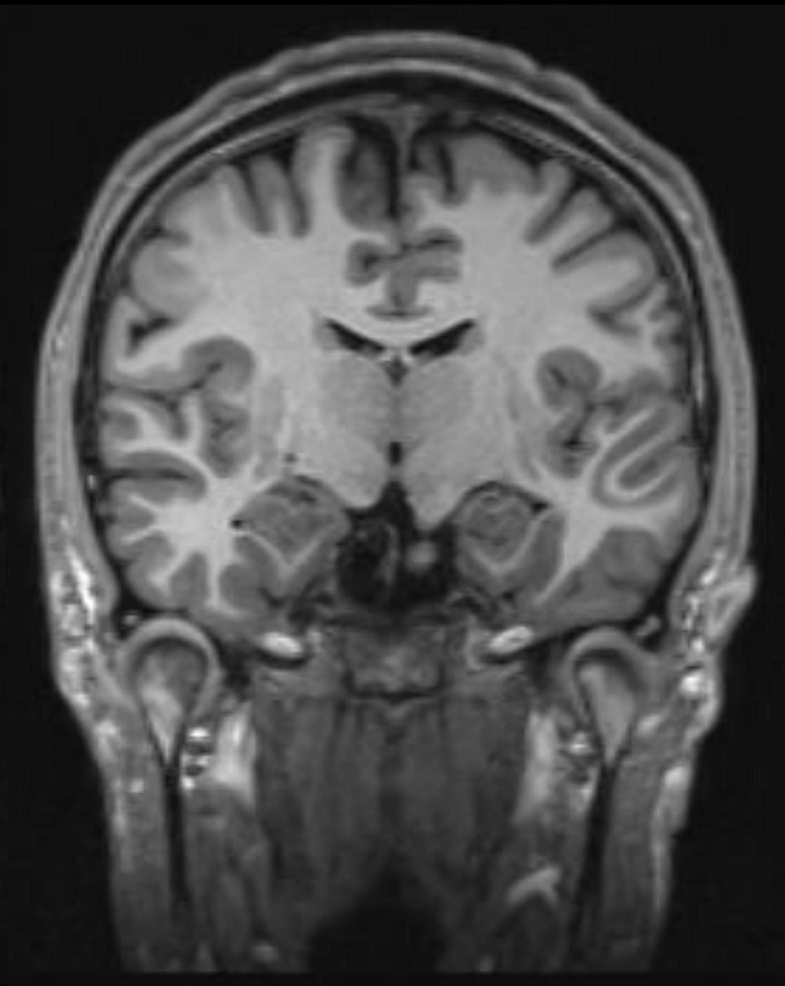


2D vs. 3D Data

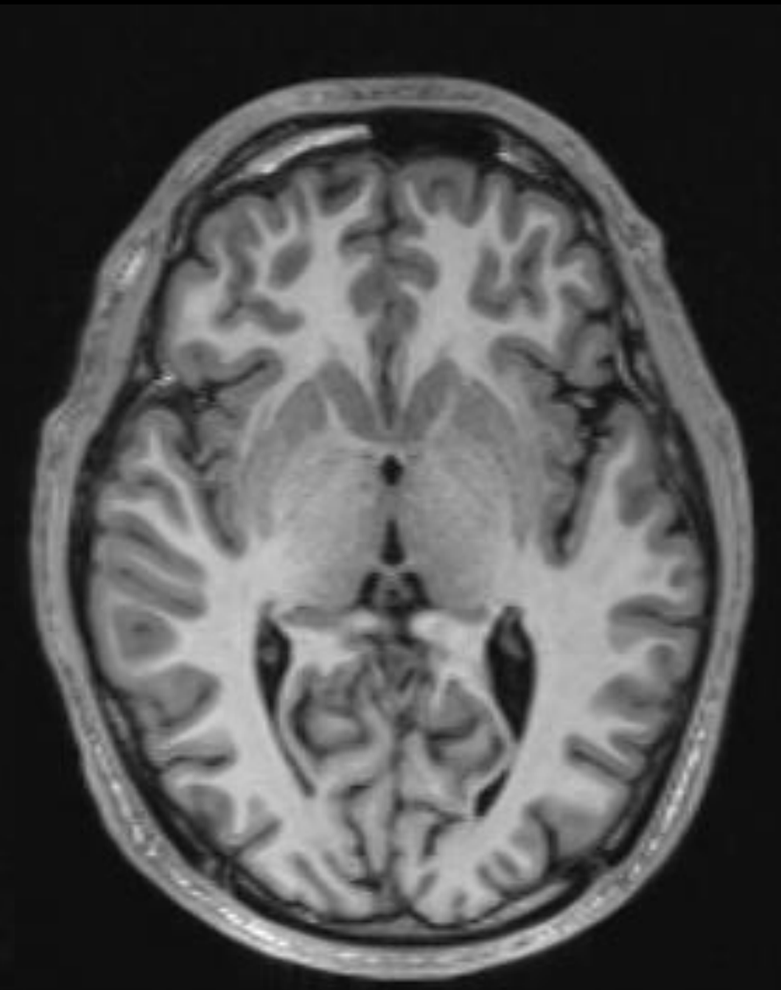
3D Sagittal MPRAGE (1 mm)



Coronal Reformat



Axial Reformat



Planning MR-CT Fusion & Registration

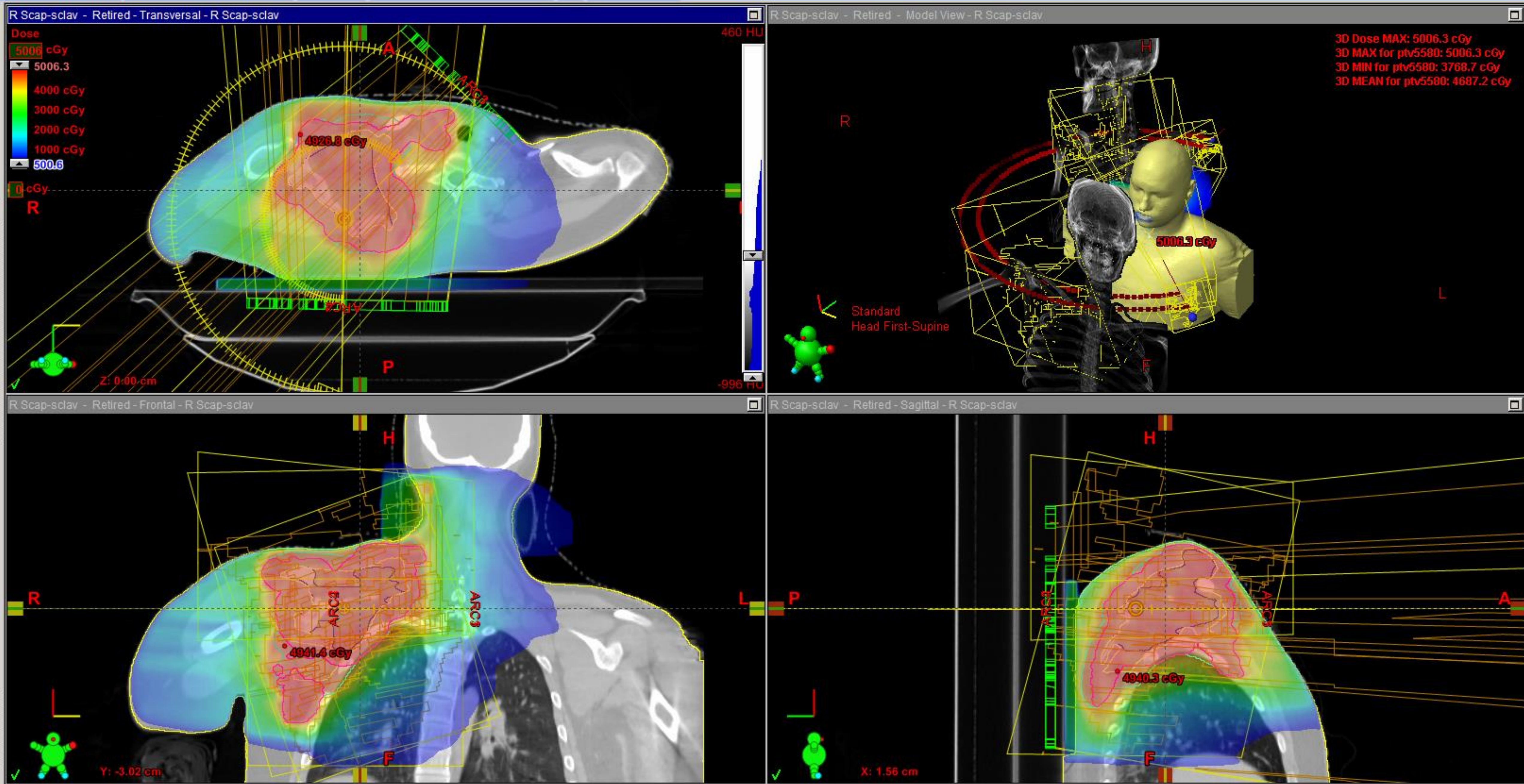
2D Ax T_2 FS

CT-MR Fusion – Axial

CT-MR Fusion – Coronal

3D Coronal CUBE T_2 FS

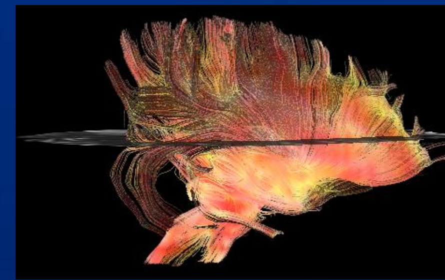
Target Volume Accuracy



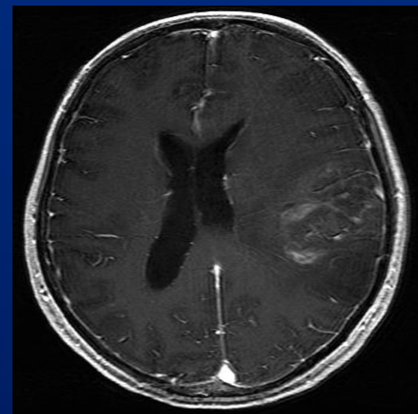
Advanced MR Techniques for Radiation Planning

- MR provides variety of both structural and functional information
- Tempting to rely on new methods (perfusion, fMRI, DTI, MRE, etc) for high precision radiation therapy planning
- Need to understand methods, reproducibility/accuracy of data, what is being measured before using information

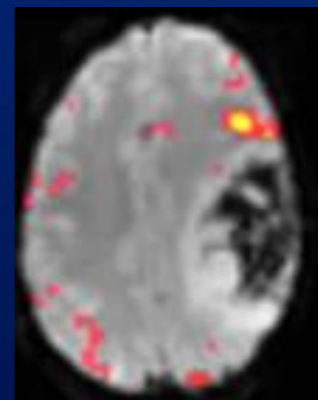
Diffusion Tensor Tractography



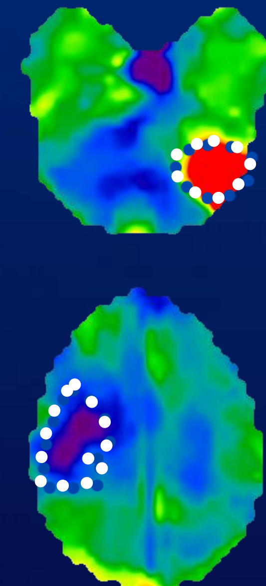
First pass perfusion



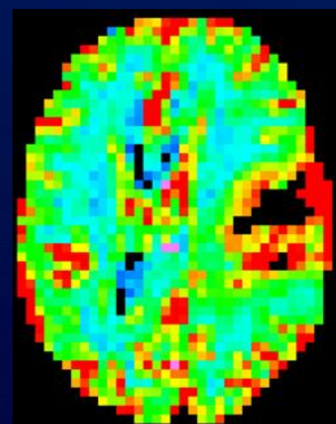
fMRI



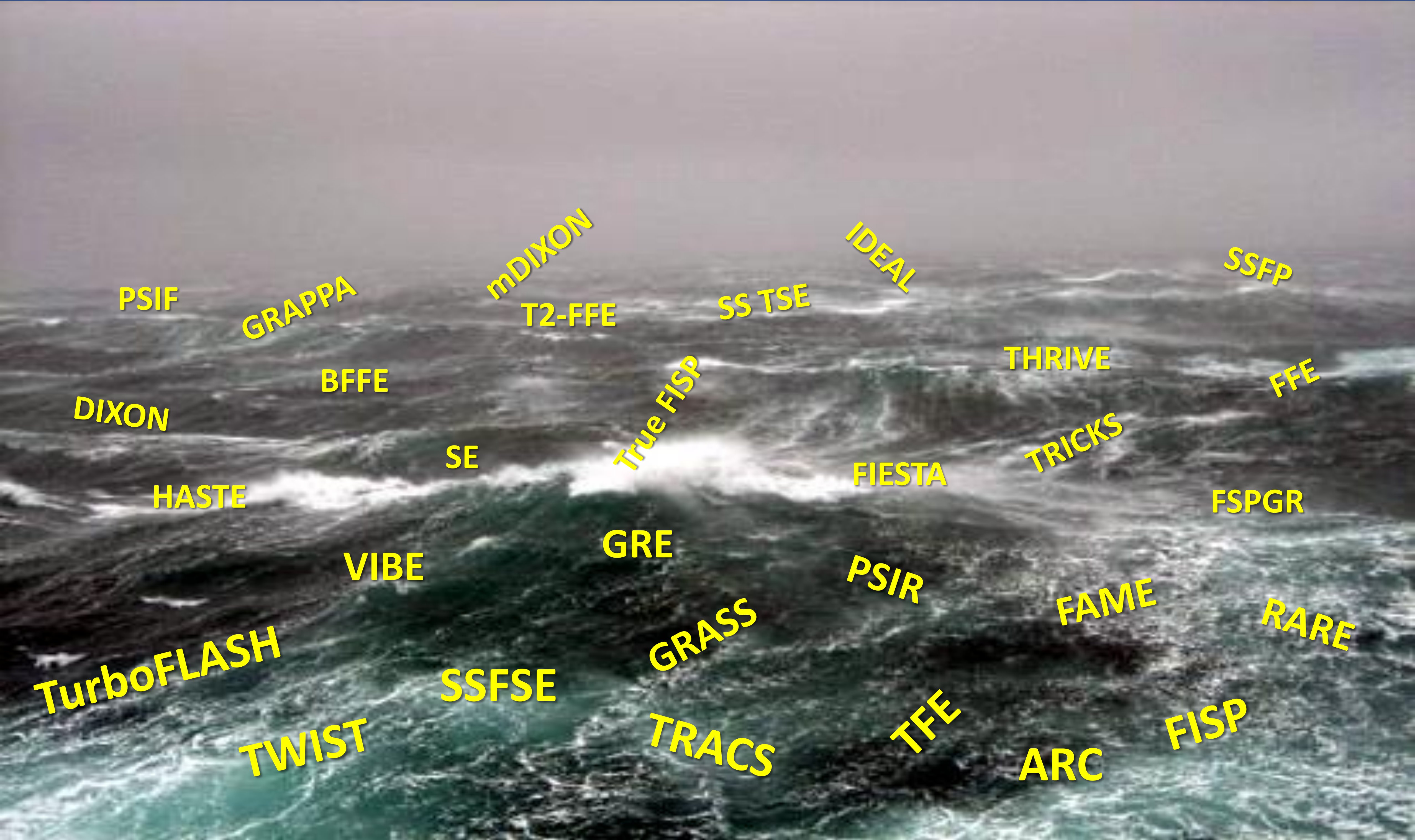
MR Elastography



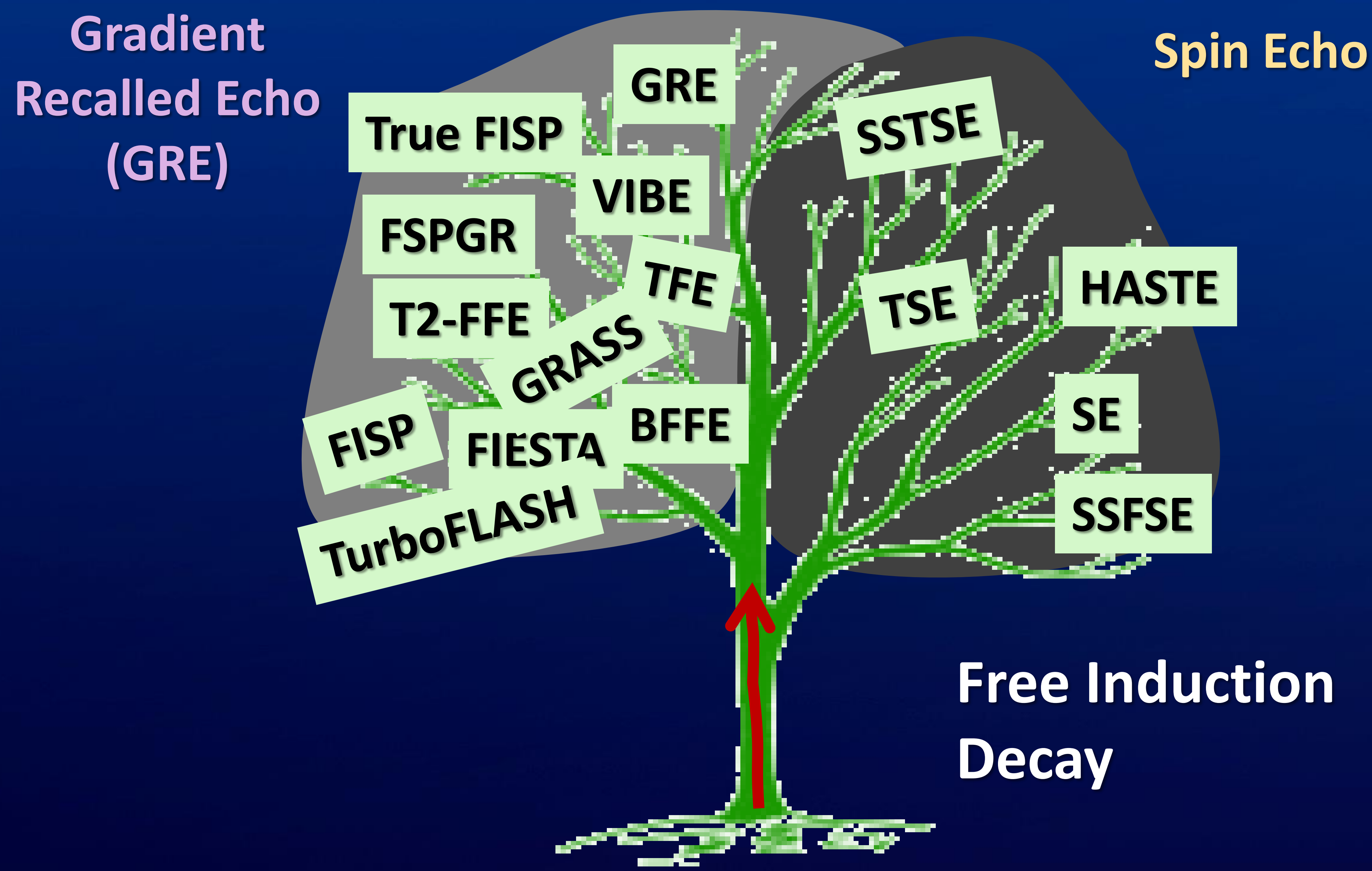
Relative cerebral blood volume



MR Imaging Techniques & Pulse Sequences

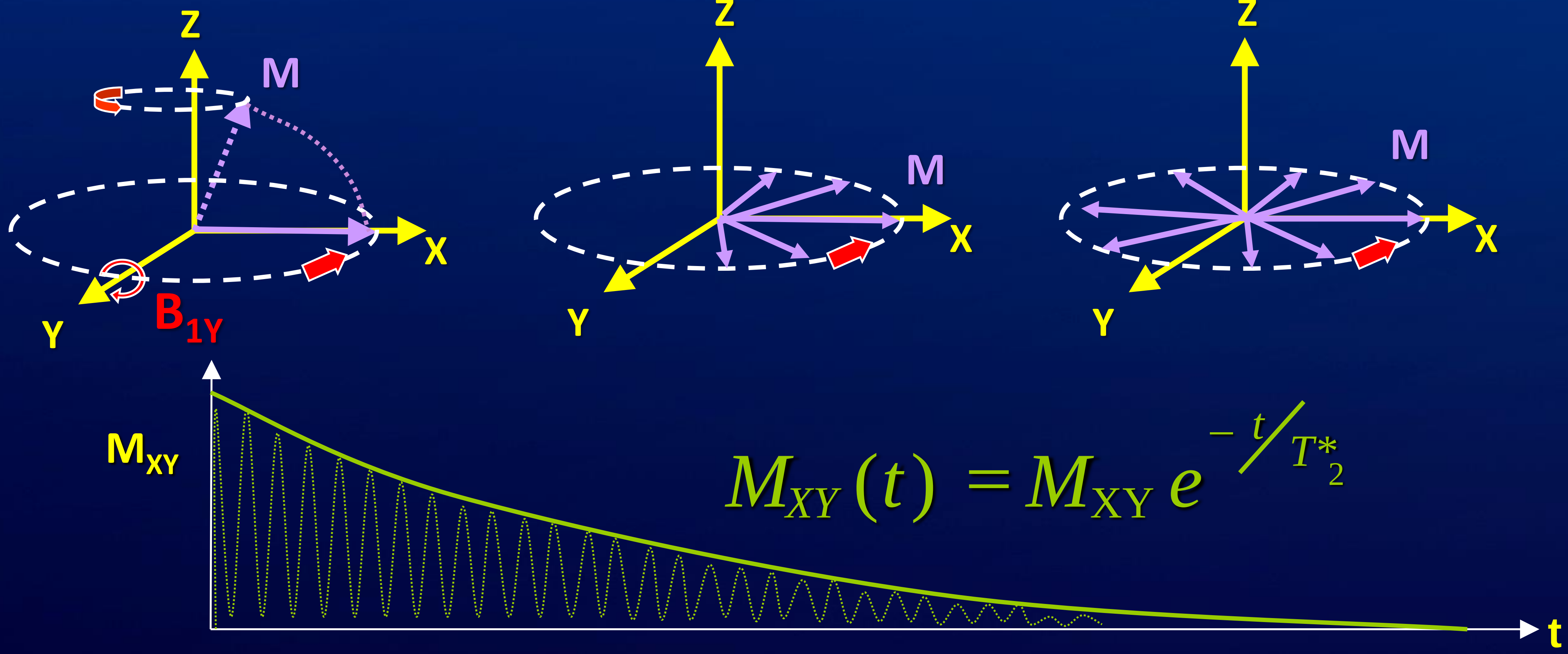

mDIXON
IDEAL
SSFP
PSIF
GRAPPA
T2-FFE
SS TSE
THRIVE
FFE
BFFE
True FISP
DIXON
TRICKS
SE
FIESTA
HASTE
FSPGR
GRE
VIBE
PSIR
FAME
RARE
GRASS
TurboFLASH
SSFSE
TWIST
TRACS
TFE
ARC
FISP

Pulse Sequence Basics



Free induction Decay

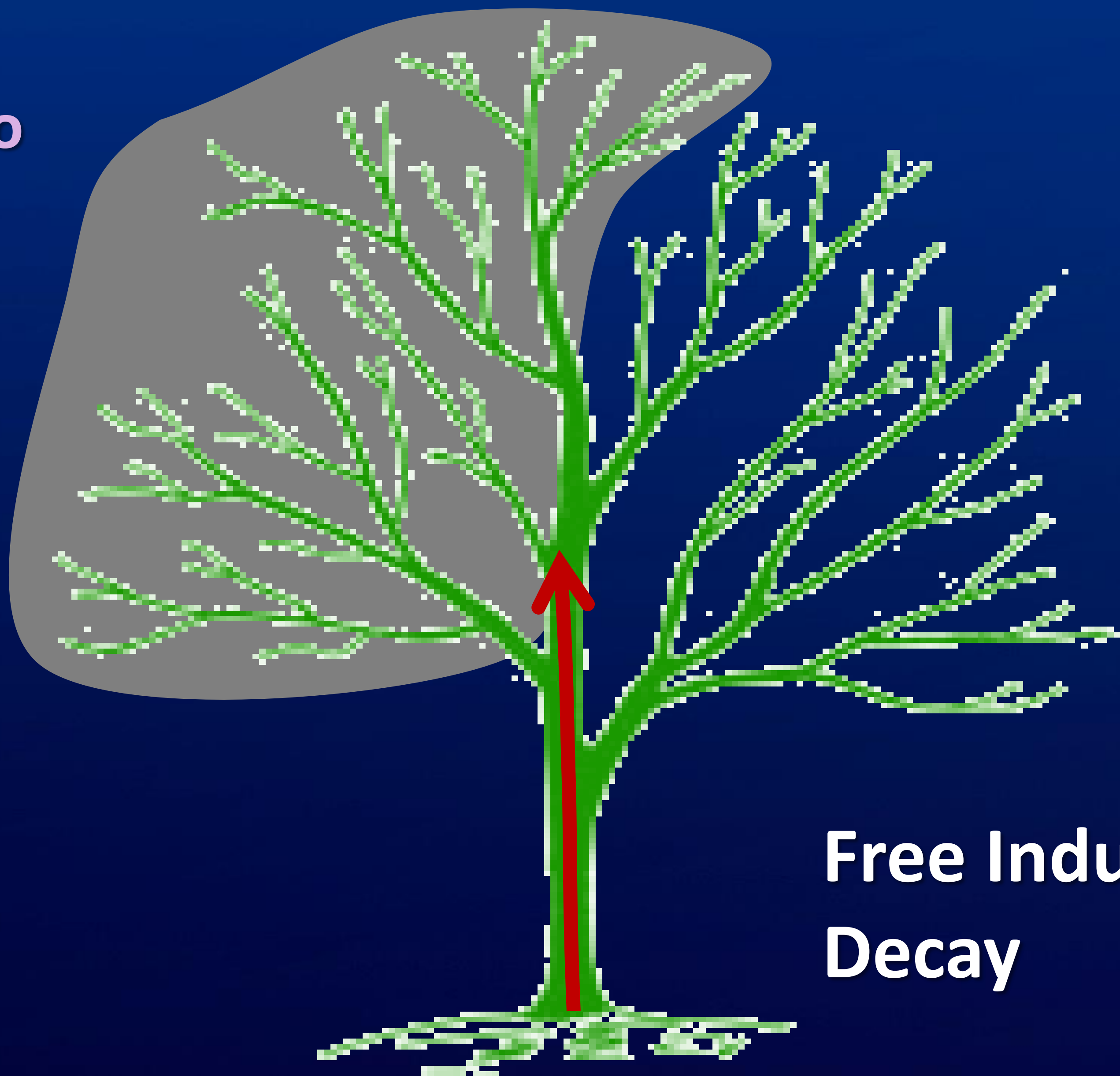
- Apply RF pulse to create transverse magnetization
- Signal will rapidly decay due to T_2* dephasing



$$M_{XY}(t) = M_{XY}\, e^{-t/T_2^*}$$

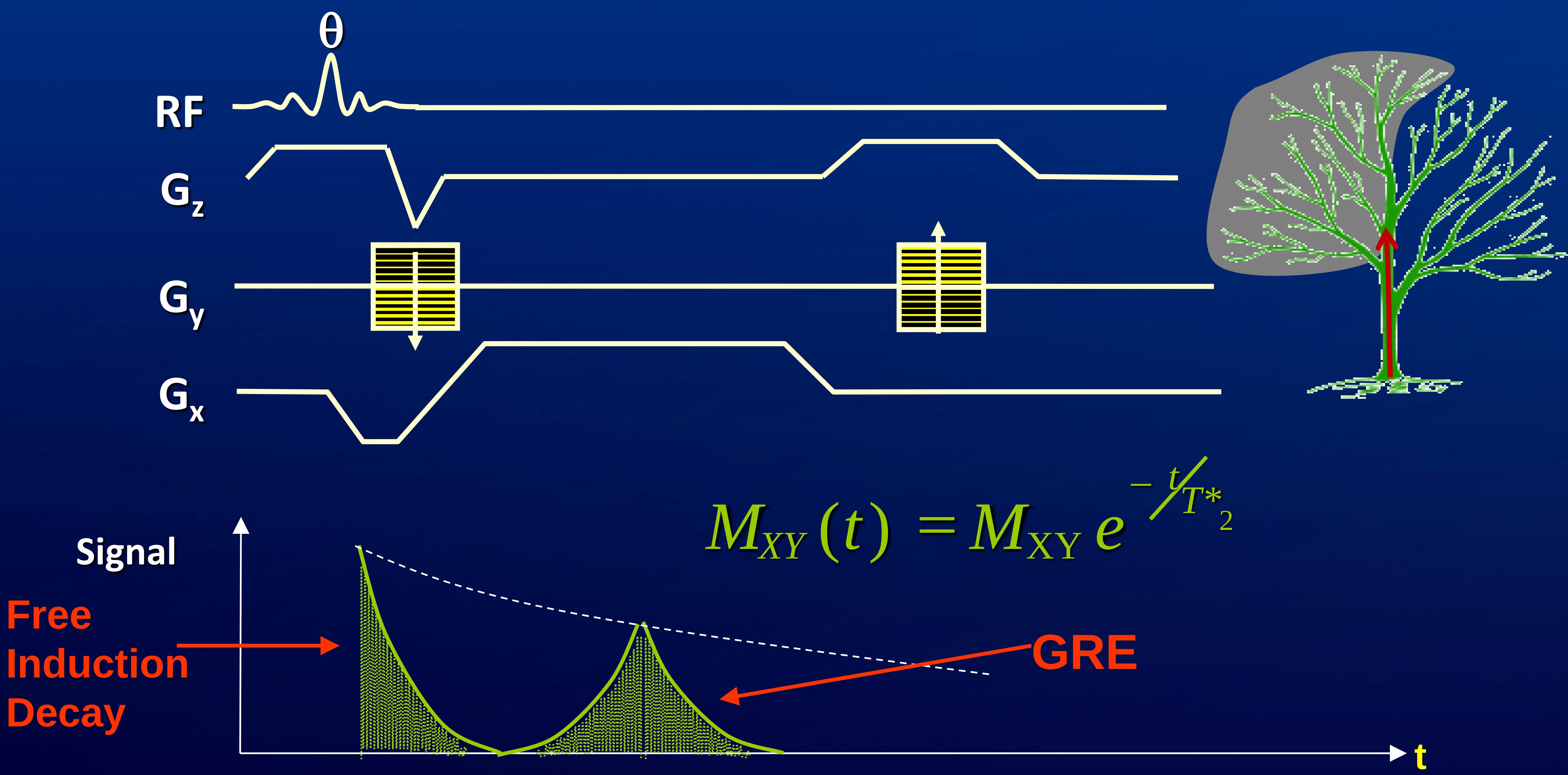
Pulse Sequence Basics

Gradient Recalled Echo (GRE)



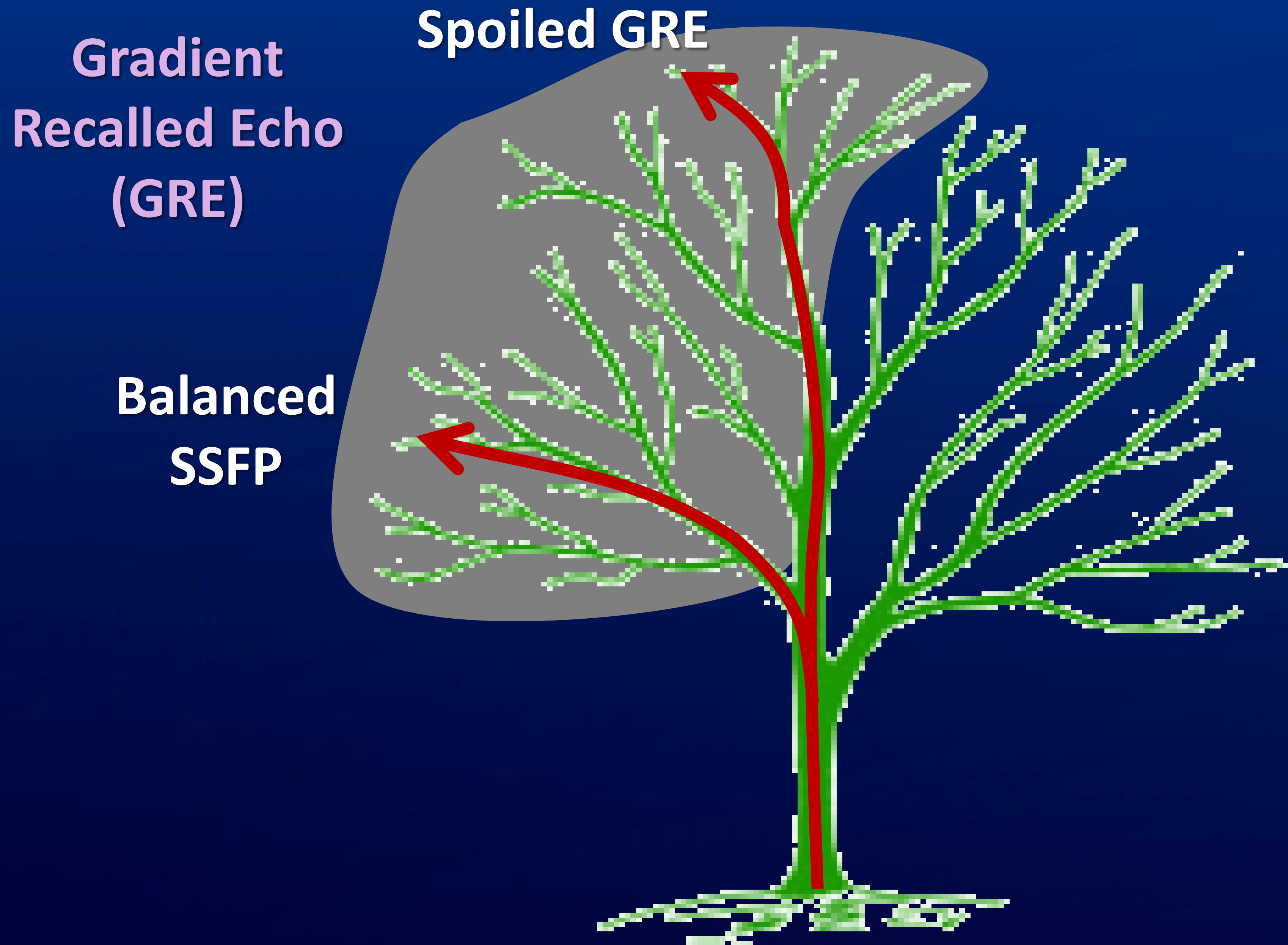
Free Induction Decay

Gradient Recalled Echo (GRE) Imaging

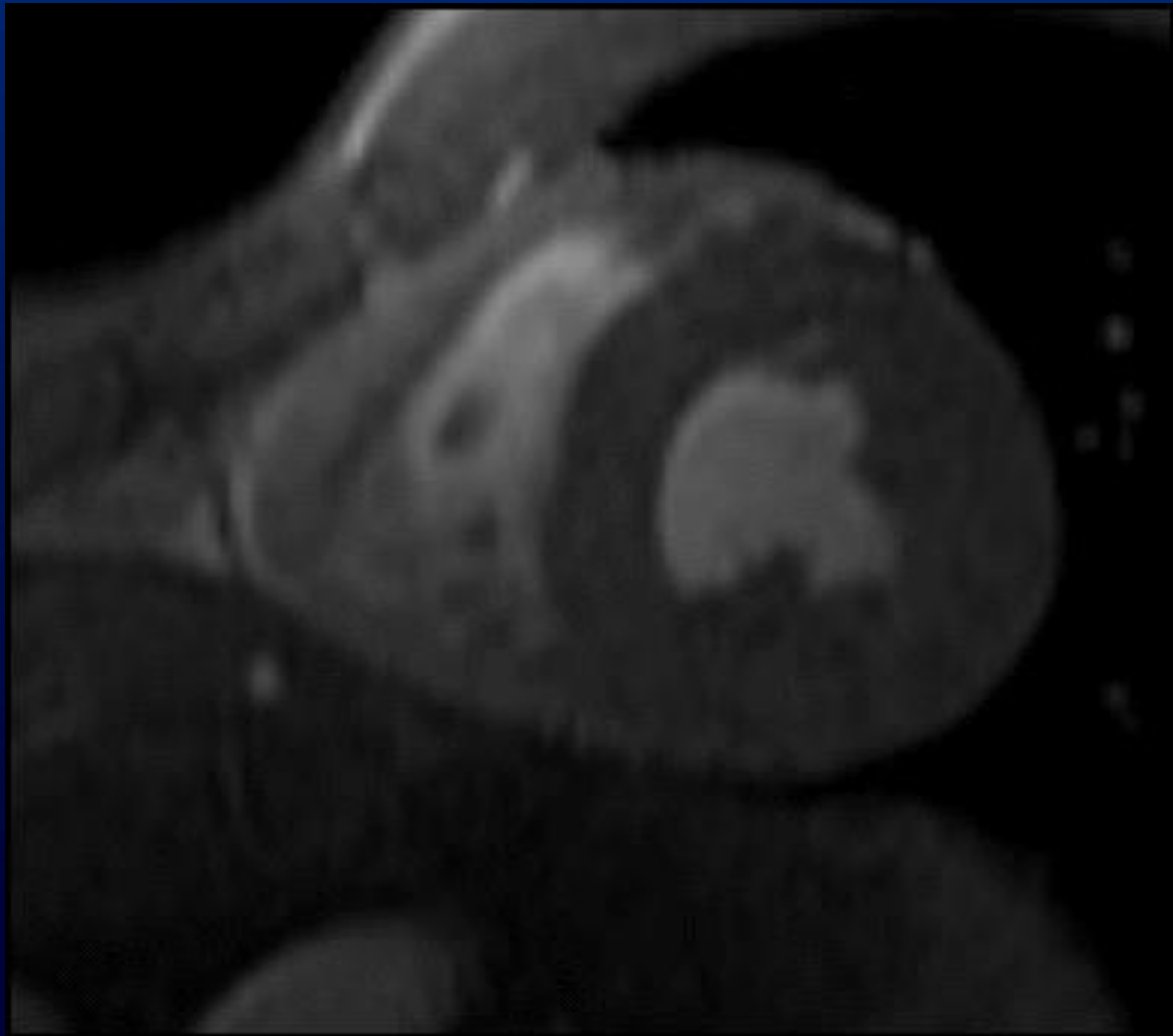


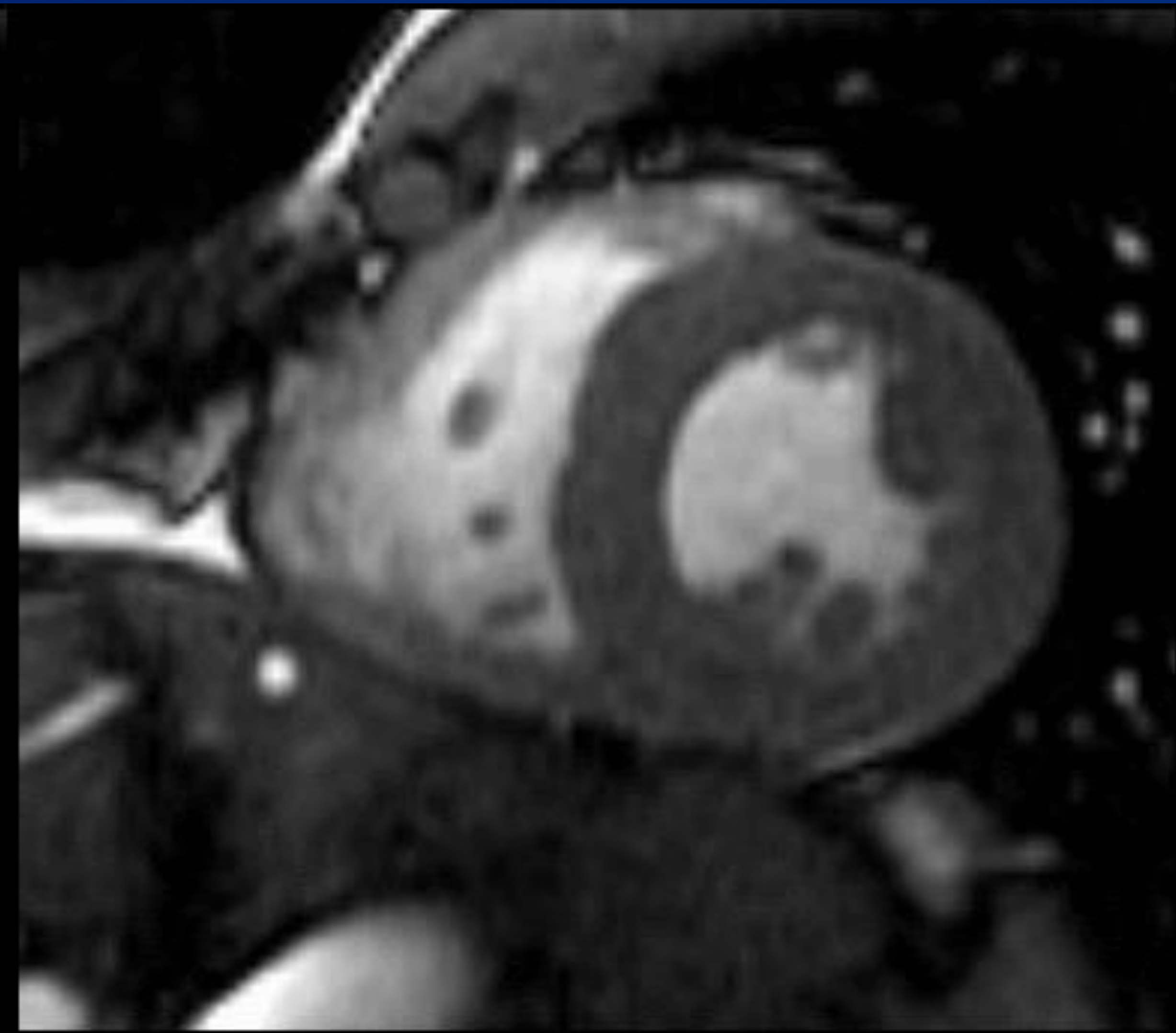
$$M_{XY}(t) = M_{XY}\, e^{-t/T^*_2}$$

Pulse Sequence Basics

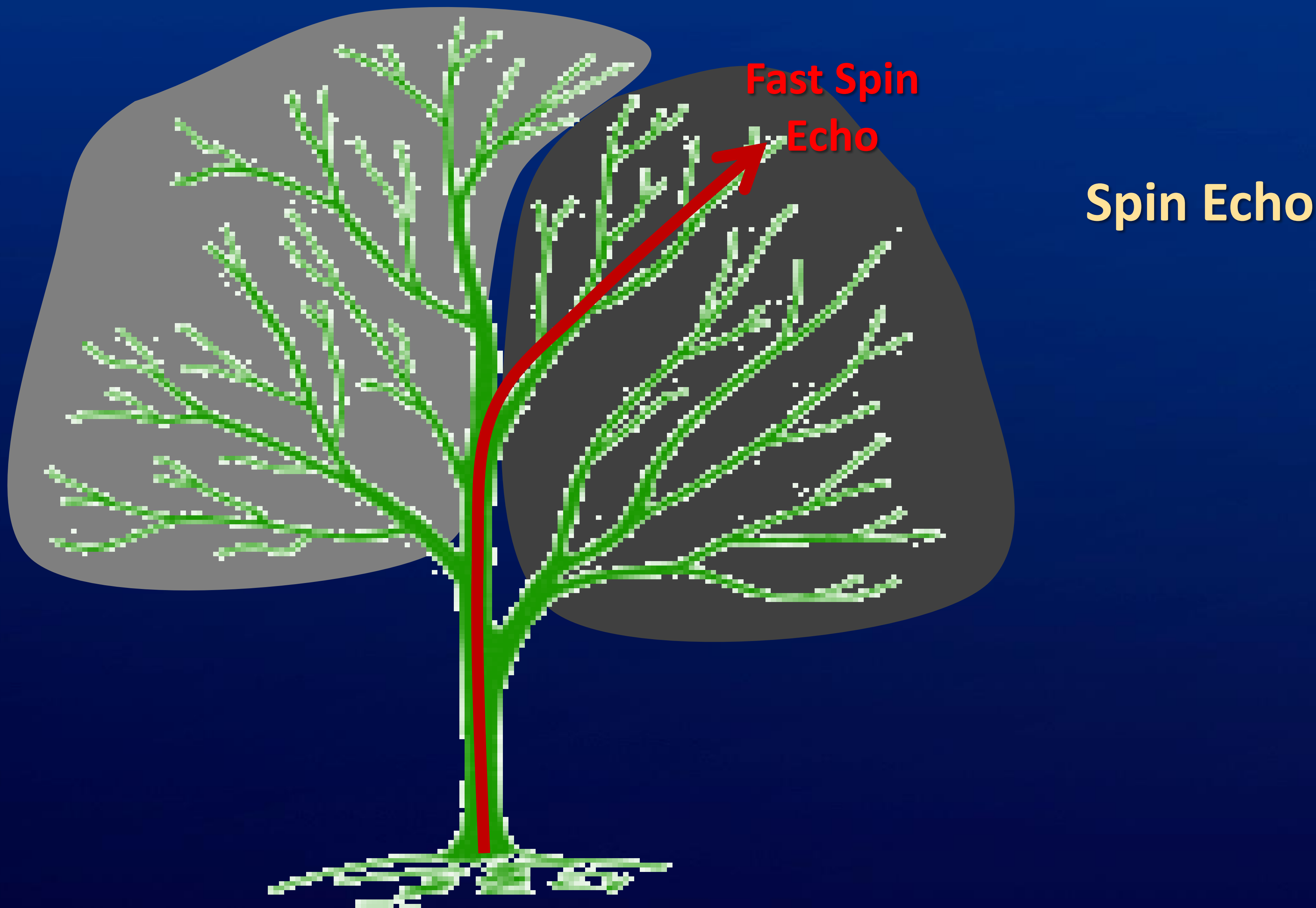


Balanced SSFP vs Spoiled GRE

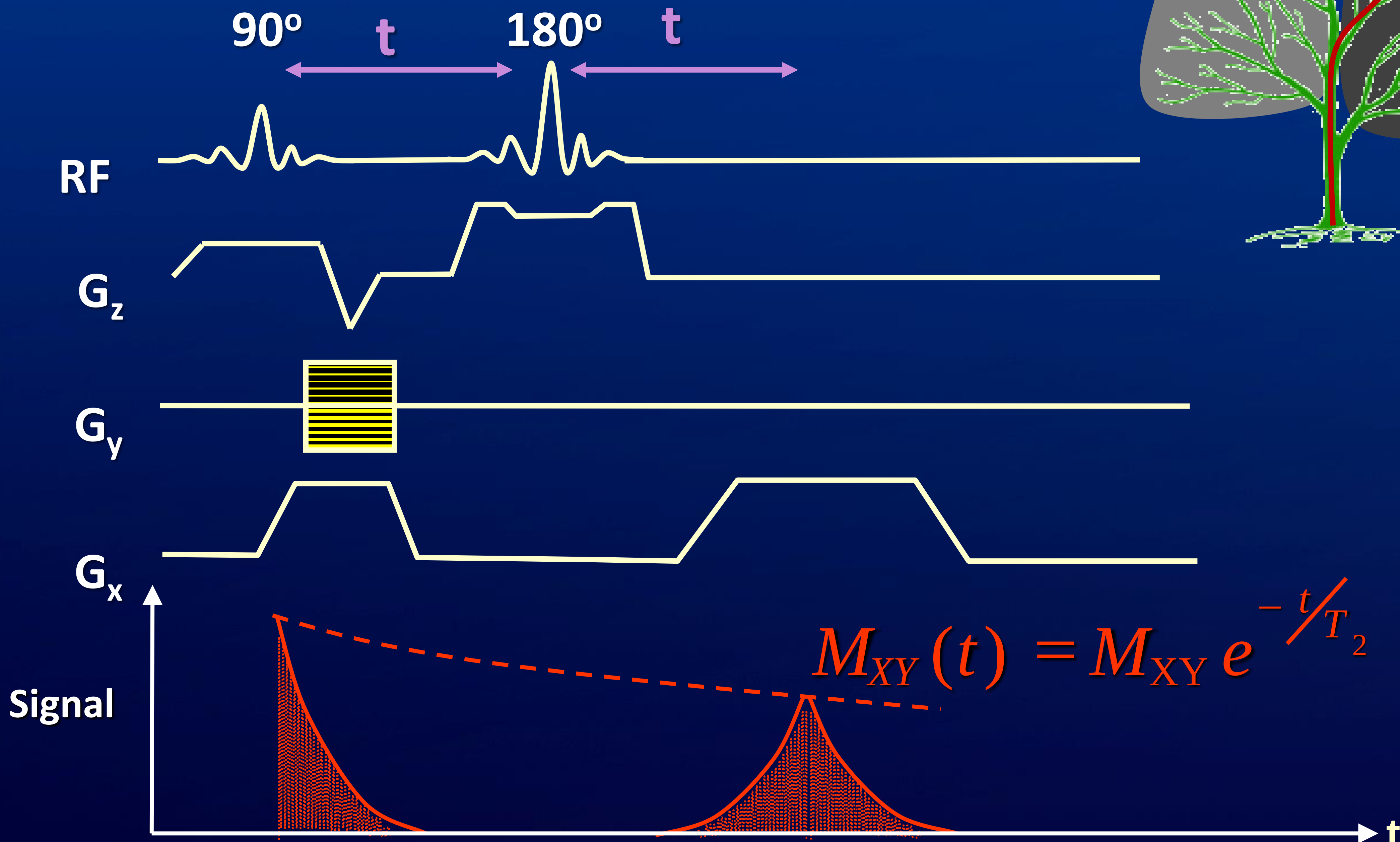




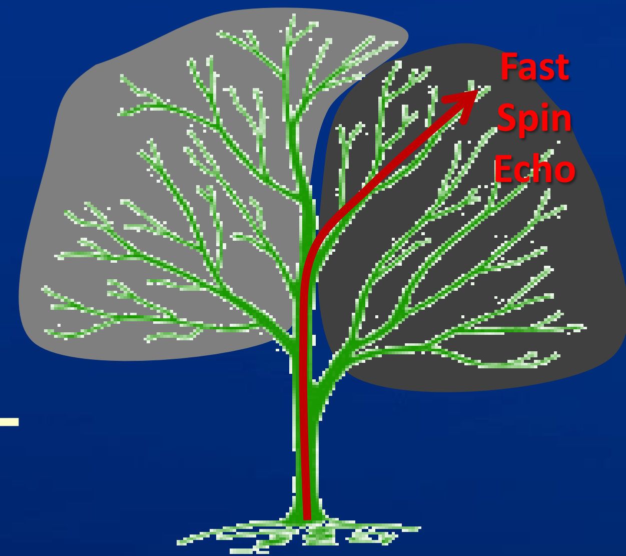
Pulse Sequence Basics



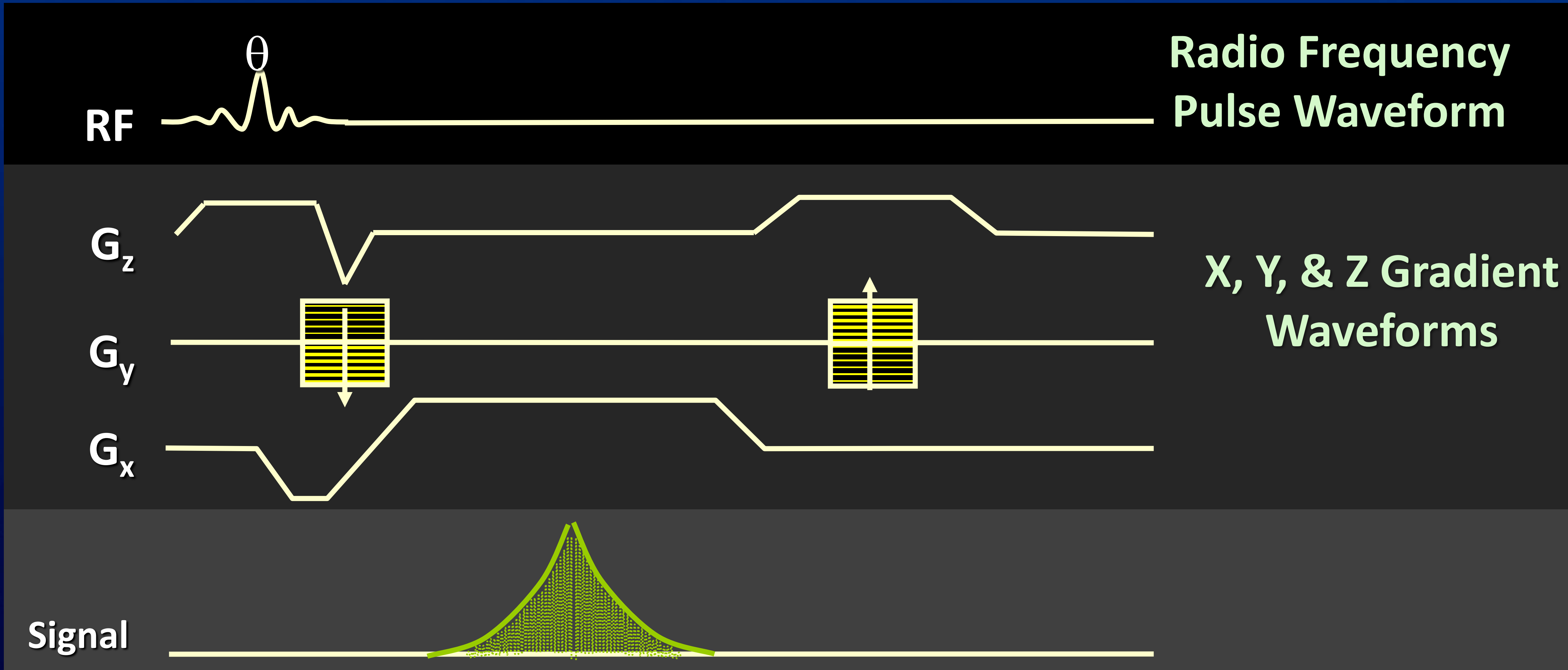
Spin Echo Imaging



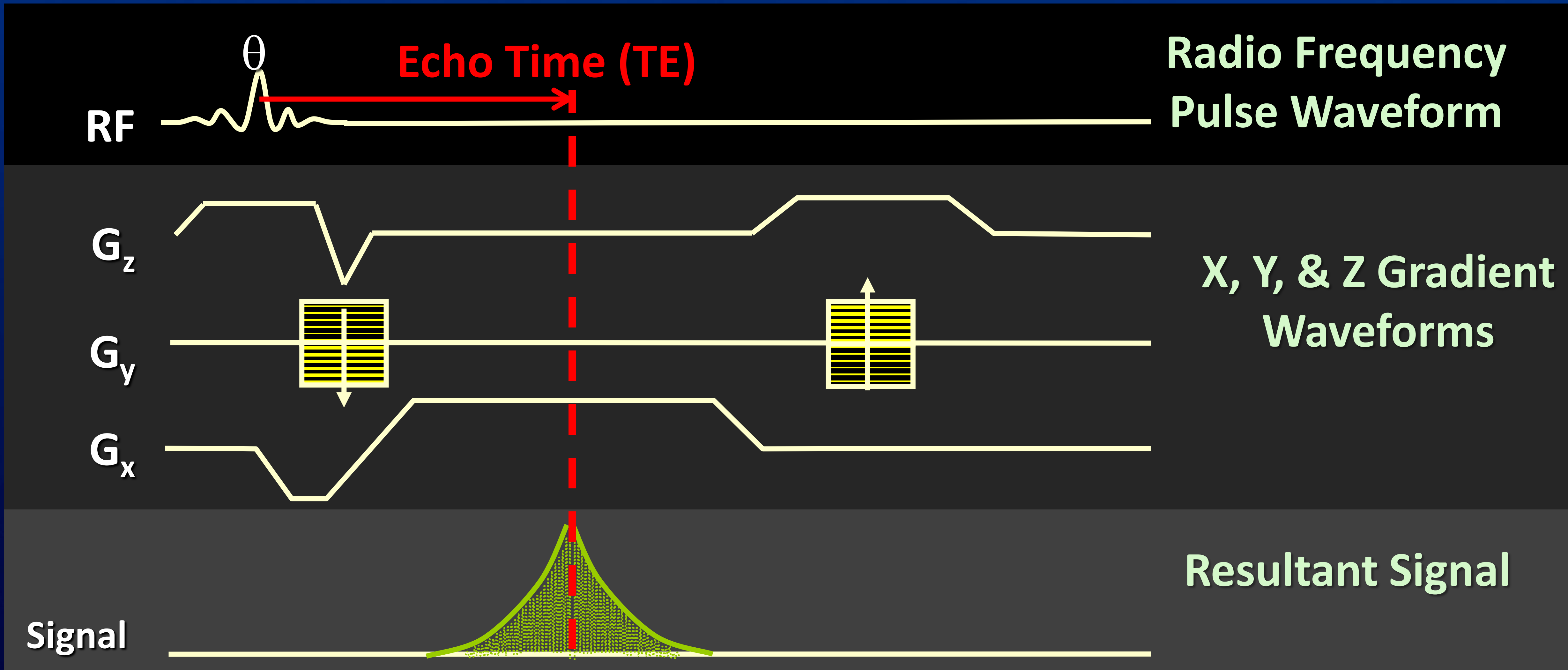
$$M_{XY}(t) = M_{XY}\, e^{-t/T_2}$$



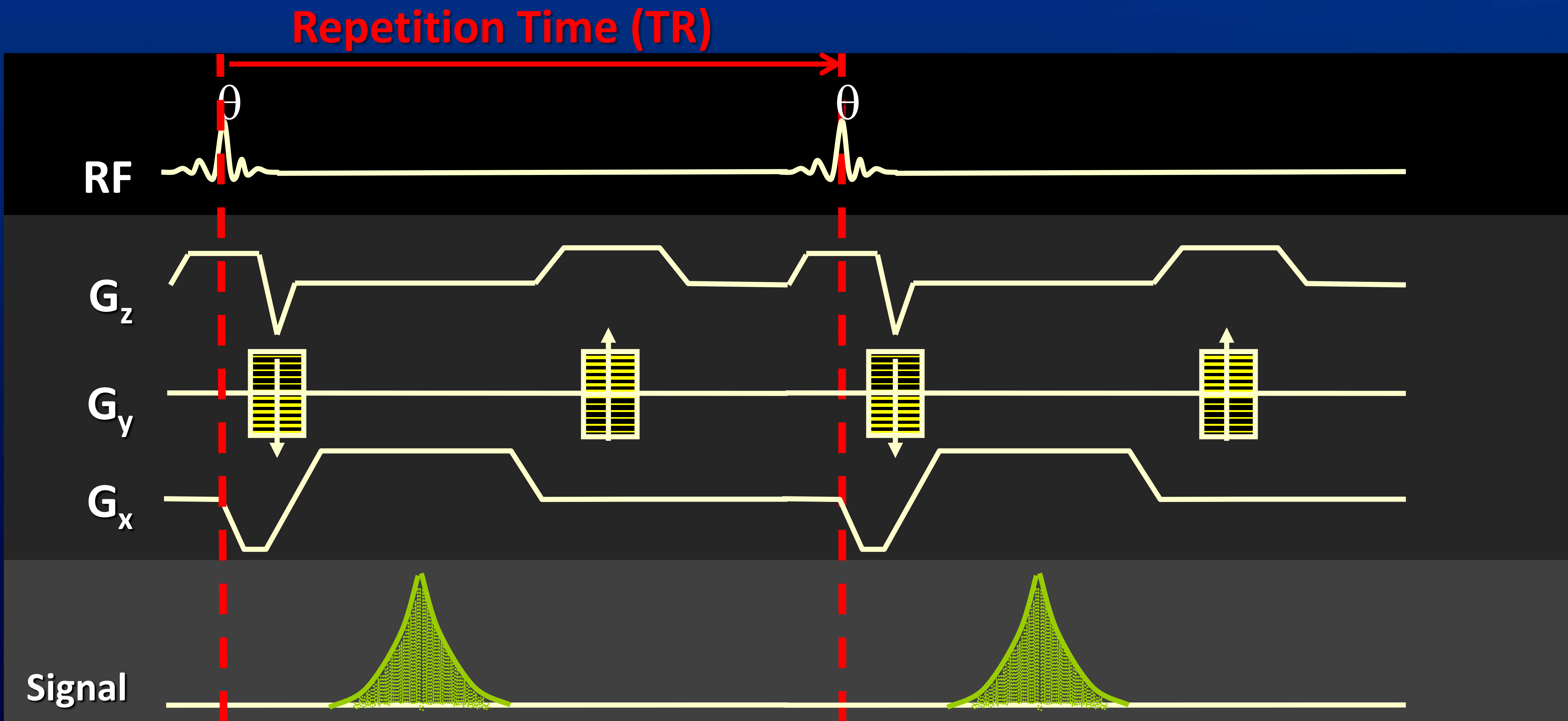
The Pulse Sequence Diagram



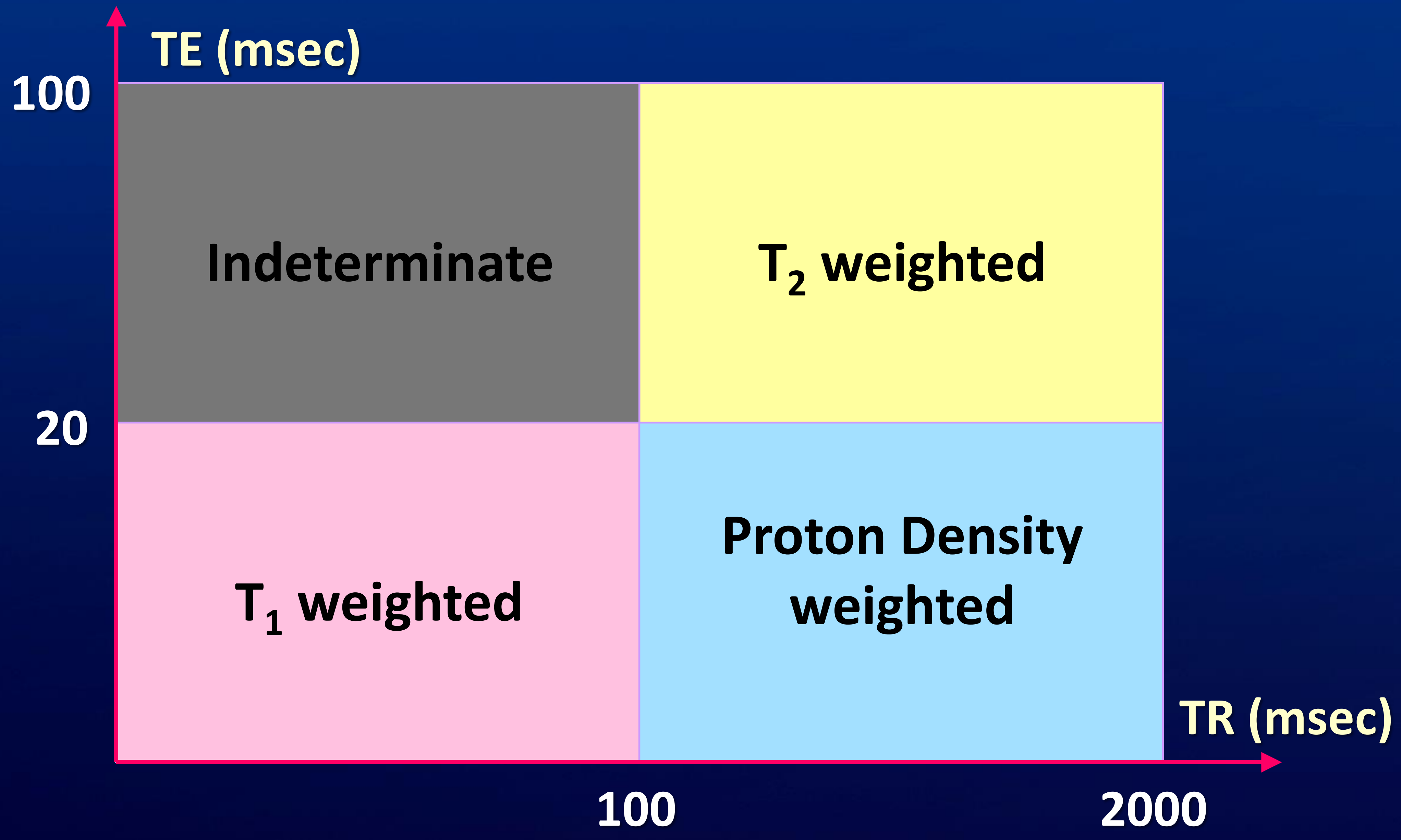
The Pulse Sequence Diagram



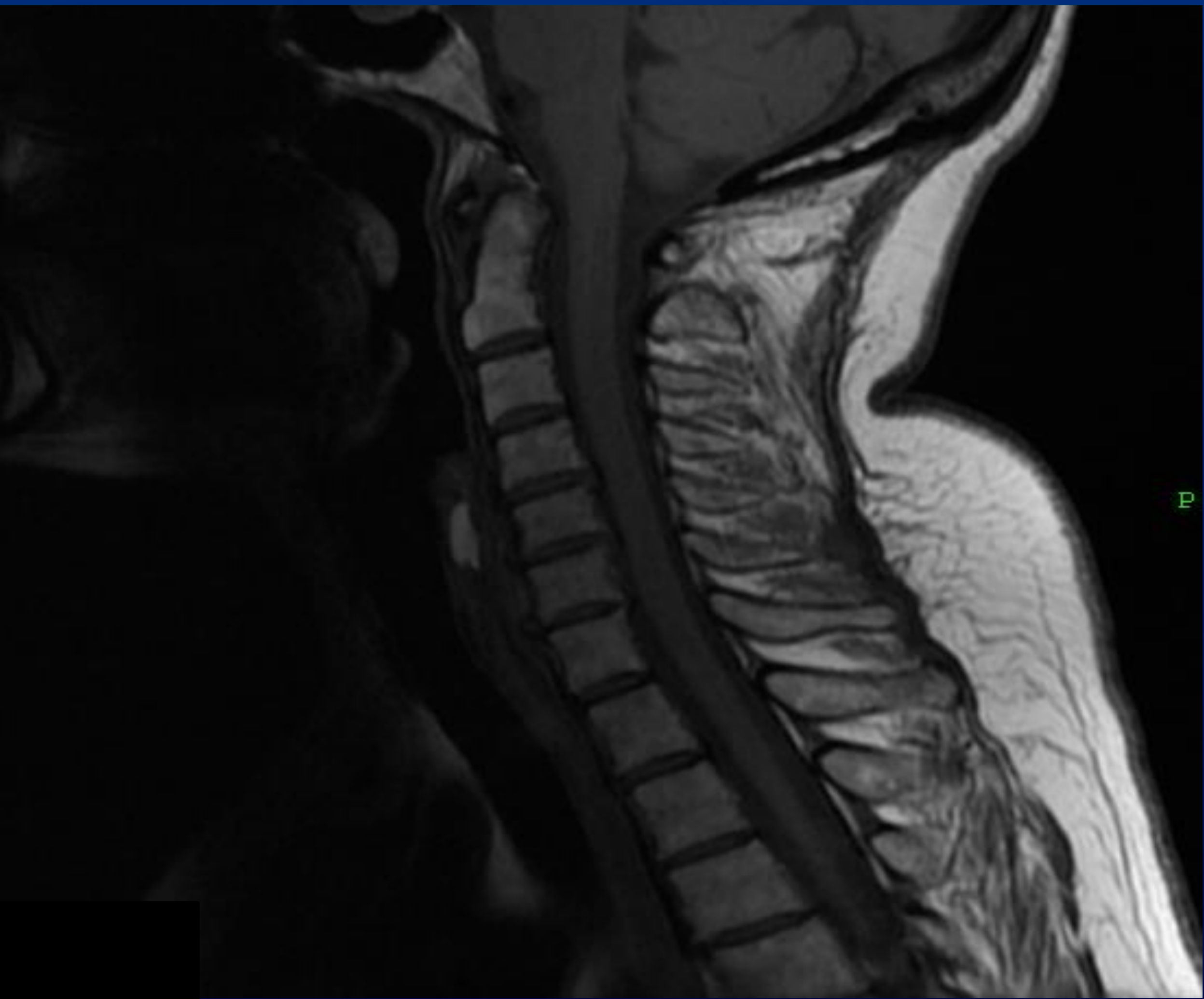
The Pulse Sequence Diagram

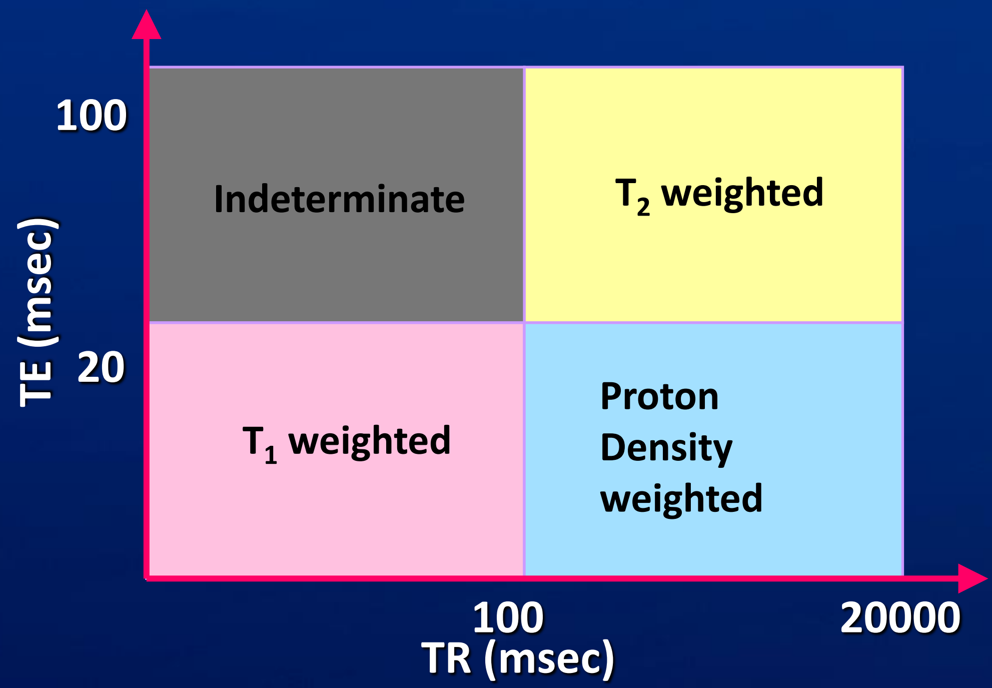


MR Image Contrast



Sagittal Spine

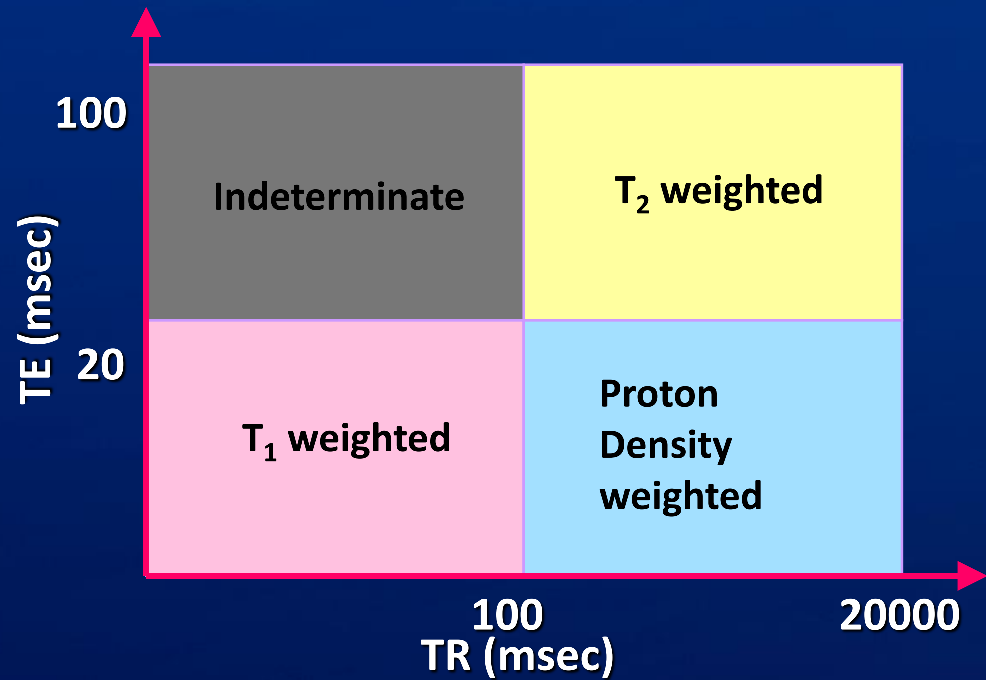




TE = 13 msec

TR = 450 msec

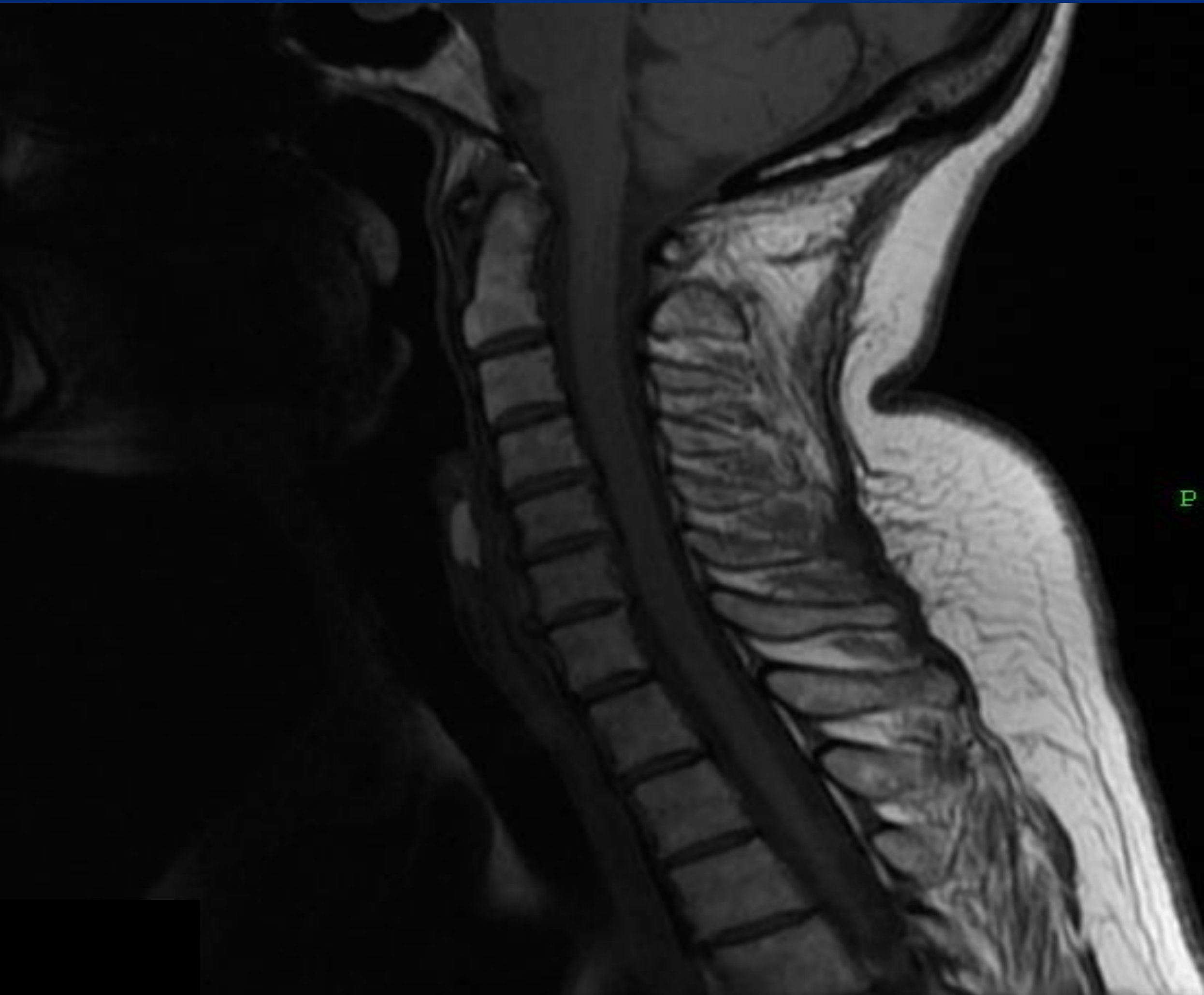
Sagittal Spine



TE = 114 msec

TR = 3267 msec

T_1-Weighted



TE = 13 msec

TR = 450 msec

T_2-Weighted

TE = 114 msec

TR = 3267 msec

MR Protocol

- Collection of imaging sequences
- Executed for a given indication/disease site
- Provide variety of contrasts and functional information

SERIES 1.

Patient (RF)		Imaging		Acquisition Timing	
Coil	Head+Neck 48	Scan plane	3-PLANE	Frequency	384
Scan Timing		Mode	2D	Phase	160
TE	80.0	Pulse sequence	Spin Echo	phase field of view	1.00
TR	Minimum	Imaging Options	Seq, EDR, Fast, SS, ARC	phase correct	No
BW1	83.33	**Additional Parameters**		swap phase & frequency	Unswap
		User CVs		autoshim	Auto
		CV1	1.00	**Range / Prescription**	
		CV2	240.00	field of view	44.0
		CV13	1.00	slice thickness	10.0
		CV15	0.00	slice spacing	15.0

SERIES 2

Patient (RF)		Imaging		Acquisition Timing	
Coil	Head+Neck 48	Scan plane	CORONAL	Frequency	384
Scan Timing		Mode	3D	Phase	256
TE	Minimum	Pulse sequence	Cube	NEX	1.00
TR	650.0	Imaging Options	NPW, EDR, Fast, ZIP2, FR, ARC	phase correct	No
ETL	24	**Additional Parameters**		swap phase & frequency	S/I
BW1	62.50	**User CVs**		autoshim	Auto
		CV22	3.00	**Range / Prescription**	
				slices per slab	180
				field of view	34.0
				slice thickness	1.4

SERIES 3.

Patient (RF)		Imaging		Acquisition Timing	
Coil	Head+Neck 48	Scan plane	CORONAL	Frequency	320
Scan Timing		Mode	3D	Phase	256
TE	100.0	Pulse sequence	Cube	NEX	2.00
TR	2000.0	Imaging Options	FC, NPW, EDR, Fast, ZIP2, FR, ARC	phase correct	No
ETL	110	**Additional Parameters**		Flow comp direction	Freq
BW1	62.50	**User CVs**		swap phase & frequency	S/I
		CV5	0.85	autoshim	Auto
		CV20	0.00	**Range / Prescription**	
		CV22	2.00	slices per slab	170
				field of view	34.0
				slice thickness	1.2
				number of slices	1

Comments Imaging Tip:
To prevent slab wrap, cover all anatomy from side to side.

Diagnostic vs. Radiation Planning MRI

Diagnostic MRI:

- What is the problem?
- High conspicuity
- Dedicated/customized RF coils
- Multiple sequences:
  - Varying contrast
  - Functional information
  - Often qualitative

≠

Planning MRI:

- What is the spatial extent of the problem?
- Where are the adjacent radiosensitive organs?
- High resolution 3D
- Image in treatment position
- Non ideal (surface coils)
- Relatively limited imaging sequences
- Requires large FOV data

Radiation Planning Protocols: Tissue Contrasts

- Pre Contrast T_1:
  - Identification of tumor volume, lymph node involvement and organs at risk (OAR)
- Pre Contrast T_2:
  - Visualization of fat/fluid infiltration
- Post Contrast T_1:
  - Differentiate between tumor (enhancement) and fat/edema
  - Often compare to pre contrast T_2 to improve differentiation

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The Potential for an Enhanced Role For MRI in Radiation-therapy Treatment Planning

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The exquisite soft-tissue contrast of magnetic resonance imaging (MRI) has meant that the technique is having an increasing role in contouring the gross tumor volume (GTV) and organs at risk (OAR) in radiation therapy treatment planning systems (TPS). MRI-planning scans from diagnostic MRI scanners are currently incorporated into the planning process by being registered to CT data. The soft-tissue data from the MRI provides target outline guidance and the CT provides a solid geometric and electron density map for accurate dose calculation on the TPS computer. There is increasing interest in MRI machine placement in radiotherapy clinics as an adjunct to CT simulators. Most vendors now offer 70 cm bores with flat couch inserts and specialised RF coil designs. We would refer to these devices as MR-simulators. There is also research into the future application of MR-simulators independent of CT and as in-room image-guidance devices. It is within the background of this increased interest in the utility of MRI in radiotherapy treatment planning that this paper is couched. The paper outlines publications that deal with standard MRI sequences used in current clinical practice. It then discusses the potential for using processed functional diffusion maps (fDM) derived from diffusion weighted image sequences in tracking tumor activity and tumor recurrence. Next, this paper reviews publications that describe the use of MRI in patient-management applications that may, in turn, be relevant to radiotherapy treatment planning. The review briefly discusses the concepts behind functional techniques such as dynamic contrast enhanced (DCE), diffusion-weighted (DW) MRI sequences and magnetic resonance spectroscopic imaging (MRSI). Significant applications of MR are discussed in terms of the following treatment sites: brain, head and neck, breast, lung, prostate and cervix. While not yet routine, the use of apparent diffusion coefficient (ADC) map analysis indicates an exciting future application for functional MRI. Although DW-MRI has not yet been routinely used in boost adaptive techniques, it is being assessed in cohort studies for sub-volume boosting in prostate tumors.

Key words: MRI; Radiation therapy; Radiation; Therapy treatment planning.

Abbreviations: ADC: Apparent Diffusion Coefficient; AVM: Arteriovenous Malformation; BOLD: Blood Oxygen Level Dependent; CC: Corpus Carvernosum; CT: Computed Tomography; CTV: Clinical Target Volume; 4DCT: 4 Dimensional Computed Tomography; DW: Diffusion Weighted; DCE: Dynamic Contrast Enhanced; DNP: Dynamic Nuclear Polarization; EPI: Echo Planar Imaging; fDM: Functional Diffusion Map; fV: Functional Lung Volume; FFE-EPI: Fast Field Echo Planar Imaging; FIESTA: Fast Image Employing Steady State Acquisition; FLASH: Fast Low Angle Shot; FLAIR: Fast Fluid-attenuated Inversion Recovery; fMRI: Functional Magnetic Resonance Imaging; FSRT: Fractionated Stereotactic Radiation Therapy; GTV: Gross Tumor Volume; HNSCC: Head and Neck Squamous Cell Carcinioma; IGBT: Image Guided Brachytherapy; IPA: Internal Pudental Artery; MRA: Magnetic Resonance Angiography; MRI: Magnetic Resonance Imaging; MRSI: Magnetic Resonance Spectroscopic Imaging; NSCLC: Non Small Cell Lung Cancer; PET: Positron Emission Tomography; PHIP: Parahydrogen Induced Polarization; PTV: Planning Target Volume; SPGR: Spoiled Gradient; SSFSE: Single Shot Fast Spin Echo; SRS: Stereotactic Radiosurgery; T1: Longitudinal Relaxation Time; T2: Transverse Relaxation Time; TB: Tumor Bed; TPS: Treatment Planning System; TR: Repetition Time; TrueFIST: True Fast Imaging with Steady State Precession; VMAT: Volumetric Modulated Arc Therapy.

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Tissue Contrasts

"T_1-weighted images are considered best for gross structural information (anatomy) and T_2-weighted images for ..... pathology information."

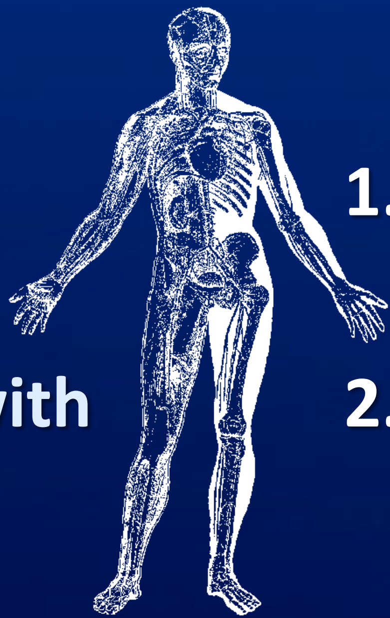
MR Protocols for Radiation Planning

Soft Tissue

1. T_1-weighed
2. T_2-weighted with fat saturation

------CONTRAST------

3. T_1-weighted with fat saturation

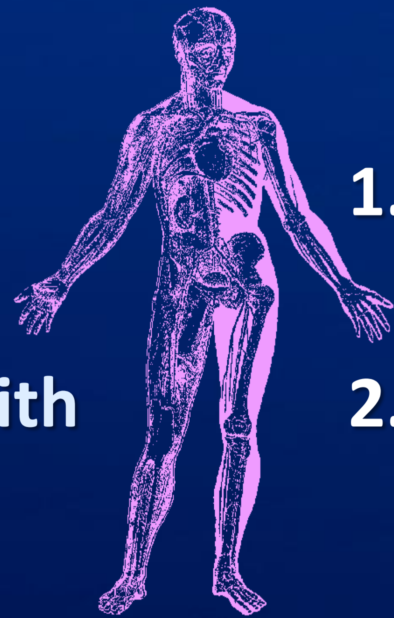


Brain

1. T_1-weighed
2. T_2-weighted with fat saturation

------CONTRAST------

3. T_1-weighted



Bone

1. T_1-weighted
2. T_2-weighted with fat saturation

------CONTRAST------

3. T_1-weighted with fat saturation

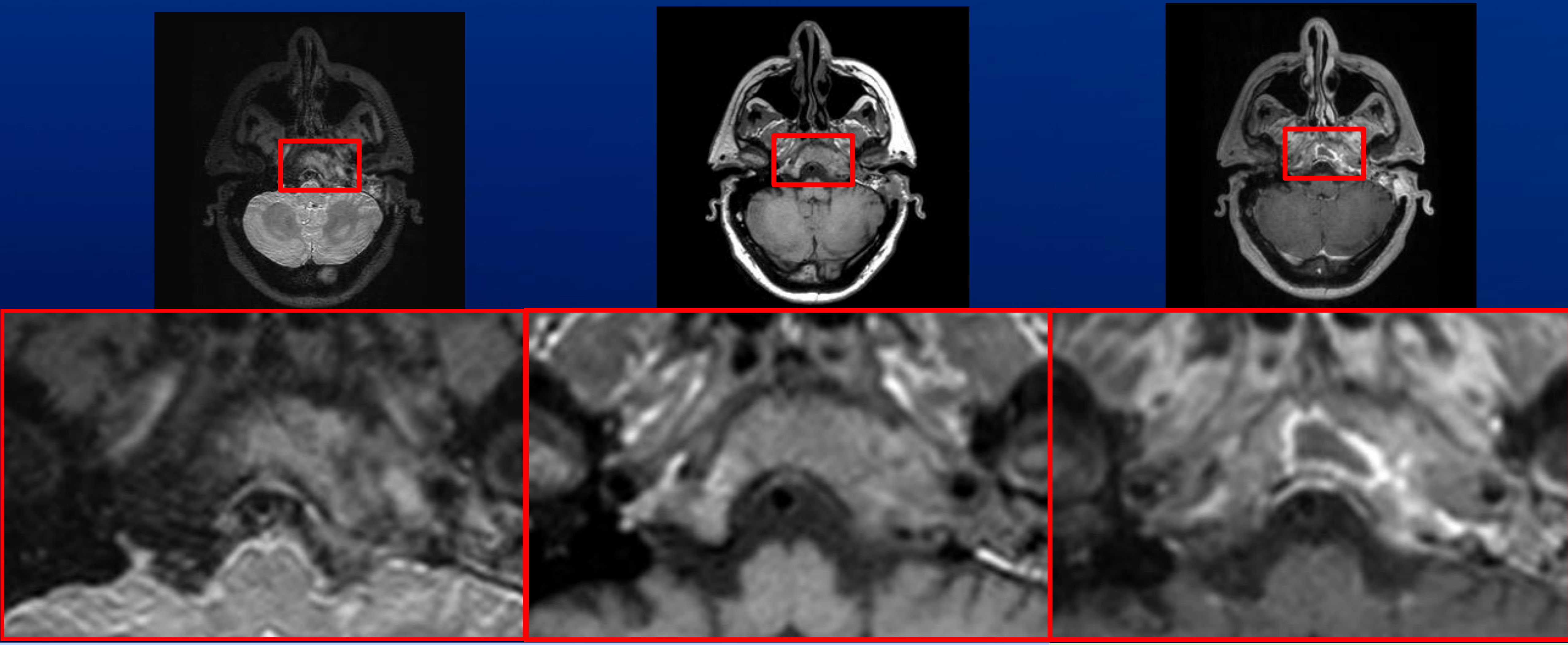
Soft Tissue Treatment Planning

Fat Saturated T_2-Weighted | **T_1-Weighted** | **T_1-Weighted**

Pre Contrast | **Post Contrast**

Soft Tissue Treatment Planning

Fat Saturated T_2-Weighted | **T_1-Weighted** | **T_1-Weighted**



Pre Contrast | **Post Contrast**

Bone Treatment Planning

Fat Saturated T_2-Weighted

T_1-Weighted

T_1-Weighted

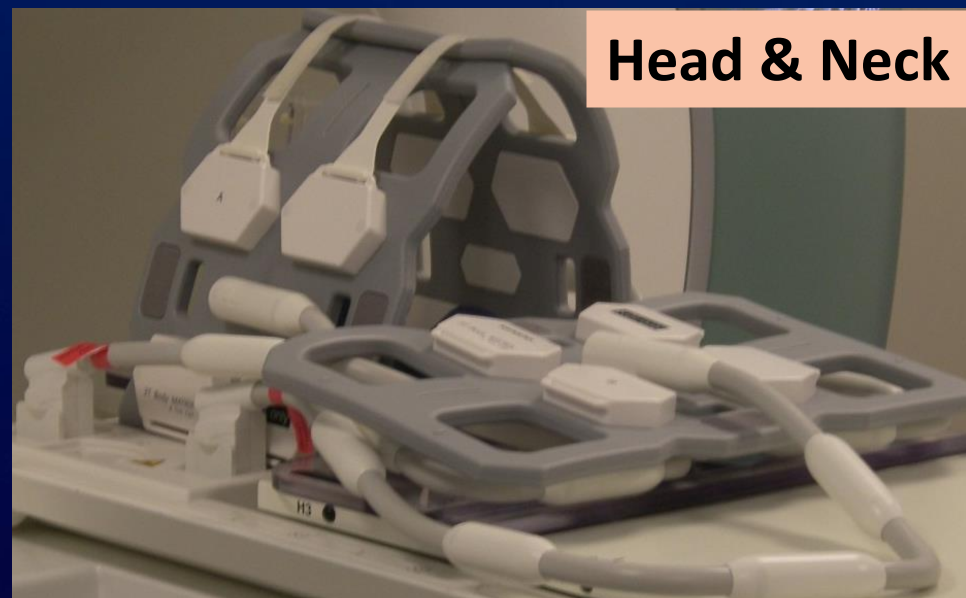
Pre Contrast

Post Contrast

MR Imaging in Treatment Position

- RF Coils and Immobilization
- Set up Instructions:
  - Coils and immobilization
  - Set up and imaging
  - Protocol Instructions

MRI in Treatment Position: Coils and Immobilization



MRI in Treatment Position: Setup & Imaging Instructions

Details and pictures highlight:

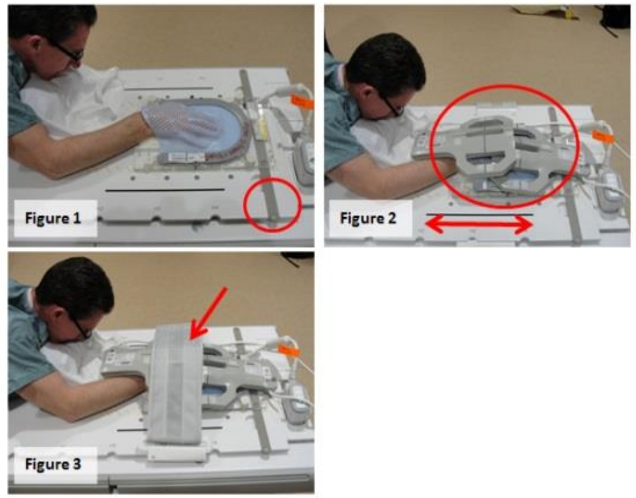
- Fabrication of immobilization
- Placement of immobilization
- Coil configuration
- Anatomy wrt coils

Typical coverage listed:

- tumor + edema + closest joint (prefer scan range to cover 4-5cm beyond extent)
- Typical coverage for proximal femur – include distal pelvis

Photons – Hand with Moldcare or Klarity and Mask, with Arm Above Head:

- *PLACEMENT:* Index the middle locking bar to H5 *(Figure 1)*
- *COIL:* Use RT HEAD (posterior array and 6 channel flex coils, *Figure 2)*
- *ANATOMY:* Confirm posterior array spans the entire region of interest *(Figure 2, arrow)*
- Secure with tape or strap *(Figure 3, arrow)*



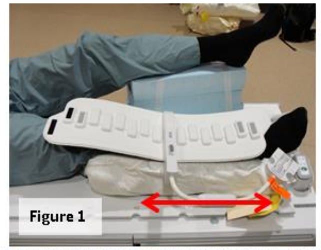
Photons – Axilla, arm at side akimbo in vacloc:

- *PLACEMENT:* Position Vacloc superiorly on the couch overlay *(Figure 4)*
- *COIL:* Use RT CHEST (posterior array and large flex coil, using foam pads to keep flex coil off of chin *(Figure 4,5)*
- *ANATOMY:* Confirm posterior array spans the entire region of interest *(Figure 5, arrow)*

Photons – Feet First / VacLoc / Contralateral leg on Styrofoam blocks:

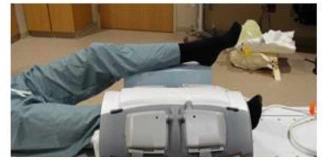
IF COVERAGE DOES NOT EXTEND SUPERIORLY BEYOND KNEE

- *PLACEMENT:* Position knee joint around H2/H1 *(Figure 1)*
- *COIL:* Use RT CHEST (posterior array and large flex coil, *Figure 1)*
- *ANATOMY:* Confirm posterior array spans the entire region of interest *(Figure 1, arrow)*



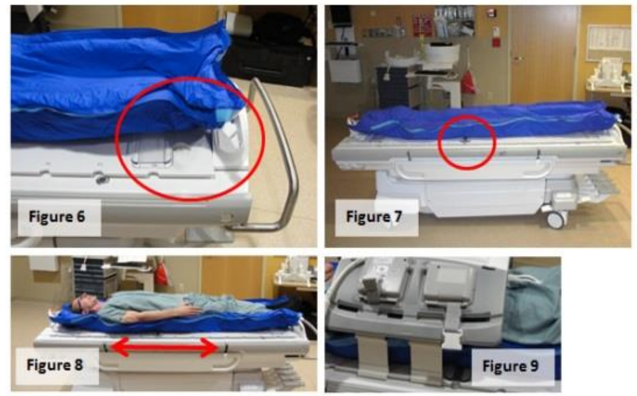
IF COVERAGE DOES EXTEND SUPERIORLY BEYOND KNEE

- *PLACEMENT:* Position Vacloc so inferior extent of region of interest is around H2/H3 *(Figure 2)*
- *COIL:* Use spine coil and anterior torso array *Figure 2)*
- *ANATOMY:* Confirm spine coil spans the entire region of interest *(Figure 2, arrow)*
- If anterior torso array is not stable, place the one side of it under the contralateral leg



Photons – Scapula SBRT, arm at side in blue BodyFix bag:

- *FABRICATION:* Build up at foot end so bag will fit on MR couch *(Figure 6)*
- *PLACEMENT:* Index the middle locking bar to F1 *(Figure 7)*
- *ANATOMY:* Confirm spine coil spans the entire region of interest *(Figure 8)*
- *COIL:* Use spine coil in table and anterior torso array supported on rainbow bridges) *(Figure 9)*



FOV / Scanning Range:

- Per Radiation Oncologist
- *Typical coverage*: want to see the tumor and edema and closest joint – would prefer to scan 4-5cm beyond extent
- *Typical coverage if proximal femur*: for very proximal femur cases, imaging the distal pelvis is required, i.e. scan proximally to 4cm rostral to the roof of the acetabulum

Data Transfer:

- Send to ONC2 (x-ray) or ONC1 (proton)
- Archive all series

MRI in Treatment Position: Protocol Instructions

- Each protocol has a document
- Indications help the dosimetrist know which protocol table to review with the radiation oncologist
- Table filled out by the dosimetrist with the area to be scanned, with any edits per radiation oncologist

RO Tx Pln – MSK Lower Extremity – MR50

Indications:

- Bone or soft tissue sarcoma in lower extremity (femur, calf, foot)

Current Protocol on MR50:

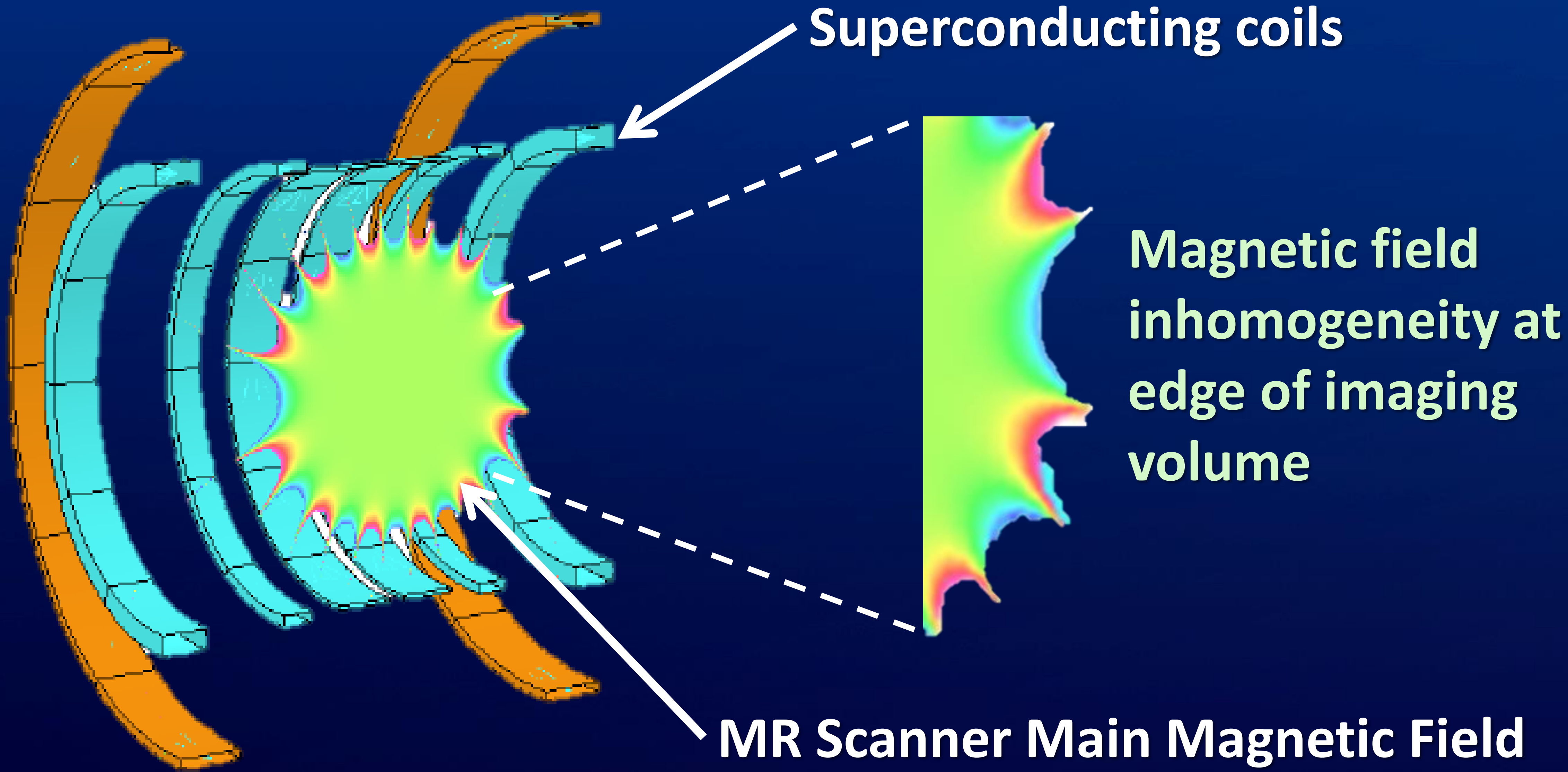
RO Tx Plan – MSK Rad Onc Lower Extremity *Switch patient to 1.5T if any metal present in volume of interest (including clips...)* *make sure 3D Distortion correction on 3D sequences before acquisition* *FOV and RF coil choice based on Radiation Therapy planning requirements and patient immobilization device*			
AREA TO BE SCANNED:			
Sequence:	**Reformat:**	DEFAULT *(required)* vs. DEVELOPMENT *(optional)*	Comment
Cor Cube T1	2mm axials AND 3mm axials	DEFAULT	*NO FS; Acquire per Radiology* *Switch to sag instead of cor if needed per positioning*
Cor Cube T2 FS	2mm axials AND 3mm axials	DEFAULT	*Switch to sag instead of cor if needed per positioning*
POST-CONTRAST			
Cor Cube T1 FS	2mm axials AND 3mm axials	DEFAULT	*RadOnc may decide they do not need a T1 gad series* *Switch to sag instead of cor if needed per positioning*

Sources of Error in MRI

Sources of error in MR

- Spatial distortion:
    - B_0 inhomogeneity
    - Gradient non linearity
- RF non uniformity
- Susceptibility induced distortion
- Motion and organ filling

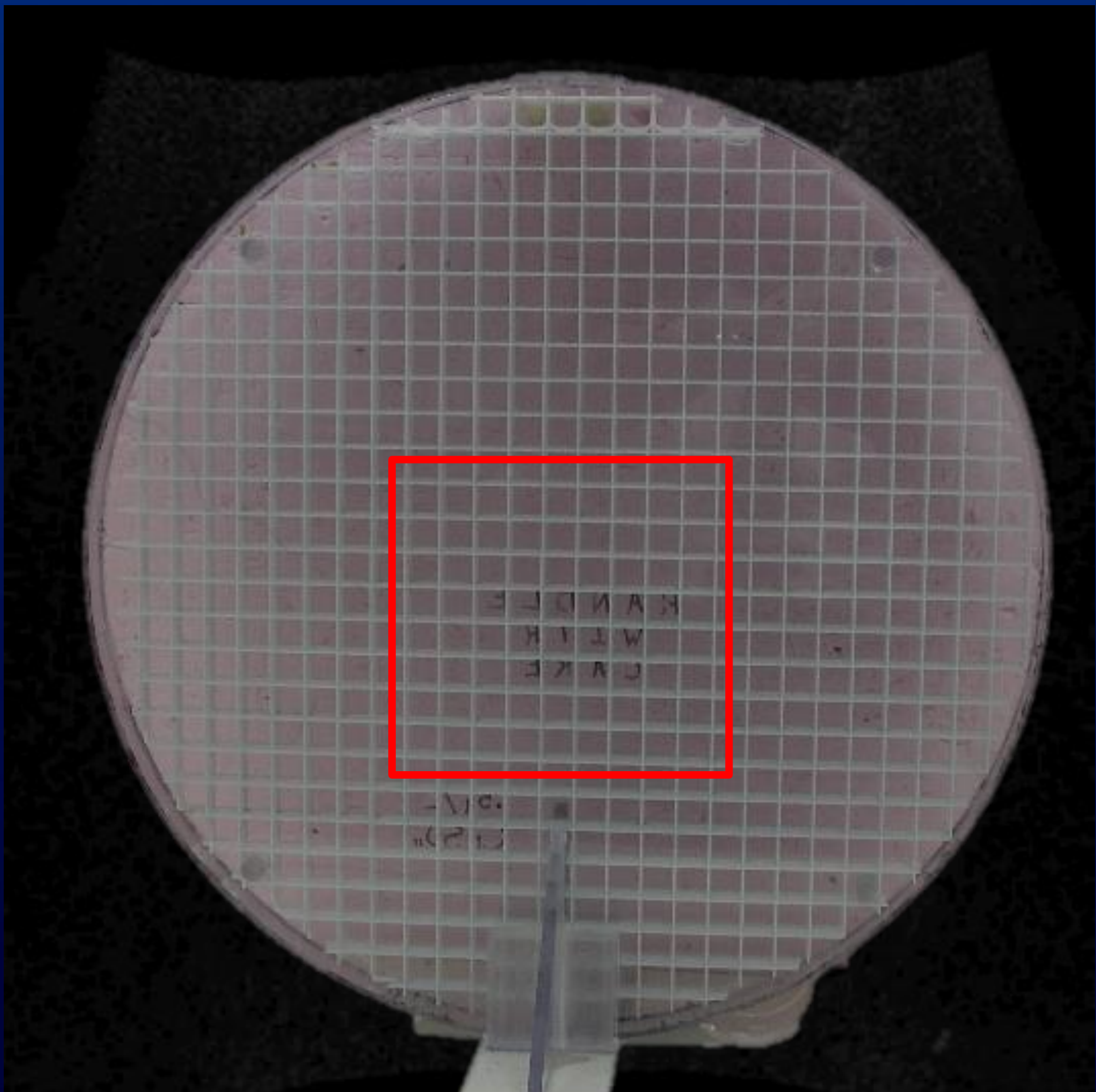
Spatial Distortion in MRI

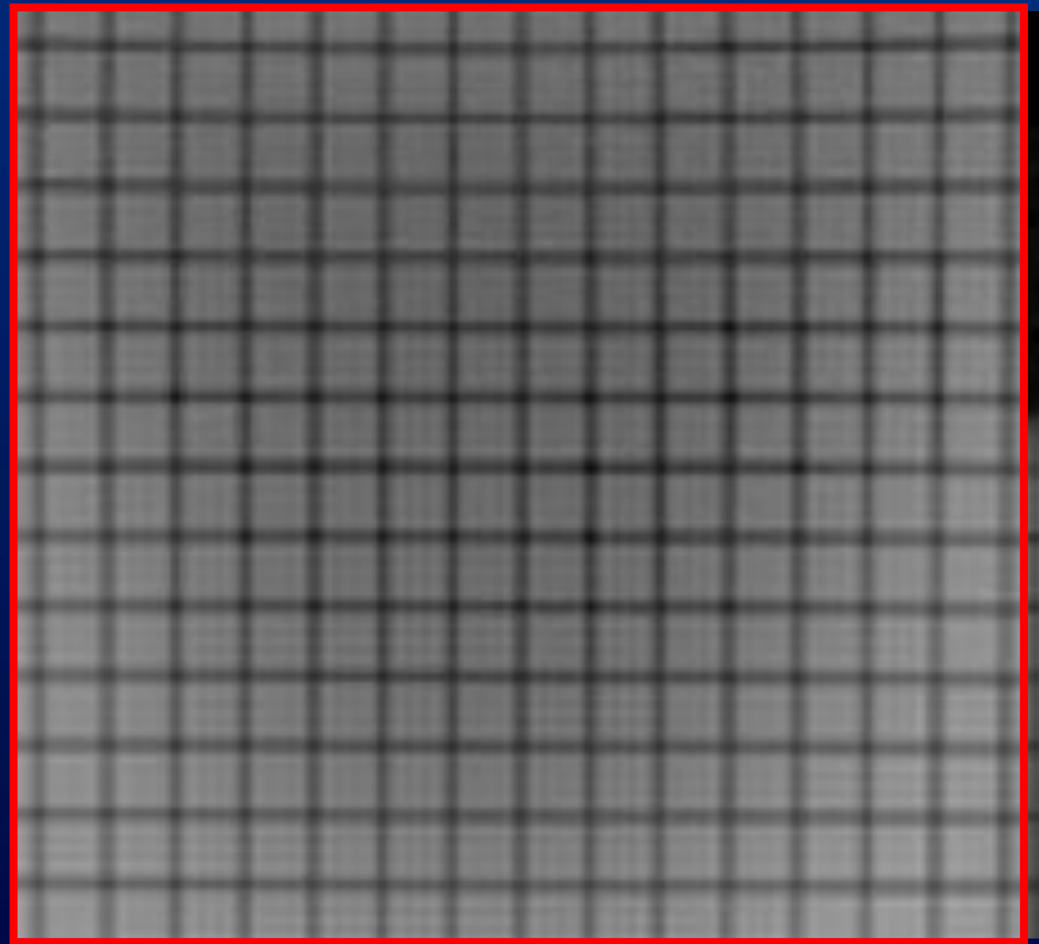


Spatial Distortion in MRI

Superior

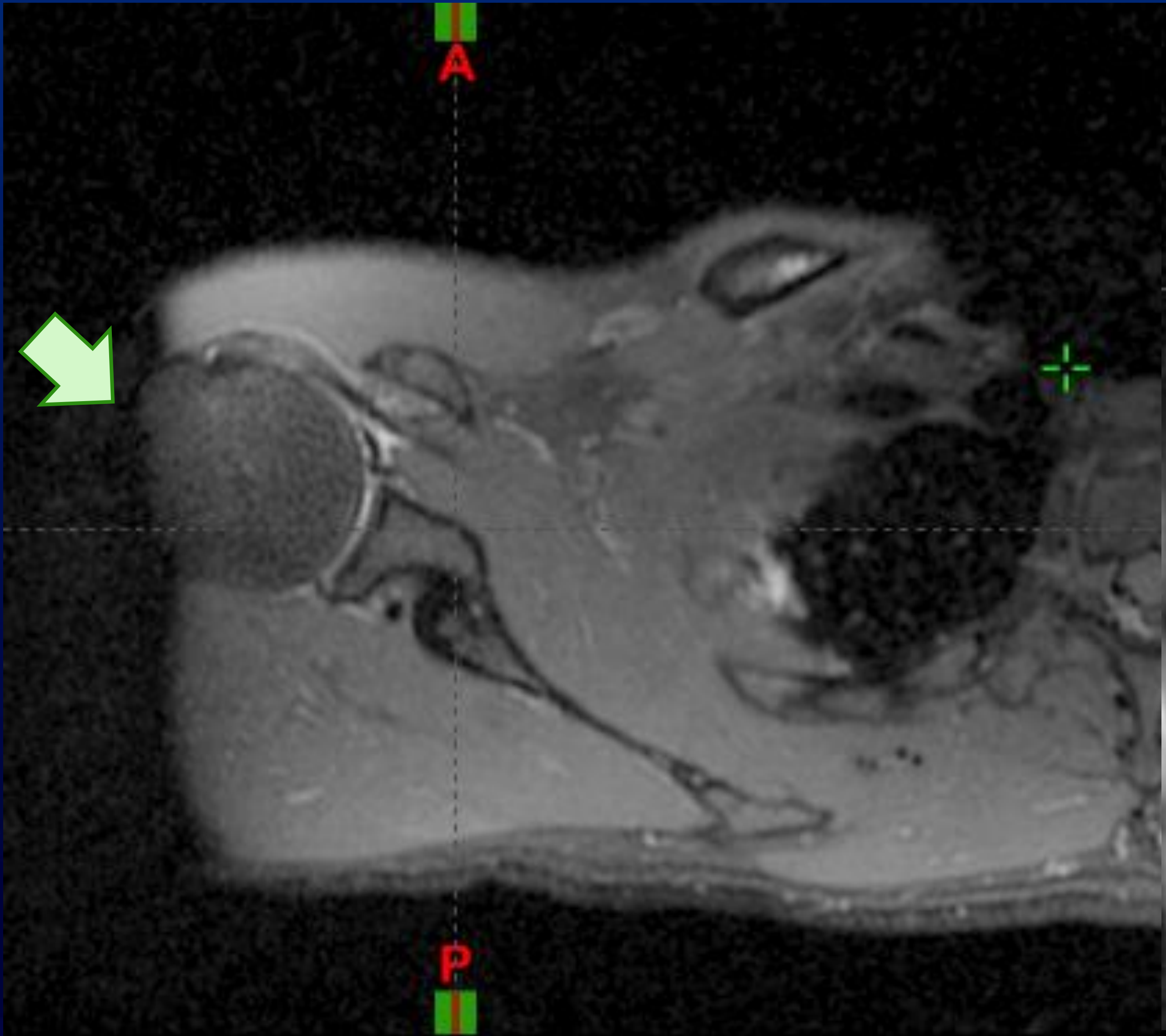
Inferior



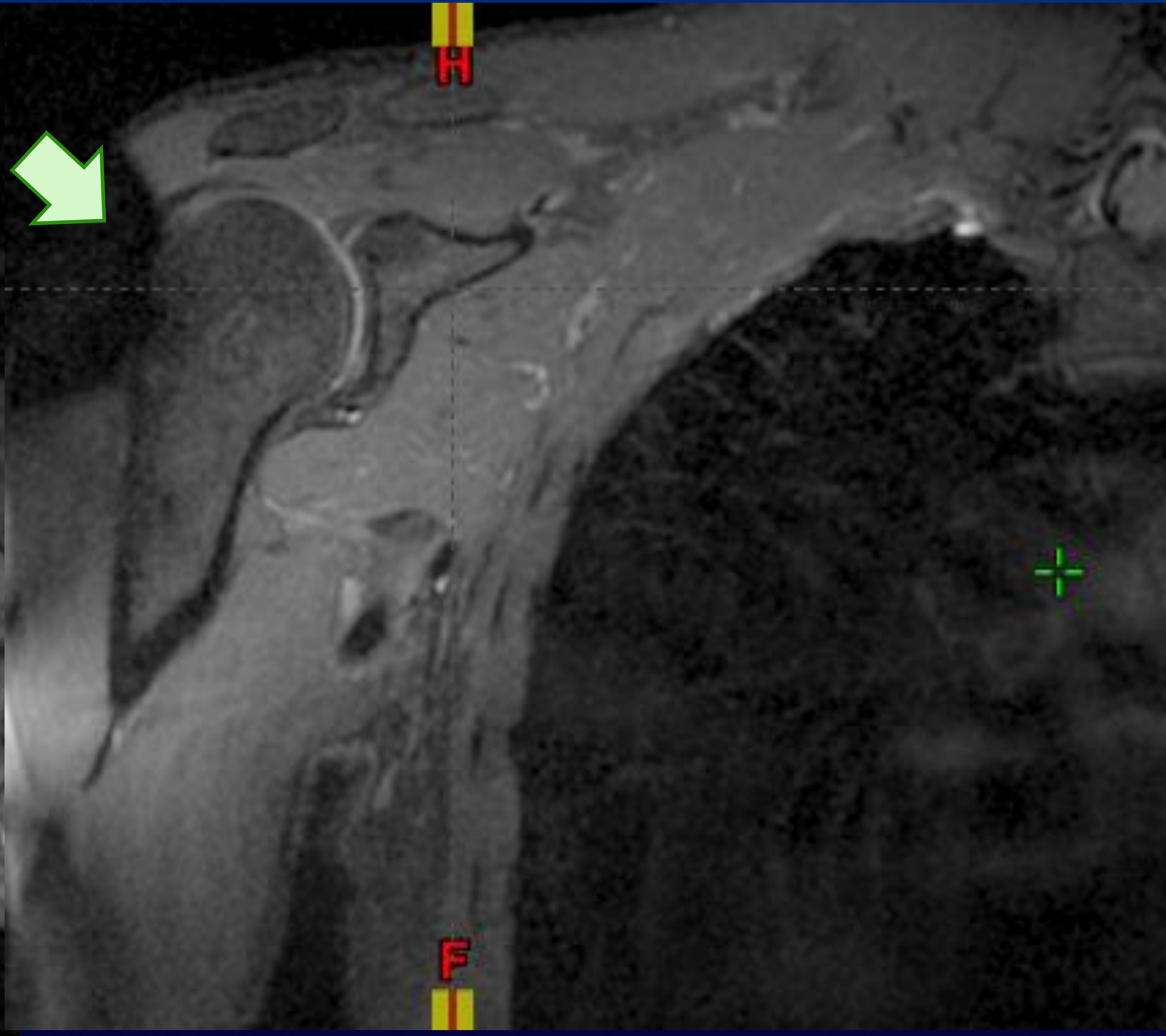


B_0 Inhomogeneity: Shoulder Imaging

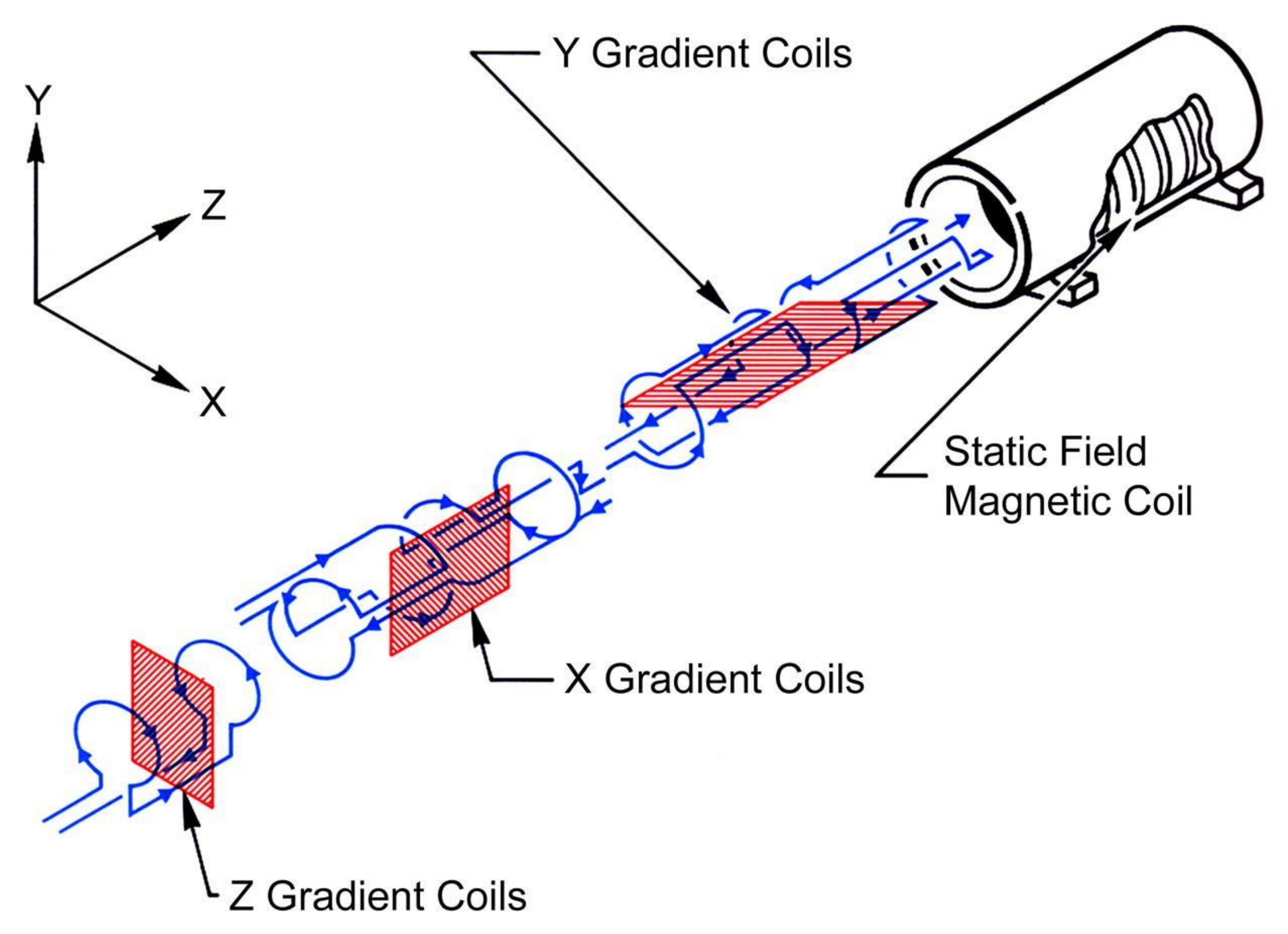
Axial



Coronal

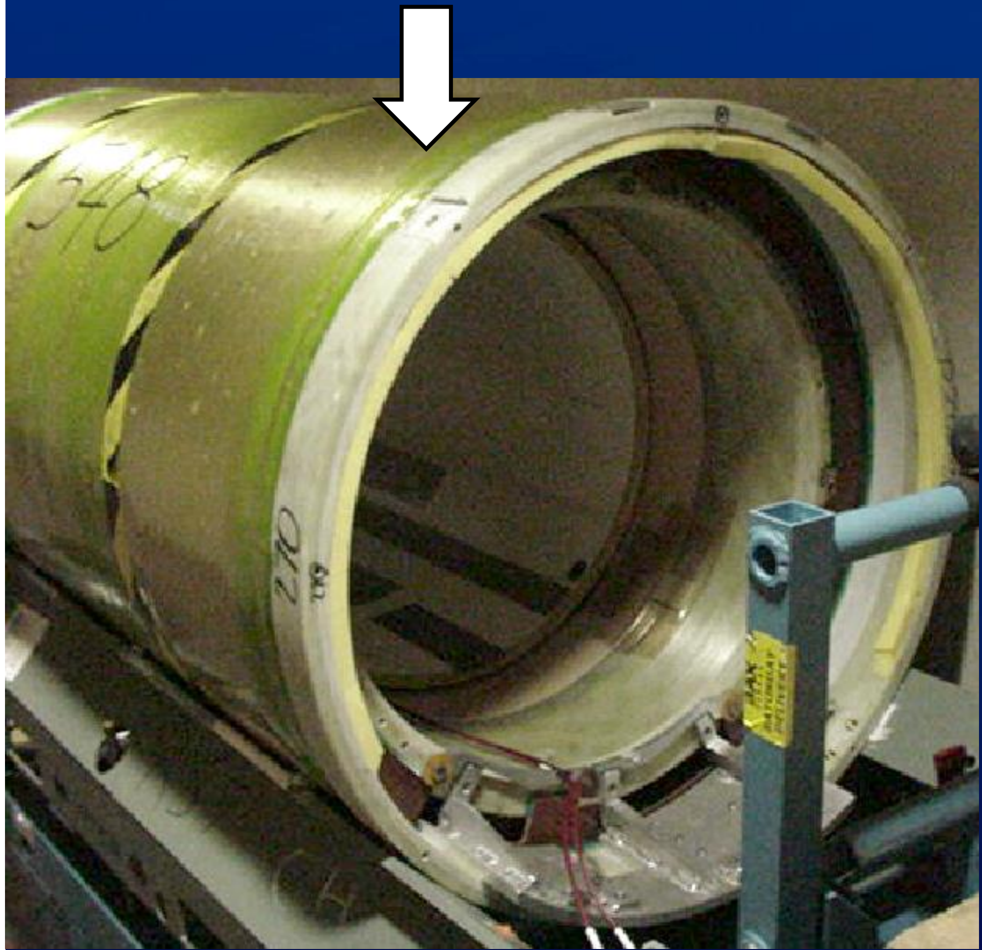


Spatial Encoding Gradient Fields

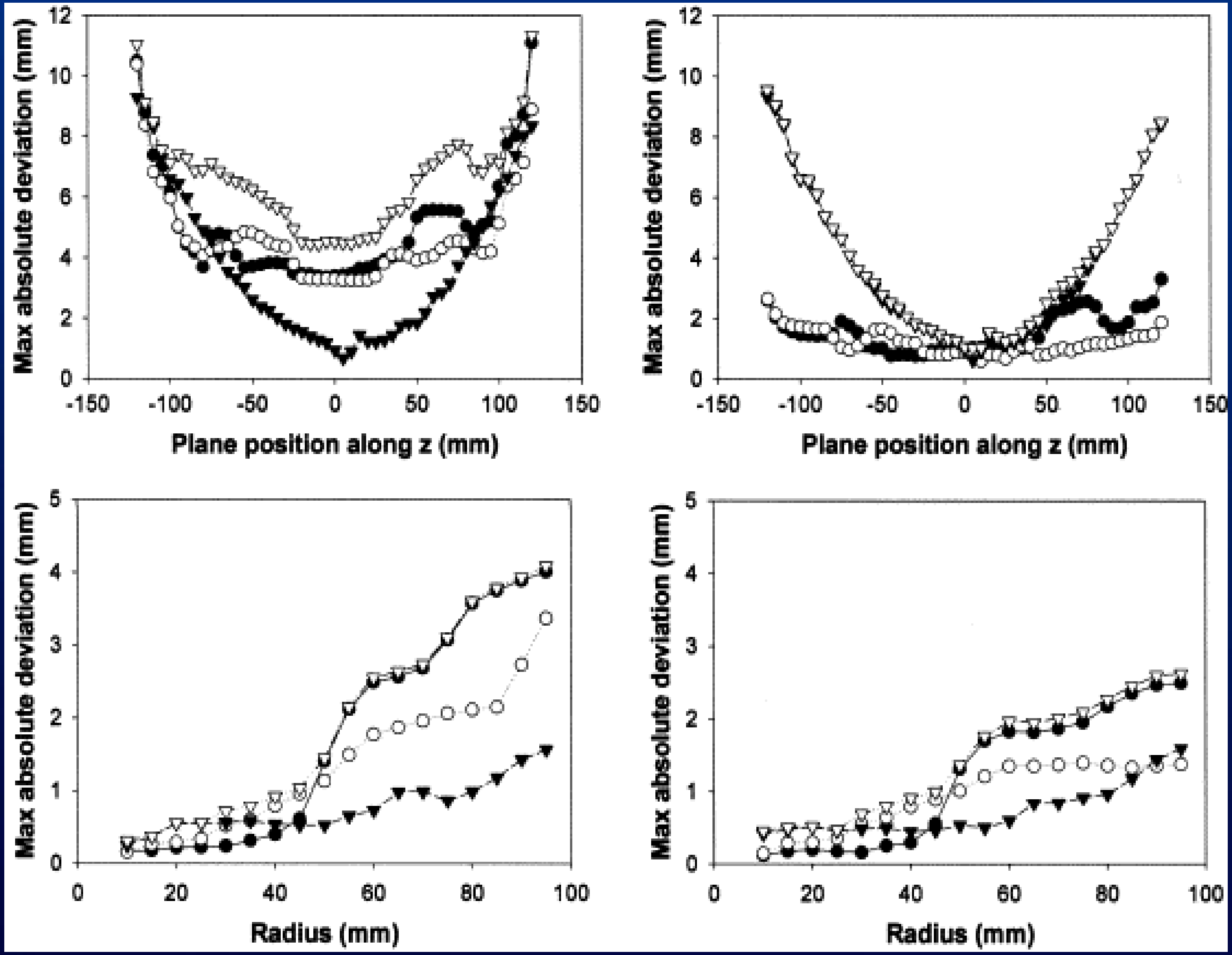


Jacobs M A et al. Radiographics 2007; 27: 1213-1229

Gradient Coils



1.5T MR Scanner Spatial Distortion



Wang et al. Magnetic Resonance Imaging, Volume 22, Issue 9, 2004, 1211 - 1221

Acceptable Spatial Distortion Limits

Characterization, prediction, and correction of geometric distortion in 3 T MR images

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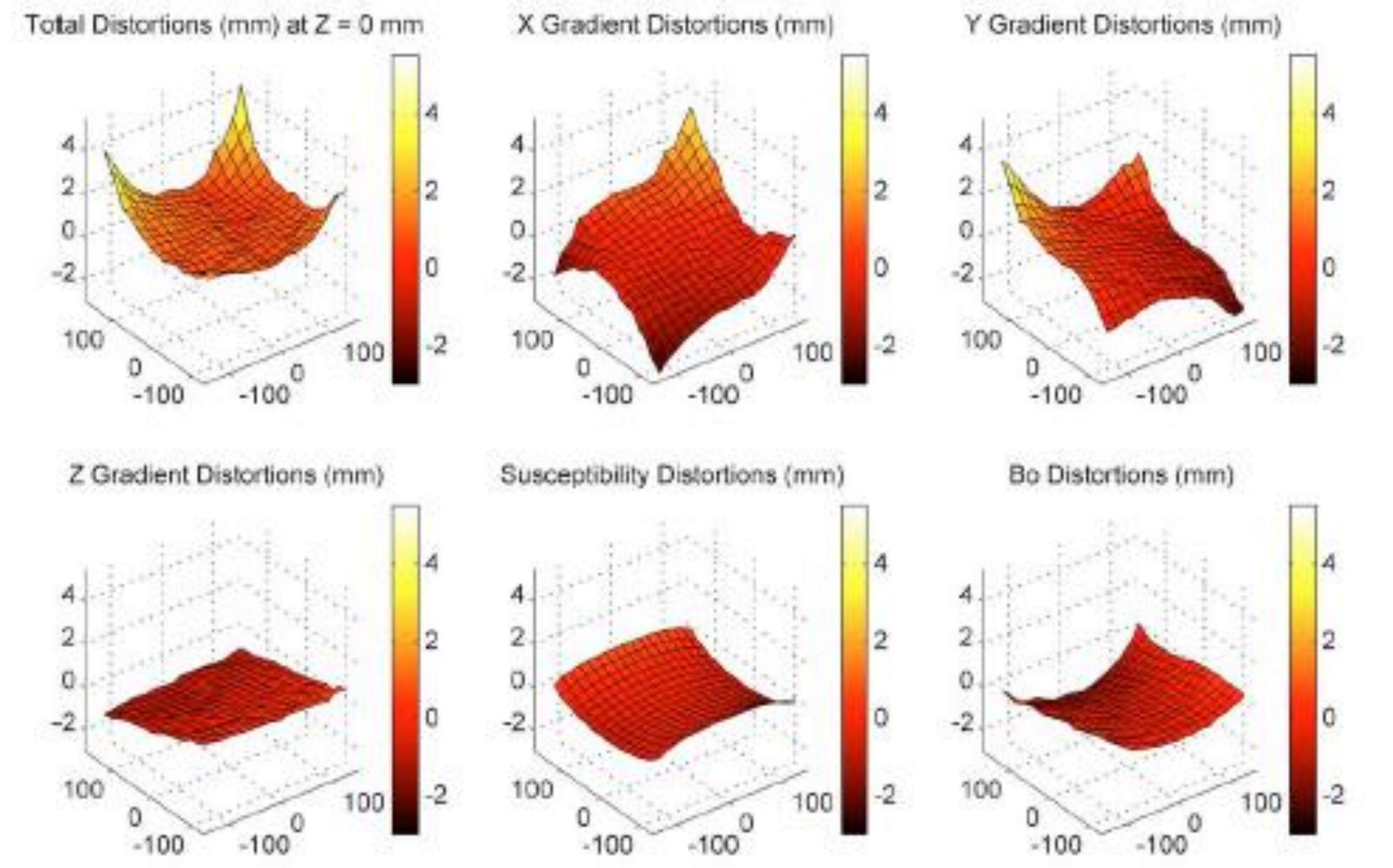
(Received 9 July 2006; revised 4 October 2006; accepted fc
published 8 January 2007)

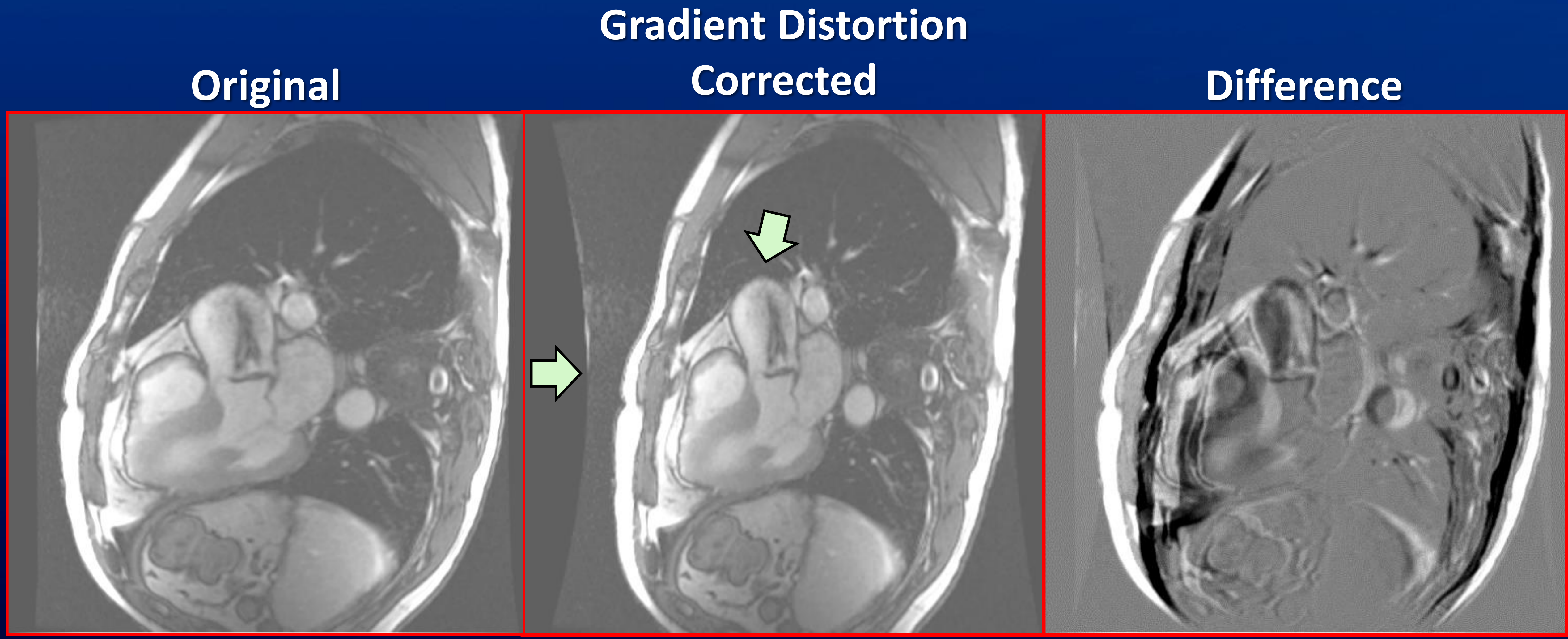


- **Baldwin et al reported on spatial distortion of ~ 5mm within 20 cm radius centered at isocenter for a 60 cm 3T scanner (Med. Phys. 34(2), 2007)**

Spatial Distortion: Correction Methods

- B_0 Corrections:
  - Passive and active shimming techniques
- Gradient Field Corrections:
  - Distortion can be modeled and corrected
  - Correction algorithms applied for all 3 gradient axes
  - <u>Check to make sure that gradient distortion correction is on!</u>

Gradient Non Linearity: Corrections

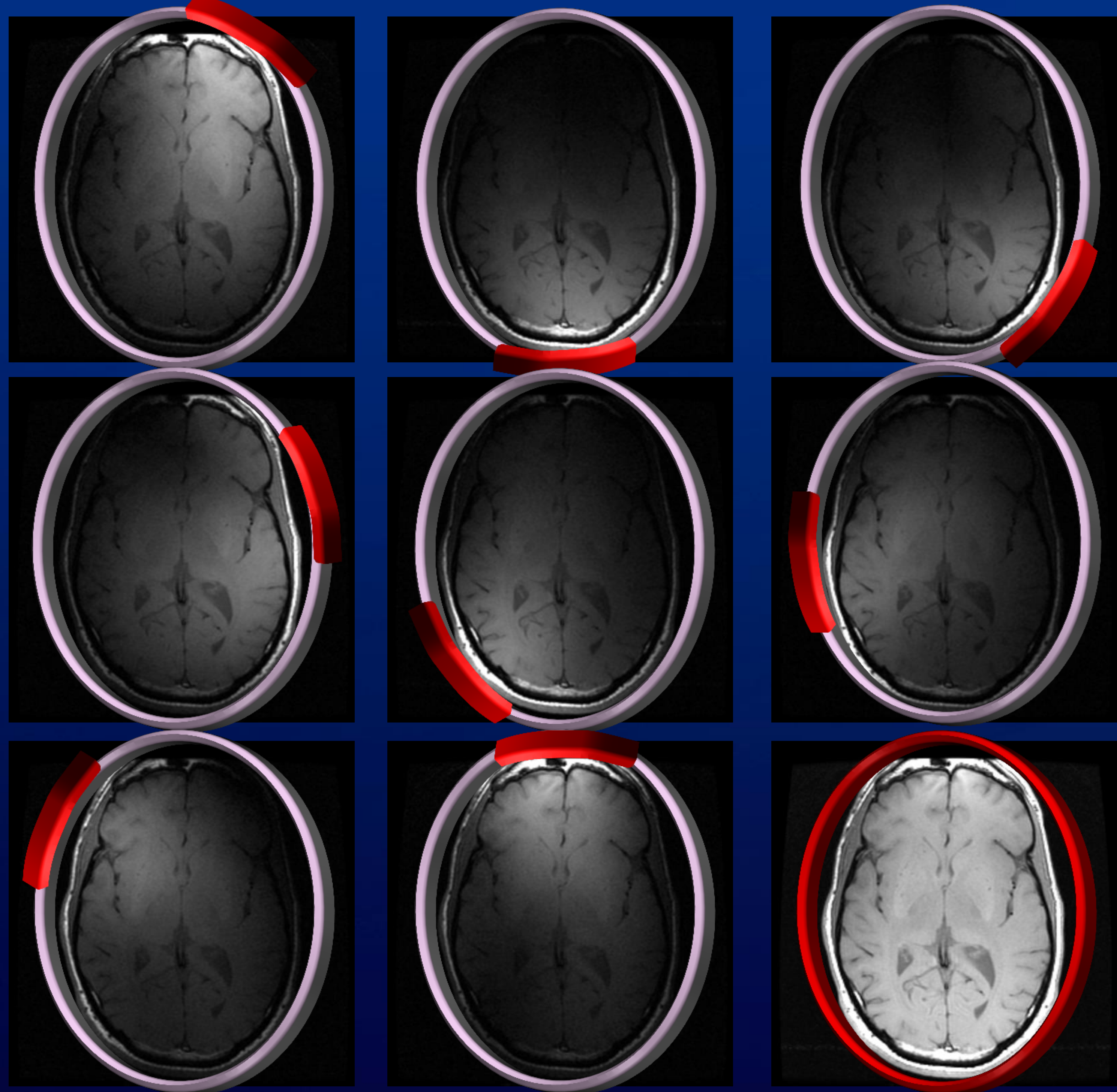


RF Non Uniformity

- RF field (coil sensitivity) falls off nonlinearly with depth from coil
- Surface (receive-only) coils create non uniform MR images
- Typically require some type of post processing to correct for non uniform image intensity

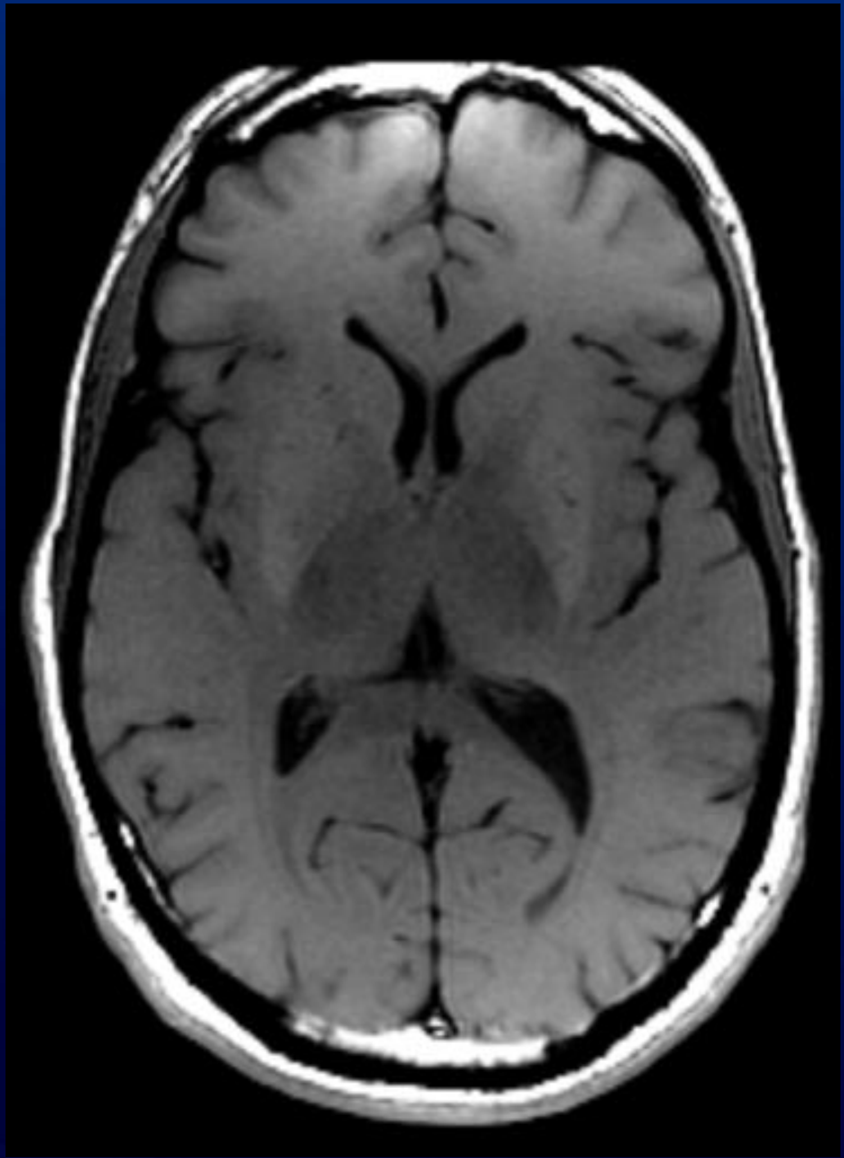
RF (B_1^-) Field Inhomogeneities

8 Channel Head Coil

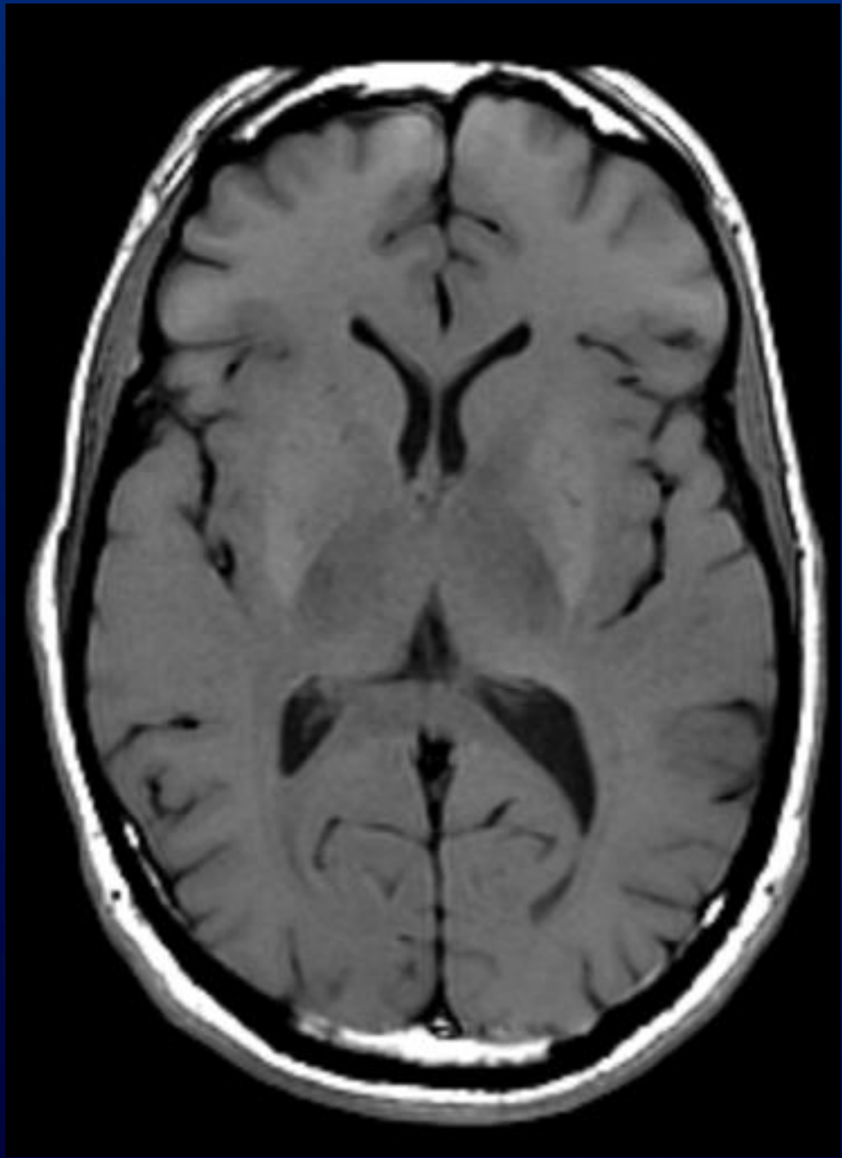


Uniformity Correction

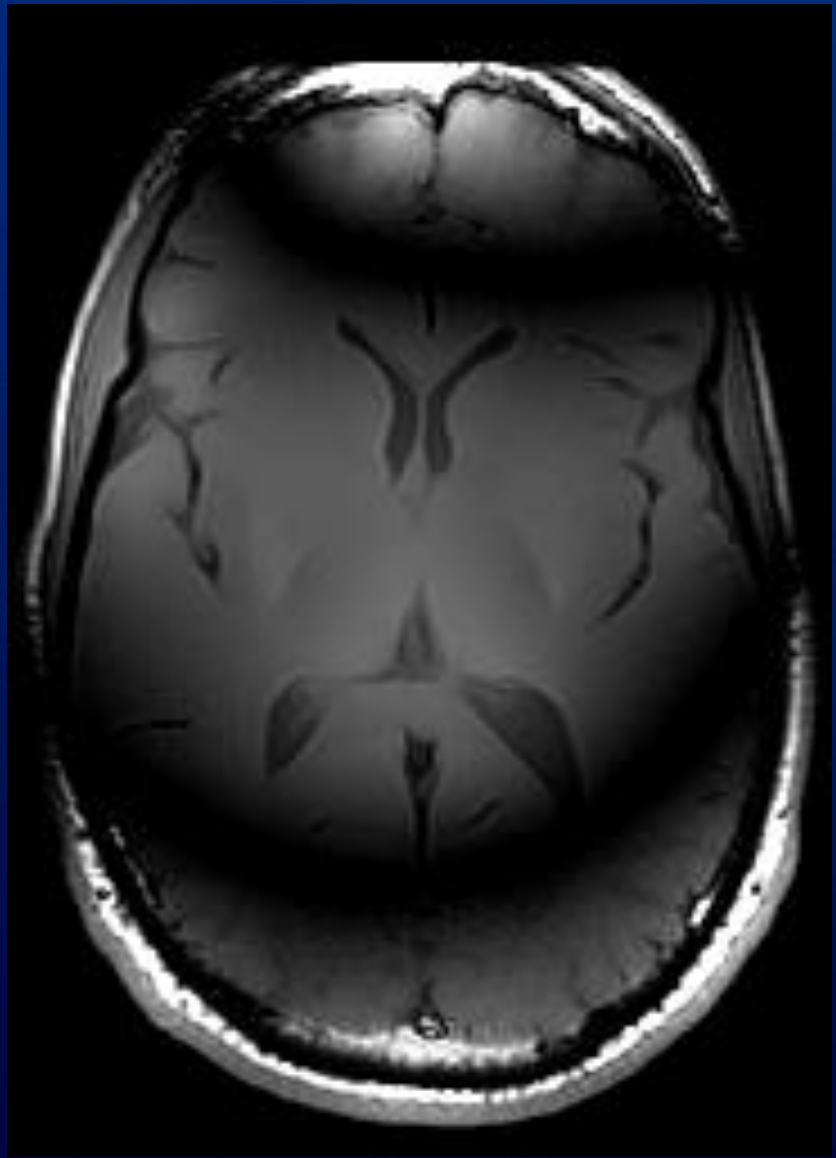
Original



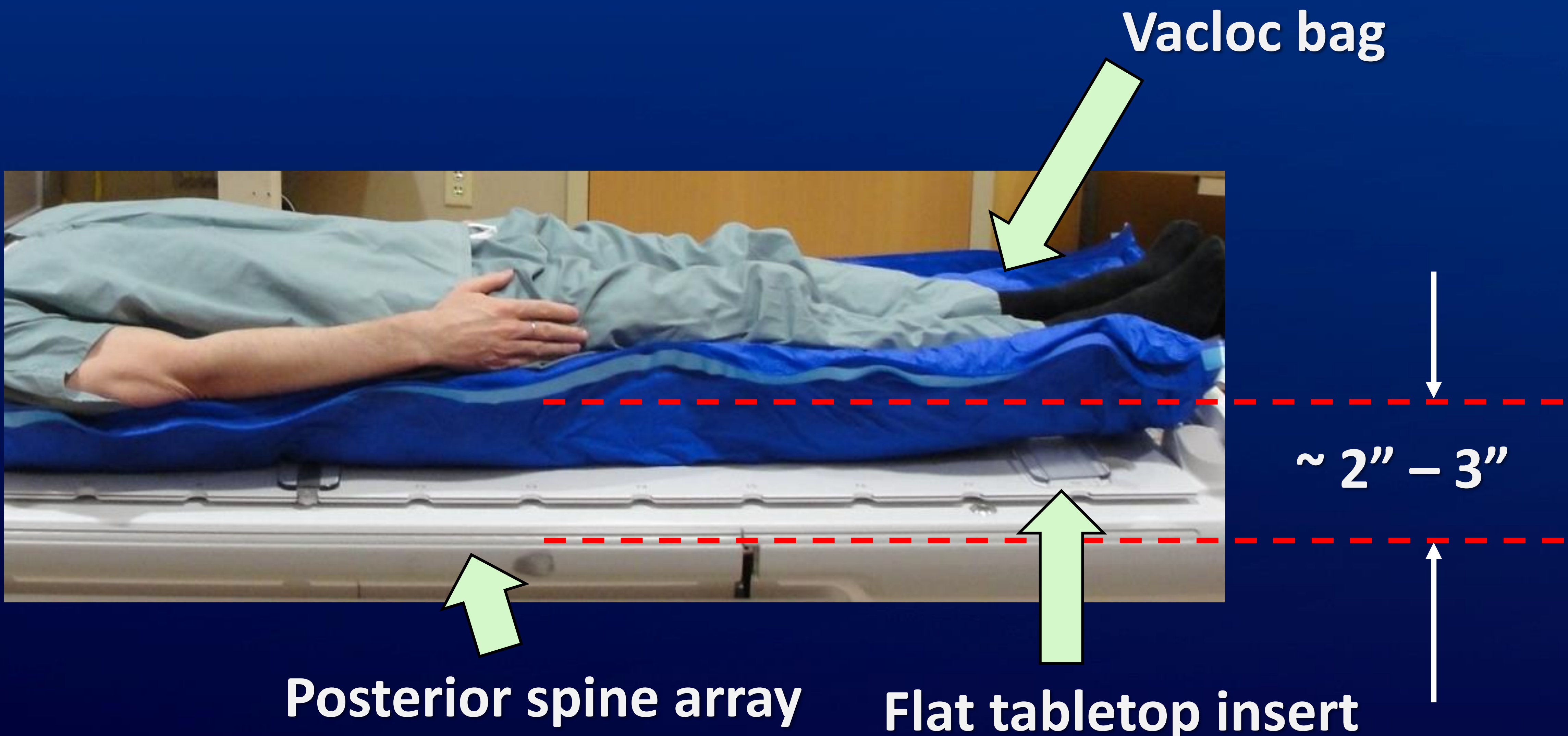
Intensity Corrected



Difference



RF Non Uniformity: Coil Sensitivity



Magnetic Susceptibility (χ)

Magnetization of a material M is given by:

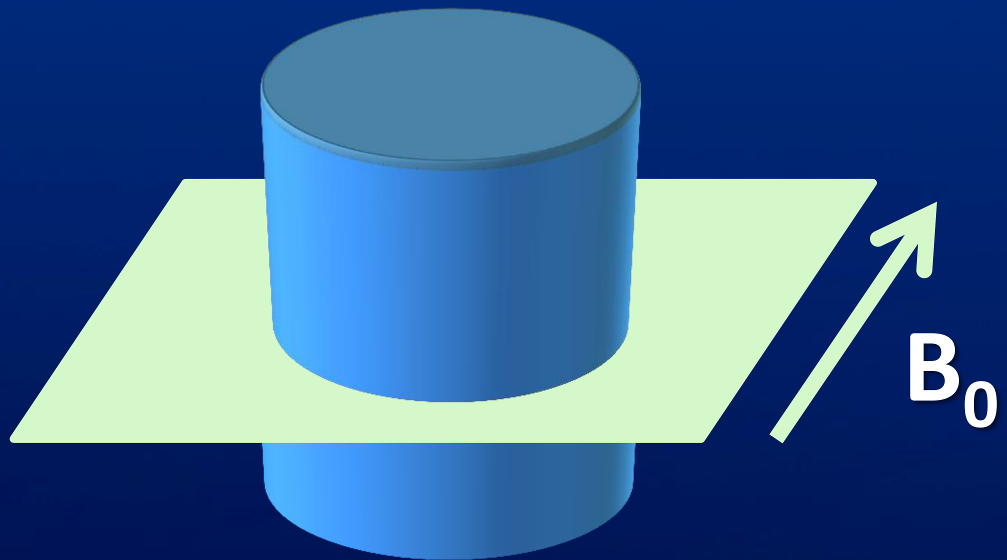
$$M = M_0 + \chi H$$

M_0 = Inherent magnetization of material

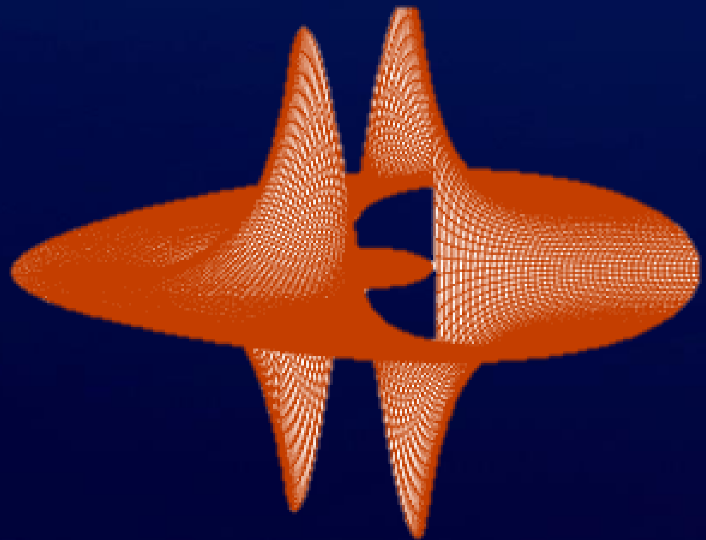
χH = Magnetization induced by externally applied magnetic field

Susceptibility Induced Field Distortion

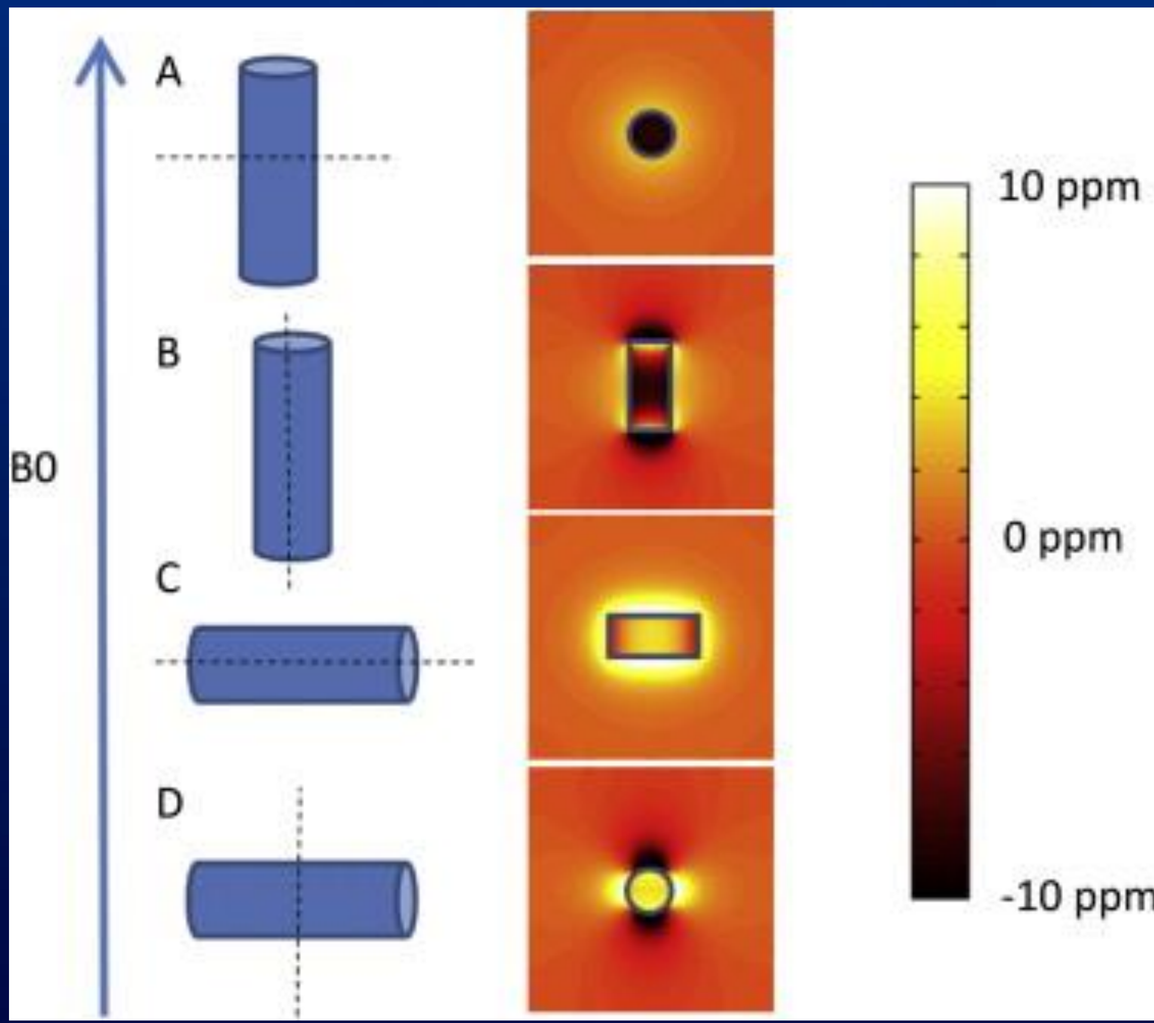
Object



Magnetic Field Perturbation (ΔB_0)

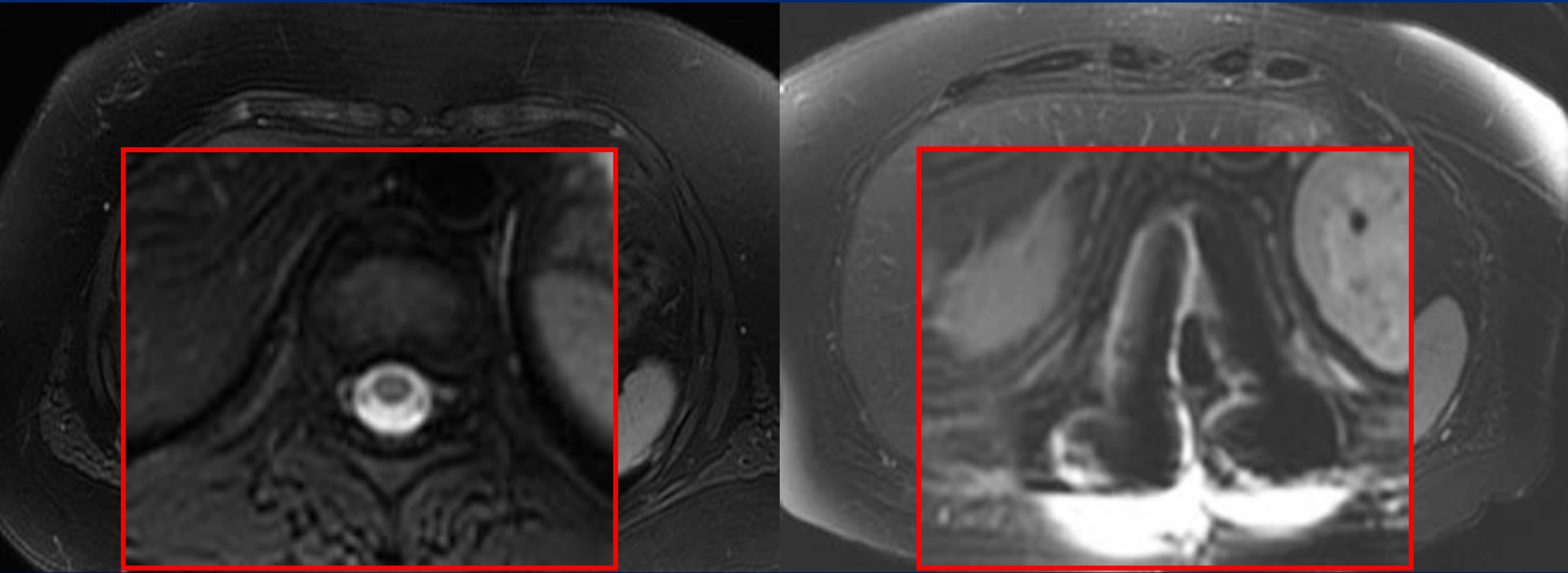


Object Orientation　　Field Map



Joakim H. et al., Internal Fiducial Markers and Susceptibility Effects in MRI: Simulation and Measurement of Spatial Accuracy, IJROBP, Vol. 82, # 5, 2012, pp 1612 - 1618

Challenges: Foreign Metal Implants



Field Strength Dependency

1.5T

- Susceptibility induced distortion scales with field strength
- 3.0T will greater artifacts compared to 1.5T

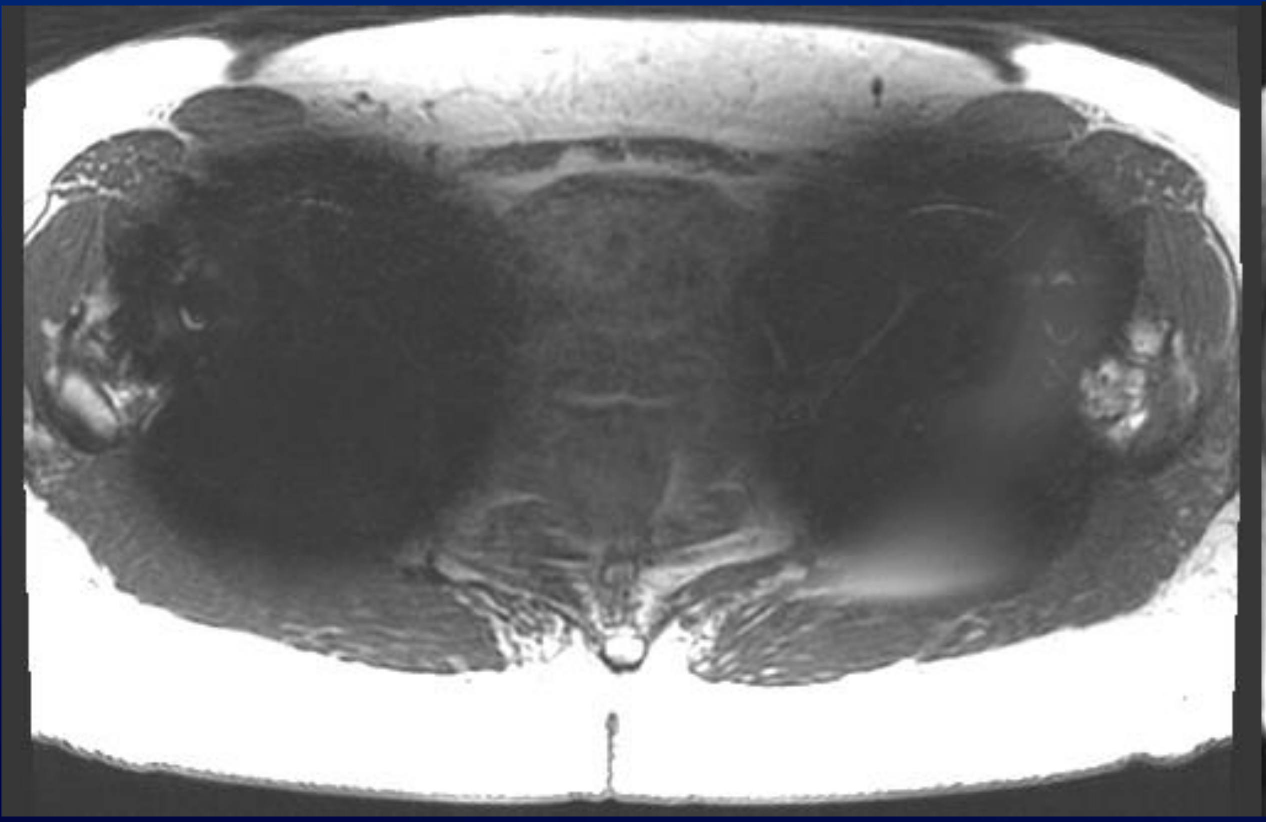
3.0T

Foreign Metal Implants

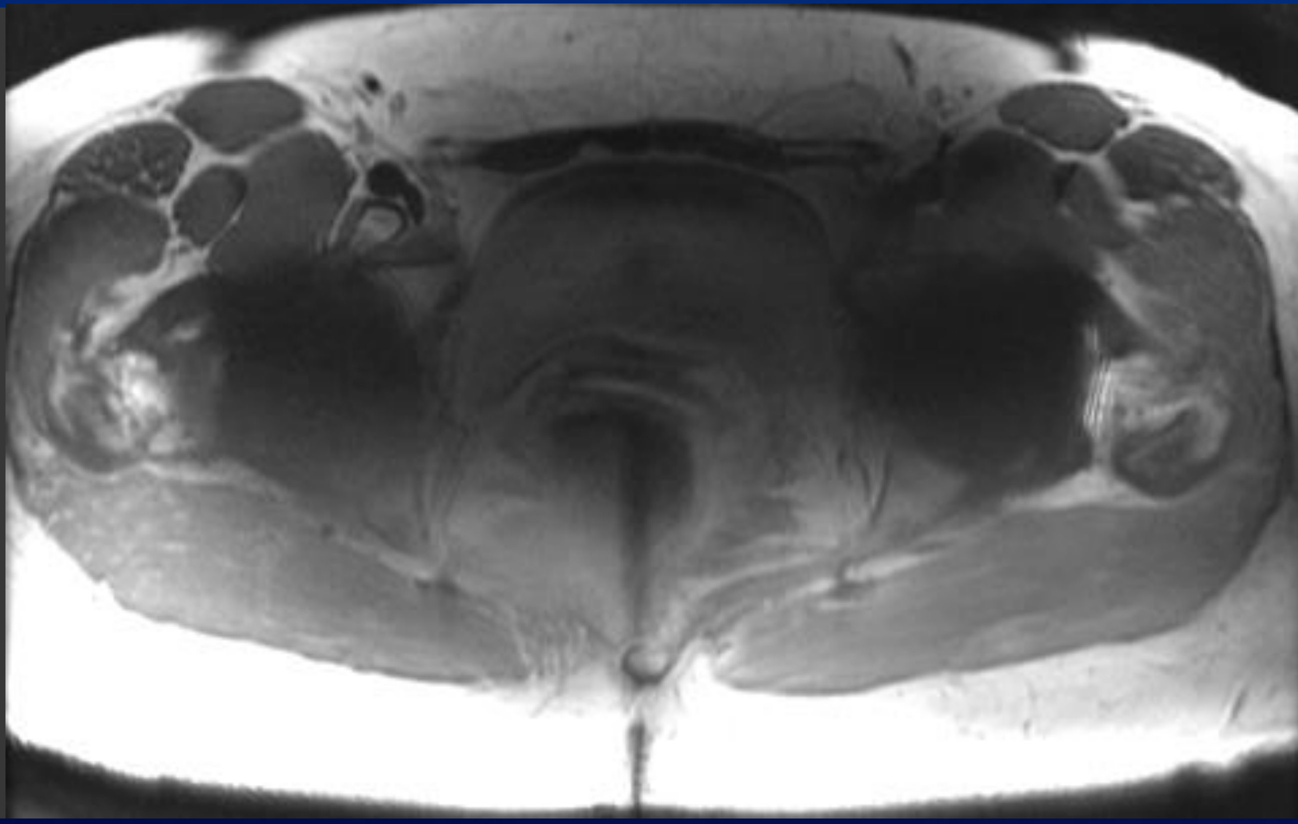
- Foreign metal implants pose significant image quality problems in MR
- Differences in magnetic susceptibility, geometry and orientation with respect to B_0 make artifacts difficult to eliminate
- Metal artifact reduction sequences designed to reduce these effects but don't eliminate them

Metal Reduction Techniques

T_1-weighted 3D Spin Echo

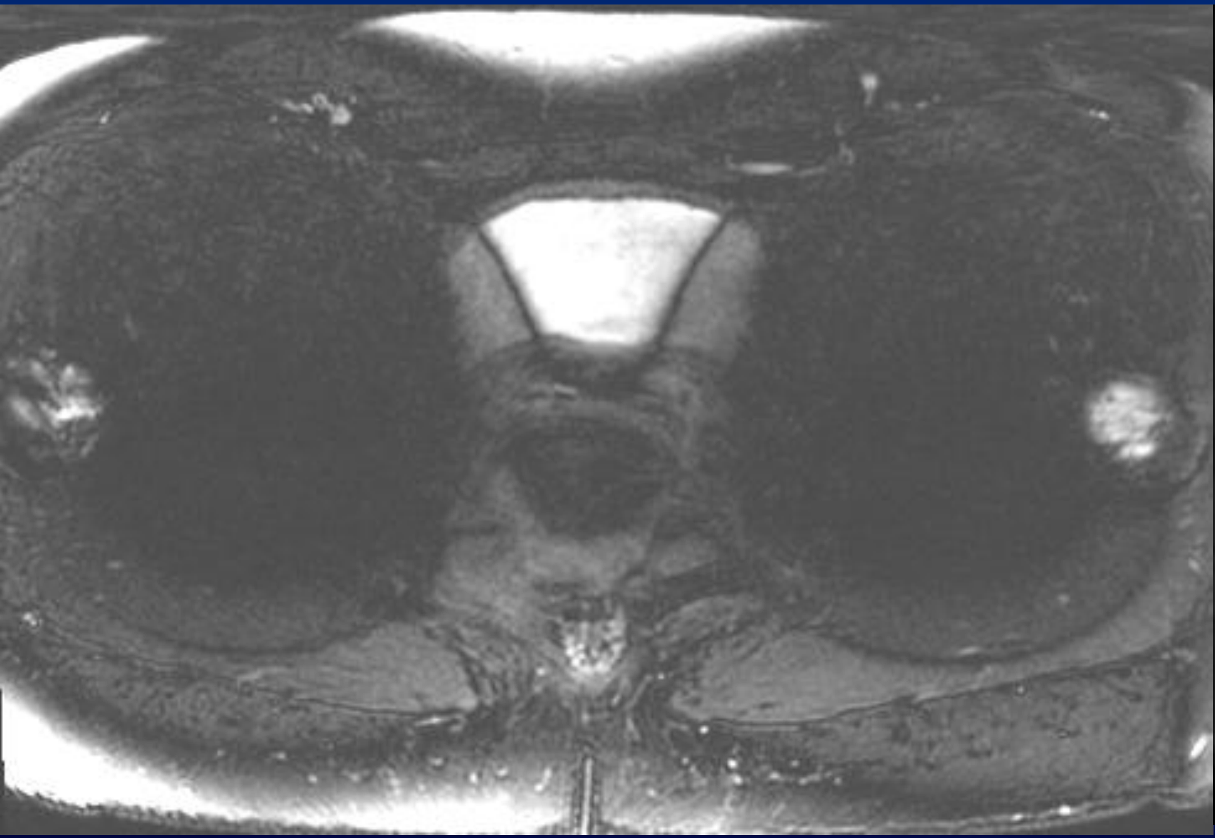


T_1-weighted 2D Metal Reduction Technique

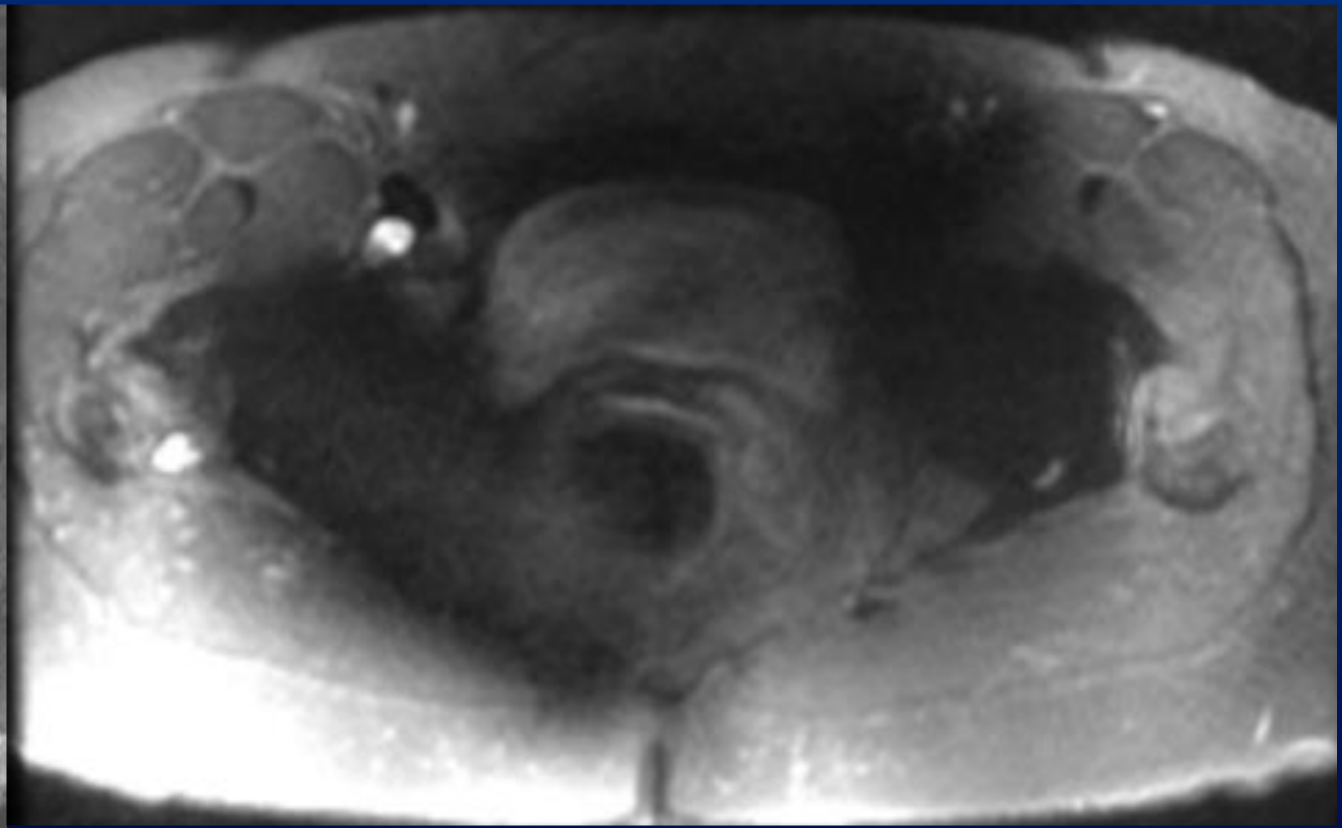


Metal Reduction Techniques

T_2-weighted 3D Spin Echo



T_2-weighted 2D Metal Reduction Technique



Organ Filling and Motion

Organ Filling for OAR

- Organ filling, most notably the bladder can cause shifts in OAR and other structures.
- Result in over/under dose of tissue and result in sub optimal treatment.
- For external beam treatment of the prostate Pinkawa et al. have reported and almost doubling of dose when bladder is empty compared to full.

ELSEVIER

Int. J. Radiation Oncology Biol. Phys., Vol. 64, No. 3, pp. 856–861, 2006

0360-3016/06/$–see front matter

doi:10.1016/j.ijrobp.2005.08.016

CLINICAL INVESTIGATION **Prostate**

PROSTATE POSITION VARIABILITY AND DOSE–VOLUME HISTOGRAMS IN RADIOTHERAPY FOR PROSTATE CANCER WITH FULL AND EMPTY BLADDER

Results: Compared with the primary scan, FB volume varied more than EB volume (standard deviation, 106 cm^3 vs. 47 cm^3), but the prostate/seminal vesicle center of mass position variability was the same (>3 mm deviation in right–left, anterior–posterior, and superior–inferior directions in 0, 41%, and 33%, respectively, with FB vs. 0, 44%, and 33% with EB). The bladder volume treated with 90% of the prescription dose was significantly larger with EB (39% ± 14% vs. 22% ± 10%; $p < 0.01$). Bowel loops received ≥90% of prescription dose in 37% (3% with FB; $p < 0.01$).

with FB and EB before and after 4 and 8 weeks of radiation therapy. The scans were matched by alignment of pelvic bones. Displacements of the prostate/seminal vesicle organ borders and center of mass were determined. Treatment plans (FB vs. EB) were compared.
Results: Compared with the primary scan, FB volume varied more than EB volume (standard deviation, 106 cm^3 vs. 47 cm^3), but the prostate/seminal vesicle center of mass position variability was the same (>3 mm deviation in right–left, anterior–posterior, and superior–inferior directions in 0, 41%, and 33%, respectively, with FB vs. 0, 44%, and 33% with EB). The bladder volume treated with 90% of the prescription dose was significantly larger with EB (39% ± 14% vs. 22% ± 10%; $p < 0.01$). Bowel loops received ≥90% of prescription dose in 37% (3% with FB; $p < 0.01$).
Conclusion: Despite the larger variability of bladder filling, prostate position stability was the same with FB compared with EB. An increased amount of bladder volume in the high-dose region and a higher dose to bowel loops result from treatment plans with EB.

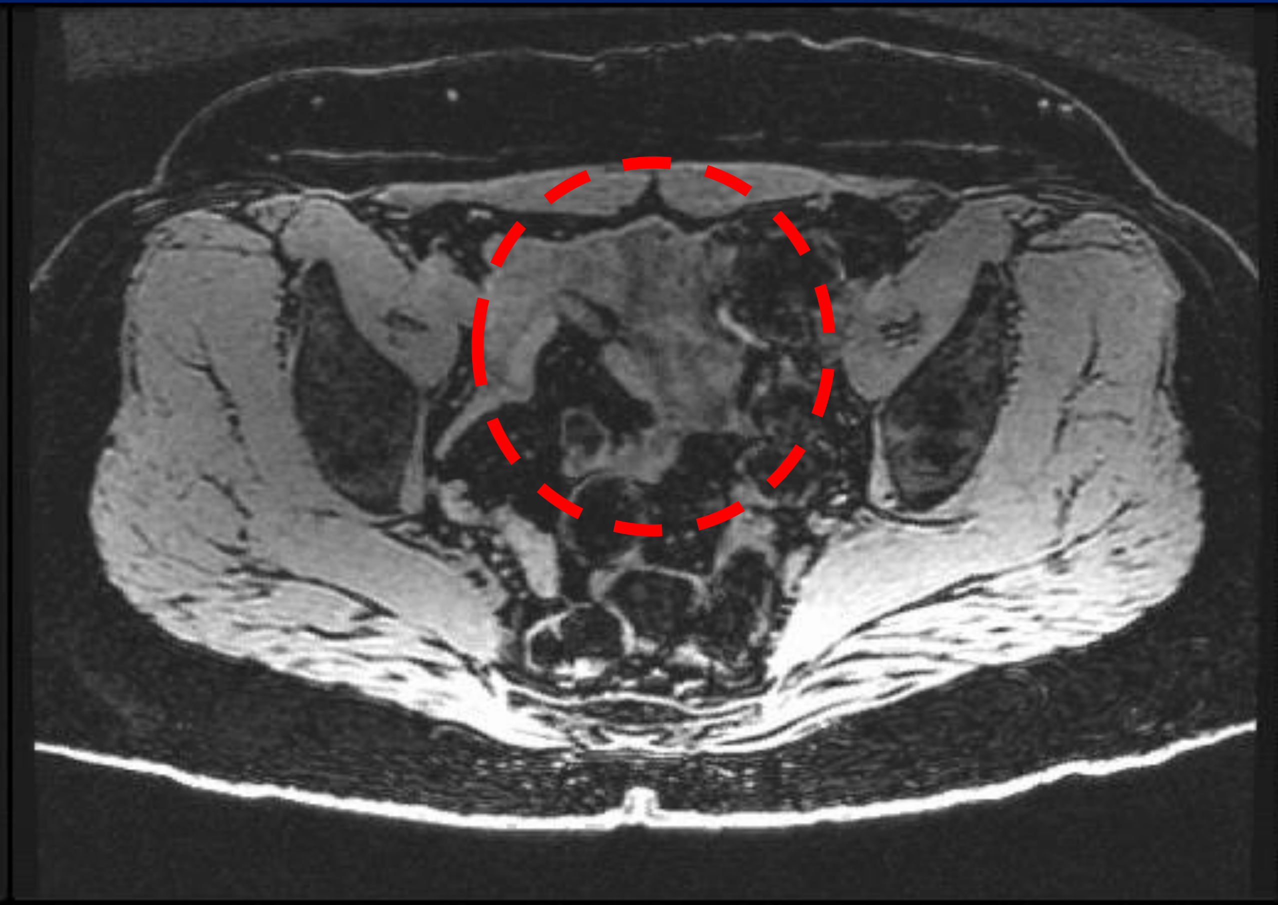
Prostate neoplasm, Radiotherapy, Organ motion, Treatment planning.

Organ Filling: Full vs Empty Bladder

ΔT = 39:23 (min : sec)

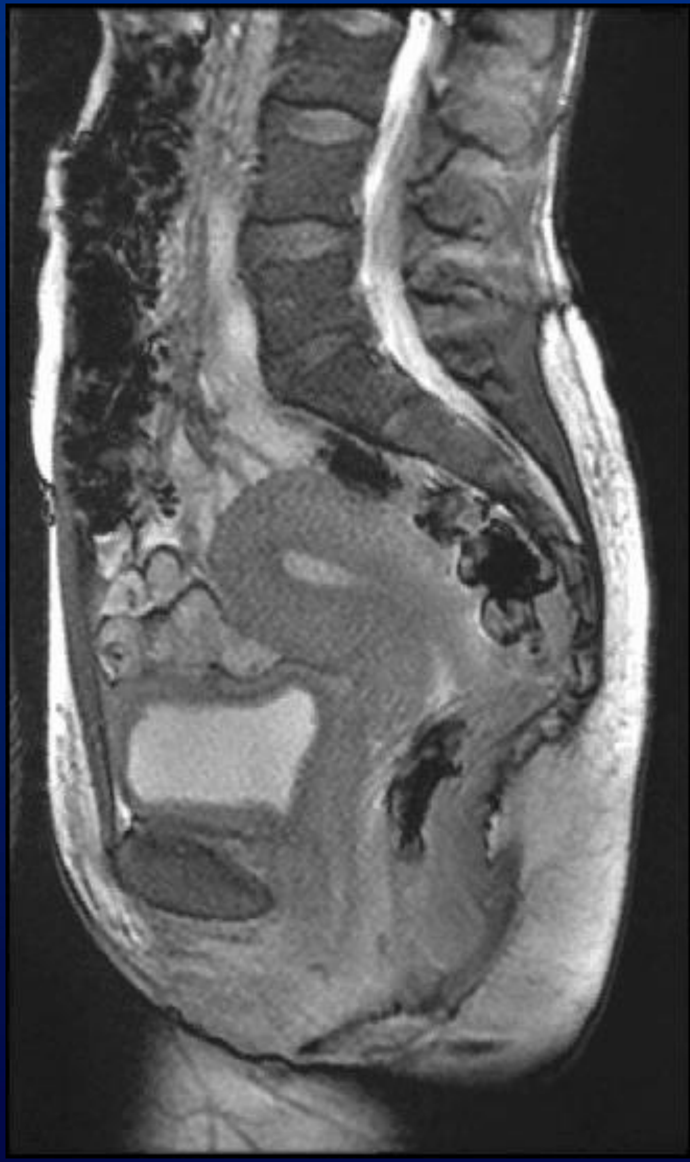
Full Bladder Volume = 245 ml

Empty Bladder Volume = 134 ml



Organ and Bulk Motion

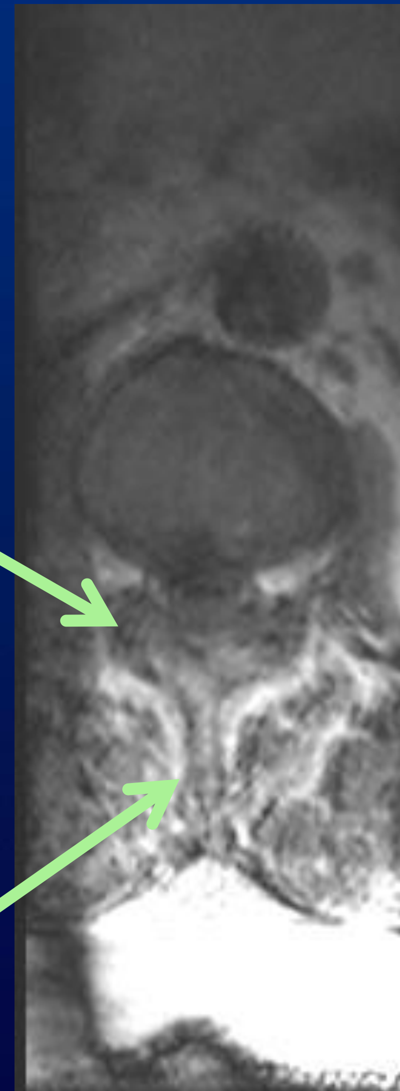
- Motion during imaging results in blurring and signal loss
- Motion sources:
    - Respiration and peristalsis
    - Bulk patient motion
- Volumetric (long) acquisitions more susceptible to these effects



Motion Example: L Spine Imaging

T_1 Sagittal Volumetric

T_1 Sagittal Volumetric – Axial Reformat

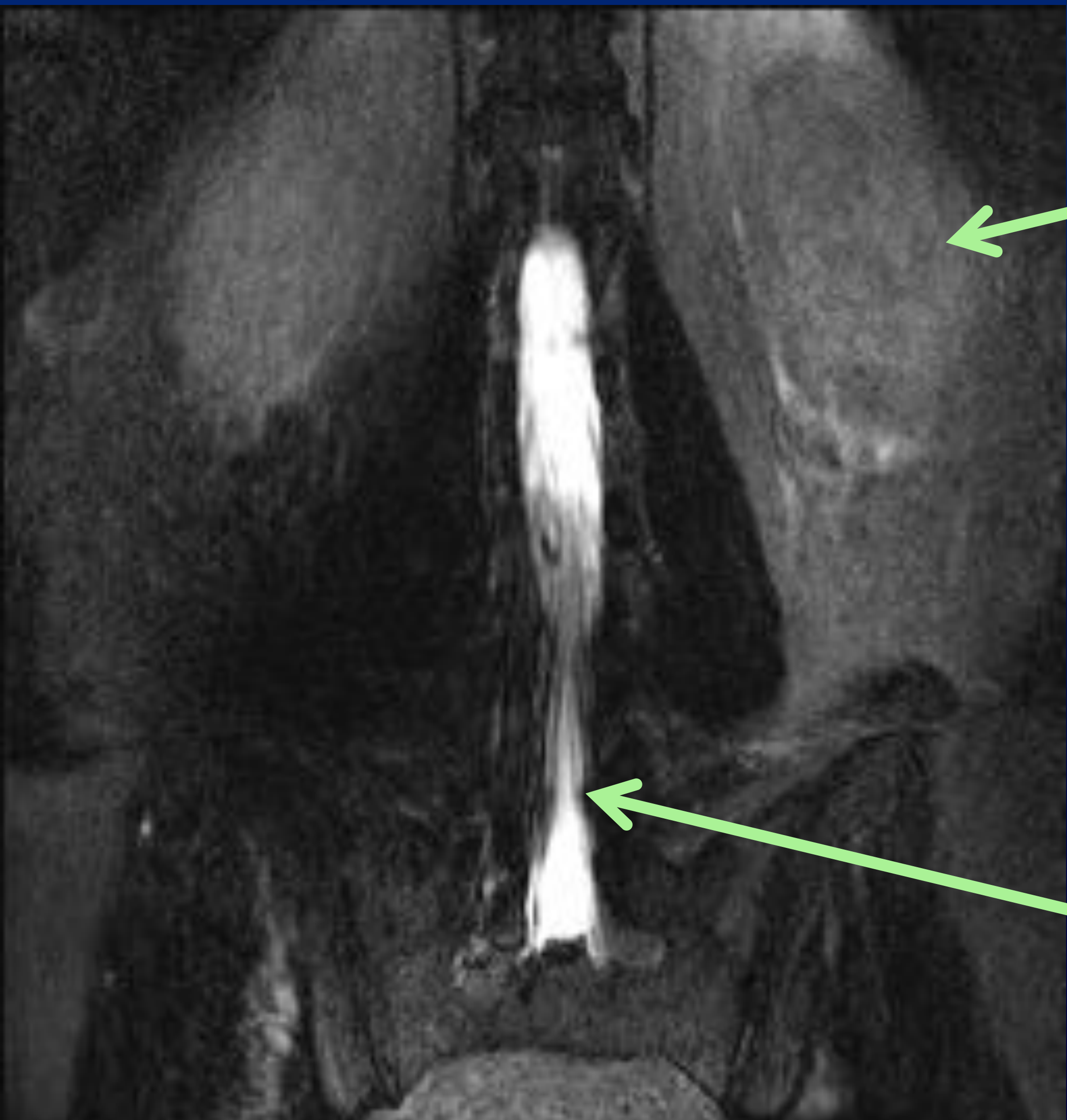


Blurring

Signal Replication

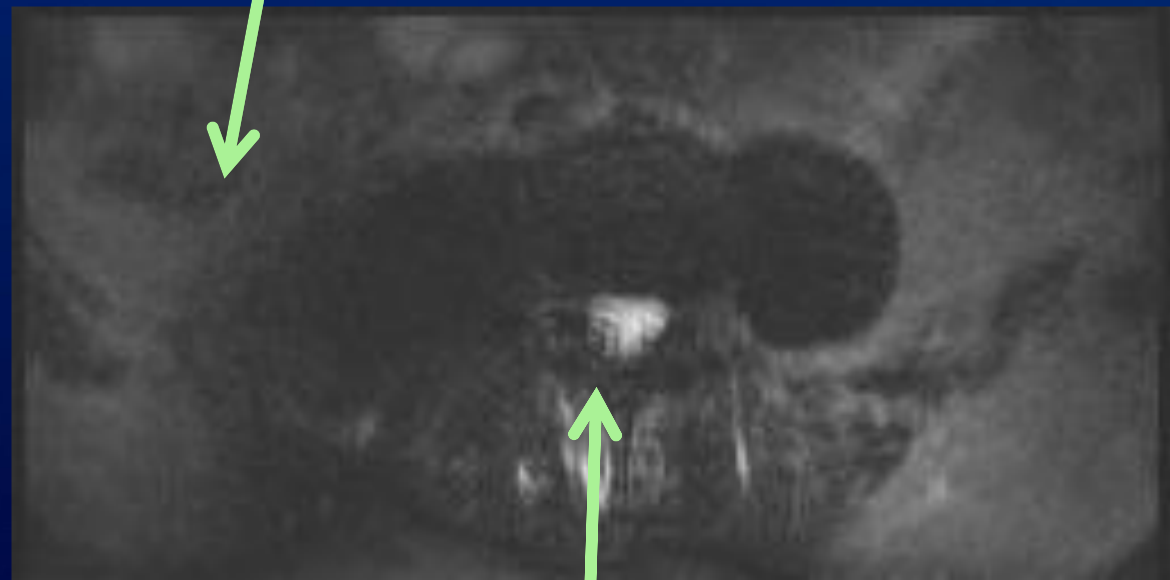
Motion Example: L Spine Imaging

T_2 Coronal Volumetric



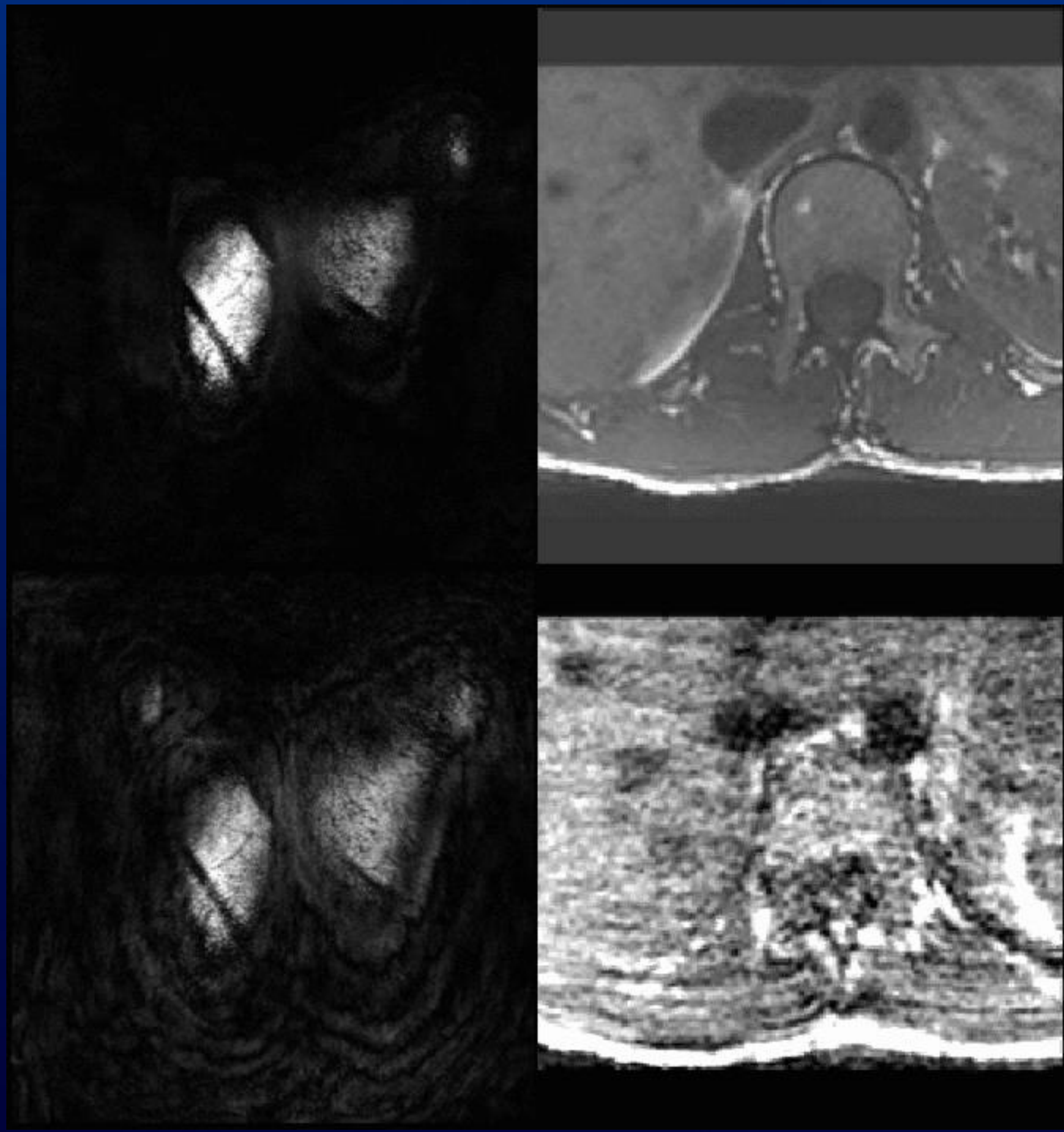
T_2 Coronal Volumetric – Axial Reformat

Blurring

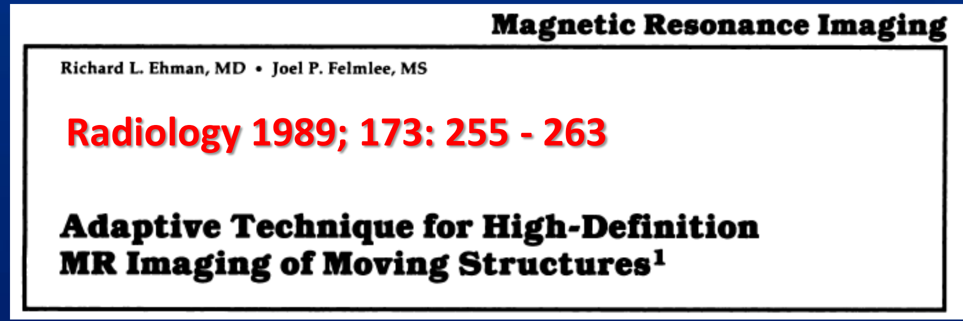


Signal Replication

Motion vs. No Motion



Motion Tracking Techniques: Navigator Echoes



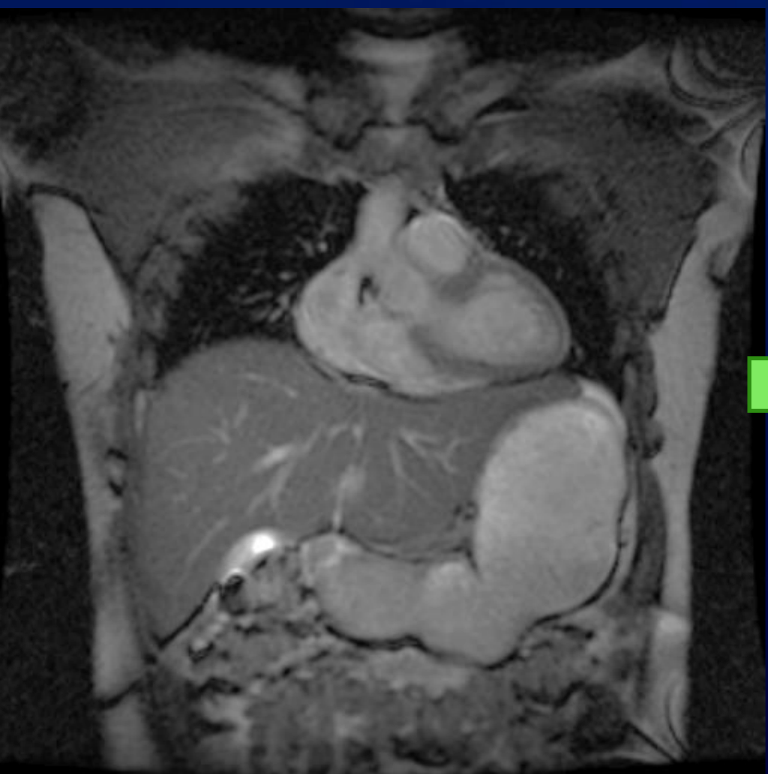
Magnetic Resonance Imaging

Richard L. Ehman, MD • Joel P. Felmlee, MS

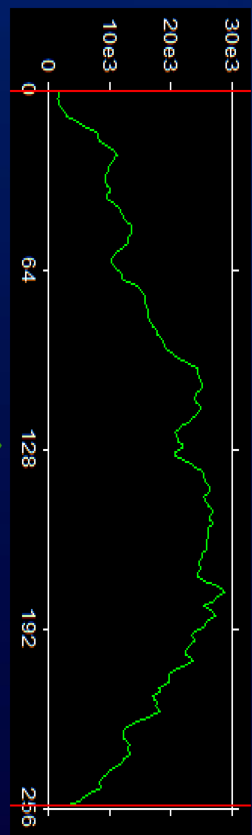
Radiology 1989; 173: 255 - 263

Adaptive Technique for High-Definition MR Imaging of Moving Structures[1]

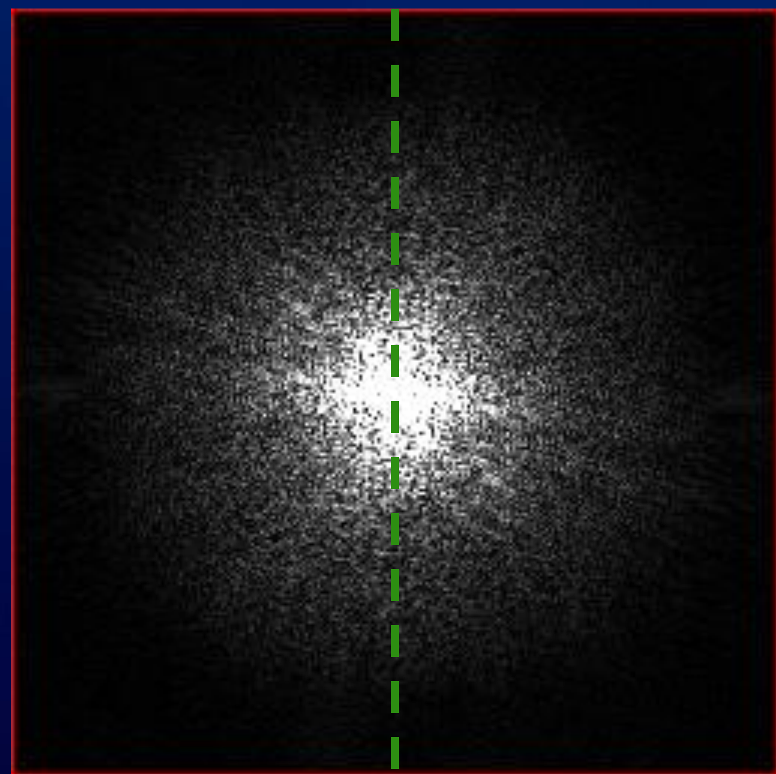
Coronal MR Image



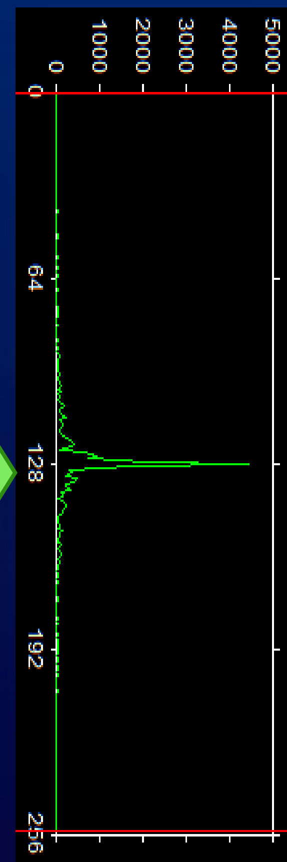
Y-axis Projection



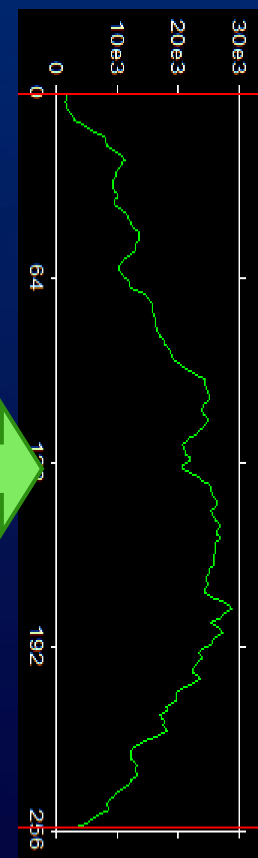
K-space



K-space

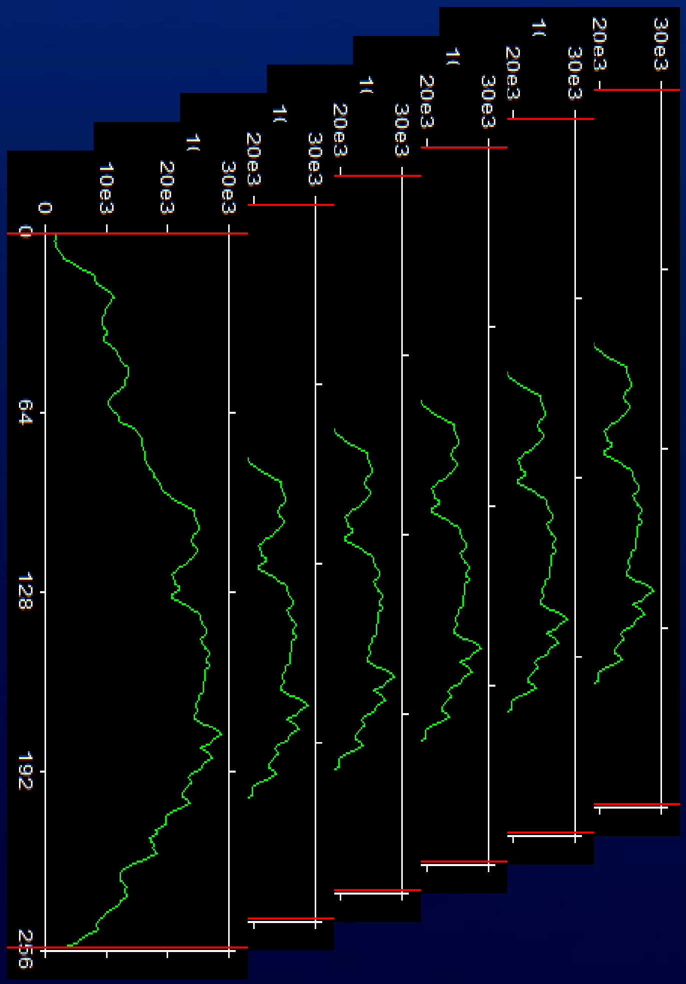


Projection



Retrospective Motion Correction: Navigator Echoes

Time

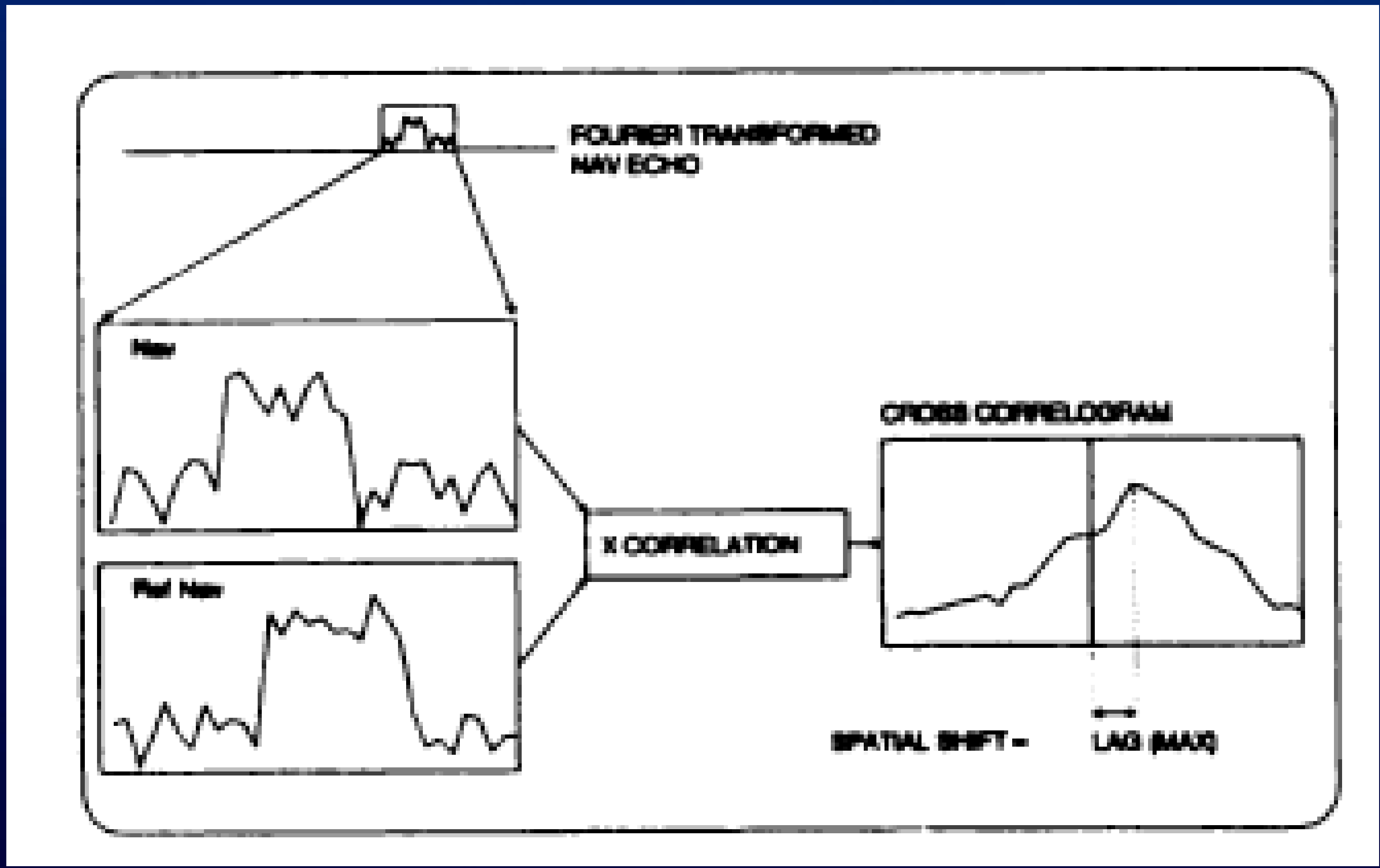


Magnetic Resonance Imaging

Richard L. Ehman, MD • Joel P. Felmlee, MS

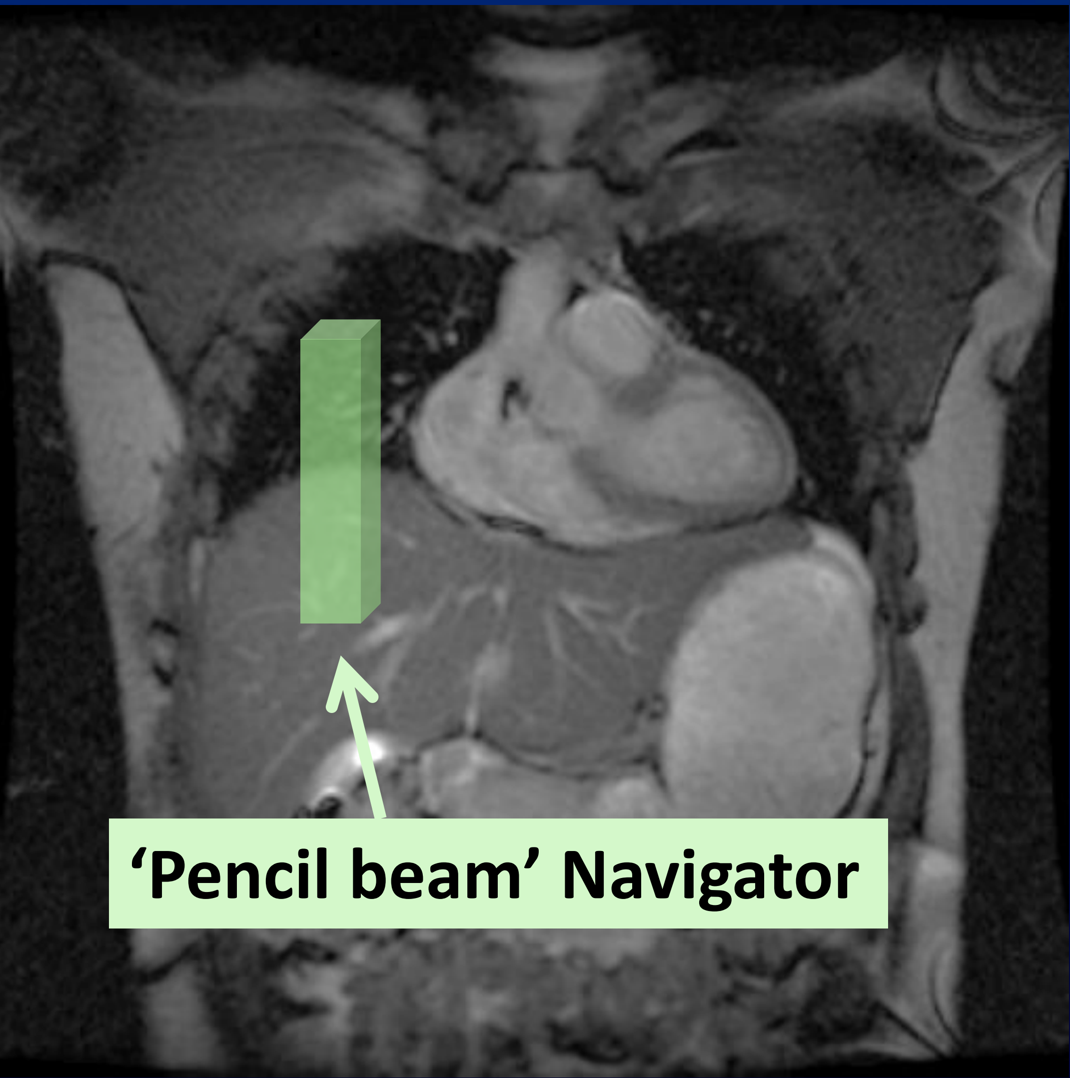
Radiology 1989; 173: 255 - 263

Adaptive Technique for High-Definition MR Imaging of Moving Structures[1]

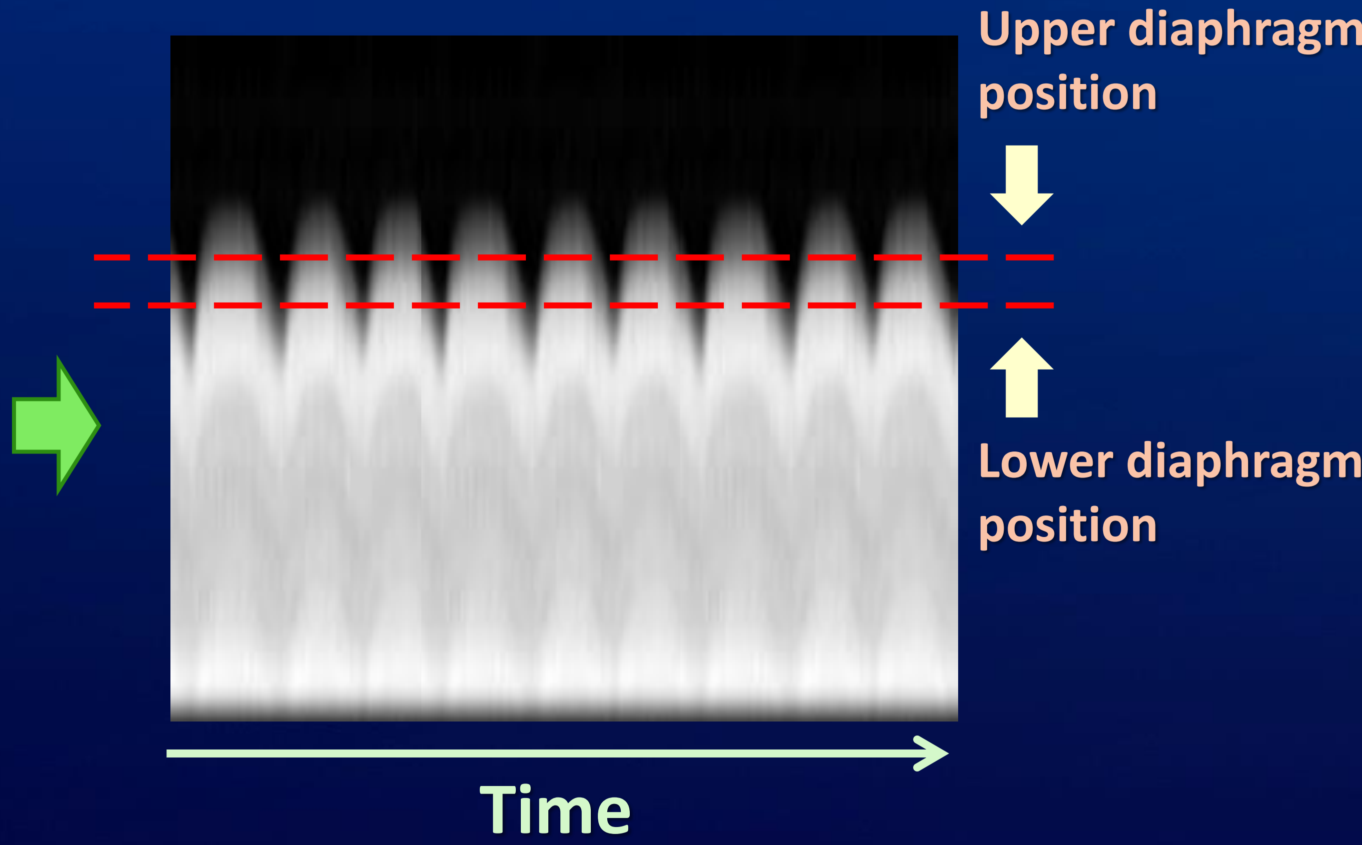


Prospective Motion Correction: Navigator Echoes

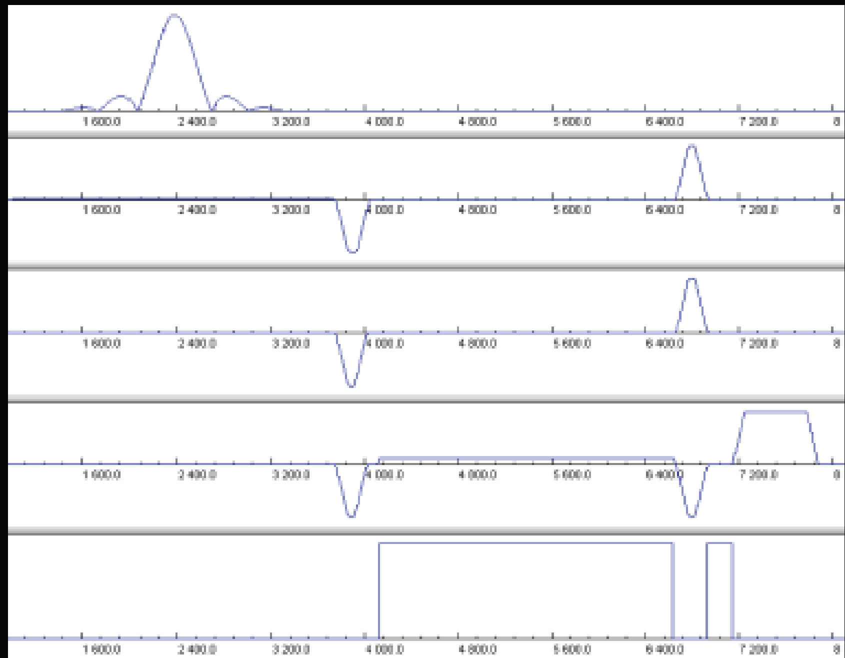
Coronal MR Image

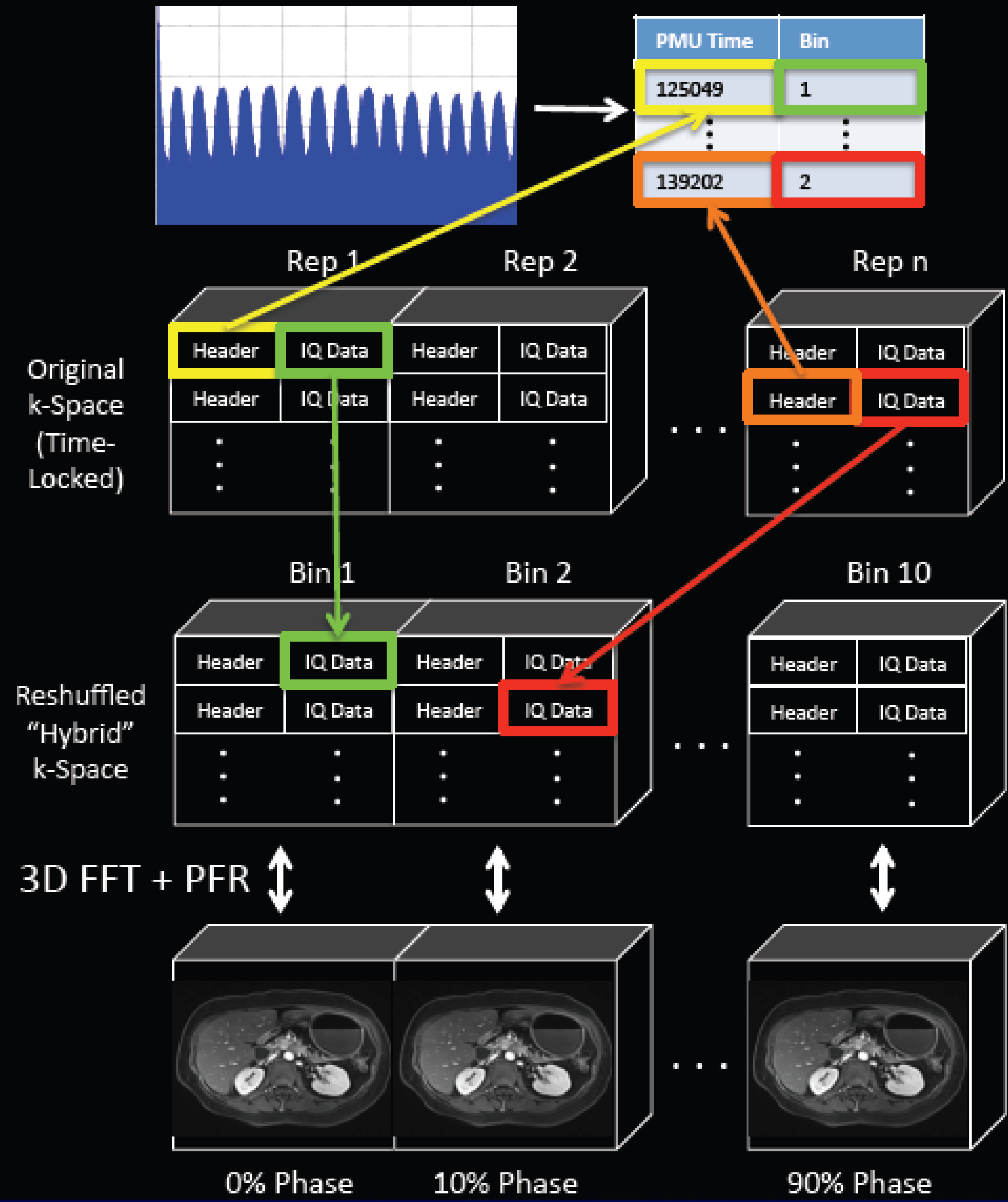


‘Pencil beam’ Navigator profile



4D-MRI





- 3D FLASH with DC navigator:
  - Self-navigated
- Time-locked temporal reshuffling of k-Space:
  - Retrospective rebinning

Paulson ES, 2nd MRI in RT Symposium, 2014

Courtesy Eric Paulson Ph.D., Medical College of Wisconsin

Quality Assurance & Quality Control

QA & QC

- Establish a QA/QC program that is traceable to established standards and tolerances
  - American College of Radiology (ACR) MR QC program
  - AAPM TG reports for other parameters
- Check with your service team/provider regarding preventative maintenance
- QA/QC program should test all aspects of process with known and measurable tolerances/limits
- Will likely involve development of additional phantoms & testing protocols

ACR MRI Weekly QC Standards

- Parameters derived from T_1-weighted sagittal and axial images of 'ACR phantom':

  Center frequency

  Transmit Gain/Attenuation

  Geometric accuracy

  High-contrast spatial resolution

  Slice thickness

  Slice position

  Image intensity uniformity

  Percent-signal ghosting

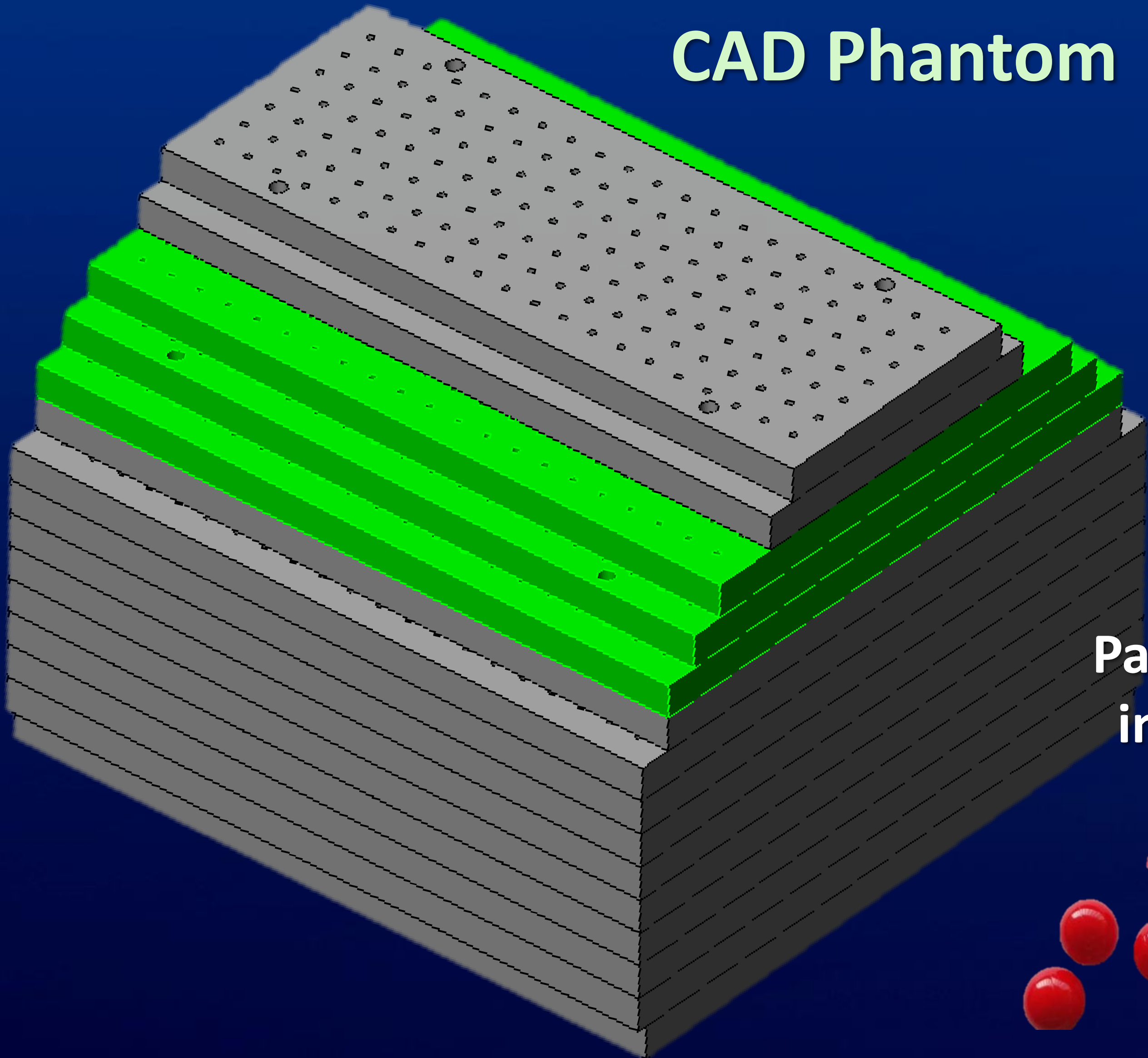
  Low-contrast object detectability

  Signal-to-noise

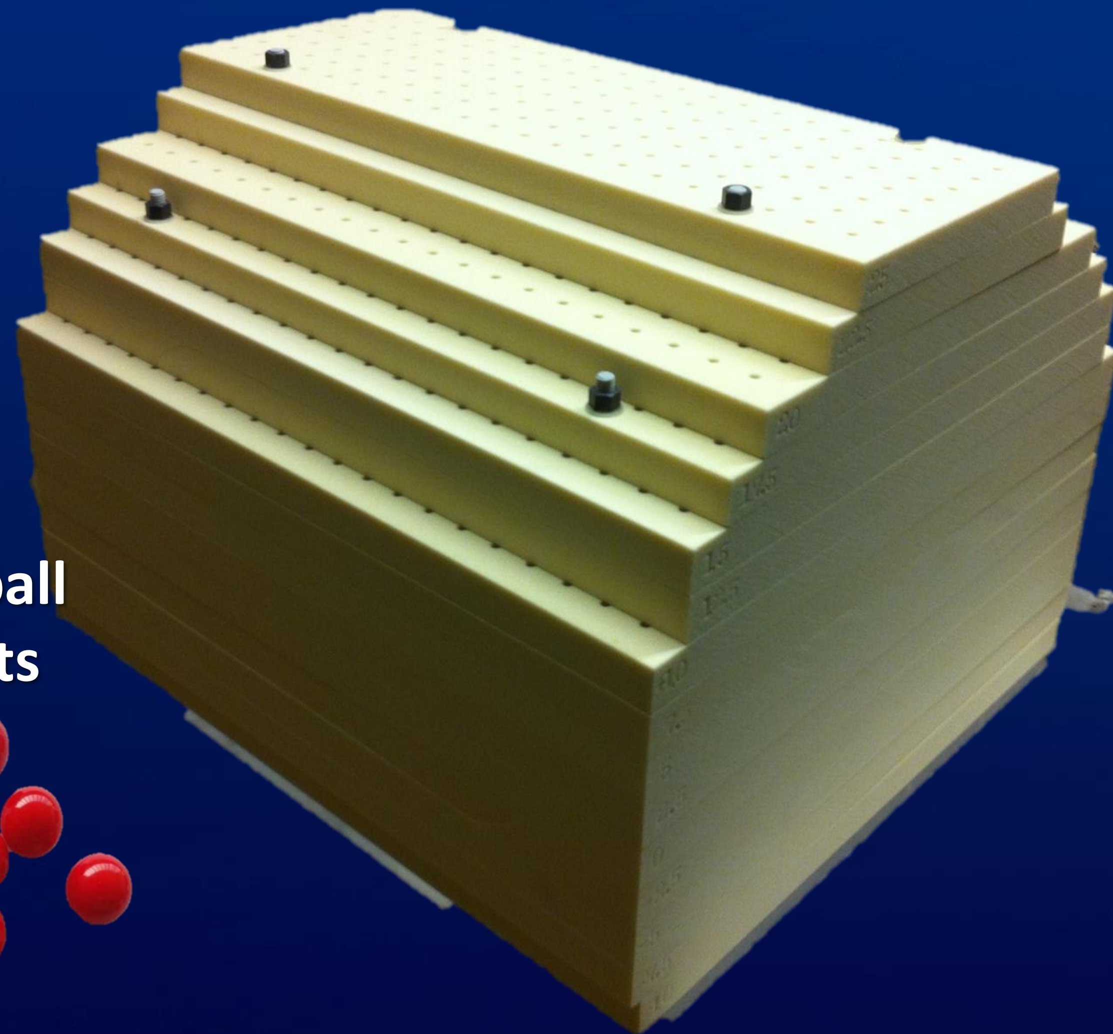
- Phantom images are reviewed and free of artifacts
- MR Table and operator console are fully functional
- Visual inspection of specified items

3D Large FOV Distortion Phantom

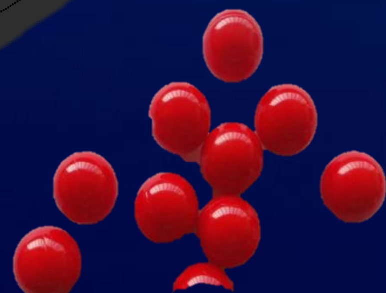
CAD Phantom



Physical Phantom

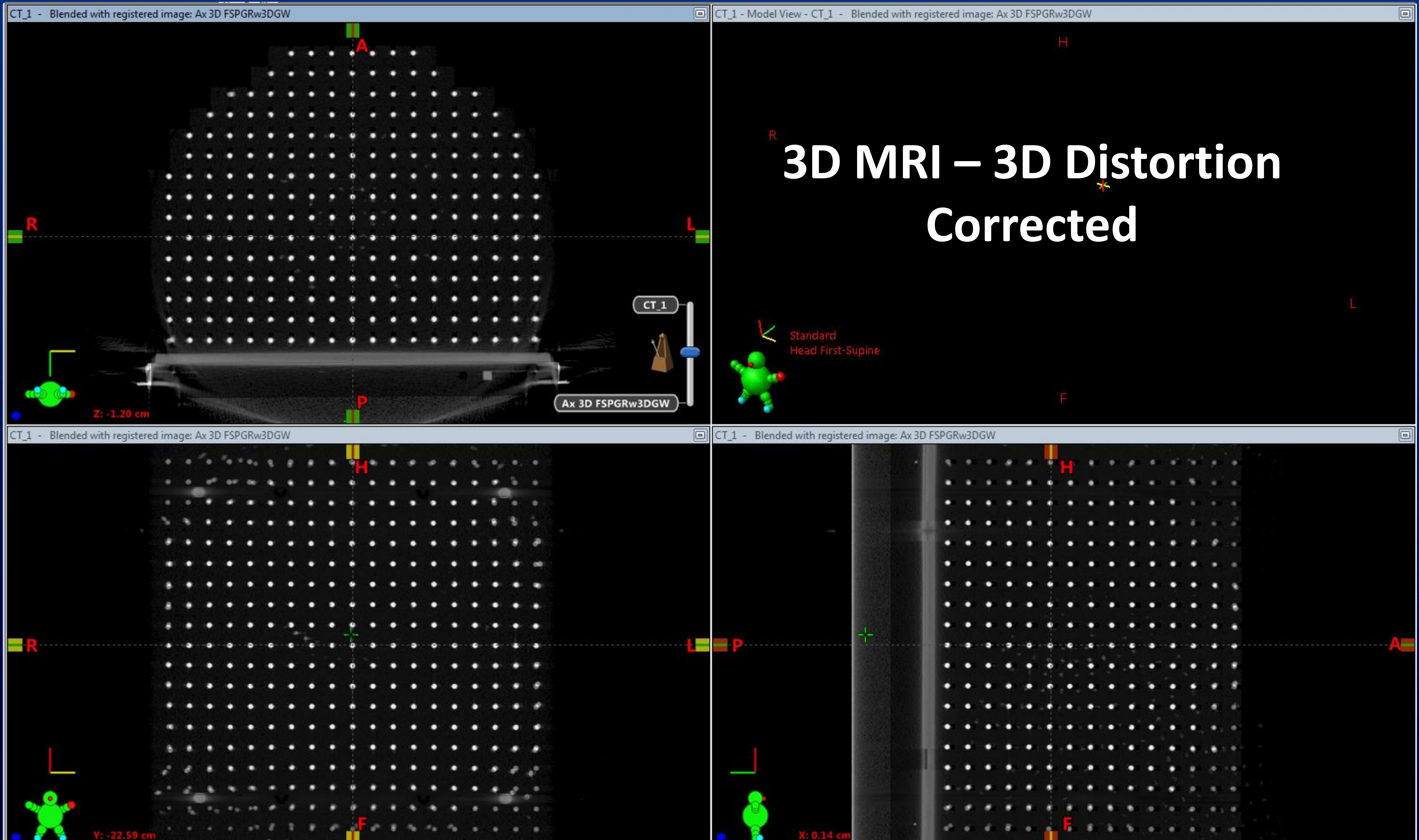


Paintball inserts



Hwang KP, Illerstam F, Torfeh T, Maier J, Shave S, Hoang M. Spatial Accuracy QA of an MR System. AAPM 2014.

3D Distortion Phantom



End-to-End QA / QC testing

	Item/Procedure	Reference	Tolerance
Siting	Vibration	AAPM Report 100	?
	Proximity to conventional linac	Earth	0.5G fringe at linac
Imaging	B0 homogeneity	AAPM Report 100	<0.5 ppm RMS
	B0 drift	AAPM Report 100	<0.25 ppm/day
	B1+ Gains	AAPM Report 100	<5% manual vs auto
	Geometric accuracy (ACR Phantom)	ACR	2 mm
	Percent image uniformity (volume coils)	ACR	>87% 1.5T, >82% 3T
	Percent signal ghosting	ACR	<2.5%
RT	External lasers/MR isocenter	TG-66	2 mm
	Couch indexing and repositioning	TG-66	1 mm

Courtesy Eric Paulson Ph.D., Medical College of Wisconsin

Conclusions

- Consider both the strengths and limitations when choosing your MR scanner:
  - Field strength
  - Bore diameter vs. gradient performance
  - RF coils
  - Software (pulse sequences and post processing options)
- Diagnostic MR ≠ Therapy planning MRI

Conclusions

- Beware of artifacts:
  - Foreign metal implants
  - Gradient and B_0 field distortion
  - RF coil uniformity
  - Motion
- When at all possible collaborate with your diagnostic colleagues
- Establish and maintain a QA/QC program