MRI-Guided Therapy Planning (I):
External Beam Radiation Treatment Planning

Eric Paulson, PhD
Radiation Oncology and Radiology
Medical College of Wisconsin, Milwaukee, Wisconsin
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MEDICAL COLLEGE OF WISCONSIN

Conflicts of Interest

- None

Outline

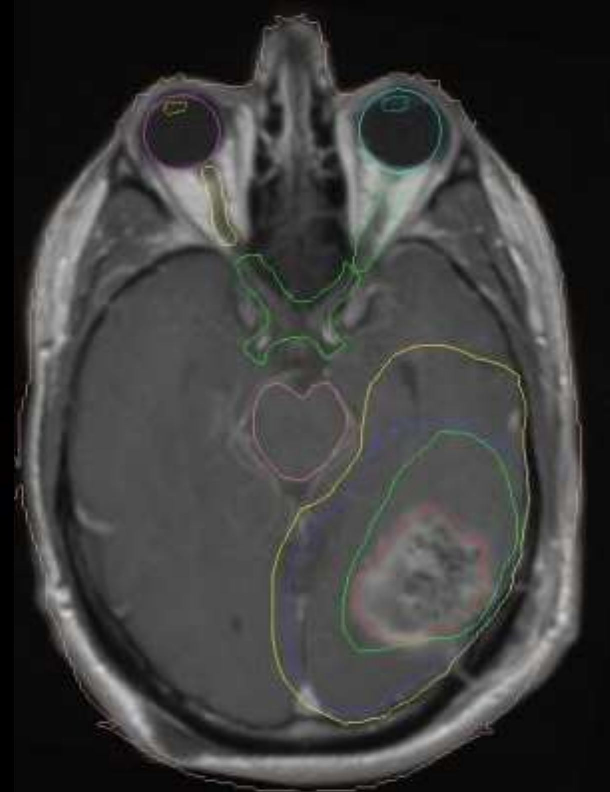
- Methodology and tools used during MRI simulations for external beam radiation treatment planning
- Management of gradient nonlinearity-induced geometric distortions
- Quality assurance for MR simulators

Why MRI in Radiation Oncology?

CT

MRI FLAIR

MRI T1+Contrast

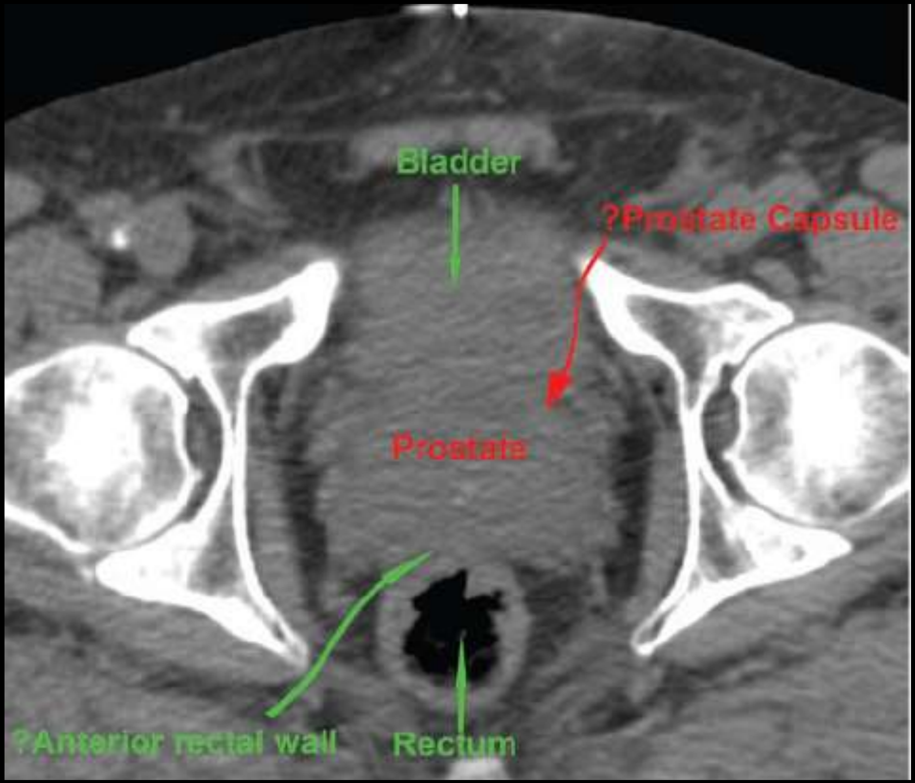


- The prerequisite for modern RTP is high fidelity, 3D morphological imaging
- Most common solid tumors have a significant soft tissue component
- Many adjacent critical structures also have significant soft tissue components
- MRI is the modality of choice for most/all soft tissue imaging

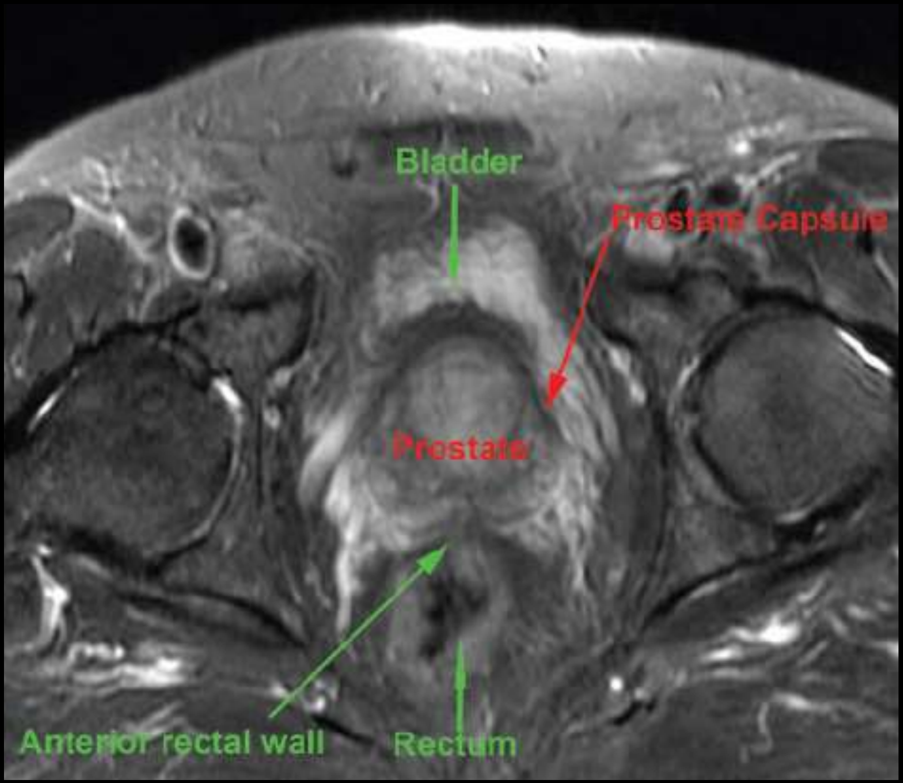
Why MRI in Radiation Oncology?

- Superior soft tissue contrast provided by MRI improves target and critical structure delineation

CT



MRI T2(F)



Khoo et.al., BJR 2006

Challenges Facing MRI in Rad Onc

<u>Treatment Machine</u>

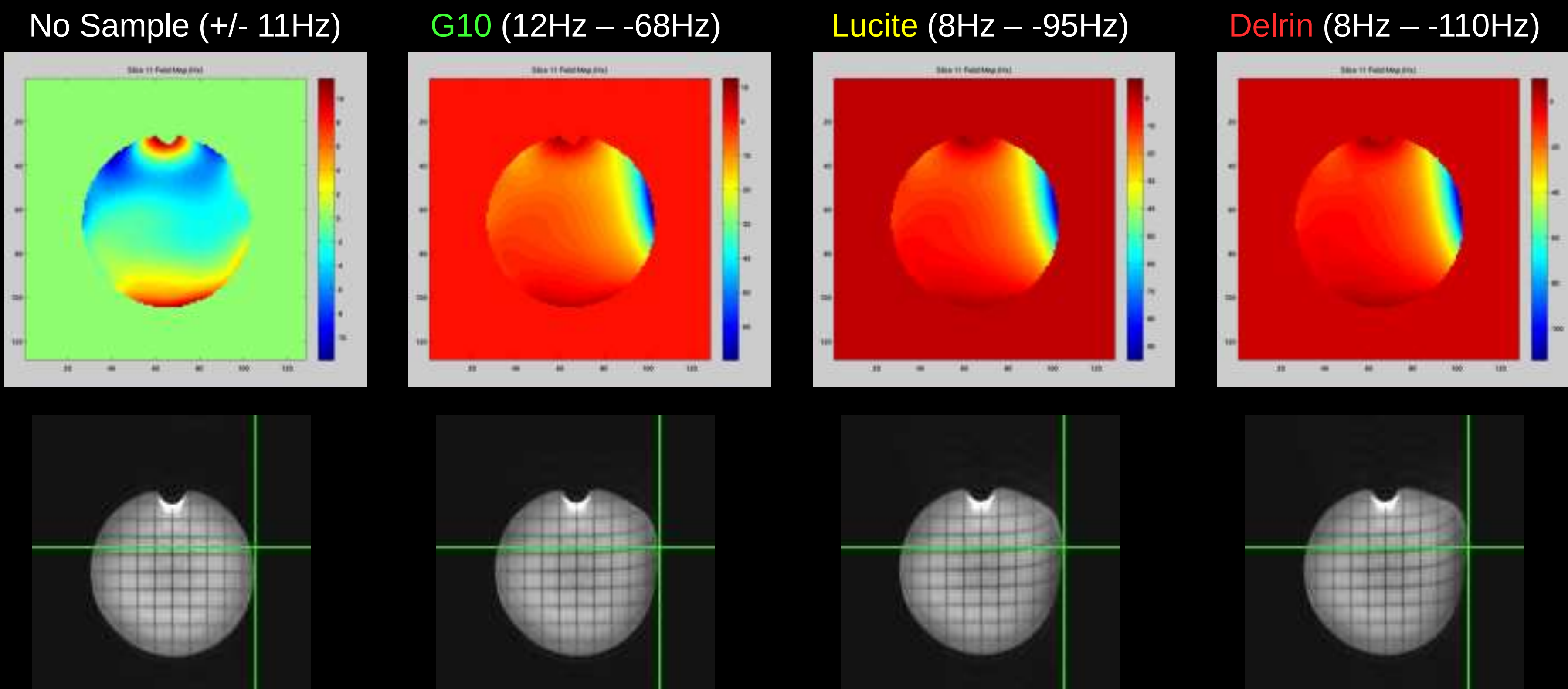
<u>MRI</u>

- Logistical issues:
  - Choreographing sequential CT/MR scans
  - Variable time for organ filling
  - Transporting patients and immobilization devices across hospital

Requirements of an MRI Simulator

- Similar to CT Simulator:
  - Hard, flat couch top (same as linac):
    - Fully indexed and compatible with immobilization devices used for treatment
  - Large bore sizes (> 70 cm)
  - Moveable laser positioning and marking system
  - Gating/4D capabilities
  - Optimized scanning protocols
- Unique to MRI:
  - High magnetic field homogeneity
    - < 0.5 ppm RMS over 35 cm FOV (AAPM Report 100)
  - High image intensity uniformity
    - > 90% at 1.5T (AAPM Report 100)
    - > 87% at 3T (ACR)
  - High gradient linearity
    - < 2mm deviation over ACR phantom (ACR)
    - < 2% (AAPM Report 100)
  - RF coils that accommodate immobilization devices

Materials Study: Susceptibility Effects

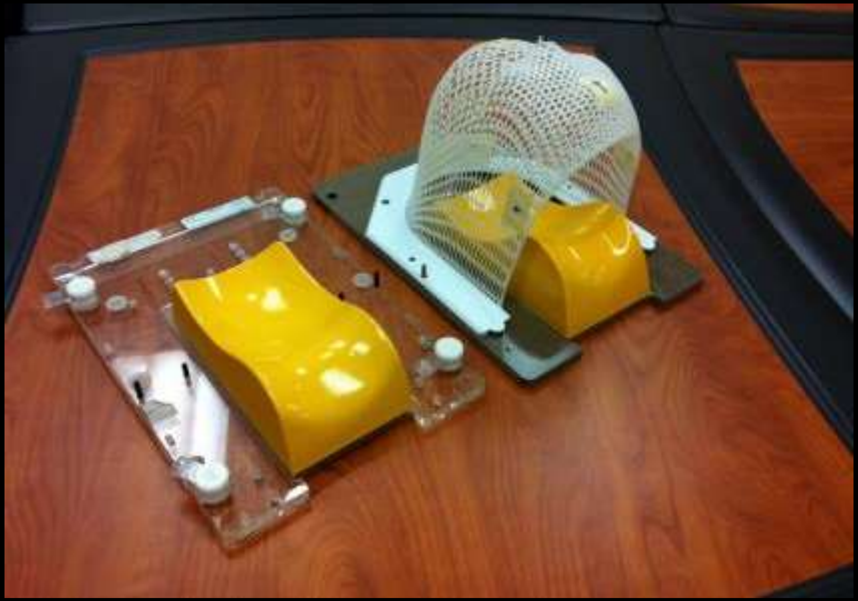


- Different materials commonly used for immobilization devices can affect magnetic field homogeneity and geometric distortion
- Delrin resulted in distortion of 11 pixels (2.4 cm)!!
- Take home: Choose MRI-optimal materials for immobilization

MR-Optimal Immobilization Devices

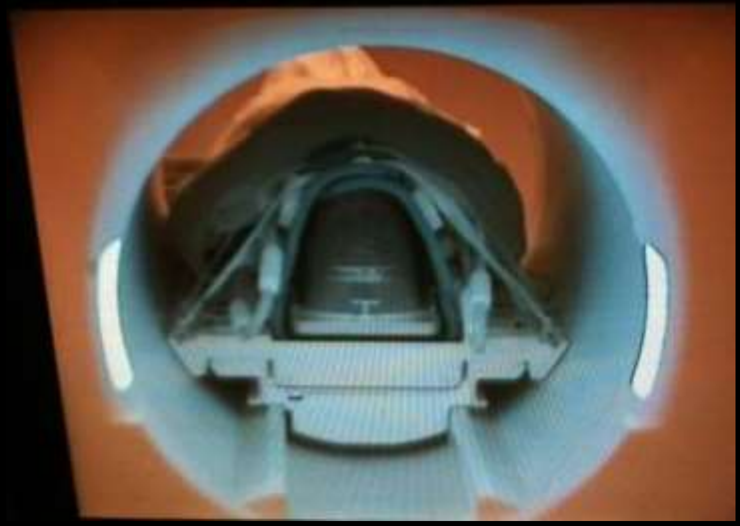
Prone Breast Bridges

Indexing Trays



- Immobilization devices optimized for radiation therapy are not necessarily optimal for MRI:
  - Carbon fiber prone breast bridges
  - Lucite trays
- Custom fabricated MR-optimal immobilization devices using G9 fiberglass

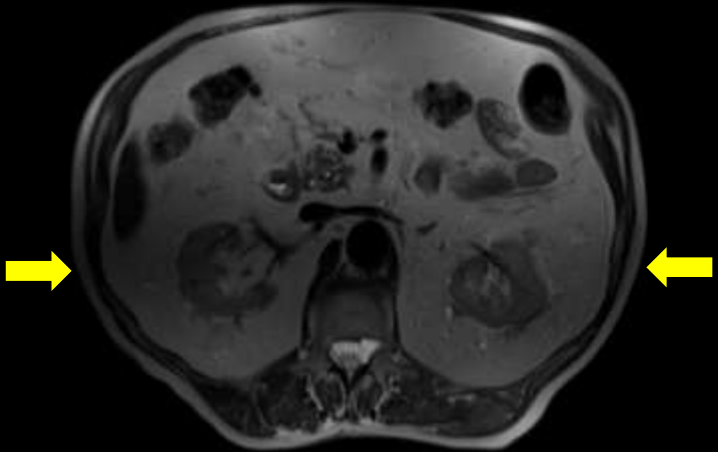
Flexible, Phased-Array RF Coils



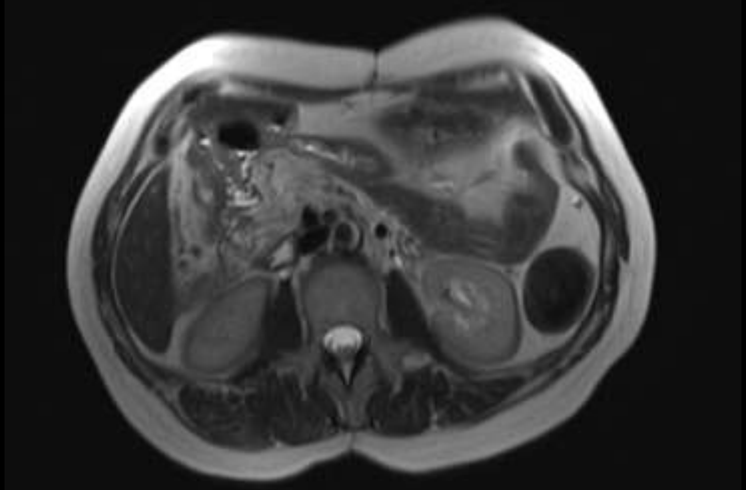
- Permits "wrapping" of coils around immobilized patients
- Versatility: Can be used with multiple sites and configurations
- High density of elements:
  - Increased SNR
  - Parallel imaging to reduced scan times
- Corrections for coil sensitivity profiles used to optimize image uniformity
- Also compatible with stereotactic radiosurgery head frames used in radiosurgery applications (e.g., gamma knife)

"Wrapping" can Improve Uniformity

Opposed RF Coils (Conventional)



Circumferentially Wrapped RF Coils

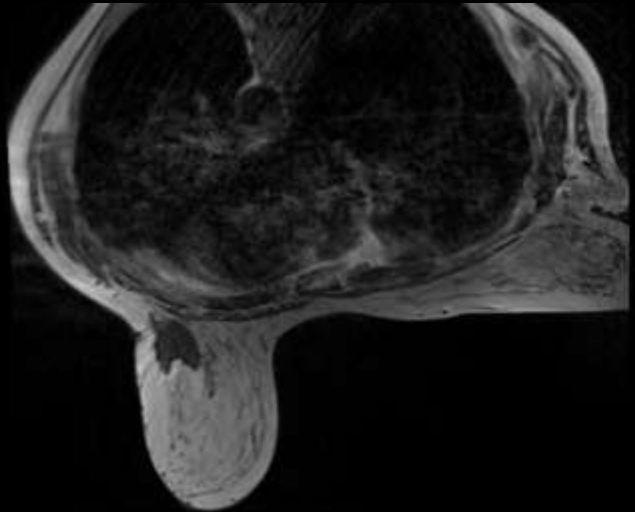


- RF coils wrapped circumferentially for abdomen and pelvis imaging
- Improves image intensity uniformity:
  - Segmentation
  - Deformable registration

Prone Breast MRI Simulation

- Bilateral prone breast imaging is a standard diagnostic MRI technique
- However, commercial prone breast RF coils are incompatible with RT setup
- Healthy breast blocked, diseased breast falls into flexible, phased-array RF coil

MRI T1



Diagnostic vs Planning Protocols

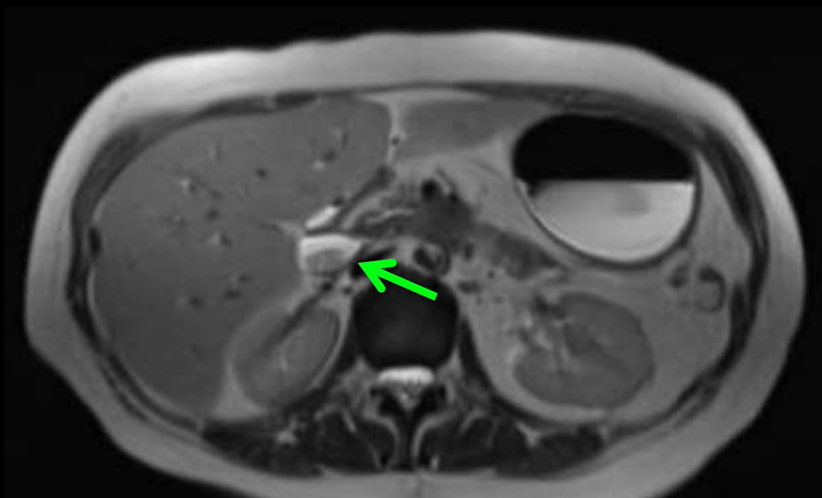
	Diagnostic Images	Planning Images
Purpose	Detection, characterization, and staging of disease	Determination of tumor extent and position relative to critical structures
Field of View	Can acquire with reduced FOV	Full cross section required on at least one scan for body contour
Slice Thickness	Typically 5 mm; may have interslice gaps	Contiguous slices; thinner slices improves DRR image quality in MR-only treatment planning
Slice Coverage	Prescribed over volume of interest	Increased coverage required for target and OAR delineation (DVHs), landmarks for registration and IGRT, etc
Geometric Distortion	Tolerated so long as diagnostic capability not affected	Required to be < 2mm in all planes over the volume of interest
Image Uniformity	Tolerated so long as diagnostic capability not affected	Increased uniformity required for image registration, auto-segmentation, etc

- Take home:
  - Radiology acquires images the way it needs to make an accurate diagnosis
  - Radiation Oncology acquires images the way it needs to treat accurately, effectively, and safely

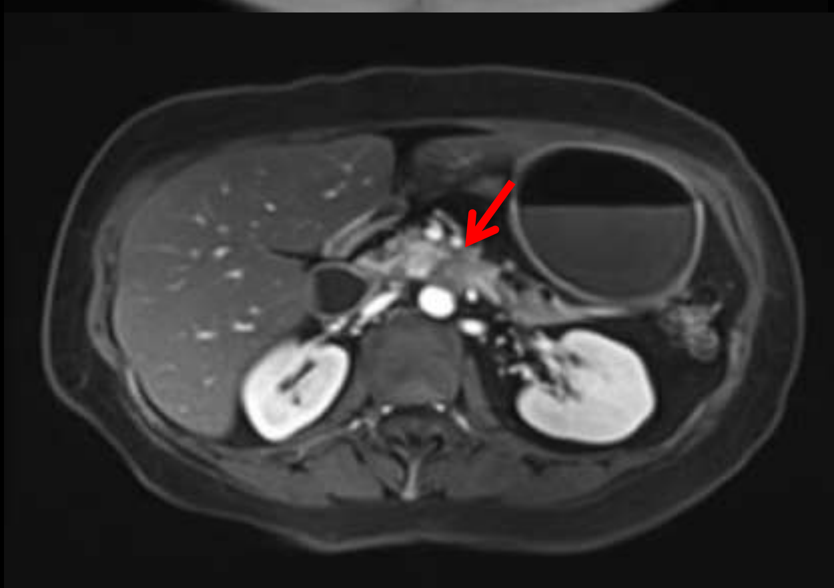
Site Specific Differences in Protocols

MRI

T2 (Gated)



LAP T1+C (BH)

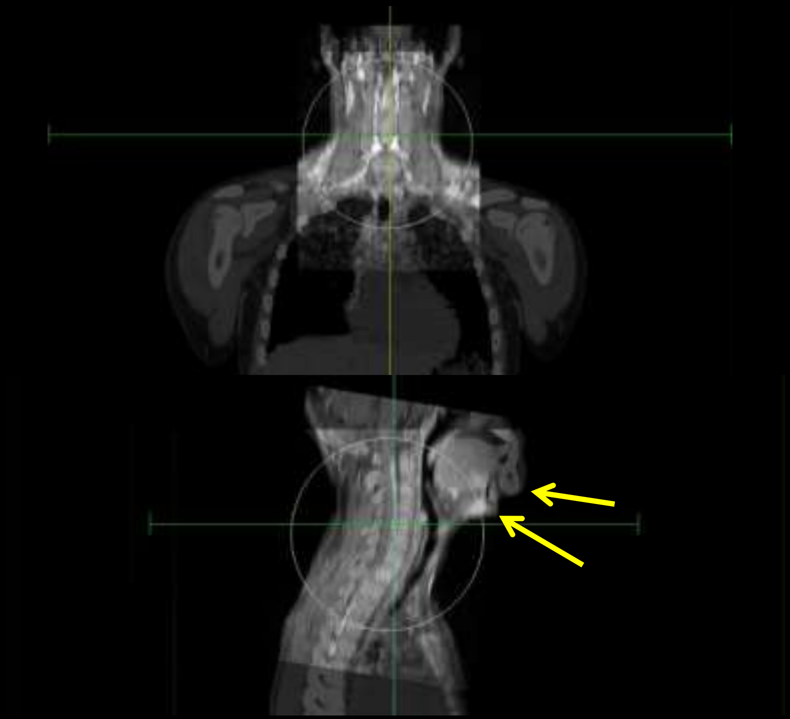


- Respiratory-triggering and breath holds correspond to phase of gating window used for treatment
- Water given as contrast agent to delineate duodenal wall

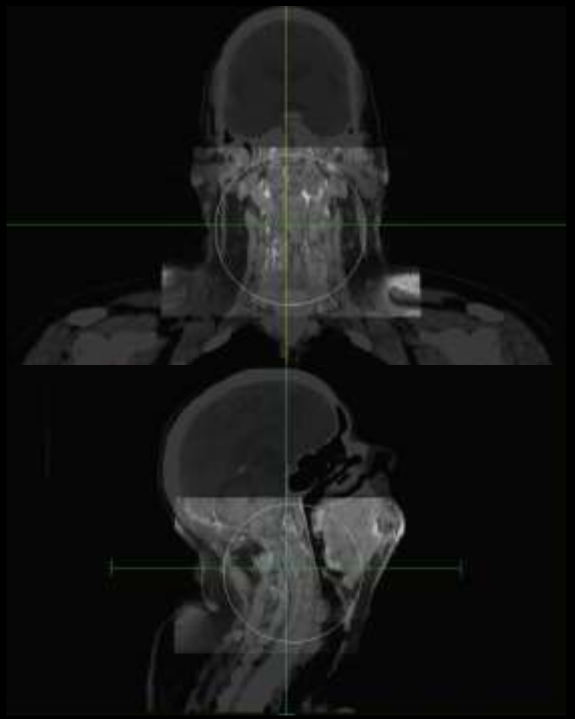
CT

Benefits of MRI Simulation

Diagnostic MRI
registered to Planning CT

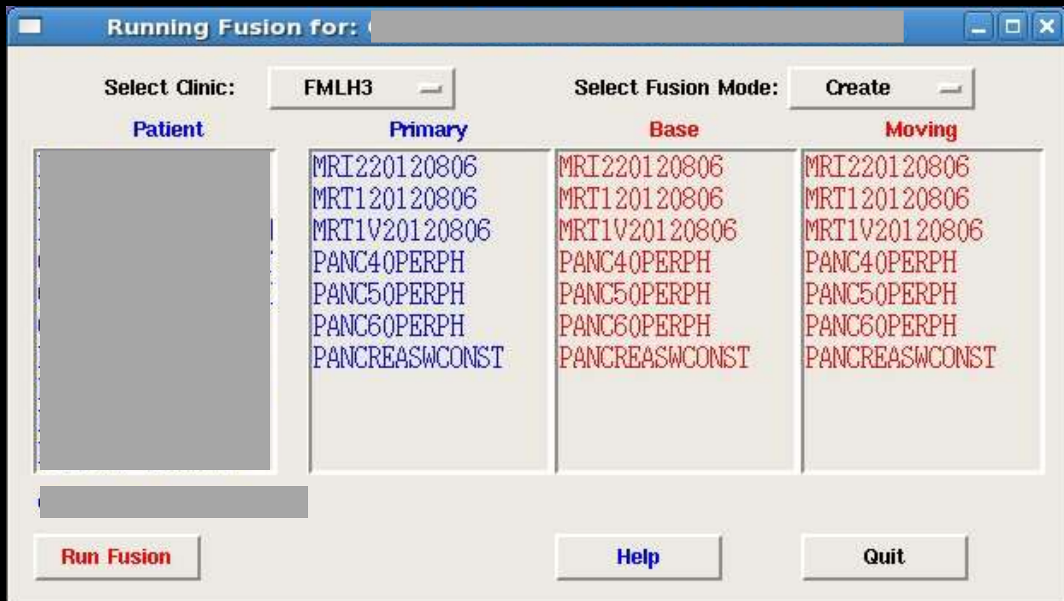


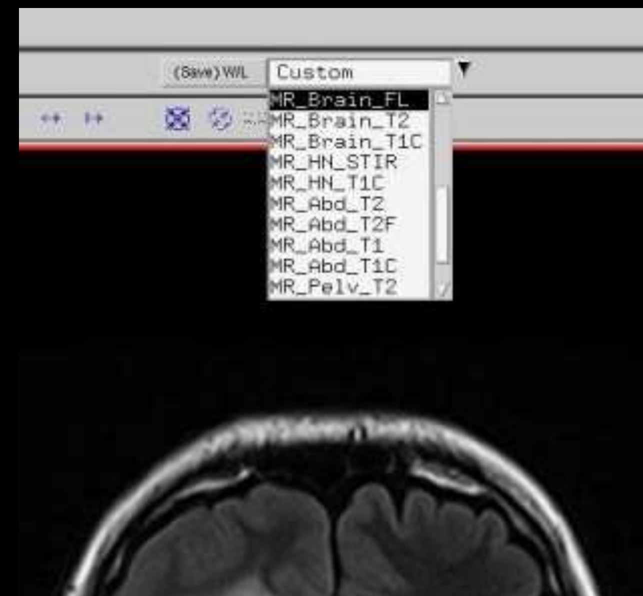
MRI Sim
registered to Planning CT



- Key Benefit: Reduction in uncertainties introduced during CT-MRI registration
- Translation: Improved radiation oncologist confidence in using MRI

Automated CT/MR Fusion, W/L Presets





- Large number of secondary MR image sets to load and fuse:
  - Increases dosimetrist workload
- Developed tools streamline CT/MRI registration:
  - Reduces registration errors
- Window/Level presets reduces inter-/intra-observer variability

MRI Sim Image Guide

Unfamiliarity with MRI in Rad Onc

- Relatively little training and exposure with MRI for radiation oncology personnel
- MRI presents a different set of challenges
- Example is setting up patients during simulation:
  - Not enough to think only about constraints imposed by CT scanner and linac
  - Positioning for optimal field homogeneity
  - Placement of RF coils as to not deform anatomy while providing good uniformity and signal
- Key Point:
  - There was also unfamiliarity with CT and now it is used daily

Outline

- Methodology and tools used during MRI simulations for external beam radiation treatment planning
- Management of gradient nonlinearity-induced geometric distortions
- Quality assurance for MR simulators

Sources of Distortion in MRI

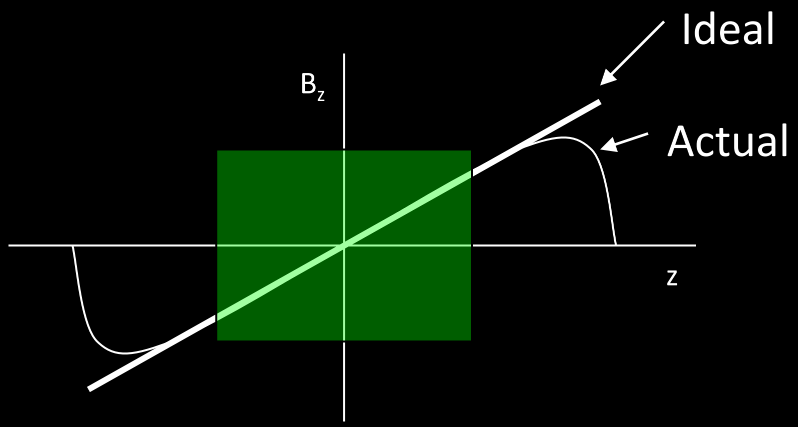
- Off-resonance effects (sequence dependent):
  - System-induced:
    - Main field heterogeneity
  - Patient-induced:
    - Main field heterogeneity (loading effect)
    - Chemical shift
    - Magnetic susceptibility variations at interfaces
- Gradient non-linearities (sequence independent):
  - System-induced

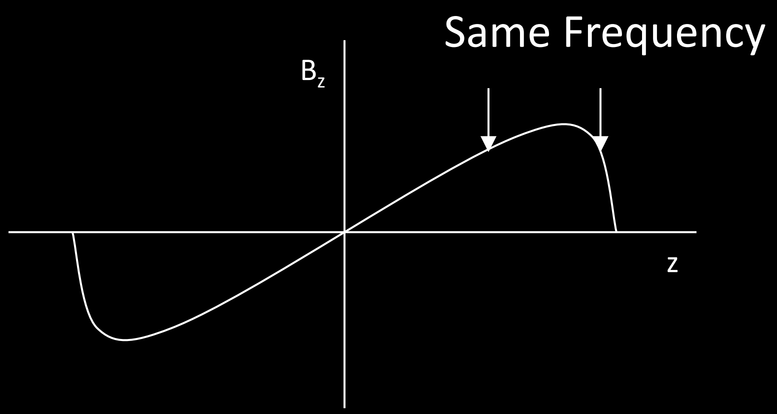
- Magnitudes:

  Can be > 2 cm

Gradient Non-Linearities

- MRI is based on assumption of linear encoding of position to frequency over FOV
- Linearity is high near gradient coil isocenter but falls off with increasing distance
- Main effects:
  - Anatomical compression (S-I)
  - Anatomical dilation (A-P, R-L)
  - Aliasing
- Field strength, sequence independent
- Arises from vendors being forced to tradeoff linearity for performance and shorter bore lengths (claustrophobia)



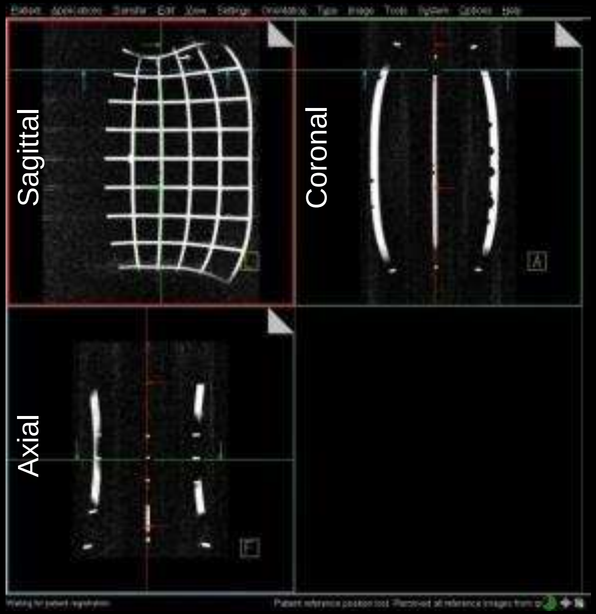


Strategies to Minimize

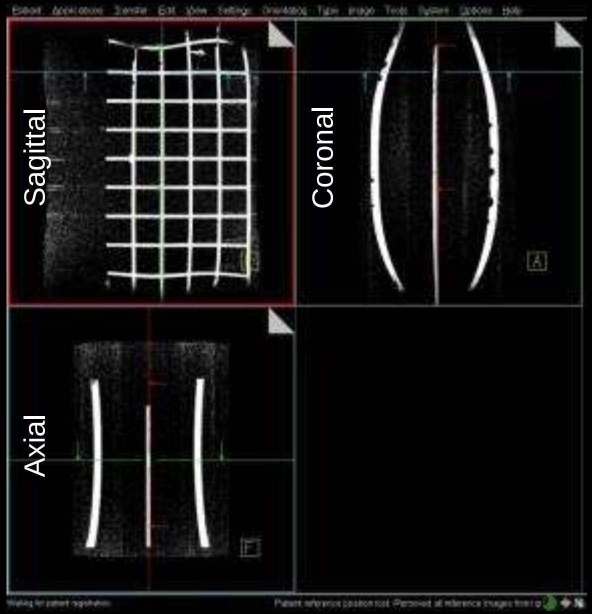
- Scan at isocenter of magnet:
  - Force imaging volume to region of highest gradient linearity
- Apply post-processing corrections:
  - Vendor-provided distortion correction algorithms:
    - Based on design of gradient coil
    - Actual coil may deviate from design
    - Residual distortions may persist
  - Measure and write custom correction algorithms
- Use alternative acquisition techniques

Post-Processing: Vendor Corrections

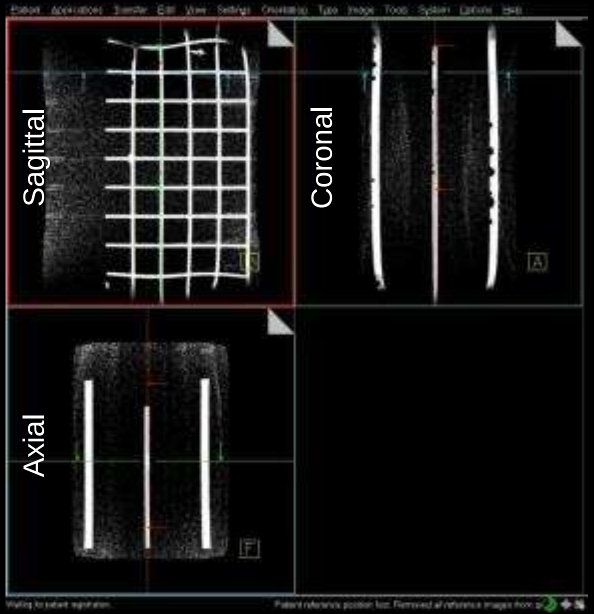
Original (No Correction)



2D Distortion Correction

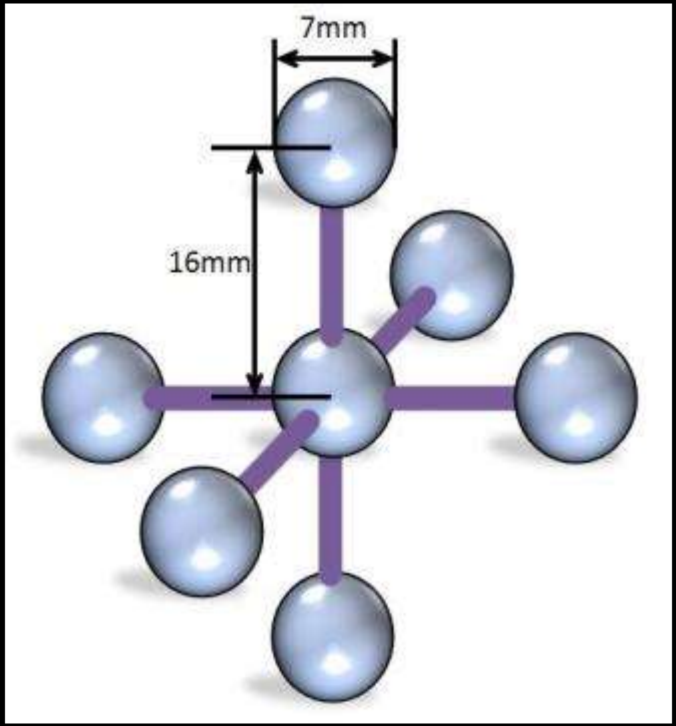


3D Distortion Correction



- 2D Distortion Correction:
  - Corrects "in-plane" distortion only; <u>other planes not corrected</u>
- 3D Distortion Correction corrects distortion in all three planes:
  - Absolutely <u>essential</u> for radiation treatment planning
  - Can be set to run <u>automatically</u> during reconstruction

Custom Corrections



- Custom distortion phantom:
  - Assembly of machined plates with half spheres and connecting channels
  - 0.4 mmol NiCl

Huang, Balter, Cao (UM), Baharom (IMT), NIH R01 EB016079

Custom Correction Algorithm

Image A (+Gx)

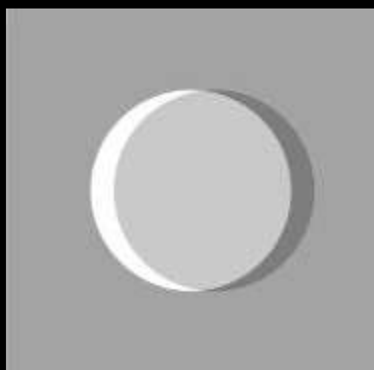


Image B (-Gx)

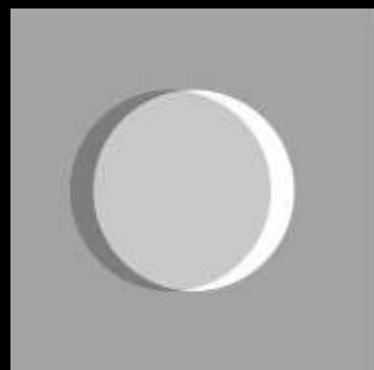
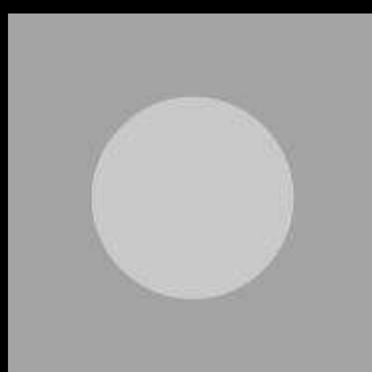


Image C (mean position)

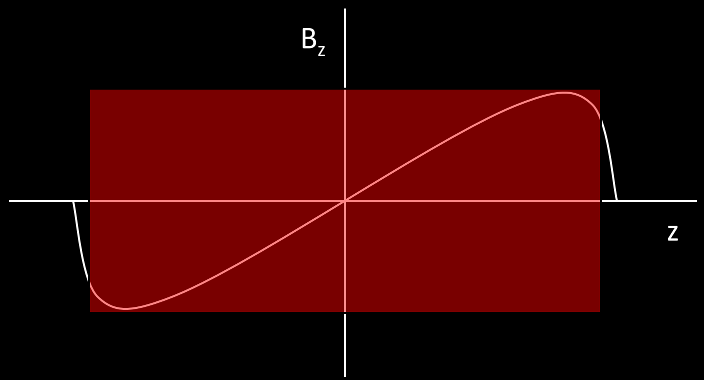


- Acquire two images (A, B) with readout gradients reversed
- Create image (C) of average spatial locations of control points in phantom
- Compare "average image" to CT image or design image of phantom
- Construct VDF to warp "average image" to actual geometry
- Calculate once for system, then apply to clinical images

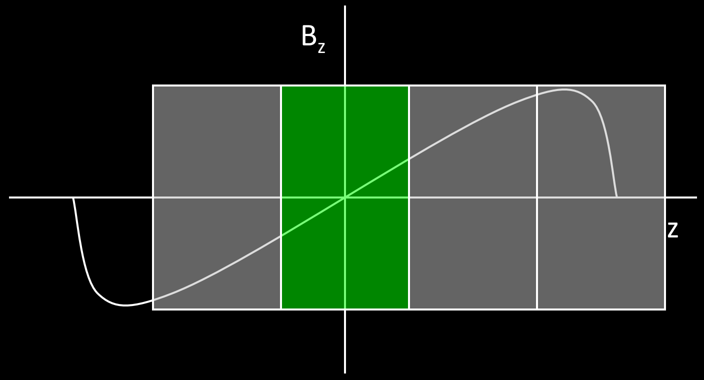
Baldwin LN, et al. Med Phys 36:3917-3926 (2009)

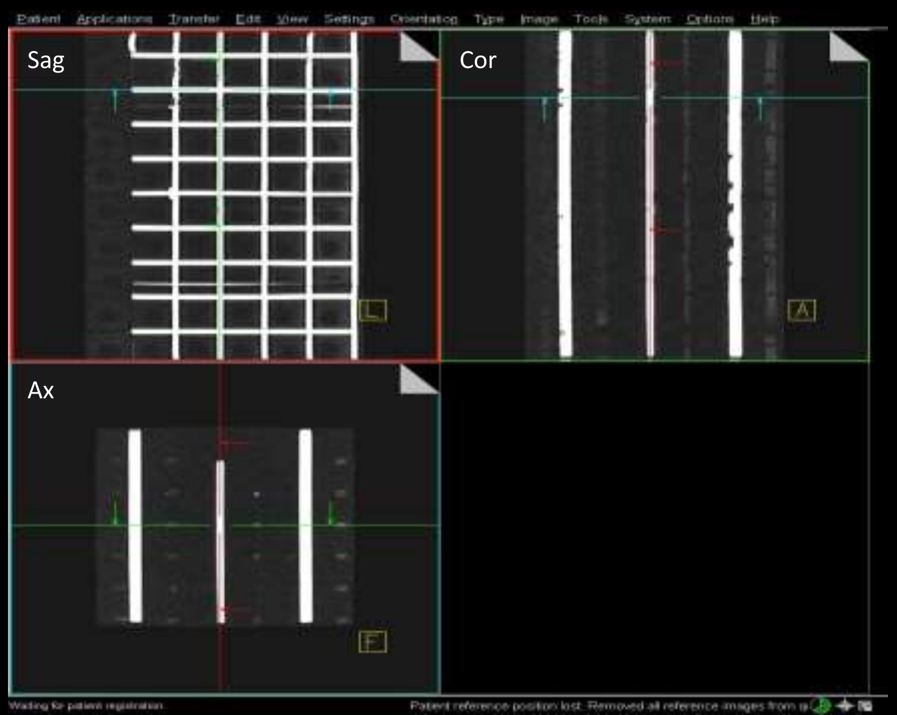
Acquisition: “Step and Shoot” MRI

Conventional MRI



“Step and Shoot” MRI





- Improved geometric fidelity across the entire FOV in all three dimensions
- Moderate increase in scan times:
  - Number of table stops dependent on scanner hardware (may not need many)

Paulson ES, et al, AAPM, 2011

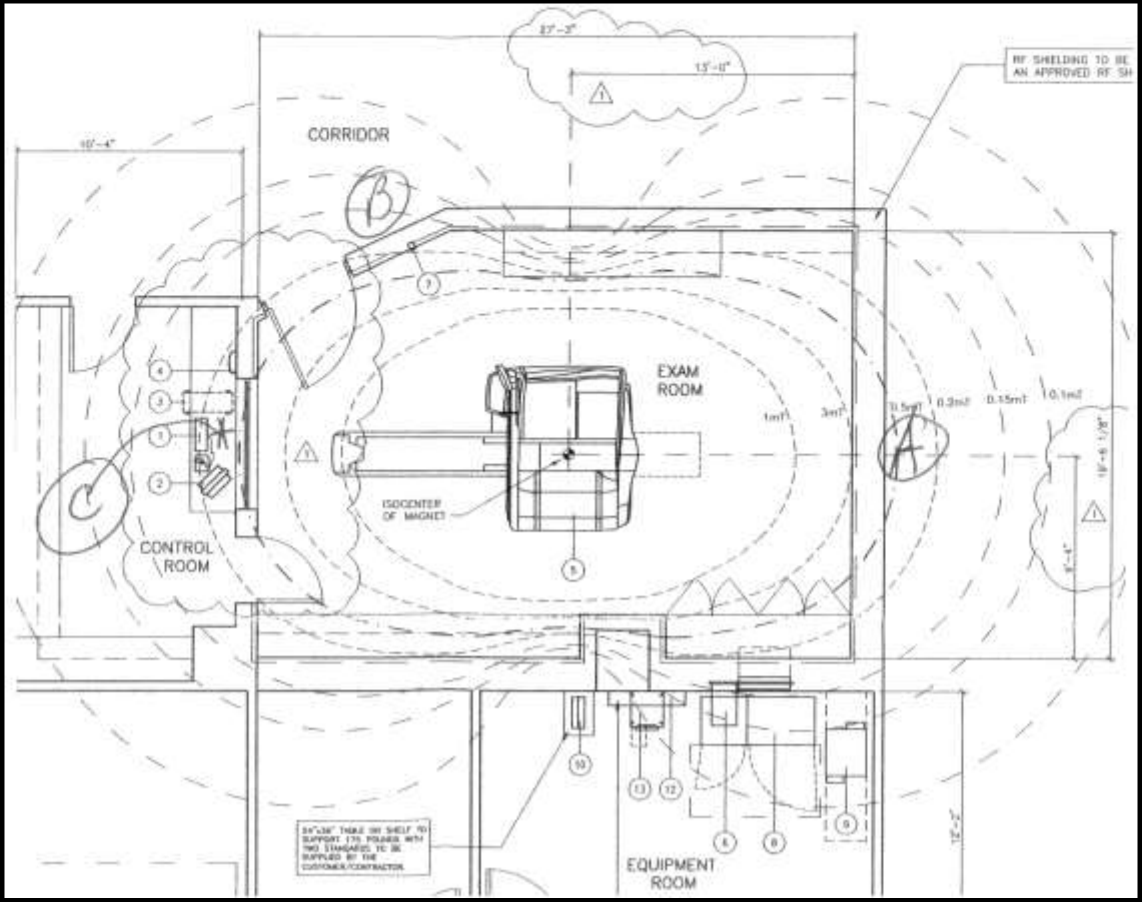
Outline

- Methodology and tools used during MRI simulations for external beam radiation treatment planning
- Management of gradient nonlinearity-induced geometric distortions
- Quality assurance for MR simulators

References for MRI AT and QA

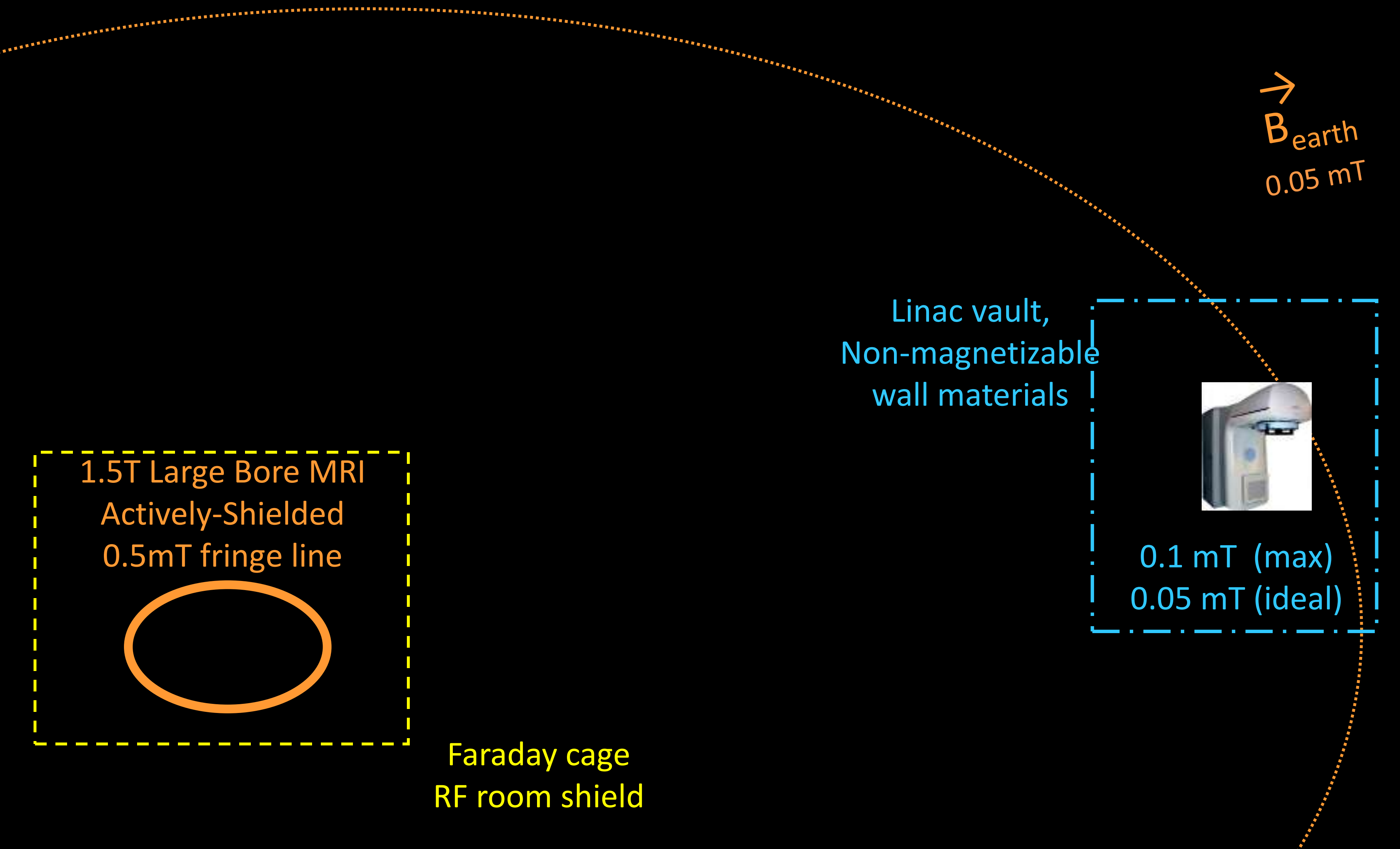
- AAPM Report 20 (1986):
  - Site planning for MRI systems
- AAPM Report 28 (1990):
  - QA methods and phantoms for MRI
- ACR MR Quality Control Manual (2004)
- ACR Phantom Test Guidance (2005)
- AAPM Report 100 (2010):
  - Acceptance testing and QA procedures for MRI facilities

Acceptance: Fringe Field Survey



- Spot checks of predicted fringe field lines
- Measured using handheld Gaussmeter

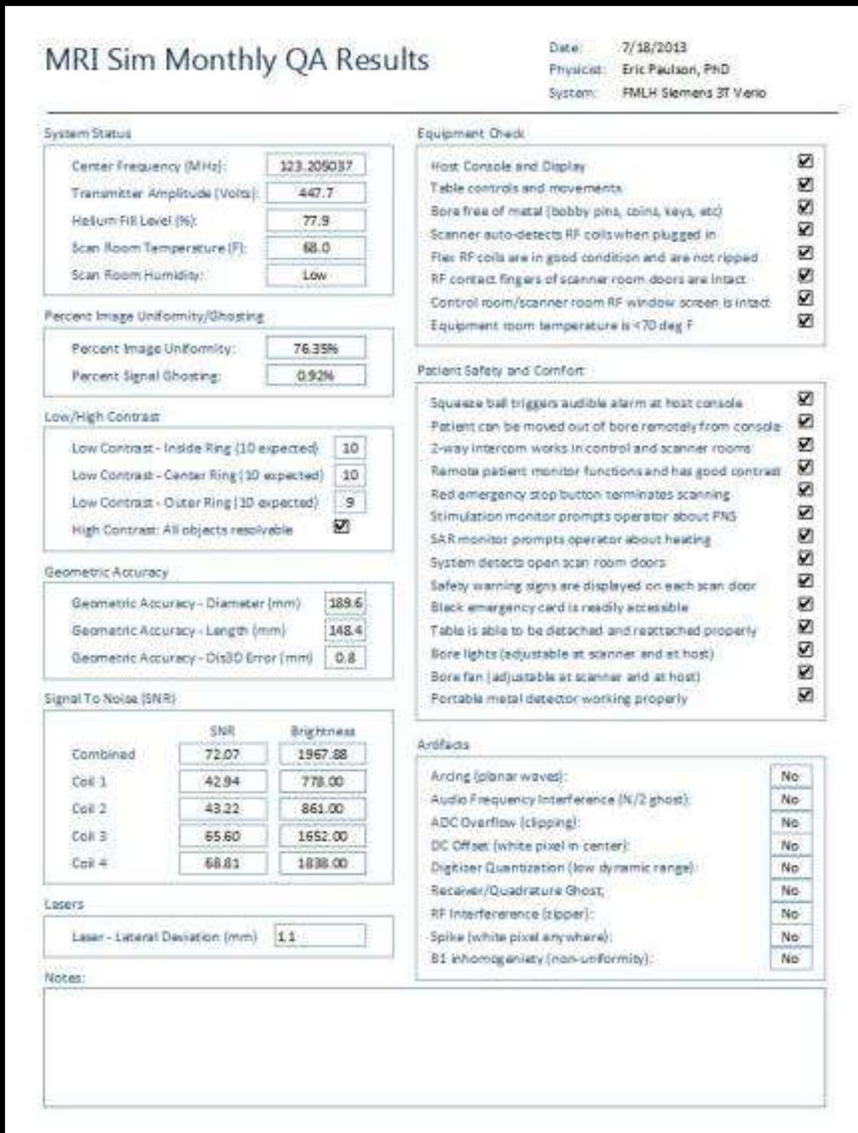
Siting an MRI in Radiation Oncology



MR Sim QA Program at MCW

- Weekly QA:
  - Performed by MR technologists/RT therapists
  - ACR Guidelines
- Monthly QA:
  - Performed by physicists
  - Check for metal in bore (bobby pins, earrings, fragments, etc)
  - Mechanicals, image quality and artifacts, geometric distortion, patient safety and comfort
- Annual QA:
  - Performed by physicists
  - Repeat monthly QA
  - B0, B1+, and gradient linearity constancy
  - RF coil integrity
- ACR Accreditation:
  - Performed by physicists

MR Sim QA: Monthly



MRI Sim Monthly QA Results

Date: 7/18/2013
Physicist: Eric Paulson, PhD
System: FMLH Siemens 3T Verio

System Status

Center Frequency (MHz):	123.205037
Transmitter Amplitude (Volts):	447.7
Helium Fill Level (%):	77.9
Scan Room Temperature (F):	68.0
Scan Room Humidity:	Low

Percent Image Uniformity/Ghosting

Percent Image Uniformity:	76.35%
Percent Signal Ghosting:	0.92%

Low/High Contrast

Low Contrast - Inside Ring (10 expected)	10
Low Contrast - Center Ring (10 expected)	10
Low Contrast - Outer Ring (10 expected)	9
High Contrast: All objects resolvable	☑

Geometric Accuracy

Geometric Accuracy - Diameter (mm)	189.6
Geometric Accuracy - Length (mm)	148.4
Geometric Accuracy - Dis3D Error (mm)	0.8

Signal To Noise (SNR)

	SNR	Brightness
Combined	72.07	1967.88
Coil 1	42.94	778.00
Coil 2	43.22	861.00
Coil 3	65.60	1652.00
Coil 4	68.81	1838.00

Lasers

Laser - Lateral Deviation (mm)	1.1

Equipment Check

Host Console and Display	☑
Table controls and movements	☑
Bore free of metal (bobby pins, coins, keys, etc)	☑
Scanner auto-detects RF coils when plugged in	☑
Flex RF coils are in good condition and are not ripped	☑
RF contact fingers of scanner room doors are intact	☑
Control room/scanner room RF window screen is intact	☑
Equipment room temperature is <70 deg F	☑

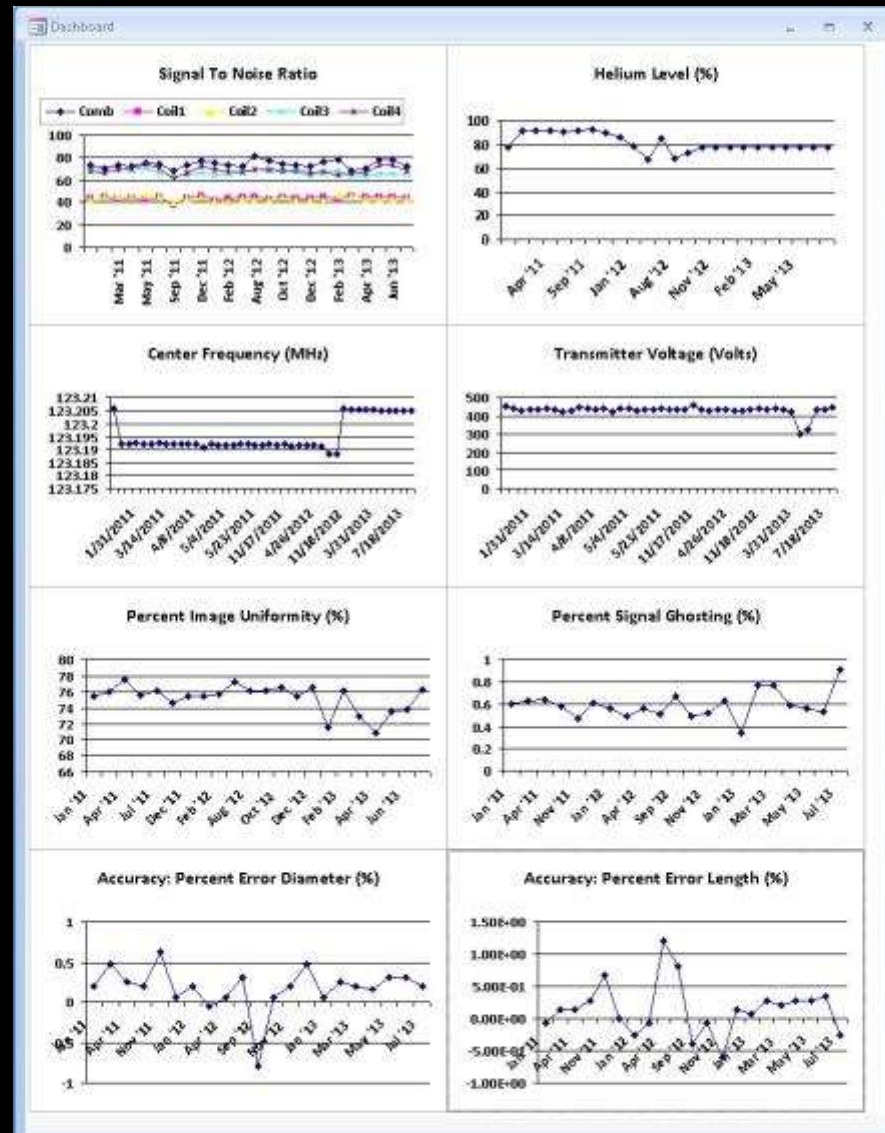
Patient Safety and Comfort

Squeeze ball triggers audible alarm at host console	☑
Patient can be moved out of bore remotely from console	☑
2-way intercom works in control and scanner rooms	☑
Remote patient monitor functions and has good contrast	☑
Red emergency stop button terminates scanning	☑
Stimulation monitor prompts operator about PNS	☑
SAR monitor prompts operator about heating	☑
System detects open scan room doors	☑
Safety warning signs are displayed on each scan door	☑
Black emergency card is readily accessible	☑
Table is able to be detached and reattached properly	☑
Bore lights (adjustable at scanner and at host)	☑
Bore fan (adjustable at scanner and at host)	☑
Portable metal detector working properly	☑

Artifacts

Arcing (planar waves):	No
Audio Frequency Interference (N/2 ghost):	No
ADC Overflow (clipping):	No
DC Offset (white pixel in center):	No
Digitizer Quantization (low dynamic range):	No
Receiver/Quadrature Ghost:	No
RF Interfererence (zipper):	No
Spike (white pixel anywhere):	No
B1 inhomogeniety (non-uniformity):	No

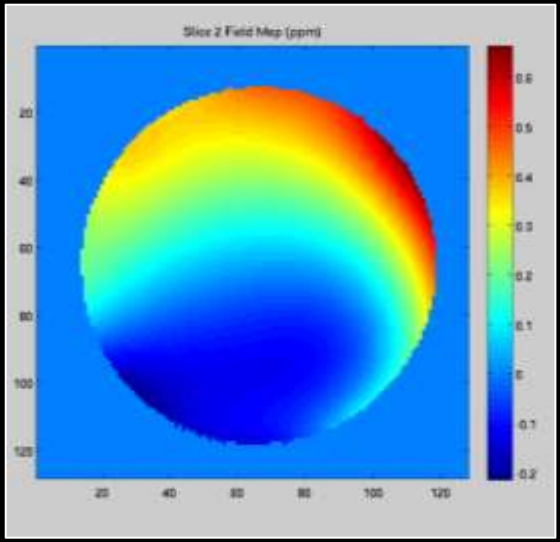
Notes:

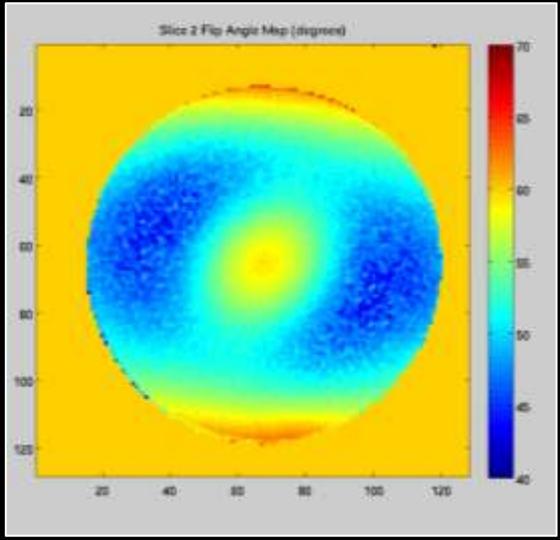


MR Sim QA: Annual (B0, B1+ Constancy)

- 40 cm diameter phantom

Plane	Min (ppm)	Max (ppm)
Axial	-0.9371	0.6619
Coronal	-1.3793	0.5924
Sagittal	-1.2737	0.8894





MR Sim QA: Annual (RF Coil Integrity)

Body (T)

Large Flex (R)

Small Flex (R)

Spine (R)

<table>
<tr><th>Element</th><th>Measured SNR</th><th>Lower Limit</th><th>Upper Limit</th></tr>
<tr><td>B01</td><td>1685</td><td rowspan="4">650</td><td rowspan="4">2600</td></tr>
<tr><td>B02</td><td>1735</td></tr>
<tr><td>B03</td><td>1563</td></tr>
<tr><td>B04</td><td>1752</td></tr>
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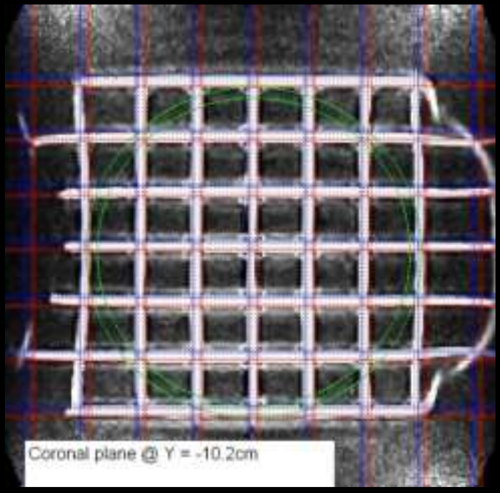
MR Sim QA: Annual (Gradient Linearity)



Plane	Distortion free distance (<2mm, dia)
Axial	30 cm
Coronal	30 cm
Sagittal	30 cm

Summary – Part I

- MRI is not an exotic device, but rather an essential tool providing high contrast, morphological images proven to be useful in Radiation Oncology
- Several factors (including MRI hardware, logistics, scan protocols, and experience) play a role in the successful utilization of MRI in radiation treatment planning
- Strategies exist to manage past perceived challenges associated with gradient nonlinearity-induced geometric distortions
- A rigorous QA program is essential to maintain the accuracy and integrity of the MRI simulation process

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