Integration of MR in Radiation Therapy: Practical Safety Considerations

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Learning objectives

• Describe general development and special requirements for MR guided radiotherapy

• Identify the safety challenges of integration of MRI into radiation therapy workflow

• Describe the strategies and references for establishing a MR safety program in radiation therapy
Advantage of MR guided RT (MRgRT)

- **Patient Setup**
- **Treatment Gating**
- **Adaptive planning**
- **Functional imaging**

Tyran M et al. Cureus 10(3): 2018

Challenges of integration of MRI with Linac

- Radiofrequency (RF) interference
  - MR measures very weak signal from patient
  - RF noise from outside generates image artifacts and distort images
  - Medical linear accelerator as major source of RF noise
Challenges of integration of MRI with Linac

• Magnetic field interference
  • Asymmetric dose kernel
  • Electron return effect

Raaijmakers et al. PMB. 53 (2008)
Strategies of integration of MR with Linac

- Radiofrequency (RF) interference
  - shielding of RF components

Courtesy of ViewRay Inc.

Shvartsman S. et al. ISMRM 2017
Strategies of integration of MR with Linac

- Magnetic field interference
  - Lower magnetic strength
  - Active magnetic shielding
  - Align beam direction with magnetic field
  - Compensate through planning optimization

Kirkby et al.: Medical Physics, V37(9), 2010
Elekta MRI-Linac Unity™ (1.5T)

ViewRay MRIdian (0.35T)

The Australian MRI-Linac program (1.0T)

MagentTx Aurora-RT™ (0.5T)
<table>
<thead>
<tr>
<th>MRgRT system</th>
<th>Radiation</th>
<th>Magnet field</th>
<th>Configuration</th>
<th>Orientation</th>
<th>Strength</th>
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<tr>
<td>ViewRay MRIIdian Linac</td>
<td>6 MV</td>
<td>split superconducting close bore</td>
<td>Perpendicular</td>
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<td>0.35 T</td>
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<td>MagnetTx Aurora RT</td>
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<td>Parallel/Perpendicular</td>
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<td>1.0 T</td>
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<td>Elekta Unity</td>
<td>7 MV</td>
<td>superconducting close bore</td>
<td>Perpendicular</td>
<td></td>
<td>1.5 T</td>
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</table>
Special imaging considerations for RT

• Spatial distortion
  • ≤1mm for SRS/SBRT treatment

• Acquisition volume
  • 3D acquisition with full FOV
  • high spatial resolution (1-3mm)

• Acquisition time
  • fast acquisition (a few minutes for IGRT)
  • continuous imaging during treatment

• Image information
  • electron density / bony anatomy

RT specific MR imaging sequences are required
Major challenge of MRgRT: MR safety

• Static Magnetic Field ($B_0$):
  • Magnetic force/torque and projectile effect

• Time varying gradient magnetic field ($G_{x,y,z}$):
  • Induced voltages/currents (e.g. eddy current)
  • Peripheral nerve and muscle stimulation (PNST)
  • Acoustic Noise

• Time varying radiofrequency (RF): Thermal effect

• Cryogen: Quench

• Clinical logistic: Contrast agent / claustrophobia / Anesthesia …
Magnetic force/torque and projectile effect

• Interfere with:
  • Medical equipment and devices
  • Implanted devices (passive and active)
  • Neighboring equipment/machine

• Strategies:
  • Site access restriction
  • Patient and personnel screening
  • Device and object labeling
RF induced thermal effect

- Time varying RF power can deposit energy into patient’s tissue as heat
- Thermal effect depends on the amount of energy absorbed
- Most heat is deposited at periphery of body
- Focal heating at regions with high resistance

CM Collins et al., JMRI 19:2004
RF induced thermal effect - SAR

• Specific Absorption Rate (SAR) is defined as the energy dissipated in tissue per kilogram of tissue mass (W/kg)
  
  • 1W/kg ≈ 1 C/hr temperature increase in an insulated tissue slab
  
  • SAR \propto B_0^2 \times (\text{flip angle})^2 \times (RF \text{ duty cycle})
  
  • Whole body vs. local SAR

• Temperature change depends on many factors: SAR, perfusion, conduction, patient geometry, implants…

• Impractical to measure temperature increase in patient
RF induced thermal effect

- Special consideration for RT:
  - Continuous imaging during treatment (sequence selection and optimization)
  - SAR induced in implants and immobilization devices
  - Comply with IEC/FDA limits

![Graph showing temperature change over time](image)

<table>
<thead>
<tr>
<th>Limit</th>
<th>Whole-Body Average</th>
<th>Heat Average</th>
<th>Head, Trunk Local SAR</th>
<th>Extremities Local</th>
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<td>IEC (6-minute average)</td>
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<td>Normal (all patients)</td>
<td>2 W/kg (0.5°C)</td>
<td>3.2 W/kg</td>
<td>10 W/kg</td>
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<td>Localized heating limit</td>
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<td>38°C in 10 g</td>
<td>40°C in 10 g</td>
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<td>FDA (4 W/kg for 15 min)</td>
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<td>3 W/kg for 10 min</td>
<td>8 W/kg in 1g for 10 min</td>
<td>12 W/kg in 1g for 5 min</td>
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</table>
MR safety program in RT environment

• Site planning and access restriction
• Patient and personnel screening procedure
• RT specific devices:
  • QA equipment selection and labeling
  • RT specific patient implantable devices
  • Patient treatment immobilization devices
• Policy and procedure
• Personnel training
Survey and map of fringe field

• Static magnetic field’s strength exceeds $5\text{-Gauss}$ should be clearly marked as being potentially hazardous.
Impact of fringe field on neighboring machines

Up to 4% change in beam symmetry/flatness was observed for Linac A after 1.5T magnet ramp up.

Fig. 1. Layout of the treatment rooms. The MR-Linac is installed in the upper left corner and surrounded by 3 standard linear accelerators, A, B, and C at distances of respectively, 7.5, 5.5 and 11 m. The displayed Gauss lines are 0.5 G (Outer) and 2 G (Inner), and are taken from the vendor specifications.

Perik T et al. Phys and Img in Rad Onc 2017(4)
Site access restriction

MRI Functional Diagram

Outpatient Entrance
- Patient Waiting
  - Reception
  - Toilet
  - Patient interview
  - Changing/Gowning
- Ferrous Quarantine
- Patient Screening
- Ferromagnetic Detection
- Secured Patient Access

Inpatient Entrance
- Safety Zone I
  - Safety Zone II
  - Post-Screened Patient Holding
    - Induction Recovery
    - Curtain Preparation/Bed Holding
    - Control Room
    - Vestibule
  - MRI Scanner Room

Safety Zone III
Safety Zone IV
ViewRay Vault

Patient waiting area

Nurse station

Exam Room

Front Desk
Patient MR safety screening

• Patients are screened in accordance with our hospital MR Safety Policy
  • Initial screening by a trained nurse during consultation
    • Screening questionnaire form
    • Review existing medical records and MR imaging
  • 2nd screening by a trained therapist during simulation
• RT patients receive treatment on daily basis
  • Daily screening is performed to monitor for change in the patient safety status.
MRI SAFETY SCREENING QUESTIONNAIRE – UC EMPLOYEES AND OTHER INDIVIDUALS/VISITORS

NAME: Date of Birth: 
EMPLOYEE ID: DEPT: 

The MRI system has a very STRONG MAGNETIC FIELD that may be hazardous to individuals entering the MRI environment or MRI system room.

**WARNING:** Certain implants, devices, or objects may be hazardous in the MRI environment or MRI system room. DO NOT ENTER the MRI environment (Zone 3) or MRI system room (Zone 4) if you have any question or concern regarding any implant, device, or object.

Please indicate if you have any of the following:

- **YES**
  - Anesthesia clip(s)
  - Cardiac pacemaker
  - Implanted cardioverter defibrillator (ICD)
  - Electronic implant or device
  - Magnetic resonance imaging (MRI) device
  - Artificial heart valve, coil, or implant
  - Artificial heart (prosthetic)
  - Aneurysm clip
  - Neurostimulator (TENS) Unit

- **NO**
  - Spinal cord stimulator
  - Intravenous infusion pump
  - Implanted drug infusion pump
  - Neurostimulation system
  - Any type of prosthesis or implant
  - Hearing aid(s)
  - Other implant
  - Other device

Are you pregnant or suspect that you are pregnant? Yes No

If you answered YES to any of these questions, you are required to obtain specific clearance from the MRI Technologist or Radiologist before you enter the MRI environment. I attest the above information is correct to the best of my knowledge. I have read and understood the criteria contents of this form and I have had the opportunity to ask questions regarding the information on this form.

Signature of Employee or Visitor: Signature: Date: 
Reviewed By: Print Name: Signature: Date: 

MRI Technologist MRI Assistant Radiologist

The following items may be helpful to you during your MRI scan or may interfere with the MRI examination. Please provide a "yes" or "no" answer for every item.

**YES**
- Cardiac pacemaker or implanted cardioverter defibrillator (ICD)
- Artificial heart valve, coil, or implant
- Aneurysm clip
- Neurostimulator (TENS) Unit

**NO**
- Spinal cord stimulator
- Intravenous infusion pump
- Implanted drug infusion pump
- Neurostimulation system
- Any type of prosthesis or implant
- Hearing aid(s)
- Other implant
- Other device

Artificial joint and/or bone
- Artificial eye and/or eyelid spring
- Eye injury from a metal object (metal shavings, metal shards)
- Ear (Cochlear) implant, middle ear implant
- Hearing aid(s)
- False teeth (dentures, metal removable dental work, braces, retainers)
- Any type of implant held in place by a magnet
- Injured by a metal object (shrapnel, bullet, bullet)
- Any medical device (implantable, contraceptive, drug device)
- Soft or Softly adjustable and programmable pressure valve
- Spinal fixation device, spinal fusion, and/or halo vest, spinal cord stimulator
- Surgical clips, staples, or surgical mesh
- Intravenous (IV) device
- Pacemaker
- Pessary
- Drug allergy

**YES**
- Kidney disease
- Diabetes
- Liver disease
- Asthma
- Allergic reaction to MRI contrast (Gadolinium based)
- Drug allergy

**NO**
- Latex allergy
- Pregnancy
- Breastfeeding

If you are still menstruating, please provide the date of your last period:

**Female Patients:**
- Are you pregnant? Yes No
- Are you breast-feeding? Yes No

UCLA Health System

Page 1 of 2
Device and object labelling

• all portable metallic or partially metallic devices to be brought into Zone IV

• labeled using the current FDA labeling criteria (ASTM F2503)

• challenges for RT:
  • Various mobile equipment and devices
  • Lack of clear safety labelling
Equipment consideration during site planning

• Review of existing equipment for MR safety
• Inventory of MR safe equipment
• Bundled in major capital purchase
• Dedicated storage areas for equipment
Site planning consideration for equipment

RF filter
General considerations for RT QA devices

• Ferromagnetic components:
  • “MR safe” label (never assume safe)
  • Check by handheld magnet

• Electronic components:
  • Damaged by $B_0$
  • RF noise interference

  Distance and RF shielding

  • Ferromagnetic components in power adapter and electric motors

  • Piezoelectric, ultrasonic, pneumatic and hydraulic actuators
General considerations for RT QA devices

• Image quality: metal artifacts
  • Signal loss from dephasing
  • Susceptibility variations -> Geometric distortion
  • Failure of fat suppression

• Measurement accuracy under magnetic field

• It is important to develop a MR safe commission process for RT QA devices
Device MR safety commission process

• Identify manufacture and model
• Contact vendor/online resources – safety label and MR safety sheet
• After receiving the device:
  • check by handheld magnet
  • check electronic components
  • image quality check and dosimetry evaluation
  • label device if not available and document test results
  • identify proper storage area
RT QA devices – Ion Chamber

- Non-ferrous Ion chambers: minimizing imaging artifacts
- Absolute dosimetry: effect of $B_0$ field

<table>
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<th>Detector</th>
<th>$k_{B\parallel}^{Q_{\text{meas}}}$</th>
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<td>0.956</td>
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</table>

O’Brien et al. Medical Physics, Vol. 43(8), 2016
After 3 month MR (3T) exposure, radiation sensitivity of OSLDs was found to be within $5.2 \pm 2.4\%$ of the control.
RT QA devices – Water phantom

24(LR) x 40(FH) x 11.5(AP) cm³

RT QA Devices – dosimetry and motion phantoms

Image courtesy – Dr. Dongsu Du
RT QA Devices – Film

• Radiochromic film: safe and useful for relative dosimetry and QA

• Impact of magnetic field on film dosimetry:

  - The response decrease by up to 15% in the red and green channels.
  - The SEM imaging showed changes in the rod-like crystal orientation within the active layer under magnet

Reynoso et al. Medical Physics, Vol. 43, 2016
Patient implantable devices – orthopedic

- Most are made of nonferromagnetic materials
- MR related heating may be a concern
- Check material database or contact vendor if not sure
- Image metal artifact and distortion are major concern
Patient implantable devices – fiducial markers

- Made of gold, nitinol, platinum etc.
- Negligible magnetic field interaction and heating effect
- Image artifacts and distortion are major concerns
  - Imaging sequences
  - Marker orientation

JH Jonsson et al. IJROBP, 82(5) 2012
Implantable devices – EM positioning transponder

• Electromagnetic positioning transponder system (e.g. Calypso®) provides real-time tumor tracking
• Consists of a passive circuit with ferromagnetic inductor
  • displacement (<1mm)
  • heating (<0.2° C)
  • image artifacts

*Varian.com*  
*Wikstrom et al. Anticncer Research, 37. 2017*

*X Zhu et al 2009 Phys. Med. Biol. 54 N393*
Patient implantable devices – Infusion port

- Identify the vendor and specific model
- Look for safety label and specific conditions
- Ensure that MR scan meets all conditions
- Optimize imaging parameter to reduce image artifacts
Other “mysterious implants” – Patient ingestion

Image artifacts caused by vitamin pill

Image artifacts caused by iron-fortified food (Grape-nuts cereal)

Patient immobilization devices

• Safety considerations:
  • Magnetic force/torque
  • RF heating
  • Imaging artifacts

• Other considerations:
  • Setup within limited bore size
  • Setup with MR coils

• MR safe immobilization devices are available from multiple vendors
• AAPM TG 334 – immobilization devices and accessories in MR environment
Patient immobilization devices – Vacuum cushions

• No ferromagnetic component
• Minimal heating effect
• Image artifacts - metal spring in the valve
• Place valve away from imaging area

MRI SAFETY INFORMATION

• Non-clinical testing and scientific rationale has demonstrated that the Vac-Lok™ Cushion is MR Conditional. A patient with this device can be safely scanned in an MR system meeting the following conditions:
  • Static magnetic field of 1.5 T and 3.0 T
  • Maximum spatial field gradient of 2,000 gauss/cm (20 T/m)
  • Maximum MR system reported, whole body averaged specific absorption rate (SAR) of 4 W/kg (First Level Controlled Operating Mode)
• Under the scan conditions defined above, the device is expected to produce a maximum temperature rise of less than 0.4°C after 15 minutes of continuous scanning.
Patient immobilization devices

- Carbon fiber is commonly used:
  - Lightweight with strong strength
  - Low radiation attenuation
- Is electrically conductive:
  - Heating effect
  - Image artifact and distortion
- Replacing materials:
  - Fiberglass, Acrylic…

A – without carbon fiber
B – with carbon fiber

Jafar MM et a. BJR. 89 (2016)
Personnel training

• MR safety is a new paradigm to majority of RT staff

• All RT staff (physician, physicists, residents, dosimetrists, therapists, nurses etc.) has an annual MR safety training (level I training)

  • Included in the onboarding process for new hires and trainees

• Personnel work in zones 3 and 4 receive extensive training (level II training):

  • Competency evaluation before work unaccompanied

<table>
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<tr>
<th>Category</th>
<th>Competency</th>
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<td>Document 12 Hours</td>
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<td></td>
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</tr>
<tr>
<td># of hours =</td>
<td></td>
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</tr>
</tbody>
</table>
Personnel training

• Training and coordination:
  • housekeeping and facilities
  • fire and police department

• Policy and procedure:
  • written policies and procedures must be developed and enforced
  • reviewed and updated frequently
  • emergency response procedures (code, fire, quench...)

Police officer has service gun wrenched from his hand by MRI machine while responding to burglary in medical center

By SNEJANA FARBEROV
PUBLISHED: 12:42 EST, 9 February 2013 | UPDATED: 12:44 EST, 9 February 2013
MR Safety Incident Report

• ACR guideline 2013:
  • MR safety incidents, or ‘near incidents” to be reported to the medical director in a timely manner

• RO•ILS (Radiation Oncology Incident Learning System) used in our department to report MR safety incident
  • Patient related incident reviewed within 24 hours
  • Process improvement reviewed during weekly quality meeting
Resources

- ACR MRI safety website
- FDA MRI safety website
- http://www.mrisafety.com/
- ASTM Standards F2052, F2119, F2181 and F2213

Do you forget your radiology colleagues!
Summary

- MR safety is one of the major challenges in incorporating MRI in RT workflow

- Develop a RT specific MR safety program:
  - site planning, access restriction and screening
  - device/equipment safety commissioning process
  - comprehensive policy/procedures with periodic review and update
  - consistent and continuous vigilant personnel training

- Close collaboration and cross-training with diagnostic physicists
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