QA of MRI for Radiation Oncology

James Balter

Disclosures

- Research support from Siemens Medical Systems
- NIH R01 EB016079, P01 CA59827

Learning objectives

- Appreciate some existing QA and commissioning needs for MRI
- Discuss some QA concerns unique to combined MRI and treatment systems

MRI simulators

- Introduced over 10 years ago
- Intended to have MRI work operationally as a simulator with or without CT
- Issues include:
  - Geometric accuracy
  - Support of dose calculations and IGRT
  - Appropriate immobilization systems/coils
  - Scan Optimization

Integrated treatment and MRI systems

- Designed to support “live” image guidance:
  - Positioning
  - Gating
  - “tracking”
  - adaptation
- Wide variety of field strengths (0.35-1.5 T)
- Issues include:
  - Isocenter location
  - Radiation calibration
  - Interference of MRI with treatment (and vise versa)
  - Effects of magnetic field on radiation measurements

Viewray system

Multi-use MRI (PMH, Varian/Siemens)

Courtesy of David Jaffray, PMH

Princess Margaret Hospital
University Health Network

High field MRI/Linac system (Utrecht/Philips/Elekta)

- Current complete prototype system has been installed and is undergoing evaluation

(Courtesy of Jan Lagendijk, Utrecht)

Current standard guidance for MRI in Radiation Oncology

- No guidance is currently available to help medical physicists routinely manage MRI QA specifically for Radiation Oncology needs

Some guidance documents commonly used for diagnostic MRI

- AAPM MR TG 1
  - Tests to perform
  - General guidance on ways to perform tests
- AAPM MR TG 100
  - Commissioning requirements
- ACR QA phantom procedure
  - Image quality tests (in widespread use)

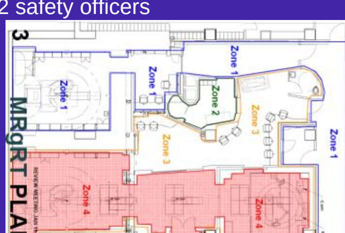
MRI Safety

Safety

- Affected populations
  - Individual patient (pacemakers, metal, environmental risks)
  - Staff (magnetic field effects on health, environmental hazards)
  - Public
  - Equipment - linacs may be very sensitive to small (e.g. less than 0.02 T) magnetic fields

Safety – staff and public

- General safety education
- 4 zone design
- Level 2 safety officers

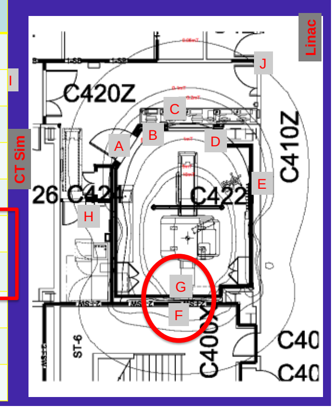


Courtesy of David Jaffray, PMH

MRI Simulator field mapping at UM

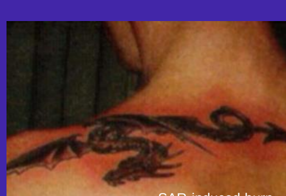
- Performed as part of acceptance of the room after the magnet was ramped to field
- Used a Hall effect probe (AlphaLab GM-1-ST)
- Measured the magnetic field at locations initially calculated to be critical for shielding estimates

Place	Reading (gauss)
A	3.0
B	50.2
C	2.6
D	47.9
E	2.5
F	4.6
G	145.8
H	1.5
I	4.7
J	2.9



Safety - patients

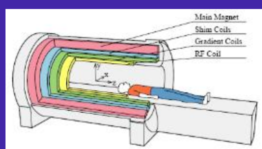
- Screening questionnaire
- MR safety and conditional status of materials introduced to zone 4



SAR-induced burn

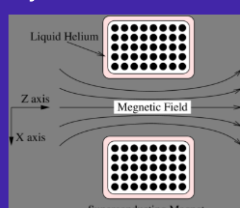
Geometric accuracy

- Sources of distortion
  - System level magnetic field uniformity
  - Subject-induced inhomogeneity
  - Gradient non-linearity
  - Scan sequence parameters



B_0 field

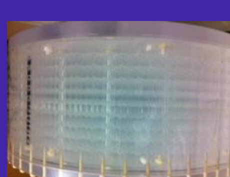
- Uniform region
- Fringe field
- Homogeneity influenced by
  - Basic design
  - Passive shimming
  - Active shimming



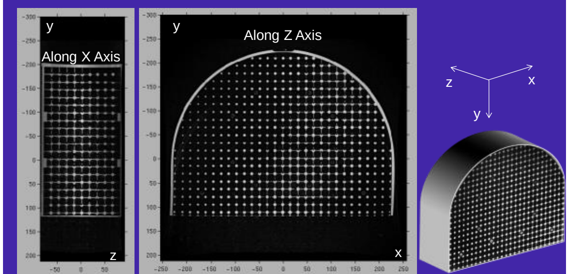
www.projectrhea.org

Geometric accuracy – phantom measurement

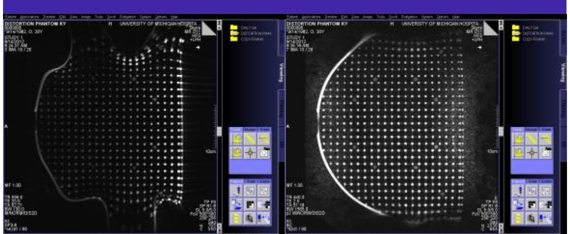
- Custom-designed large volume geometric distortion phantom (IMT and UM)



Phantom oriented axially



Phantom oriented along sagittal axis

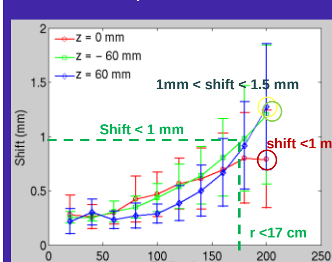


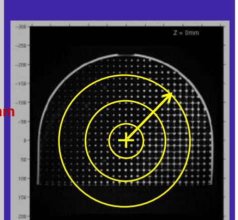
Narrow bandwidth

Wide bandwidth

Characterization of system-level distortion

- Automated extraction of sphere centers
- Compare measured and designed locationa

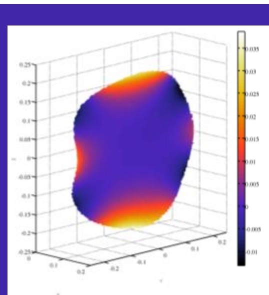




Non-linearity of gradient coil: slice distortion

- Cause: non-linearity of gradient coil fields
- Effect: curvature of excited slice (up to centimetres)
- Problems when doing therapy guidance based on 2D images
- There is little to no attention to this problem!

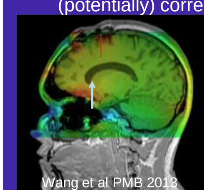
Sjoerd Crijns, University of Utrecht

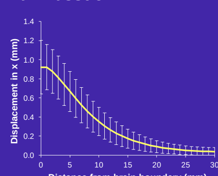


Slice distortion in experimental system, 10cm off-centre slice in 50cm DSV (all quantities in metres)

Subject-induced distortion

- Greatest at areas of significant susceptibility difference (e.g. air cavities, implanted metal)
- Increases with:
  - Higher field strength
  - Lower bandwidth
- Can be assessed on a subject-specific basis and (potentially) corrected within tissue



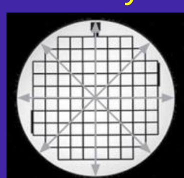


Typical QA equipment – ACR QA phantom

ACR phantom tests

1. Geometry accuracy
2. High-contrast spatial resolution
3. Slice thickness accuracy
4. Slice position accuracy
5. Image intensity uniformity
6. Percent-signal ghosting
7. Low-contrast object detectability

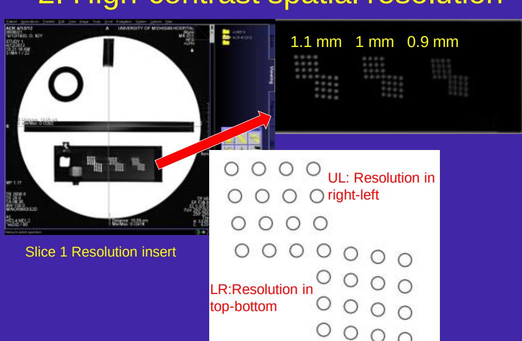
I. Geometry accuracy



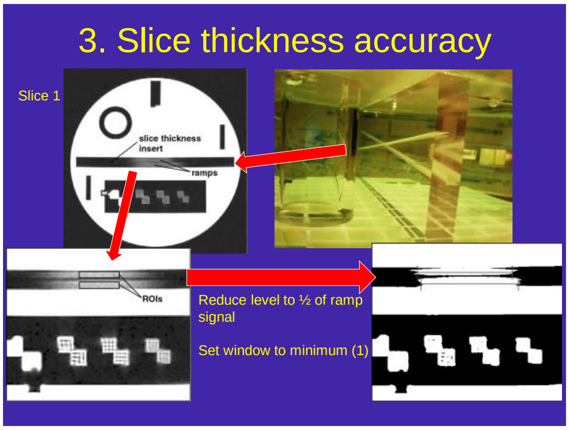
Possible causes of failure:

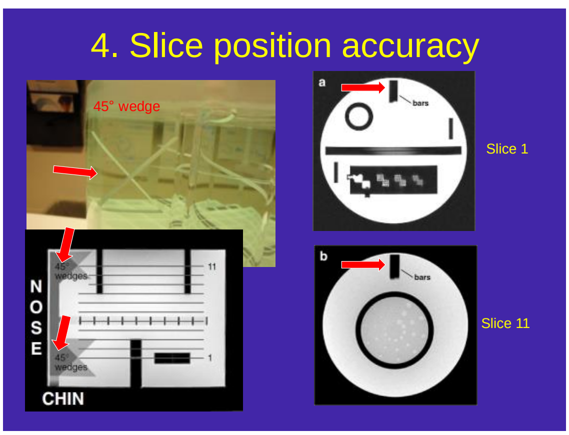
- Miscalibrated gradient (most common)
- Acquisition bandwidth too low
- Abnormally high B0 inhomogeneities (uncommon)

2. High-contrast spatial resolution



Slice 1 Resolution insert


3. Slice thickness accuracy
Slice 1
slice thickness insert
ramps
ROIs
Reduce level to ½ of ramp signal
Set window to minimum (1)


4. Slice position accuracy
45° wedge
a
bars
Slice 1
b
bars
Slice 11
45° wedges
45° wedges
11
1
NOSE
CHIN


5. Image intensity uniformity
ROI 195 ~ 205 cm²
Large ROI
Low intensity
High intensity
2 Min/Max: 2373 /2421
2 Mean/SD: 2395.9 /11.8
2 Area: 0.97 sq.cm
2 Pixel: 102
2 Min/Max: 2910 /3038
2 Mean/SD: 2974.7 /34.8
2 Area: 0.95 sq.cm
2 Pixel: 100
1 cm² circle

6. Percent-signal ghosting

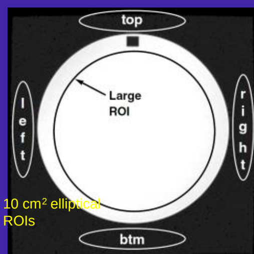
- Ghosting ratio

= | ((top + btm) – (left + right)) / (2 × large ROI) |

- Pass: ratio ≤ 0.025
- Possible causes of failure

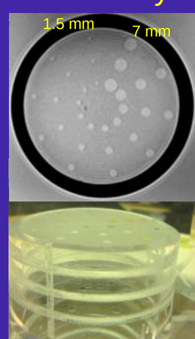
  Nonspecific sympton

  Receiver, transmitter, or gradient subsystems.



7. Low-contrast object detectability

- 10 spokes of low-contrast small disks on slice 8 through 11
- Disk diameter decreases progressively from 7.0 mm to 1.5 mm.
- Contrast values are 1.4%, 2.5%, 3.6%, and 5.1%.

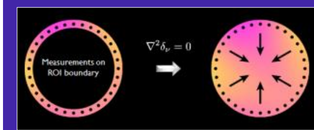


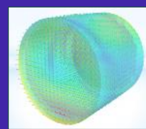
ACR QA test results (Viewray at WUSTL)

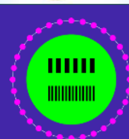
Quality assurance test	Results	Specification	Status
Geometric accuracy	148.6mm	148mm ± 2mm	Pass
	190.2mm	190mm ± 2mm	Pass
Spatial resolution	0.9mm	<1.0mm	Pass
Slice thickness	5.4mm (T2)	5.0mm ± 0.7mm	Pass
Slice position accuracy	3.1mm (slice #1 on T1)	±5mm	Pass
	0.0mm (slice #11 on T1)	±5mm	Pass
	3.0mm (slice #1 on T2)	±5mm	Pass
	0.0mm (slice #11 on T2)	±5mm	Pass
Image intensity uniformity	93% (T1)	>87.5%	Pass
	92% (T2)	>87.5%	Pass
Percent ghosting	0.0016 (T1)	<0.025	Pass
Low contrast detectability	10 (T1)	≥9	Pass
	13 (T2)	≥9	Pass

Slide courtesy of Yanle Hu and Olga Green, WUSTL

Harmonics-based distortion analysis integrated in phantom design (PMH)







3D distortion field - Harmonic analysis:

a. Distortion vectors measured at a reduced number of control points located on the boundary of the phantom
b. Laplace equation is solved to generate the distortion field at any desired location inside the volume of the phantom
c. Analysis can be performed for any arbitrary phantom shape

T. Stanescu, PhD, MCCPM

Radiation Oncology
UNIVERSITY OF TORONTO

MRI Simulator commissioning at MCW (Courtesy of Eric Paulson)

- Acceptance testing and establishment of baseline constancy benchmarks
  - B0, B1 homogeneity, SNR for coils, image intensity uniformity, ghosting, low/high contrast resolution
- Characterization of gradient non-linearity-induced distortions:
  - Residuals after vendor's 3D correction (and develop in-house further correction)
- Optimize MR scanning protocols for RT:
  - Differences between CT+MR vs MR-only workflow
- Perform end-to-end tests using RT add-ons:
  - Lasers
  - Flat table insert
  - RF coil configurations and bridges

MR Sim QA Program at MCW

- Weekly QA (RT/RTT):
  - ACR Phantom Test
- Monthly QA (Physicist):
  - Test performed based on AAPM Report 28 (1990), ACR MR Quality Control Manual (2004), ACR Phantom Test Guidance (2005), AAPM Report 100 (2010)
  - Mechanicals, image quality and artifacts, geometric distortion, patient safety and comfort, check for metal in bore (bobby pins, earrings, fragments, etc)
- Annual QA (Physicist):
  - Repeat monthly QA
  - Additional B0, B1+, and gradient linearity constancy tests
  - Additional RF coil integrity (SNR, brightness) tests

Courtesy of Eric Paulson

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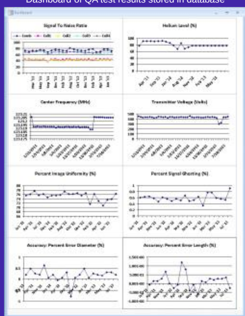
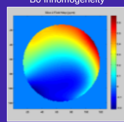
MR Sim QA Program at MCW

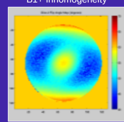
Dashboard of QA test results stored in database



B0 inhomogeneity



B1+ inhomogeneity



RF Coil Integrity

Gradient Nonlinearity

Courtesy of Eric Paulson

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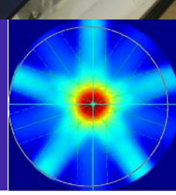
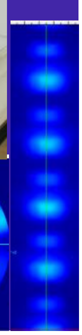
MRI-guided treatment systems – finding the isocenter

- Unlike linear accelerators/Co-60 units, the MRI isocenter is generated and calculated using magnetic fields and RF, is found by calibration
- To support image guidance, the MR isocenter needs to be determined relative to the treatment isocenter, and appropriate quality assurance standards established

Finding Isocenter (Olga Green, WUSTL)

- Cylindrical phantom filled with water
- Scribe lines for alignment to lasers
- Circular film between two halves of phantom
- Wrap-around film strip
- Once MLC accuracy is established, imaging this phantom provides information about MR-RT isocenter alignment
- Once RT isocenter is established, MR isocenter coordinate shift is implemented in software





Finding Isocenter - PMH

Couch transfers patient between MRI and Linac systems

Courtesy of Teo Stanescu,PMH

PMH – isocenter finding test

- Couch movement tested to <0.5 mm
- Phantom tolerances expected to be <1.0 mm
- MR iso tests TBD

MR Precision Guidance:
3 spheres pattern
Imaging kV / MV / MR
MR-to-linac iso co-registration
MR-MR iso verification
Table adjustment

Courtesy of Teo Stanescu, PMH

Calibration

- Integrated treatment systems present novel calibration/output check issues:
  - Influence of magnetic field on secondary electrons
  - Some mechanical constraints on measurement configurations

Setup for TG-51-based calibration

Treatment Heads 1 - 3: Solid Water Phantom

Treatment Heads 1 &3: Water Phantom

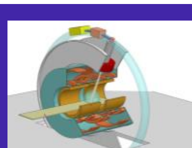
- SSD = 105 cm
- FS = 10.5 x 10.5
- D = 5 cm

Slide courtesy of Dr. S. M. Goddu, WUSTL

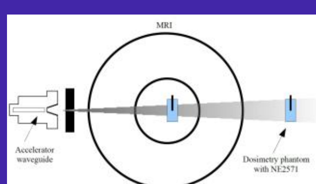
Absolute dosimetry in 1.5T for the MRL using farmer NE 2571

University Medical Center Utrecht

- Dose at electronic equilibrium is the same with and without b-field
- Ratio measured with and without 1.5 T



- Impact of 1.5 T field: Extra correction of 0.954



Bas Raaymakers, University of Utrecht

MR-compatible QA and Patient Safety Tools

Sun Nuclear corporation

Summary

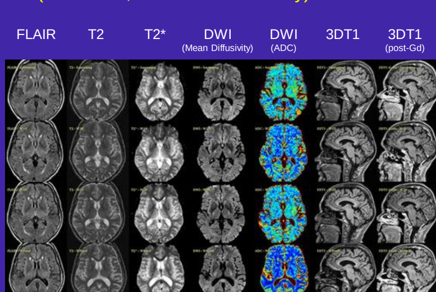
- MRI has potential to be increasingly integral to the radiotherapy process
- A number of commissioning and QA concerns unique to MRI as well as integrated systems need to be considered
- As guidance matures, the necessary skill sets and training to support commissioning and use will emerge

Acknowledgements

- Medical College of Wisconsin (Eric Paulson)
- Princess Margaret Hospital (David Jaffray, Teo Stanescu)
- University of Utrecht (Bas Raaymakers, Sjoerd Crijns, Jan Lagendijk)
- Washington University (Olga Green, Yanle Hu, SM Goddu, Rojano Kashani)
- University of Michigan (Yue Cao, Hesheng Wang, Antonis Matakos)

University of Michigan Medical School

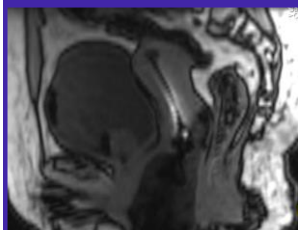
Protcol optimization: Image protocols used for diagnosis may not be optimized to guide therapy (Cliff Chao, Columbia University)

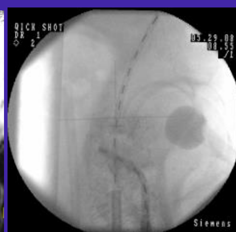


Top to bottom: 4 different timepoints over a follow-up period of one year

MRI in Brachytherapy (Yusung Kim)

1. Challenges in source-pathway reconstruction
2. Artifacts and distortions





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❖ Source-pathway Reconstruction

- Depends on material of Applicator
  - Plastic / Carbon-fiber
  - Titanium
- Due to considerable uncertainties of registration and inter-scan motions: CT-MRI fusion is not recommended for cervical cancer treatment planning (but recommended for QA)

Plastic Applicator

Titanium Applicator

(Yusung Kim, Iowa)

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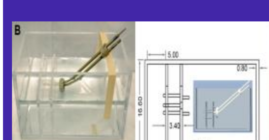
Plastic Applicator: Intracavitary

- MRI Marker Catheters are available
  - MRI-Marker catheter: CuSO4, C4, Vitamin E, Conray, Saline, Fish Oil, Agarose gel
  - Reconstruction accuracy of MRI-Marker catheter: should be commissioned over those of CT and X-ray



T1MRI (3.0 Tesla- 1mm slice thickness)		T2MRI (3.0 Tesla- 3 mm slice thickness)	
Marker Name	GYN Phantom	Marker Name	GYN Phantom
$CuSO_4$		Saline	
C_4		Fish Oil	
Vitamin E		1% Agarose Gel	
Conray		$CuSO_4$	

(Yusung Kim, Iowa)

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Titanium Applicator: Intracavitary

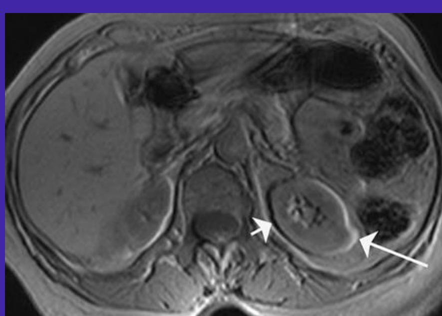
- Dummy-MRI marker catheters: not feasible
- Alternative solution: MRI Marker-Flange (Cervical Flange + MRI Marker) + applicator library

T1MRI (3.0 Tesla- 1mm slice thickness)		T2MRI (3.0 Tesla- 3 mm slice thickness)	
Marker Name	MRI-Flange Phantom	Marker Name	MRI-Flange Phantom
$CuSO_4$		Saline	
C_4		Fish Oil	
Vitamin E		1% Agarose Gel	
Conray		$CuSO_4$	

(Yusung Kim, Iowa)

University of Iowa Hospitals & Clinics
University of Iowa Health Care

Chemical shift artifacts



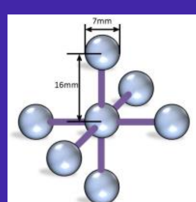
What issues need to be addressed for MRI in Radiation Oncology?

- Safety and compatibility with other equipment
- Spatial Integrity
- Ability to support consistent decisions for Radiation Oncology
- Optimization of scan protocols and utilization methods for Radiation Oncology

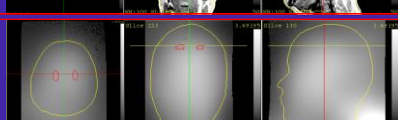
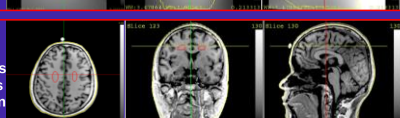
MRI Co treatment unit schematic cutaway

Distortion phantom

- Sampling volume 46.5x35.0x16.8 cm
- 4689 measurement points (spheres)



MRI bias field correction

T1 images		WM ROI: 116.7±7.2 (6%)
Bias field correction		WM ROI: 1.6±0.1 (6%)
T1 images after bias correction		WM ROI: 71.5±3.0 (4%)

ViewRay MR-IRGT System QA(Olga Green, Wash U):

- Safety:
  - MLC leakage most important concern: these are the only collimators
    - 3 heads, 30 pairs of leaves on each head
    - Doubly-focused, tongue-and-groove on adjacent and abutting sides
    - Leakage must be checked with leaves closed at different locations (not just in the center)
  - Magnetic fields affect large air cavities most – difficult to use typical large-volume ionization chambers to determine exposure at isocenter
- Mechanical accuracy:
  - Radiation-MRI isocenter coincidence with virtual isocenter (lasers)155 cm away
  - Couch: planned positions provided by treatment planning system, may apply automatic couch shifts after imaging, treatment planning system displays limits on couch positions to avoid collisions
  - No lightfield, no ODI, no scanning water tanks that work in a magnetic field
    - must rely on film to measure flatness, symmetry, penumbra (most significant feature – on the order of 8 mm), and field accuracy
- Dosimetry:
  - Small-volume ionization chambers not significantly affected, but this should not be assumed for different chamber models (WU study in preparation for publication)
  - Water tank may be used as long as manually driven – TG-51 is possible
  - RPC OSLs not affected by magnetic field – independently confirmed TG-51 results

ViewRay MR-IRGT System QA (Olga Green, Wash U):

- Treatment planning:
  - May use CT or MRI (bulk density overrides required)
  - Imaging coils stay on the patient during delivery and are modeled in the TPS
- Patient simulation:
  - Will need to acquire both CT and MR (on ViewRay) prior to planning:
    - Must evaluate patient motion and choose gating structures and planes prior to treatment
  - Will need to evaluate patient immobilization devices
    - Can't have anything that will produce imaging artifacts (e.g, non-MR registration bars)
    - Must avoid anything providing too much additional buildup
  - If using alpha cradles or other immobilization/positioning devices, must consider how they will fit with imaging coils
  - Patient will require hearing protection daily – if treating above the neck, cannot use headphones: need to have adequate ear plugs and evaluate their dosimetric effects
- Patient setup:
  - Must ensure patient MRI safety daily by using MRI checklist (make sure patient didn't get a new piercing or tattoo the day before!)
  - Must position imaging coils in same way daily
  - Must have MR-compatible step-stools, wheelchairs, or tables to enable safe transfer of patients with limited mobility

Frequency of QA varies across institutions

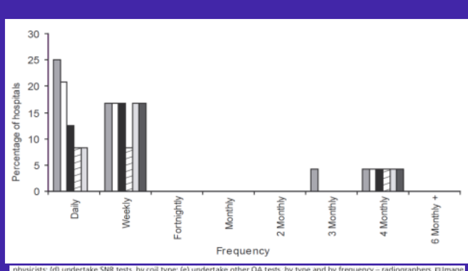


Figure 2e. The British Journal of Radiology, 79 (2006), 592–596

MRI in Radiation Oncology

- Routinely used as an adjunct to CT-based treatment planning for over 25 years
- Currently at least 60 Radiation Oncology departments in North America have direct access to MRI
- One operational, and at least 2 under development, commercial integrated MRI and external beam treatment technologies

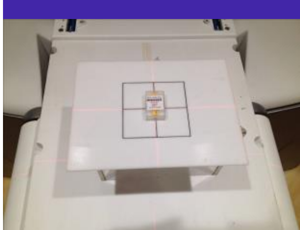
Dosimetric calibration validation of a MR-Co-60 unit

Head and irradiation angle	RDS TLDs April 2011 (Cleveland)	RPC OSLs July 2012	RDS TLDs May 2013	RPC OSLs May 2013
Head 1 at 0 deg	1.01	1.00		0.98
Head 3 at 0 deg	1.03	0.99		0.99
Head 1 at 90 deg	-	1.01	0.99	1.01
Head 2 at 90 deg	1.02	1.00	1.00	0.99
Head 3 at 90 deg	-	1.01	1.01	1.00

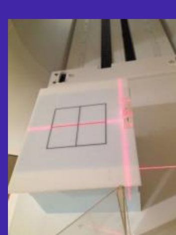
Slide courtesy of Dr. Olga Green, WUSTL

Set up for RPC OSLD irradiation

Same as a linac at 0 degrees:



At 90 degrees:



Slide courtesy of Dr. Olga Green, WUSTL