Integration of MR in Radiation Therapy: Practical Safety Considerations

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David Geffen School of Medicine

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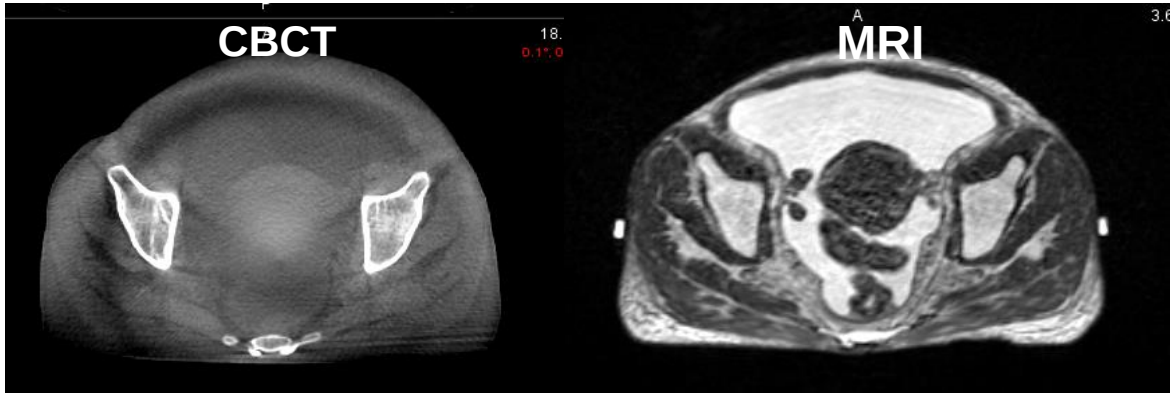
Learning objectives

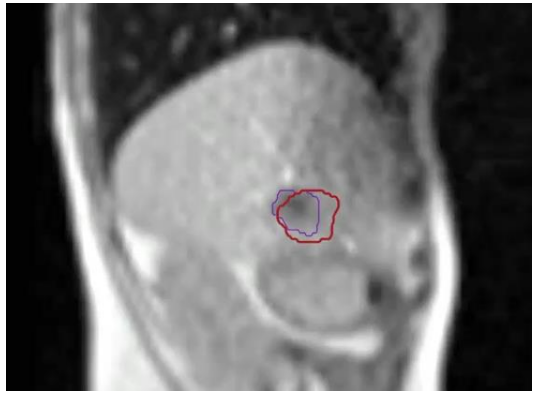
- Describe general development and special requirements for MR guided radiotherapy
- Identify the safety challenges of integration of MRI into radiation therapy workflow
- Describe the strategies and references for establishing a MR safety program in radiation therapy

Advantage of MR guided RT (MRgRT)

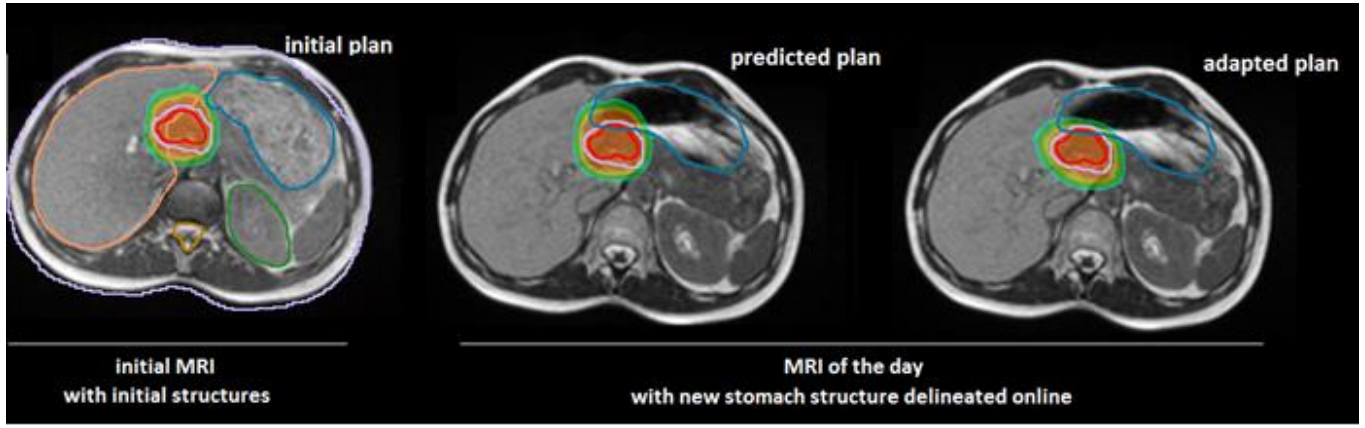
Patient Setup



Treatment Gating

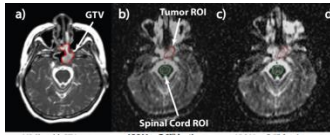


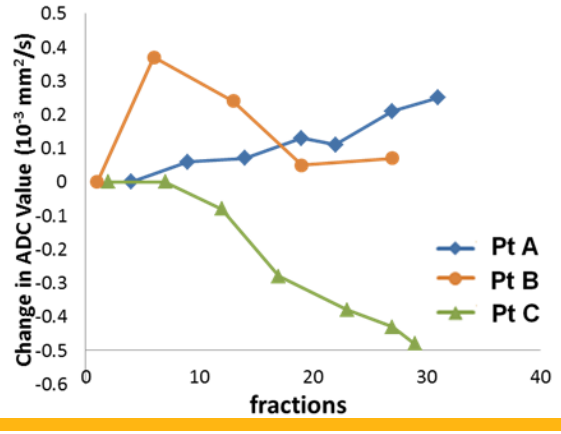
Adaptive planning



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

Functional imaging





Yang Y et al. Med Phys 43(3),2016

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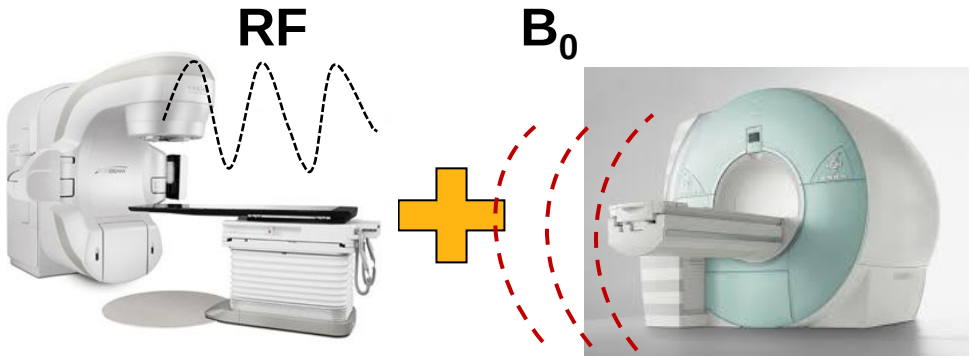
Challenges of integration of MRI with Linac

- 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



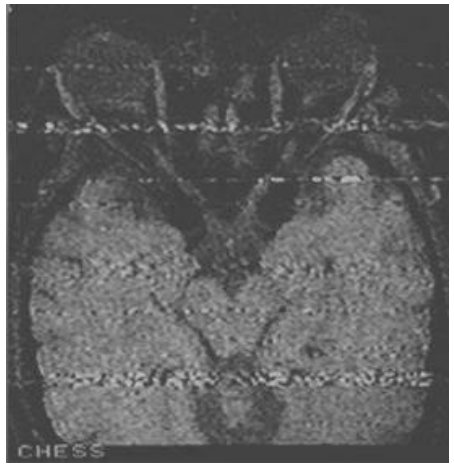
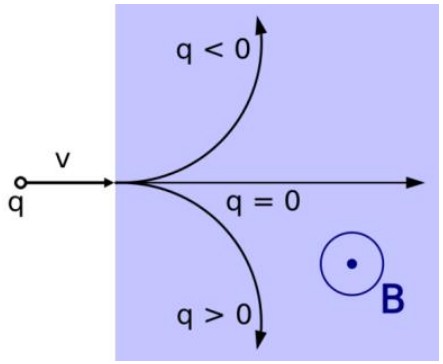


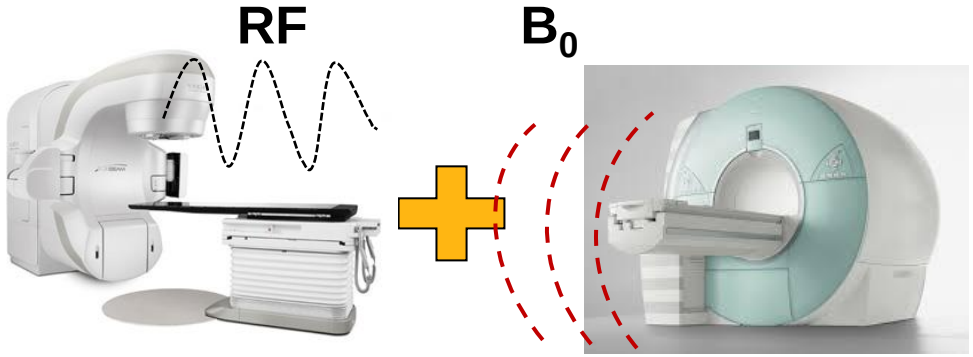
Image from Radiopaedia.org

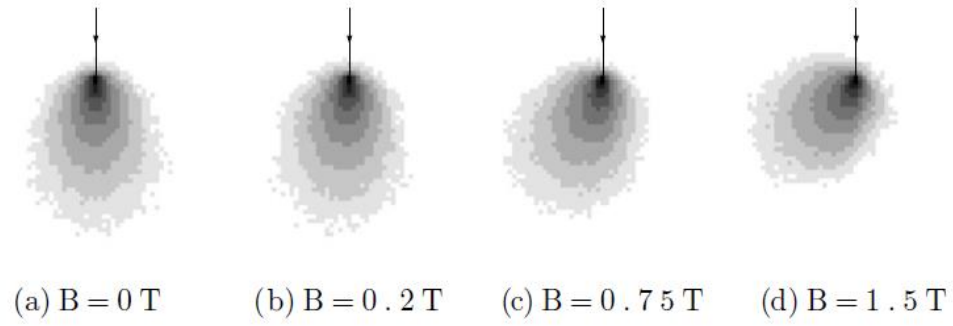
Challenges of integration of MRI with Linac

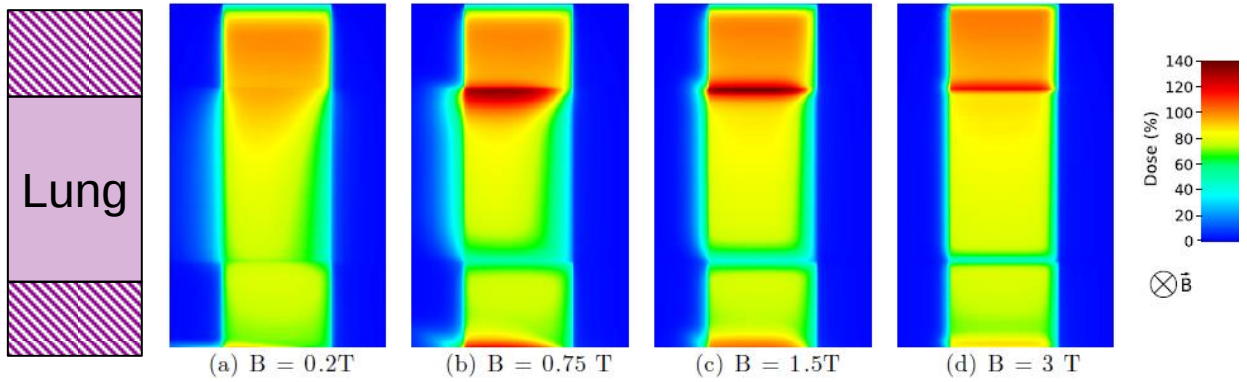
- Magnetic field interference
  - Asymmetric dose kernel
  - Electron return effect



Lorentz force



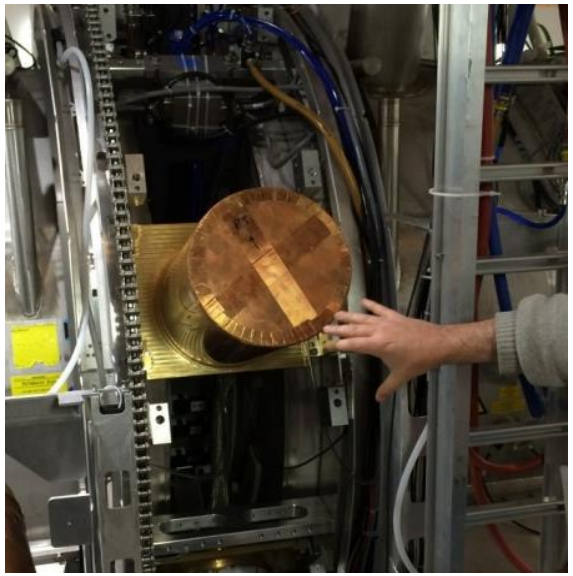


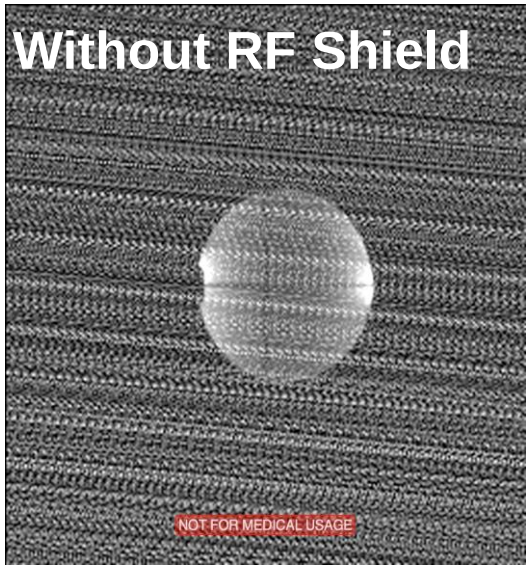


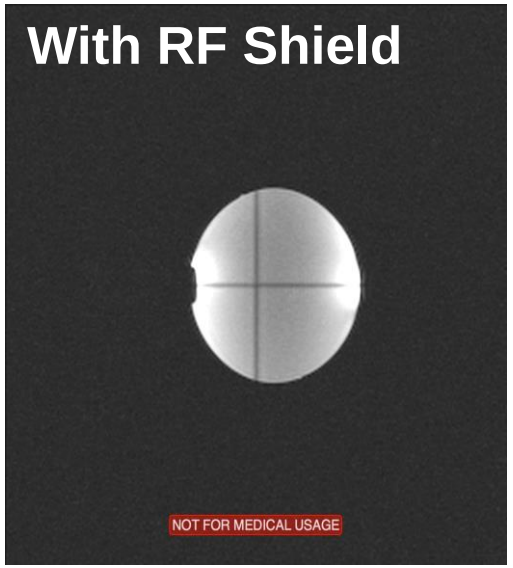
Raaijmakers et al. PMB. 53 (2008)

Strategies of integration of MR with Linac

- Radiofrequency (RF) interference
  - shielding of RF components



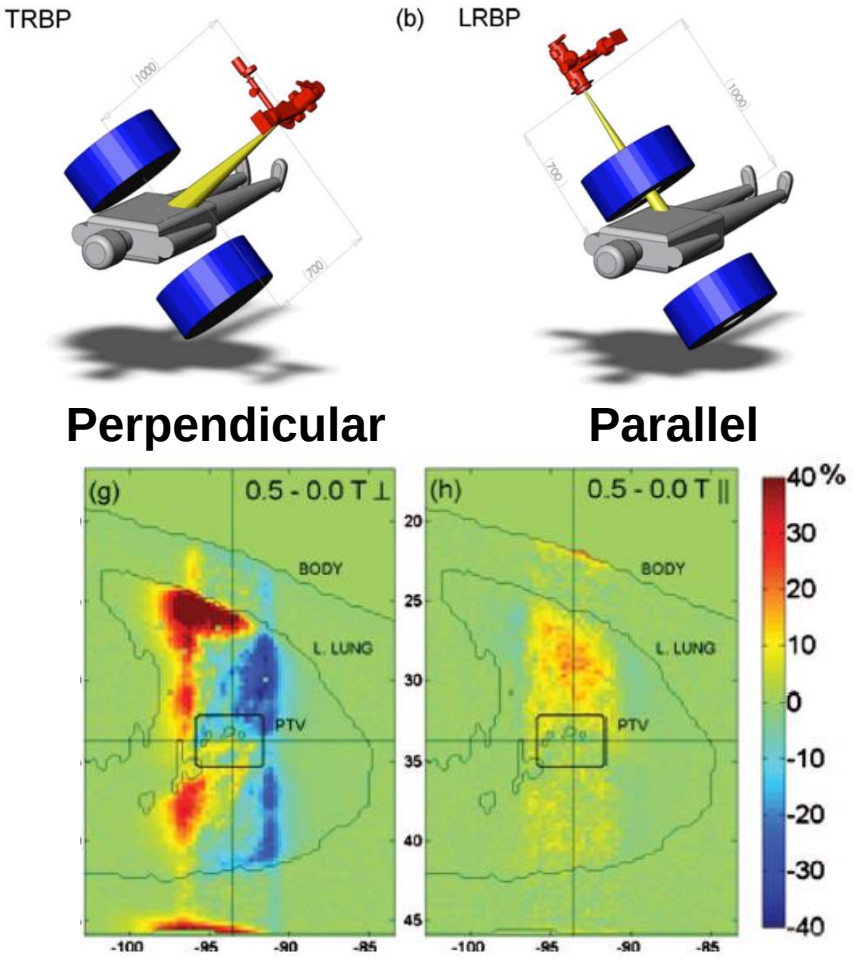




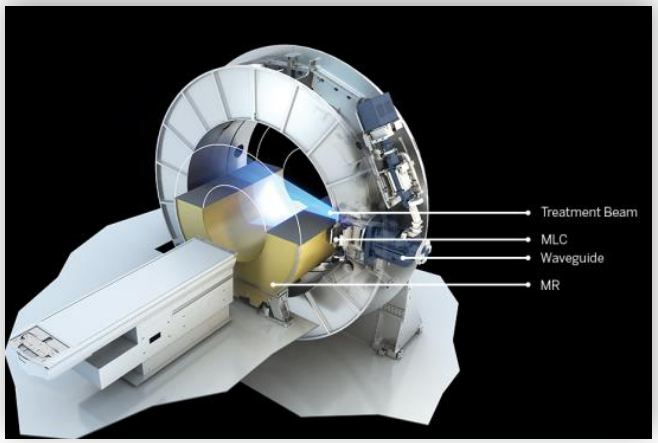
Courtesy of ViewRay Inc.

Strategies of integration of MR with Linac

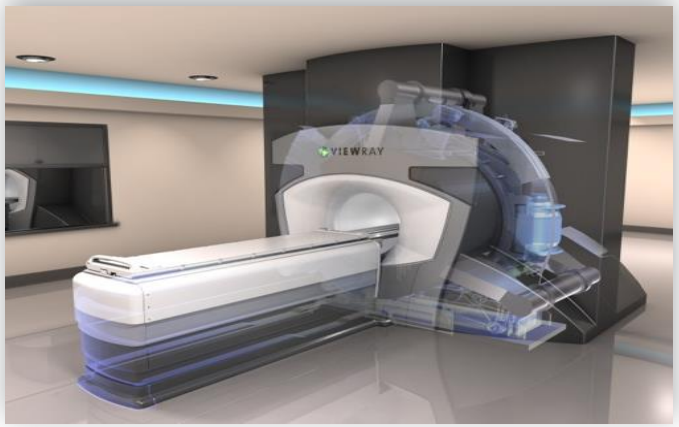
- Magnetic field interference
  - Lower magnetic strength
  - Active magnetic shielding
  - Align beam direction with magnetic field
  - Compensate through planning optimization



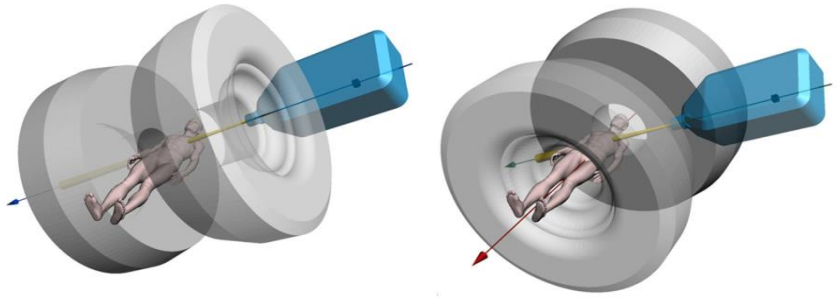
Kirkby *et al.*: Medical Physics, V37(9), 2010



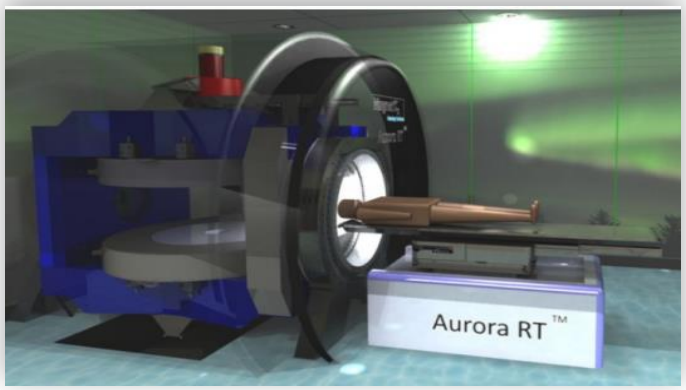
Elekta MRI-Linac Unity™ (1.5T)



ViewRay MRIdian (0.35T)



The Australian MRI-Linac program (1.0T)

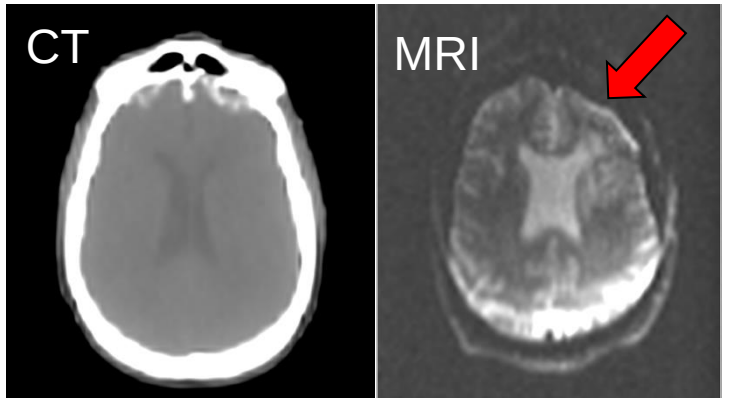


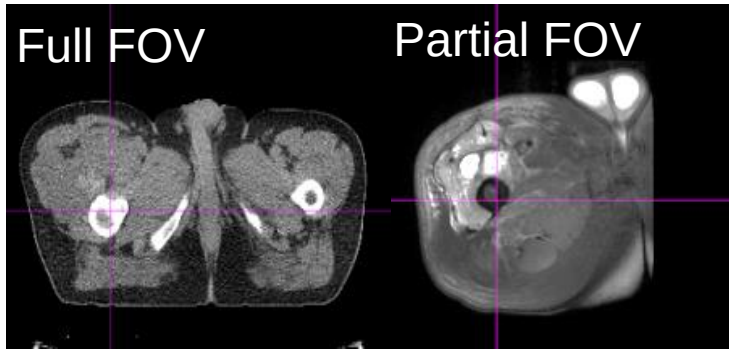
MagentTx Aurora-RT™ (0.5T)

MRgRT system	Radiation	Magnet field		
		Configuration	Orientation	Strength
ViewRay MRIdian Linac	6 MV	split superconducting close bore	Perpendicular	0.35 T
MagnetTx Aurora RT	6 MV	superconducting rotating open bore	Parallel	0.5 T
Australian MRI-Linac	6 MV	superconducting open bore	Parallel/ Perpendicular	1.0 T
Elekta Unity	7 MV	superconducting close bore	Perpendicular	1.5 T

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





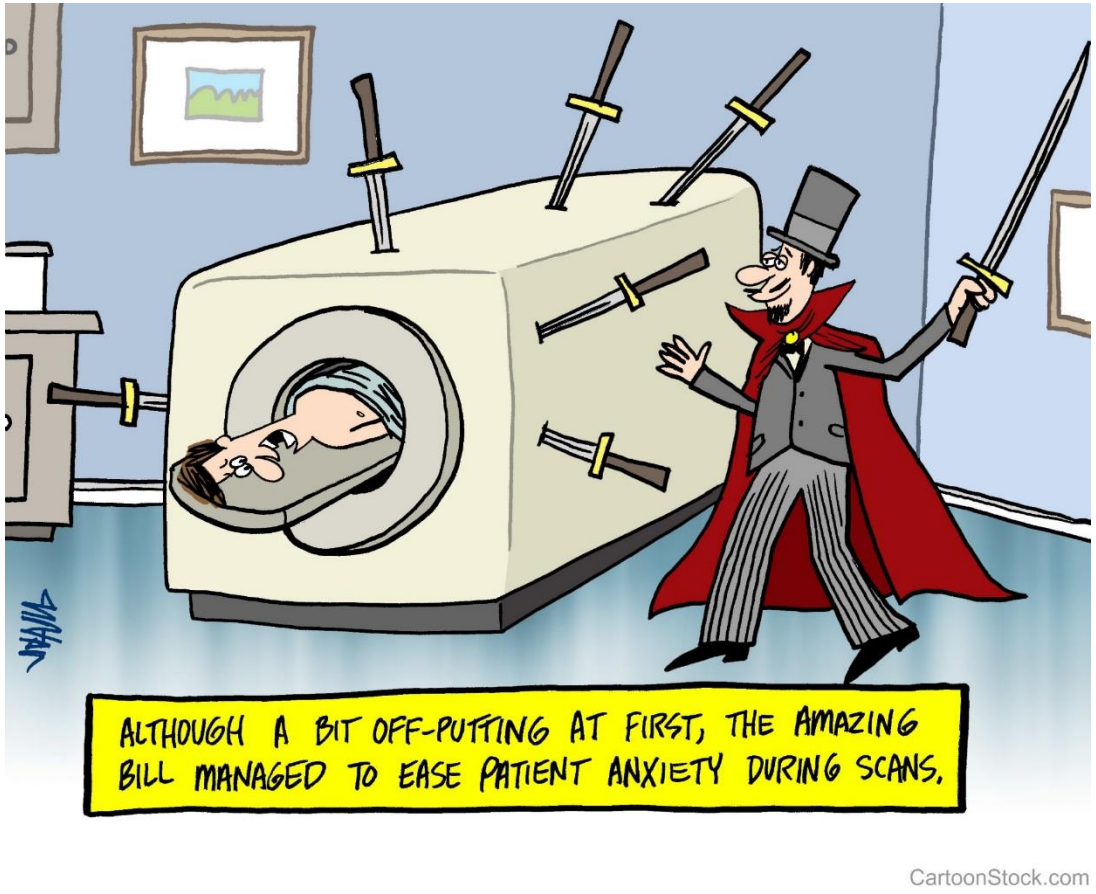
RT specific MR imaging sequences are required

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

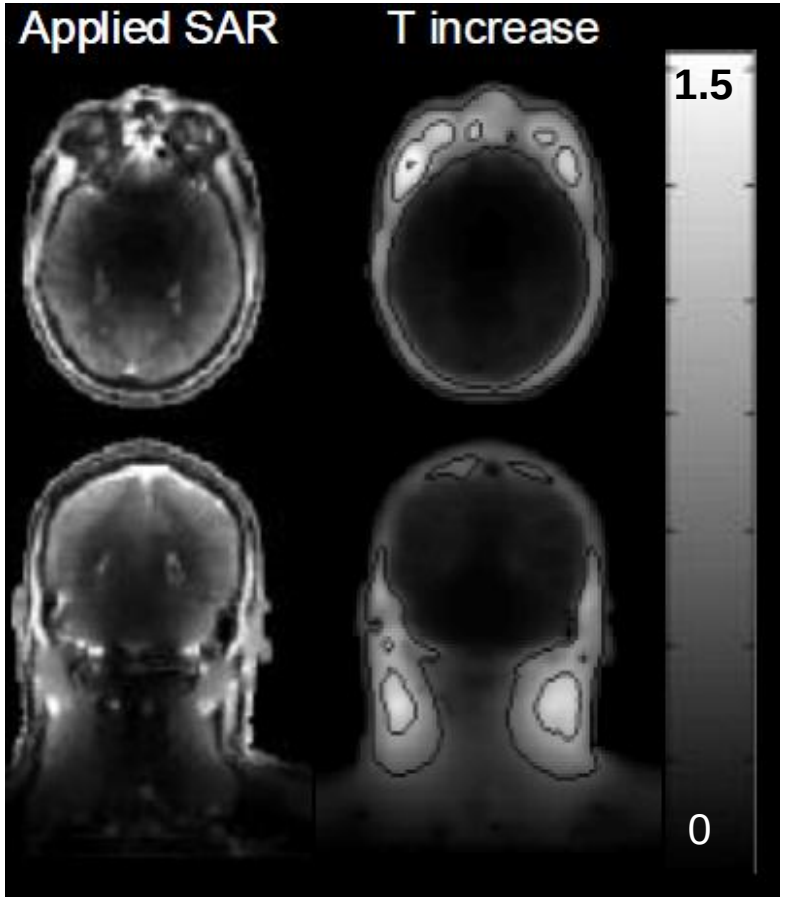
- Interfere with:
  - Medical equipment and devices
  - Implanted devices (passive and active)
  - Neighboring equipment/machine
- Strategies:
  - Site access restriction
  - Patient and personnel screening
  - Device and object labeling



CartoonStock.com

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



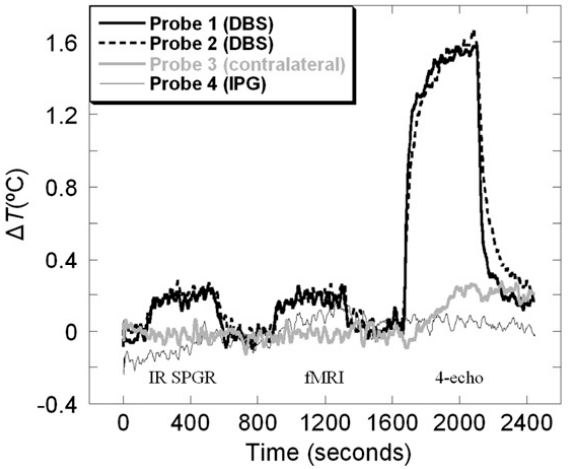
CM Collins *et al*., JMRI 19:2004

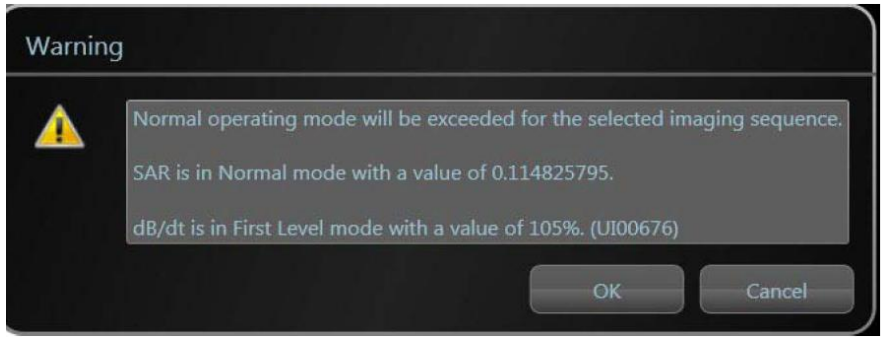
RF induced thermal effect - SAR

- 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 $\propto B_0^2 \times (\text{flip angle})^2 \times (RF\ duty\ cycle)$
  - 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





Limit	Whole-Body Average	Heat Average	Head, Trunk Local SAR	Extremities Local
IEC (6-minute average)				
Normal (all patients)	2 W/kg (0.5°C)	3.2 W/kg	10 W/kg	20 W/kg
First level (supervised)	4 W/kg (1°C)	3.2 W/kg	10 W/kg	20 W/kg
Second level (IRB approval)	4 W/kg (>1°C)	>3.2 W/kg	>10 W/kg	>20 W/kg
Localized heating limit	39°C in 10 g	38°C in 10 g		40°C in 10 g
FDA	4 W/kg for 15 min	3 W/kg for 10 min	8 W/kg in 1g for 10 min	12 W/kg in 1g for 5 min

Bottomley, J J Am Coll Radiol. 2008

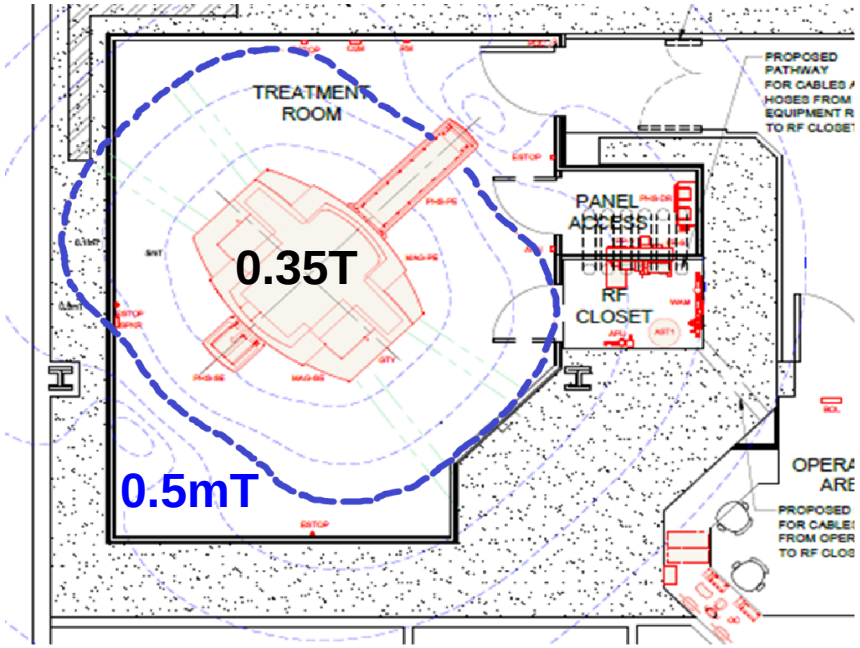
Gorny KR et al. MRI 31(5), 2013

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-Gauss** should be clearly marked as being potentially hazardous.



Impact of fringe field on neighboring machines

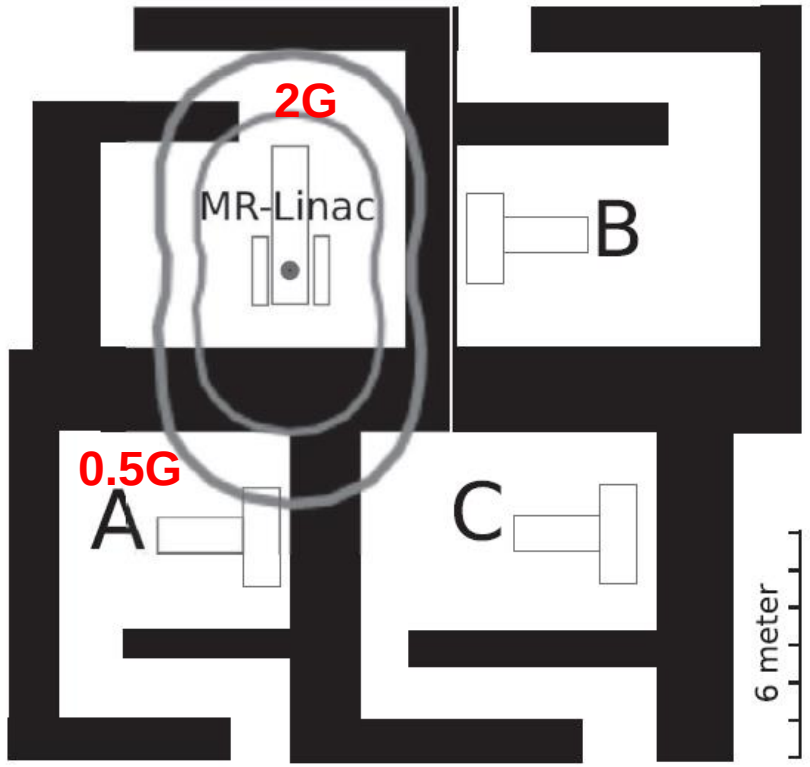
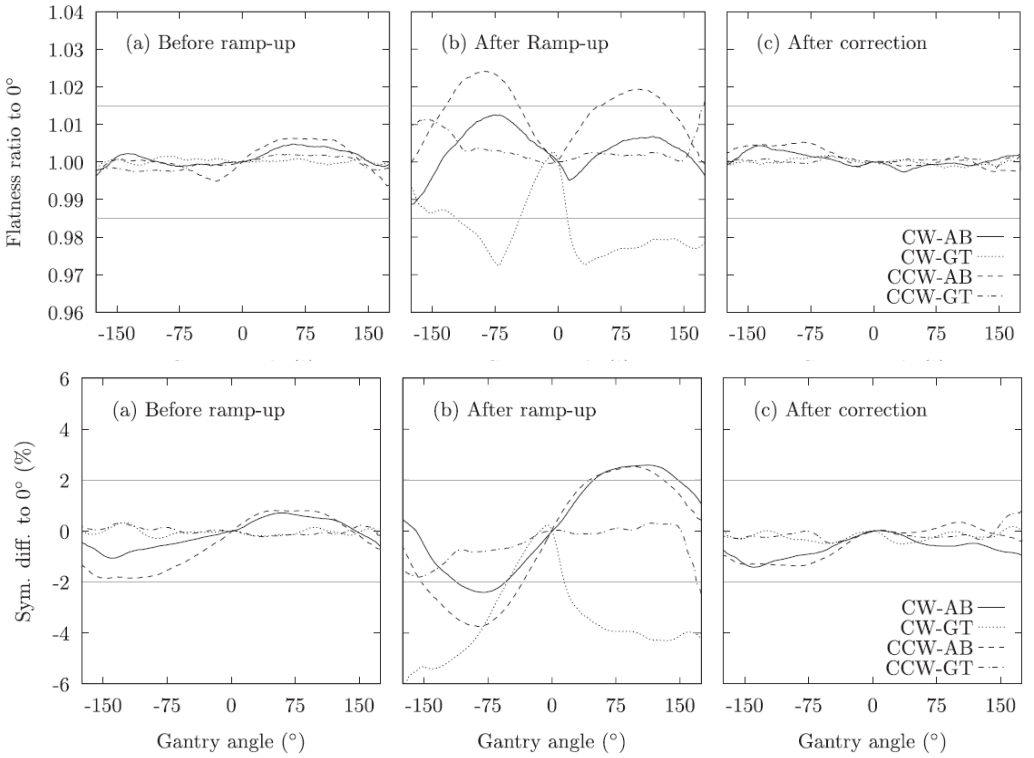
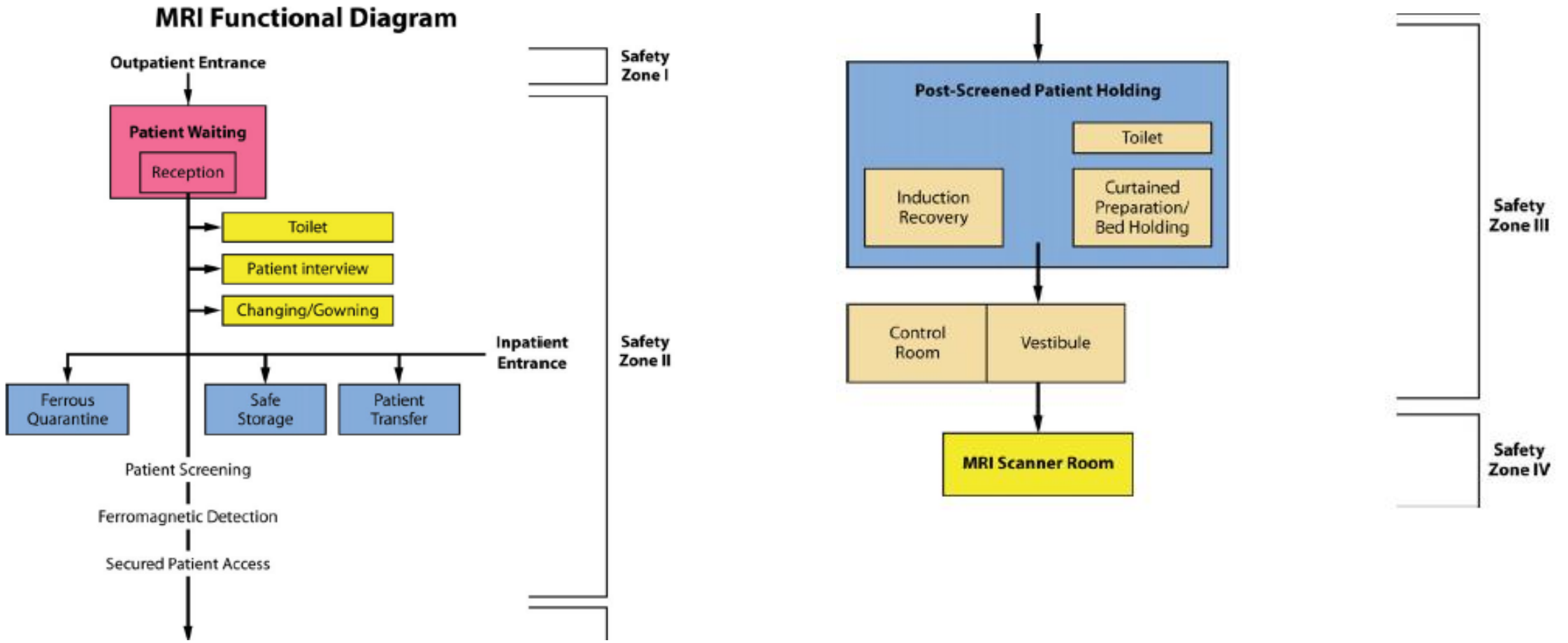


Fig. 1. Layout of the treatment rooms. The MR-Linac is installed in the upper left corner and surrounded by 3 standard linear accelerators, A, B and C at distances of respectively, 7.5, 5.5 and 11 m. The displayed Gauss lines are 0.5 G (Outer) and 2 G (Inner), and are taken from the vendor specifications.

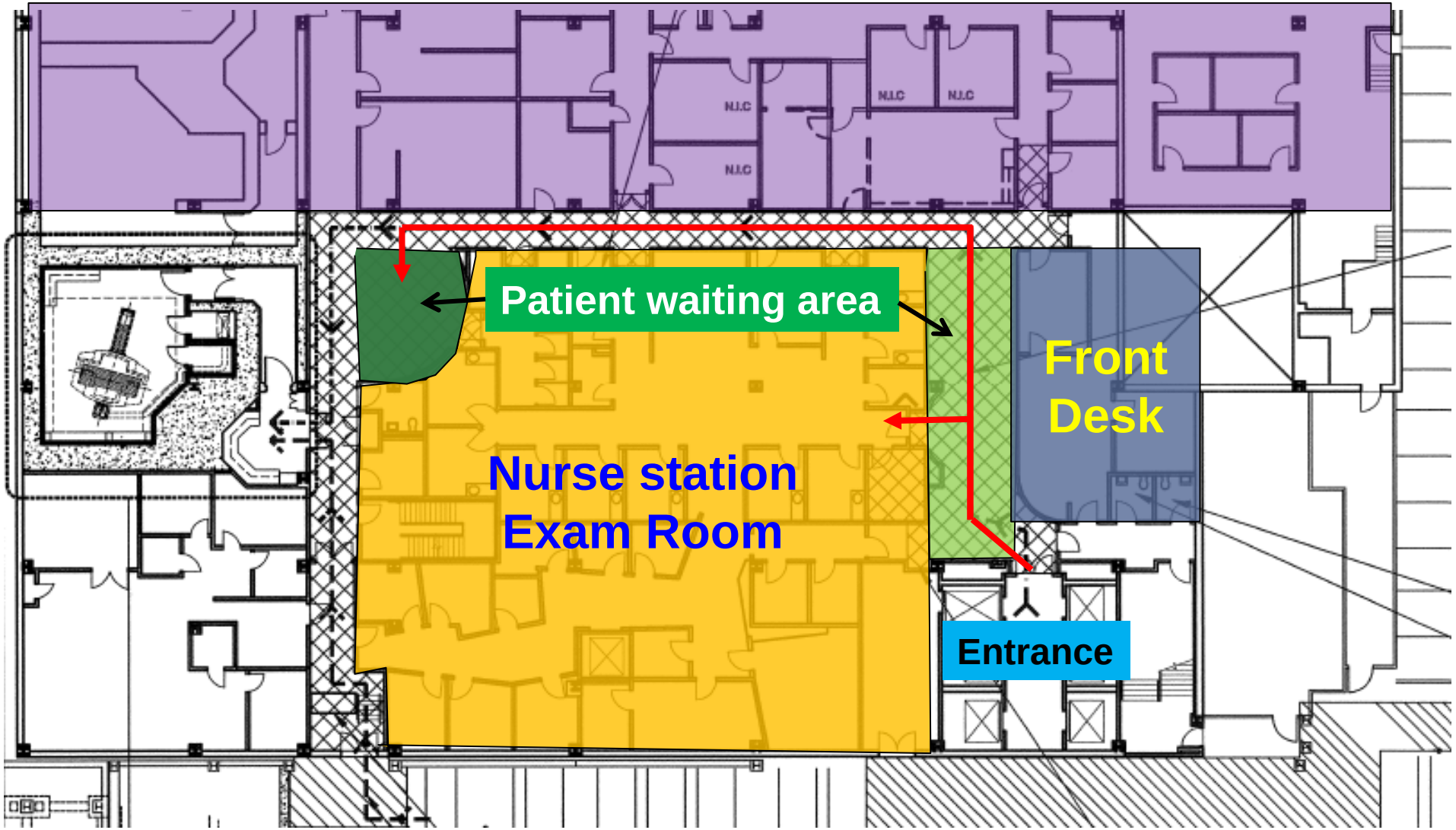


Up to **4% change** in beam symmetry/flatness was observed for Linac A after 1.5T magnet ramp up

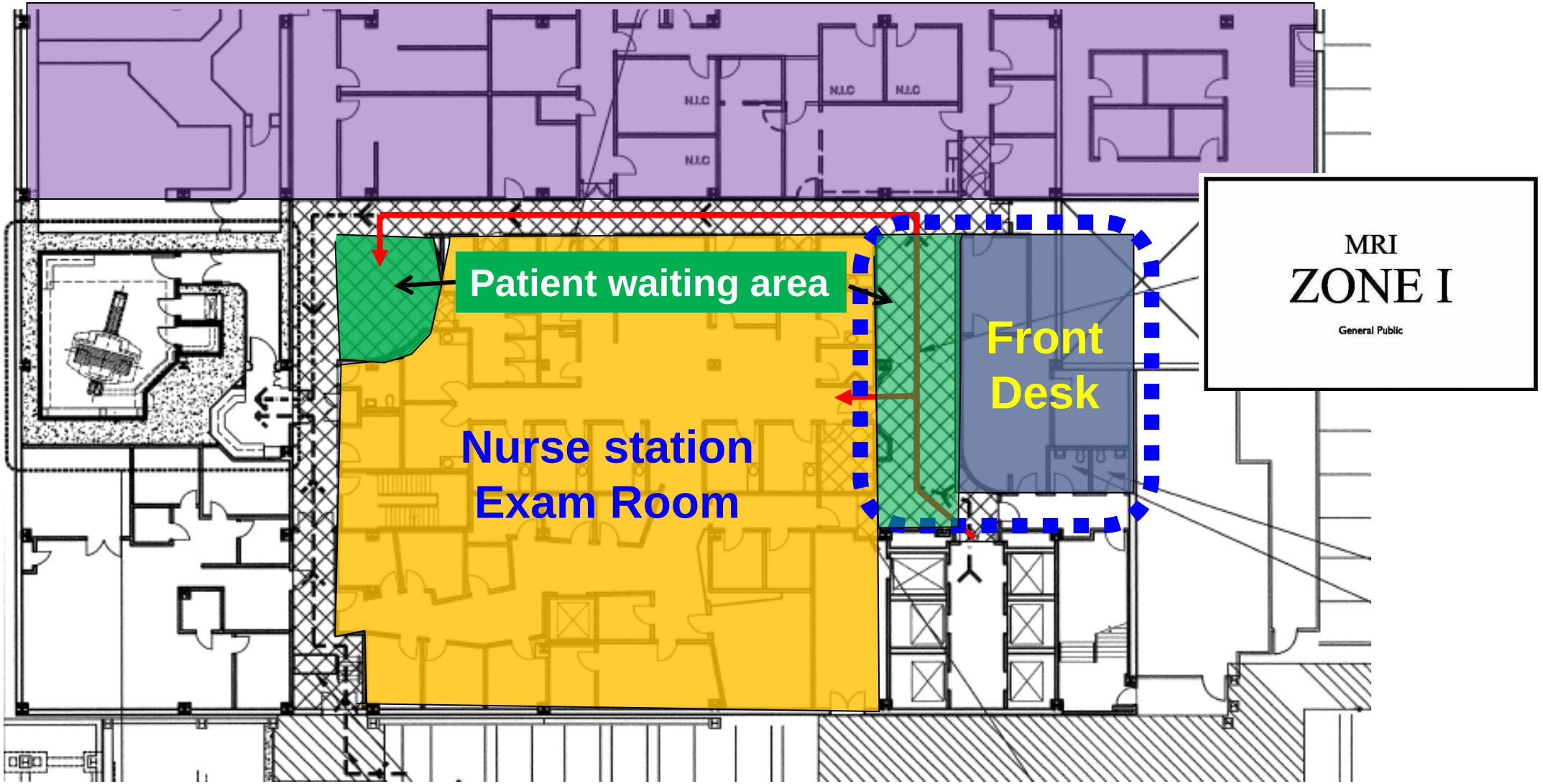
Site access restriction



ViewRay Vault



ViewRay Vault



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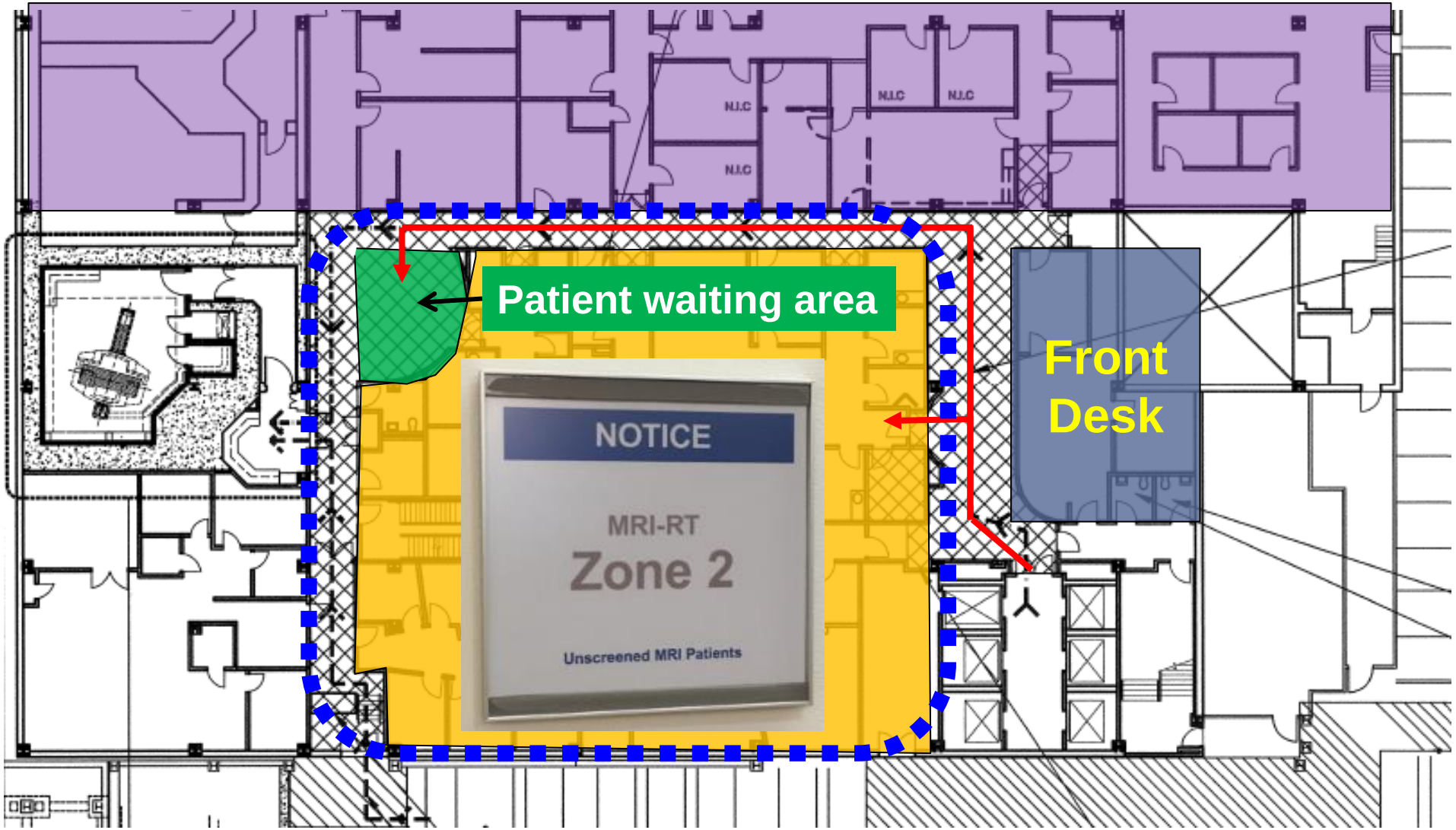

ViewRay Vault

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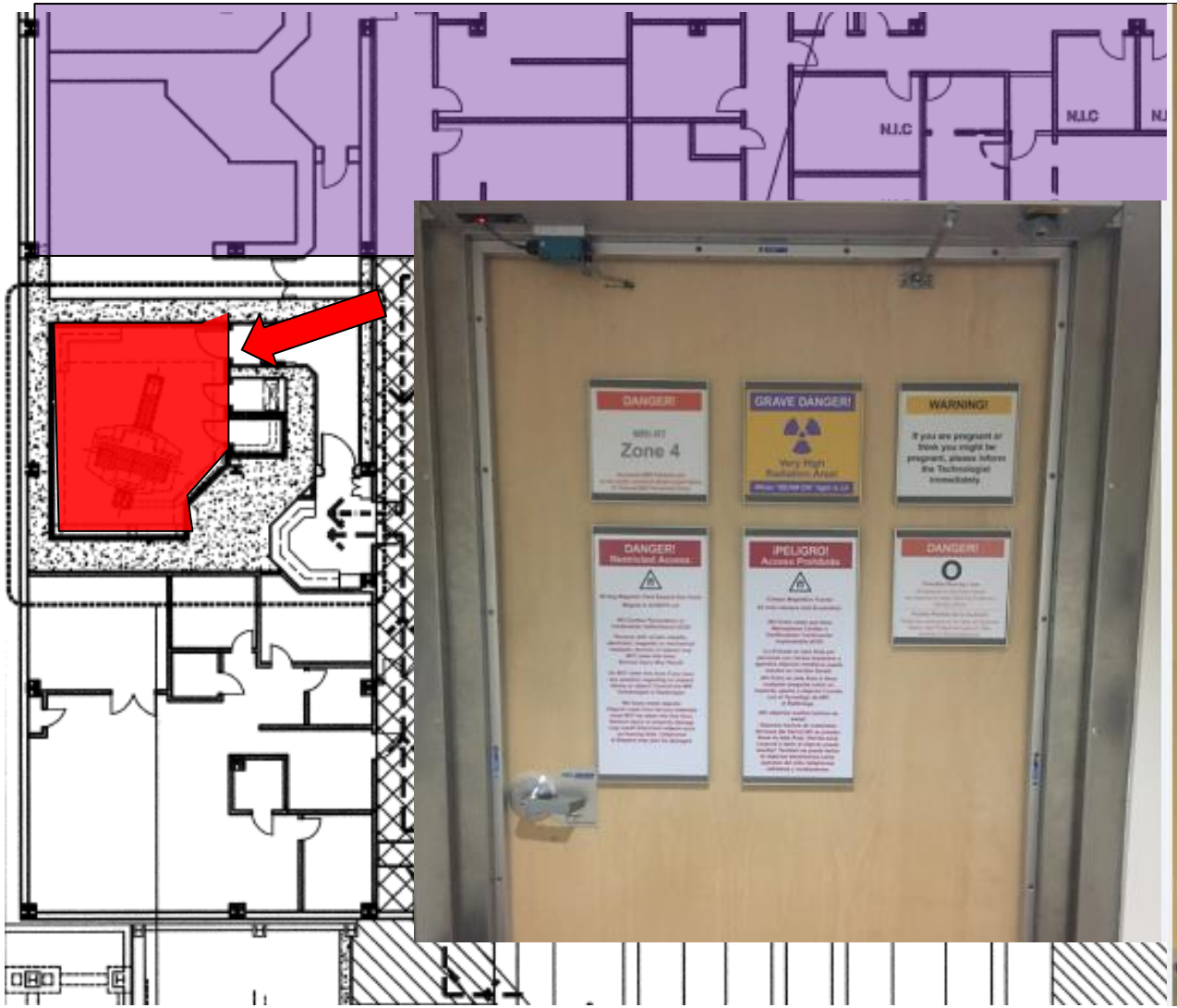
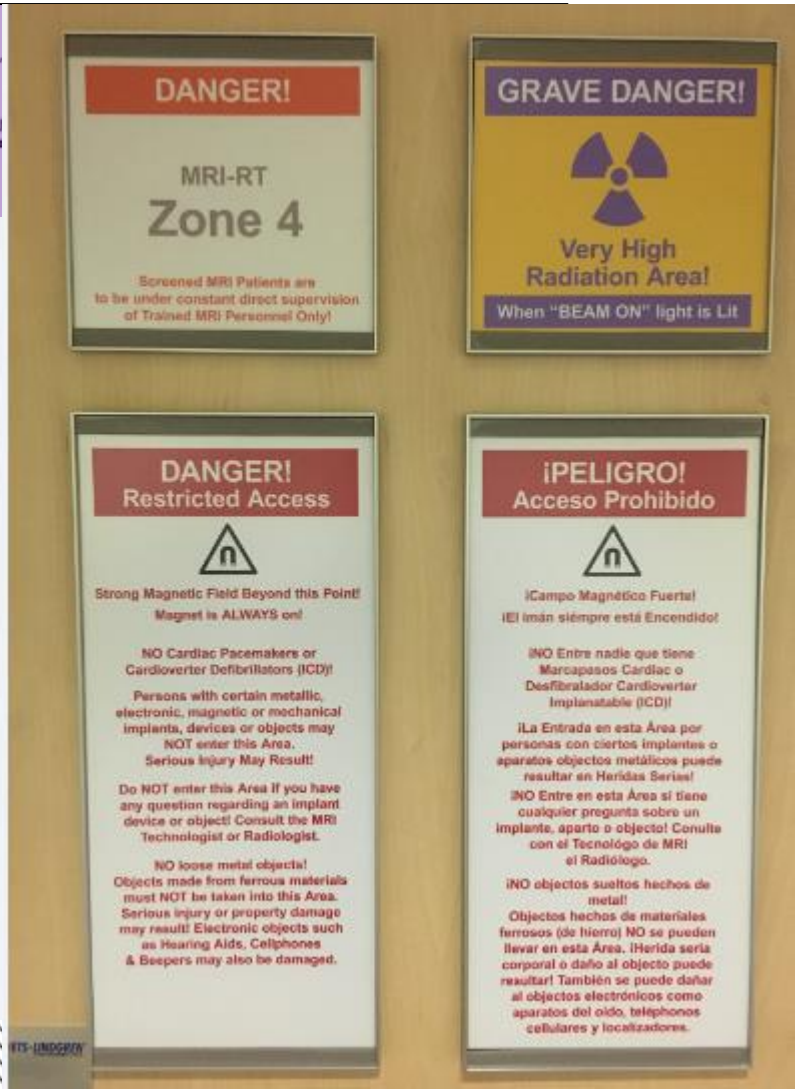




Patient MR safety screening

- 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.

UCLA Health System

MRI SAFETY SCREENING QUESTIONNAIRE – UC EMPLOYEES AND OTHER INDIVIDUALS / VISITORS

NAME:_____ DATE OF BIRTH:_____

EMPLOYEE ID:_____ DEPT:_____

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

WARNING: Certain implants, devices, or objects may be hazardous in the MR environment or MR system room. DO NOT ENTER the MR environment (Zone 3) or MR 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	NO		YES	NO	
☐	☐	Aneurysm clip(s)	☐	☐	Spinal cord stimulator
☐	☐	Cardiac pacemaker	☐	☐	Insulin or infusion pump
☐	☐	Implanted cardioverter defibrillator/ICD	☐	☐	Implanted drug infusion pump
☐	☐	Electronic implant or device	☐	☐	Neurostimulation system
☐	☐	Magnetically-activated implant or device	☐	☐	Any type of prosthesis or implant
☐	☐	Artificial or prosthetic limb	☐	☐	Hearing aid(s)
☐	☐	Any metallic fragment or foreign body	☐	☐	Other implant_____
☐	☐	Any external or internal metallic object	☐	☐	Other device_____
☐	☐	Ear (Cochlear) implant, implanted hearing aid			
☐	☐	Eye injury with a metallic object (e.g., metallic silvers, foreign body)			
☐	☐	Injury by a metallic object or foreign body (e.g., BB, bullet, shrapnel, etc)			

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

If you answered YES to any of these questions, you are required to obtain specific clearance from the MRI Technologist or Radiologist on service before you can enter the MR environment.

I attest the above information is correct to the best of my knowledge. I have read and understand the entire contents of this form and I have had the opportunity to ask questions regarding the information on this form.

Signature of Employee or Visitor :_____ Date_____
Signature

Reviewed By:_____ _____ Date_____
Print Name Signature

☐ MRI Technologist ☐ MRI Assistant ☐ Radiologist

UCLA Health System

MRI SAFETY SCREENING QUESTIONNAIRE (OUTPATIENTS)

Sex:_____ Age:_____ Height:_____ Weight:_____

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

YES	NO	
☐	☐	Cardiac pacemaker or implanted cardioverter defibrillator/ICD
☐	☐	Internal electrodes or wires (pacing wires, DBS or VNS wires)
☐	☐	Artificial heart value, coil, filter and/or stent (Gianturco coil, IVC filter)
☐	☐	Aneurysm clip(s)
☐	☐	Neurostimulator-TENS Unit, Biostimulator, bone growth stimulator, DBS, VNS
☐	☐	Implanted drug pump (for chemotherapy medicine, pain medicine)
☐	☐	External drug pump (for Insulin or other medicine)
☐	☐	IV access port (Port-a-Cath, Broviac, PICC line, Swan-Gantz, Thermodilution)
☐	☐	Implanted post surgical hardware (pins, rods, screws, plates, wires)
☐	☐	Artificial joint and /or limb
☐	☐	Artificial eye and/or eyelid spring
☐	☐	Eye injury from a metal object (metal shavings, metal slivers)
☐	☐	Ear (Cochlear) implant, middle ear implant
☐	☐	Hearing aid(s)
☐	☐	False teeth/dentures, metallic removable dental work, braces, retainers
☐	☐	Any type of implant held in place by a magnet
☐	☐	Injured by a metal object (shrapnel, bullet, BB) and required medical attention
☐	☐	Medication patch (nitroglycerine, nicotine, contraceptive, estrogen)
☐	☐	Shunt or Sophy adjustable and programmable pressure valve
☐	☐	Spinal fixation device, spinal fusion and/or halo vest, spinal cord stimulator
☐	☐	Surgical clips, staples or surgical mesh
☐	☐	Tissue expander (breast)
☐	☐	Penile implant
☐	☐	Pessary, IUD, Diaphragm
☐	☐	Radiation seeds (cancer treatment)
☐	☐	Body piercing, tattoo or permanent makeup
☐	☐	Wig, hair implants

Do you have a history of:

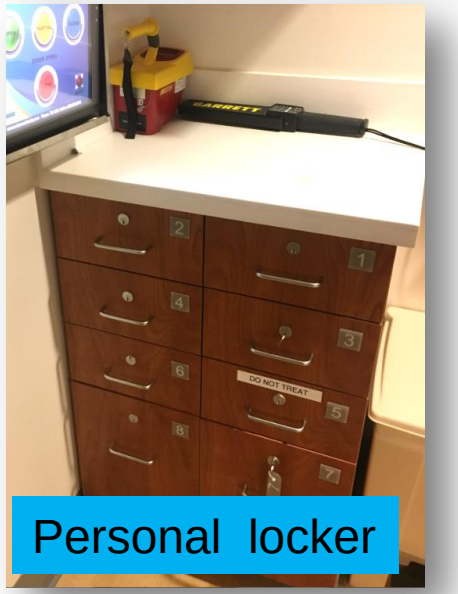
YES	NO		YES	NO	
☐	☐	Kidney disease	☐	☐	Latex Allergy
☐	☐	Diabetes	☐	☐	Allergic reaction to MRI contrast (Gadolinium based)
☐	☐	Liver disease			
☐	☐	Claustrophobia			
☐	☐	Drug Allergy, Type: _____			

Are you on dialysis? ☐ YES ☐ NO If YES, Hemodialysis or Peridialysis? (circle one)

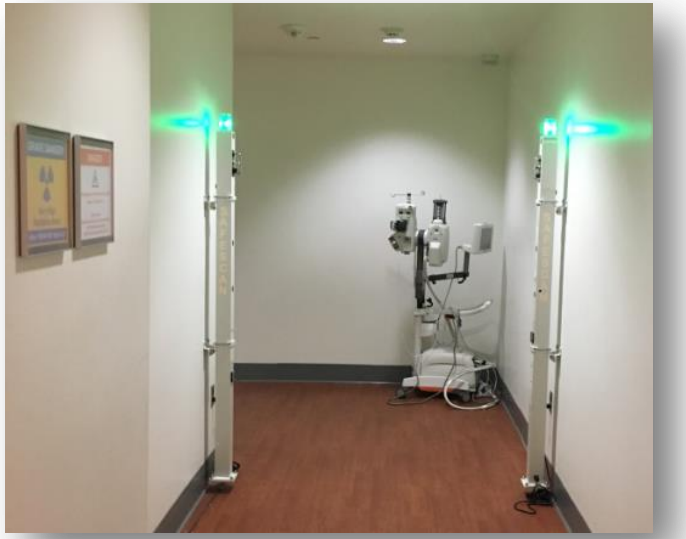
Female Patients:

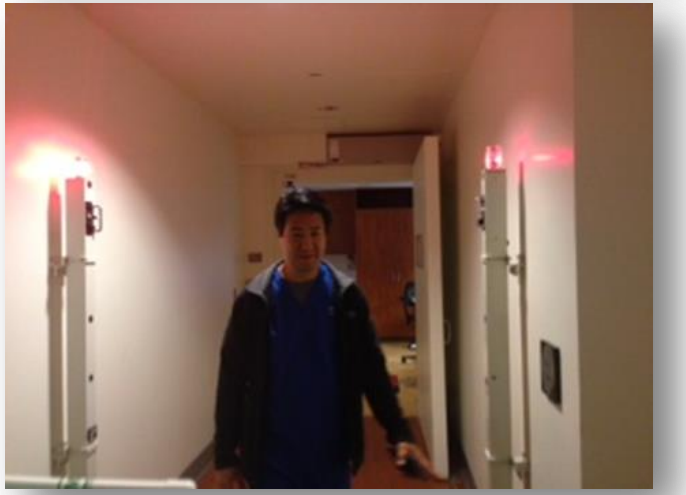
Are you pregnant? ☐ YES ☐ NO Are you breast-feeding ☐ YES ☐ NO

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



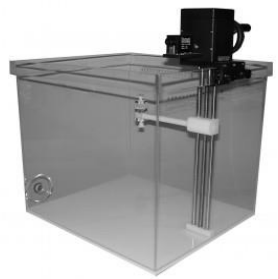
Personal locker





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

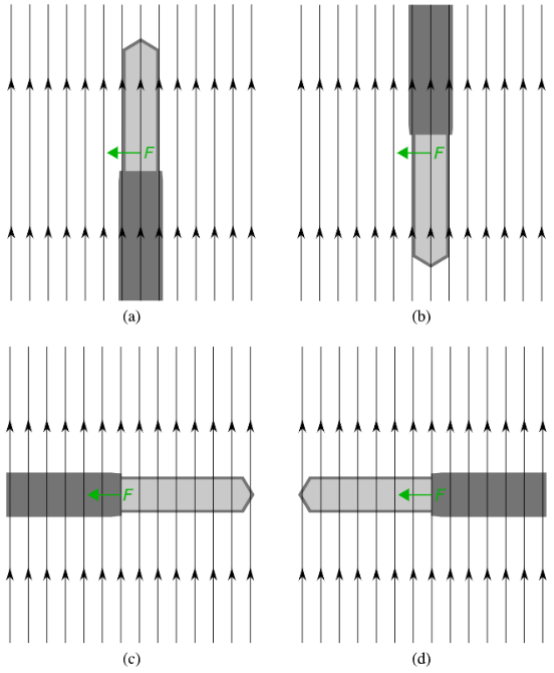
- Image quality: metal artifacts
  - Signal loss from dephasing
  - Susceptibility variations -> Geometric distortion
  - Failure of fat suppression
- Measurement accuracy under magnetic field
- It is important to develop a MR safe commission process for RT QA devices

Device MR safety commission process

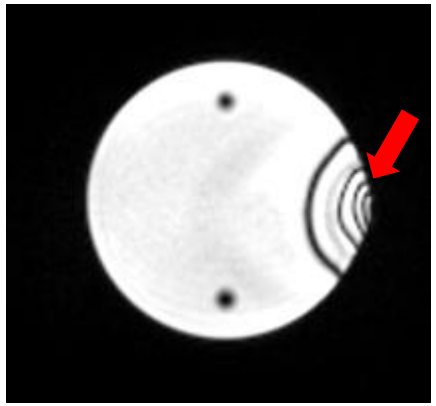
- Identify manufacture and model
- Contact vendor/ online resources – safety label and MR safety sheet
- After receiving the device:
  - check by handheld magnet
  - check electronic components
  - image quality check and dosimetry evaluation
  - label device if not available and document test results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

RT QA devices – Ion Chamber

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

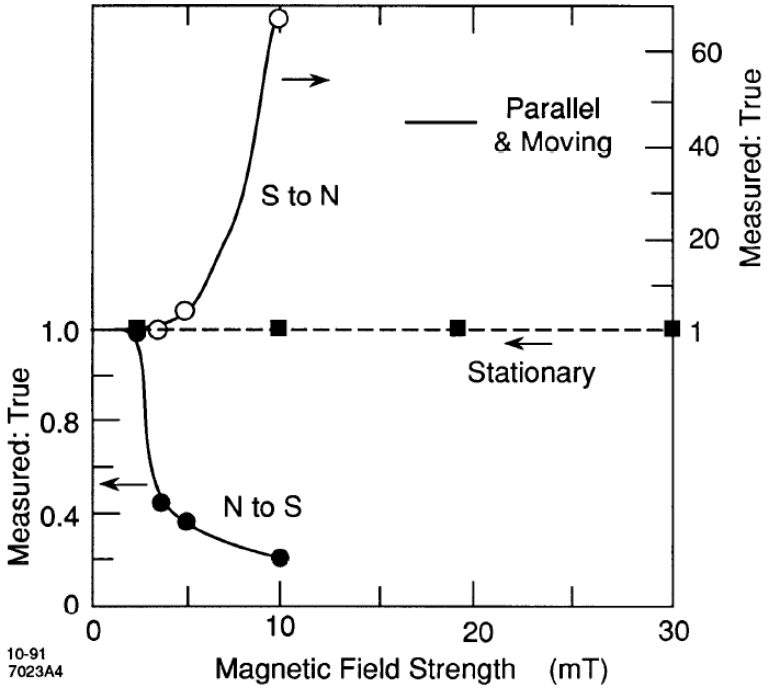


Detector	$k_{B_{\parallel}}^{Q_{msr}}$	$k_{B_{\curvearrowright}}^{Q_{msr}}$	$k_{B_{\curvearrowleft}}^{Q_{msr}}$	Uncertainty (%)
PTW 30013	0.994	0.961	0.976	0.15
PTW 30012[a]	0.992	0.958	0.970	0.25
PTW 30011[a]	1.000	0.958	0.968	0.25
PTW 30010[a]	0.996	0.961	0.975	0.25
NE2571[a]	1.003	0.962	0.973	0.20
NE2571	1.001	0.962	0.973	0.15
Exradin A19	1.005	0.962	0.956	0.25

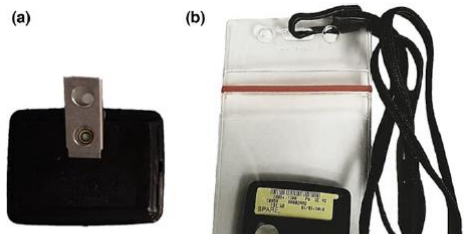


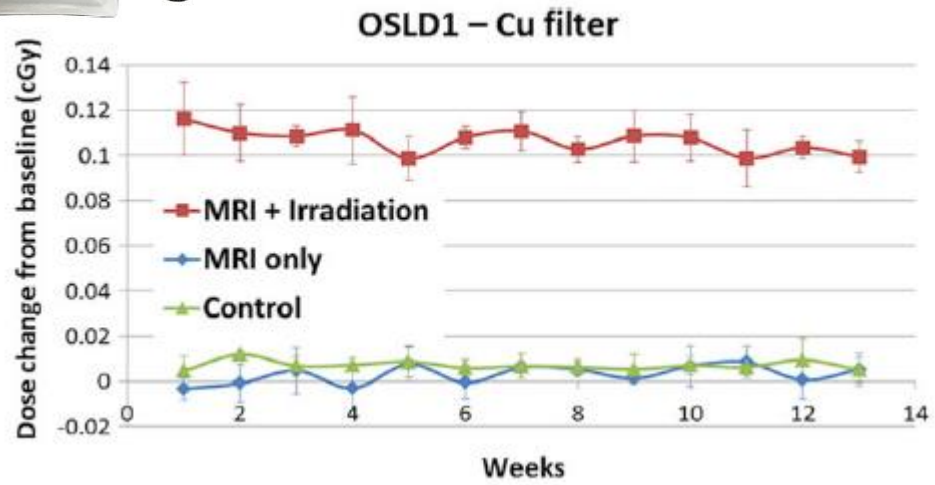
O'Brien et al. Medical Physics, Vol. 43(8), 2016

RT QA devices – Survey Meter/Personal monitor



Liu J et al. Health Phys. 1993. 64(1)





After 3 month MR (3T) exposure, radiation sensitivity of OSLDs was found to be within 5.2±2.4% of the control

TCHISTIAKOVA et al. JACMP 2017; 18:4

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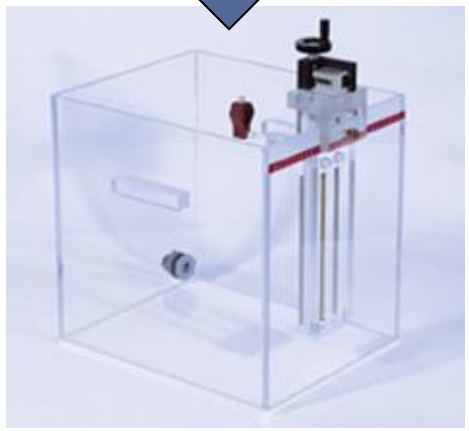
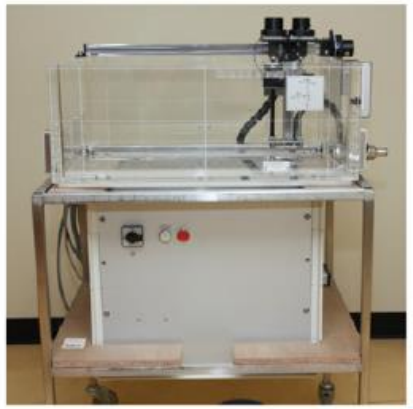
RT QA devices – Water phantom

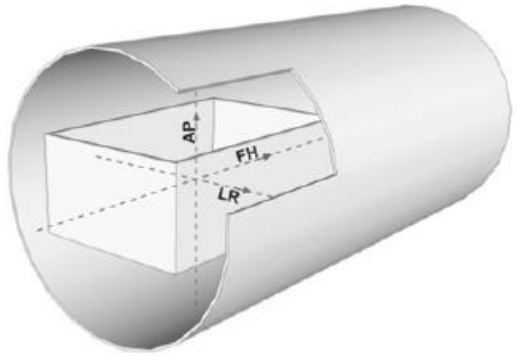


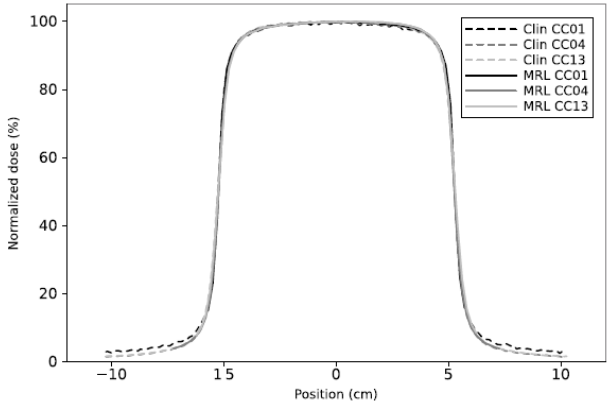


(a)

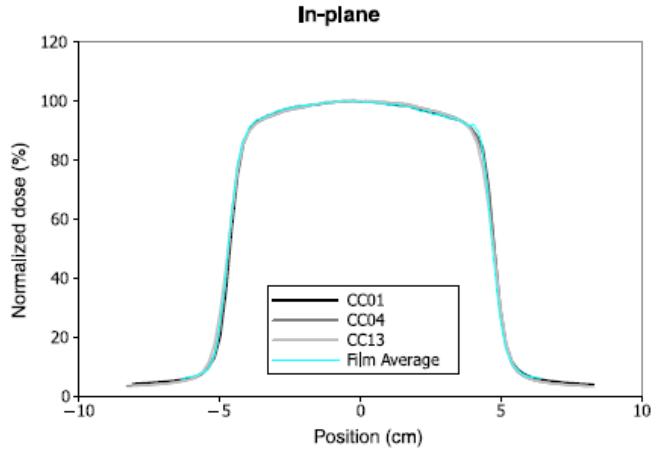
(b)

24(LR) x 40(FH) x 11.5(AP) cm^3





Regular Linac



MR-Linac

Smit J et al. Phys. Med. Biol. 59 (2014)

David Geffen School of Medicine

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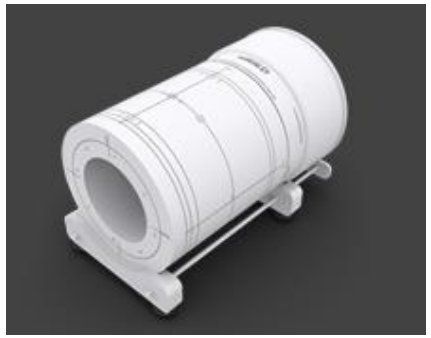
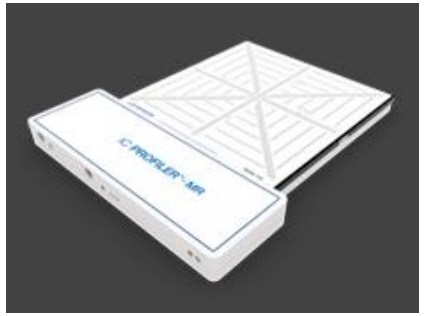
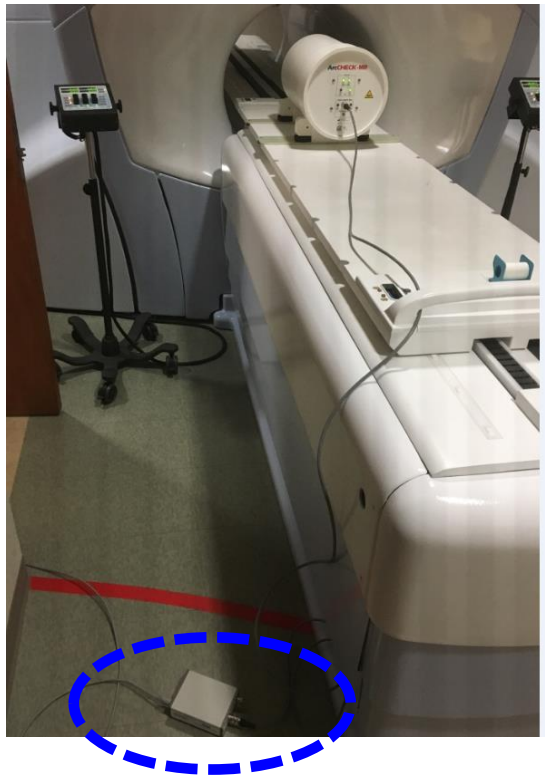
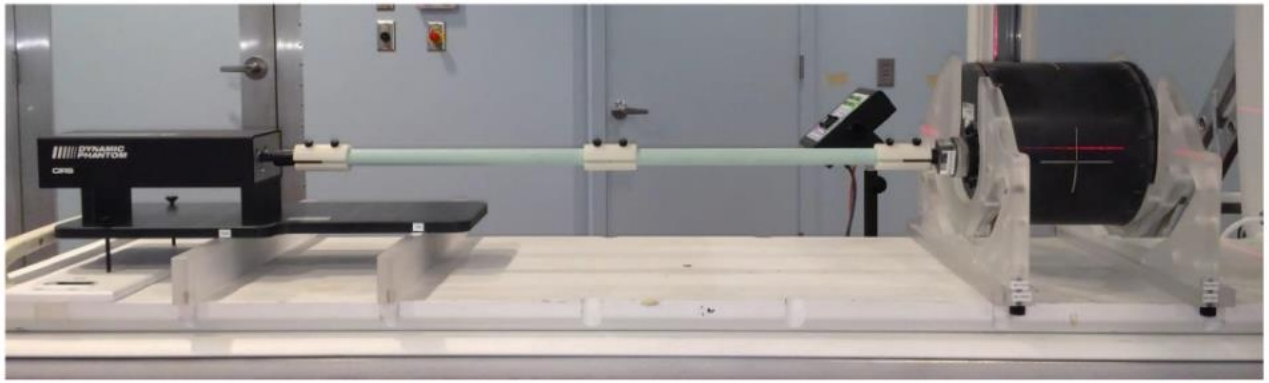
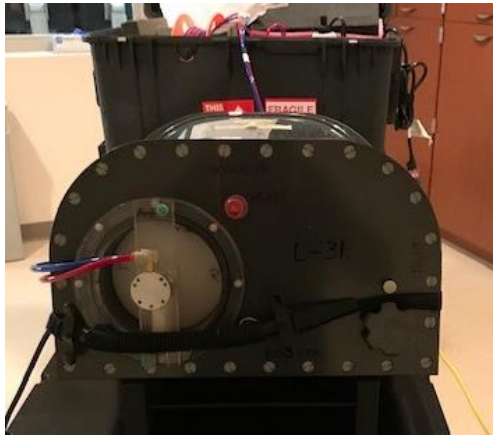
RT QA Devices – dosimetry and motion phantoms



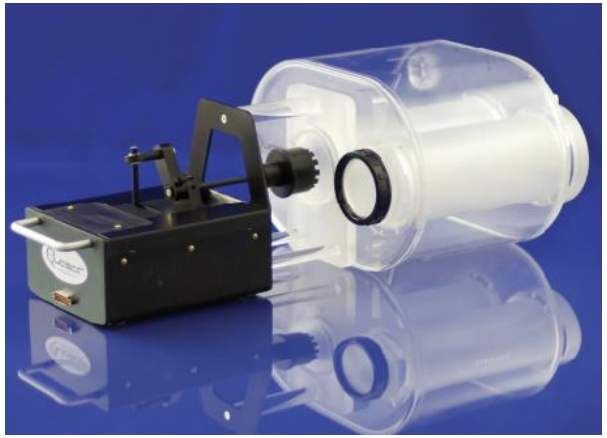








pneumatic



piezoelectric

RT QA Devices – Film

- Radiochromic film: safe and useful for relative dosimetry and QA
- Impact of magnetic field on film dosimetry:

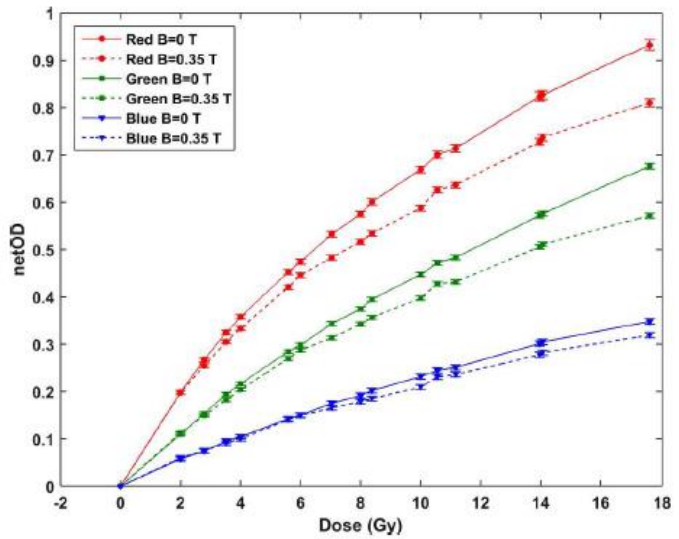
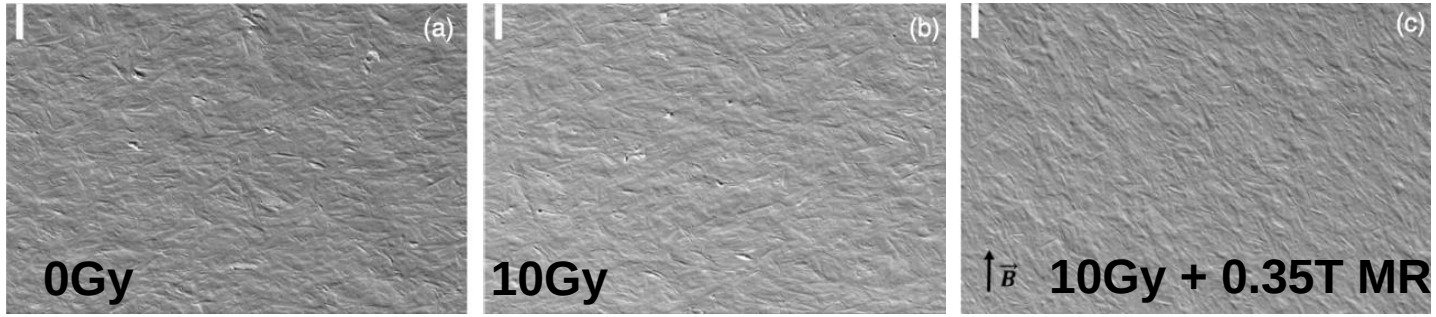


FIG. 1. Net optical density for each individual dose level between 0 and 18 Gy for the red, green, and blue channels shown with and without a magnetic field ($B = 0.35$ T) with dashed and solid line, respectively. (See color online version.)



- 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

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

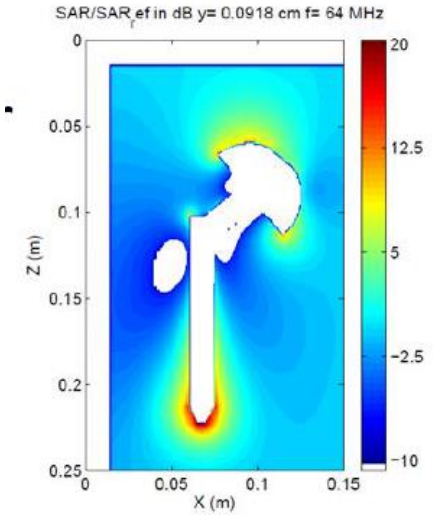
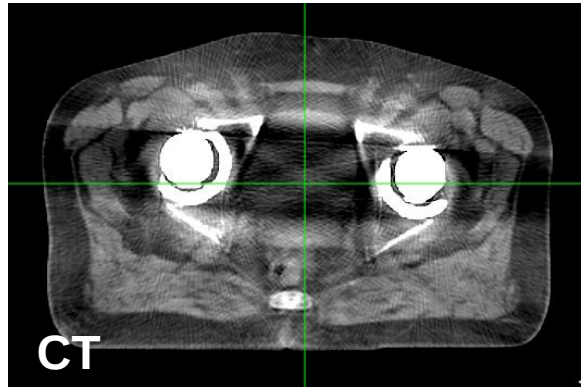
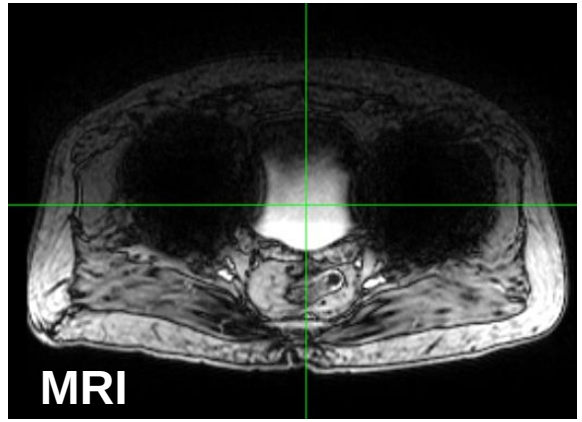


Image from John Nyenhuis

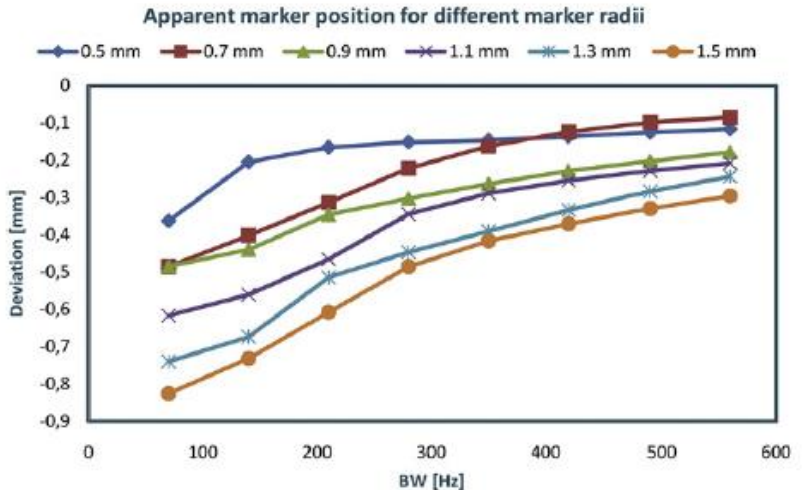




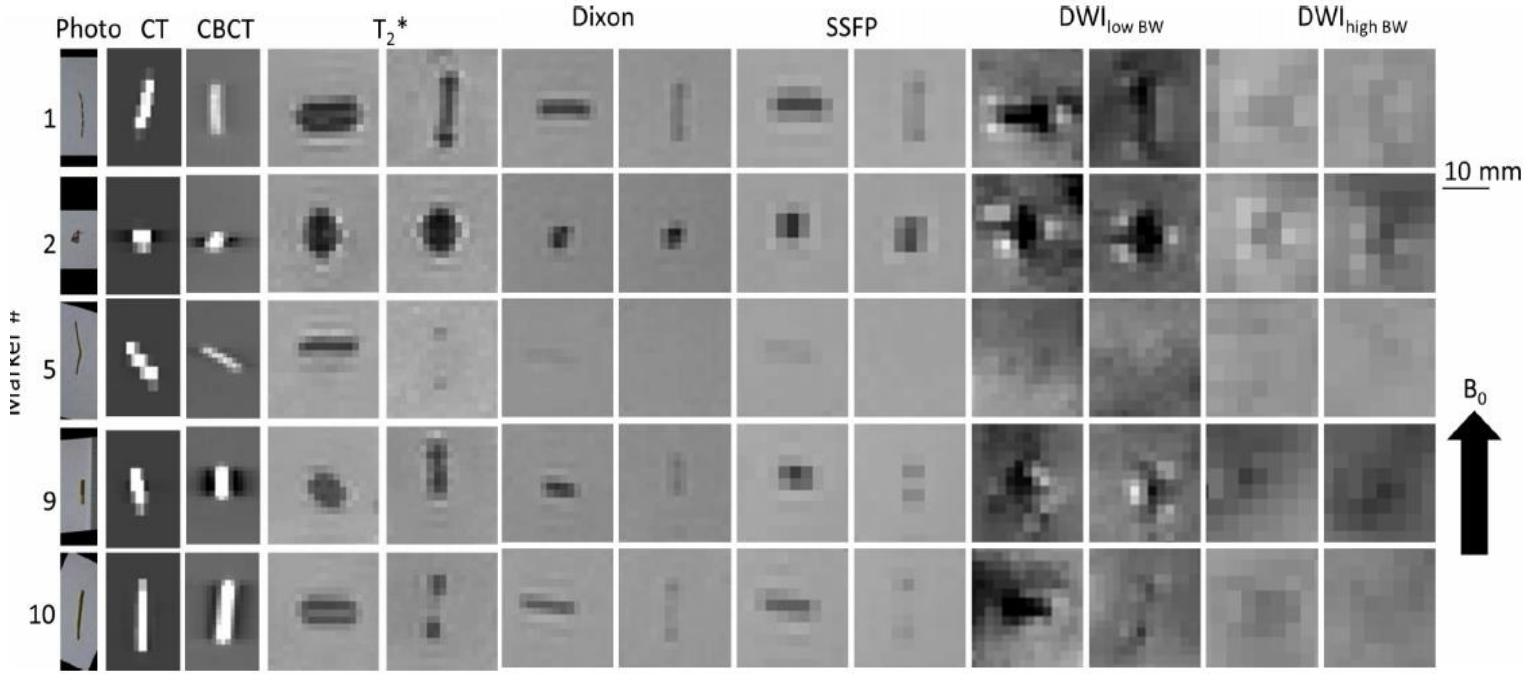
Patient implantable devices – fiducial markers

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

Civico.com



JH Jonsson et al. IJROBP, 82(5) 2012

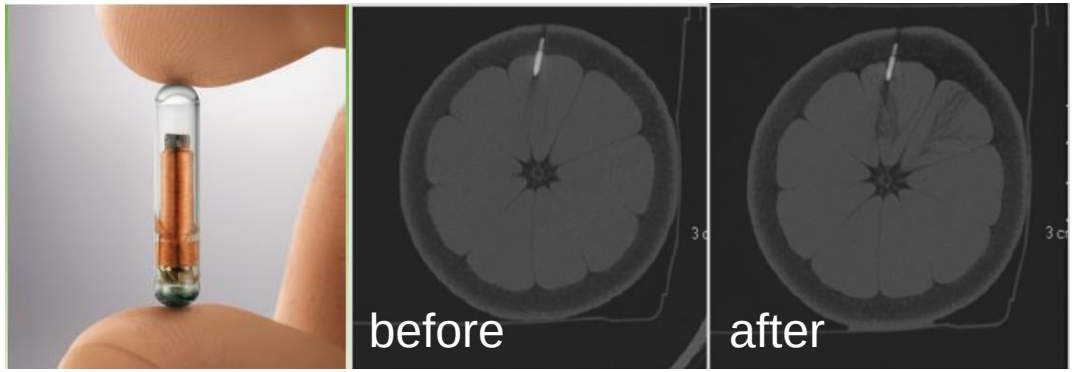


Gurney-Champion et al.: Med. Phys. 42 (5), 2015

UCLA Health

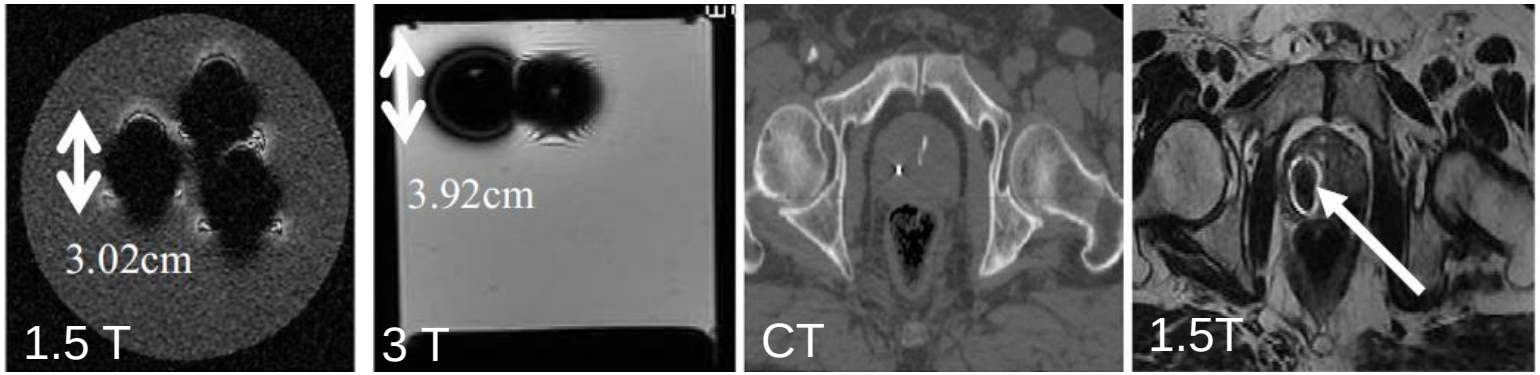
Implantable devices – EM positioning transponder

- 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

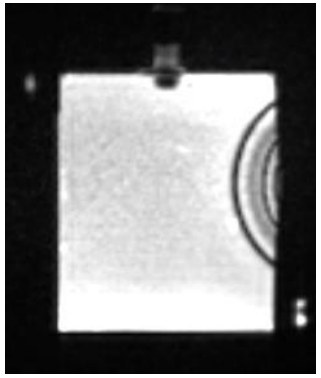
Wikstorm et al. Anticncer Research, 37. 2017



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



MR Conditional

Non-clinical testing has demonstrated that the device is "MR Conditional". A patient with this device can be scanned safely immediately after placement under the following conditions:

Static Magnetic Field
- Static Magnetic Field of 3 Tesla or less
- Maximum spatial gradient magnetic field of 3,000 Gauss/cm or less

MRI-Related Heating
In non-clinical testing, the device produced a temperature rise of up to 1.9° C during MRI performed for 15 minutes of scanning (i.e., per pulse sequence) in the 3-Tesla (3-Tesla/128-MHz, Excite, HDx, Software 14X.M5, General Electric Healthcare, Milwaukee, WI) MR system.

Therefore, the MRI-related heating experiments for the device at 3 Tesla using a transmit/receive RF body coil at an MR system reported whole body averaged specific absorption rate (SAR) of 2.9 W/kg (i.e., associated with a calorimetry-measured whole body averaged value of 2.7 W/kg) indicated that the greatest amount of heating that occurred in association with these specific conditions was equal to or less than 1.9°C.

Artifact Information
MR image quality may be compromised if the area of interest is in the exact same area or relatively close to the position of the device (within 4 – 40 cm^2, depending on port size and materials). Therefore, optimization of MR imaging parameters to compensate for the presence of this device may be necessary.

Other “mysterious implants” – Patient ingestion

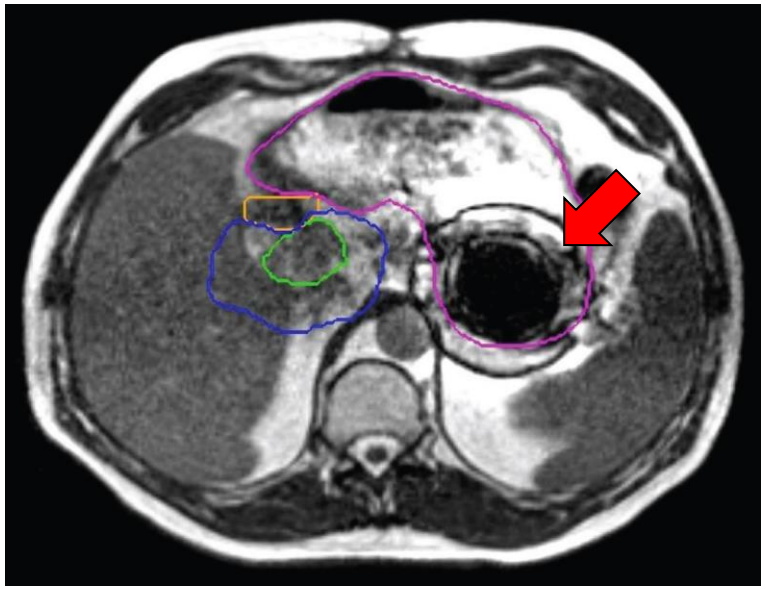


Image artifacts caused by vitamin pill

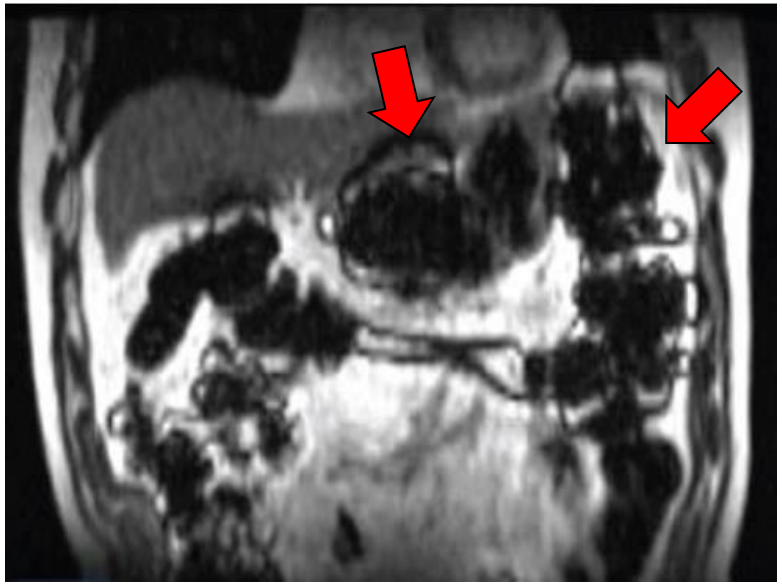
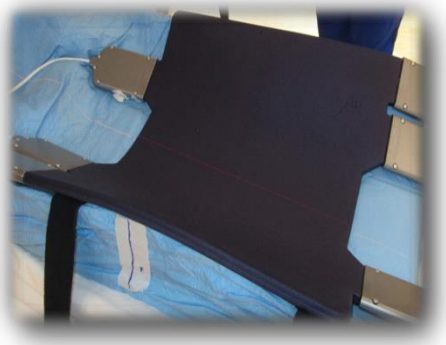
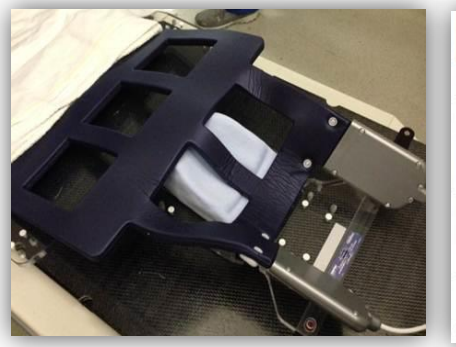
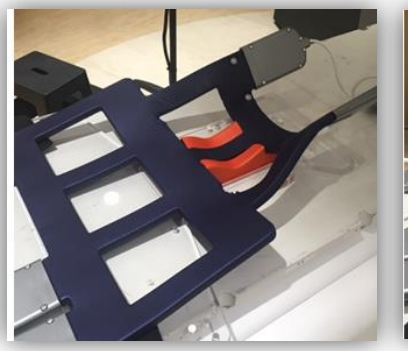
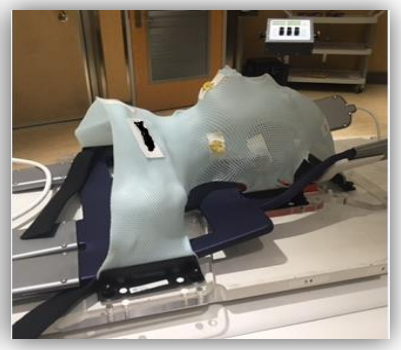


Image artifacts caused by iron-fortified food (Grape-nuts cereal)

Green O, et al. Cureus 10(3): e2359. 2018

Patient immobilization devices

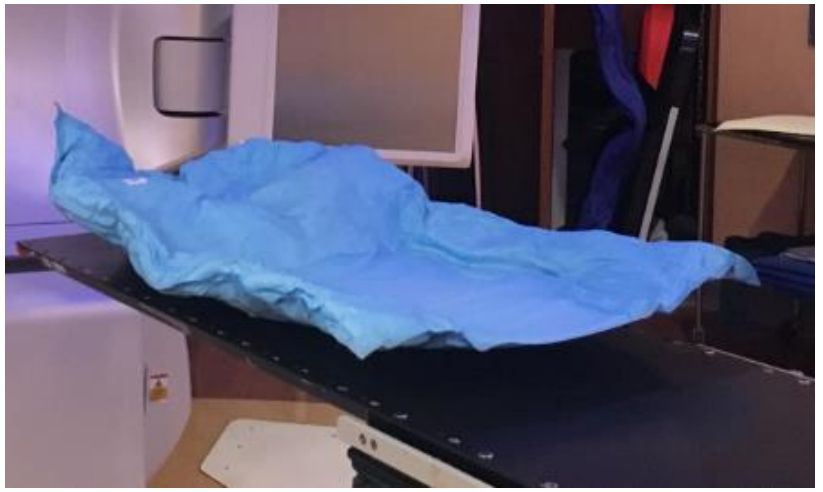
- Safety considerations:
  - Magnetic force/torque
  - RF heating
  - Imaging artifacts
- Other considerations:
  - Setup within limited bore size
  - Setup with MR coils

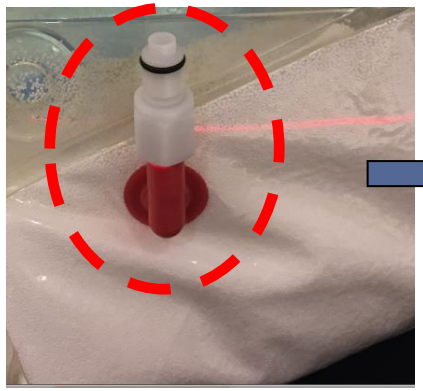






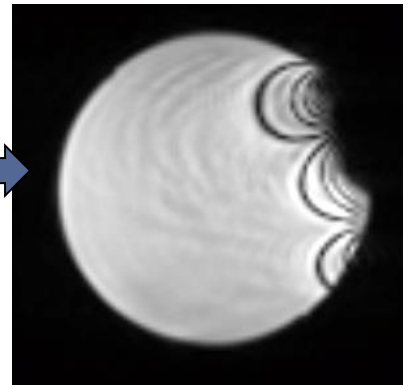
- MR safe immobilization devices are available from multiple vendors
- AAPM TG 334 – immobilization devices and accessories in MR environment

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

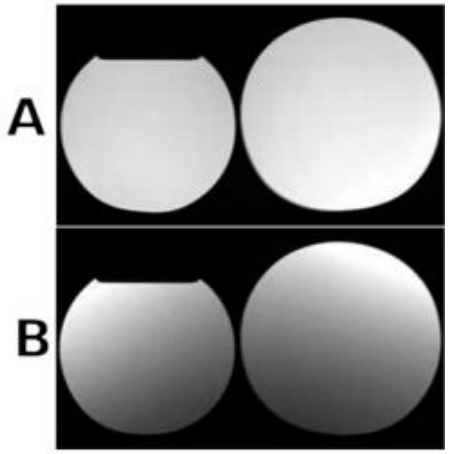
MR

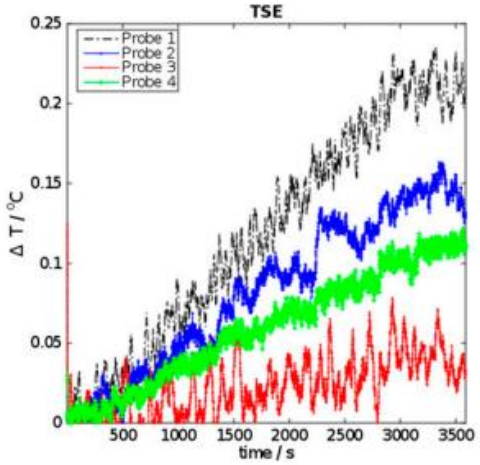
MR Conditional

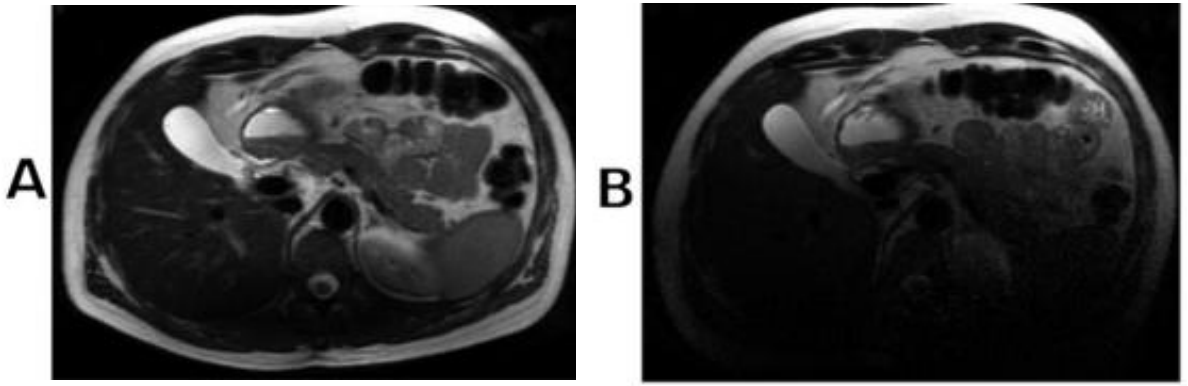
- Non-clinical testing and scientific rationale has demonstrated that the Vac-Lok™ Cushion is MR Conditional. A patient with this device can be safely scanned in an MR system meeting the following conditions:
  - Static magnetic field of 1.5 T and 3.0 T
  - Maximum spatial field gradient of 2,000 gauss/cm (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

MR Safety Training		
Category	**Competency**	**Date Met/Initials**
Observation in MR Departme	**Document 12 Hours**	
	# of hours = _____	
	# of hours = _____	
	# of hours = _____	

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

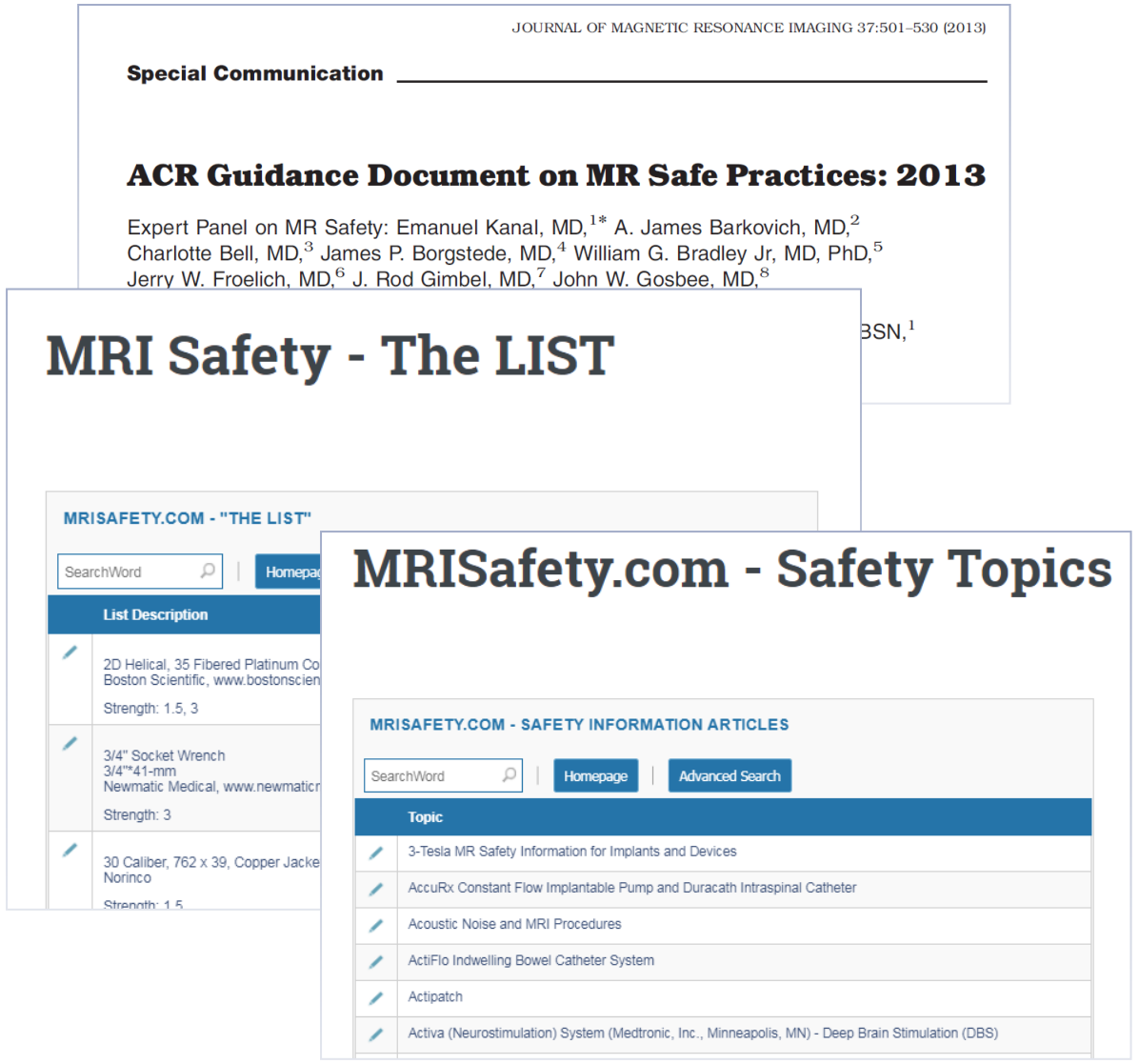
- ACR guideline 2013:
  - MR safety incidents, or ‘near incidents’’ to be reported to the medical director in a timely manner
- RO•ILS (Radiation Oncology Incident Learning System) used in our department to report MR safety incident
  - Patient related incident reviewed within 24 hours
  - Process improvement reviewed during weekly quality meeting

RO•ILS | RADIATION ONCOLOGY® INCIDENT LEARNING SYSTEM
Sponsored by ASTRO and AAPM

Resources

- ACR Guidance Document on MR Safe Practices 2013
- 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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- Dave Rebeno

David Geffen School of Medicine

UCLA Health