Introduction to MR-Guided Radiation Therapy and the Added Value of Volumetric Dosimeters

Hannah J. Lee, PhD

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April 16, 2018

Background

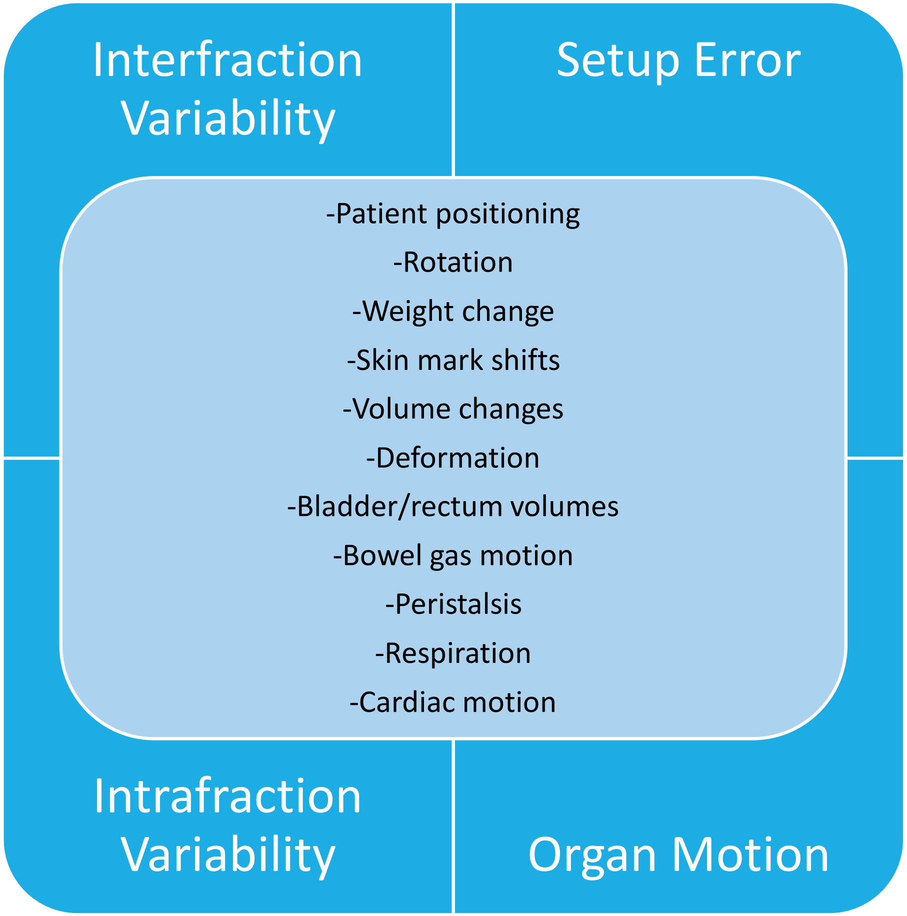
- Evolving technologies

Background

- Evolving technologies
- One thing in common: fancier image-guidance

Background

- Target uncertainty in radiation therapy
  - Setup variation
  - Internal organ displacement
  - Volume change and deformation
  - Interfraction and intrafraction changes
  - Etc…



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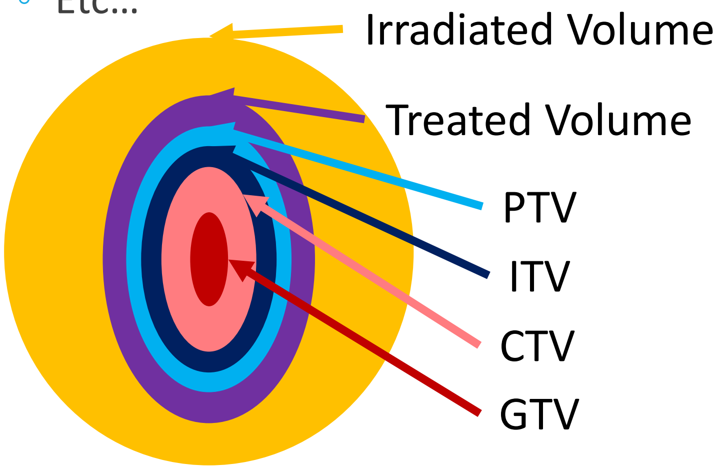
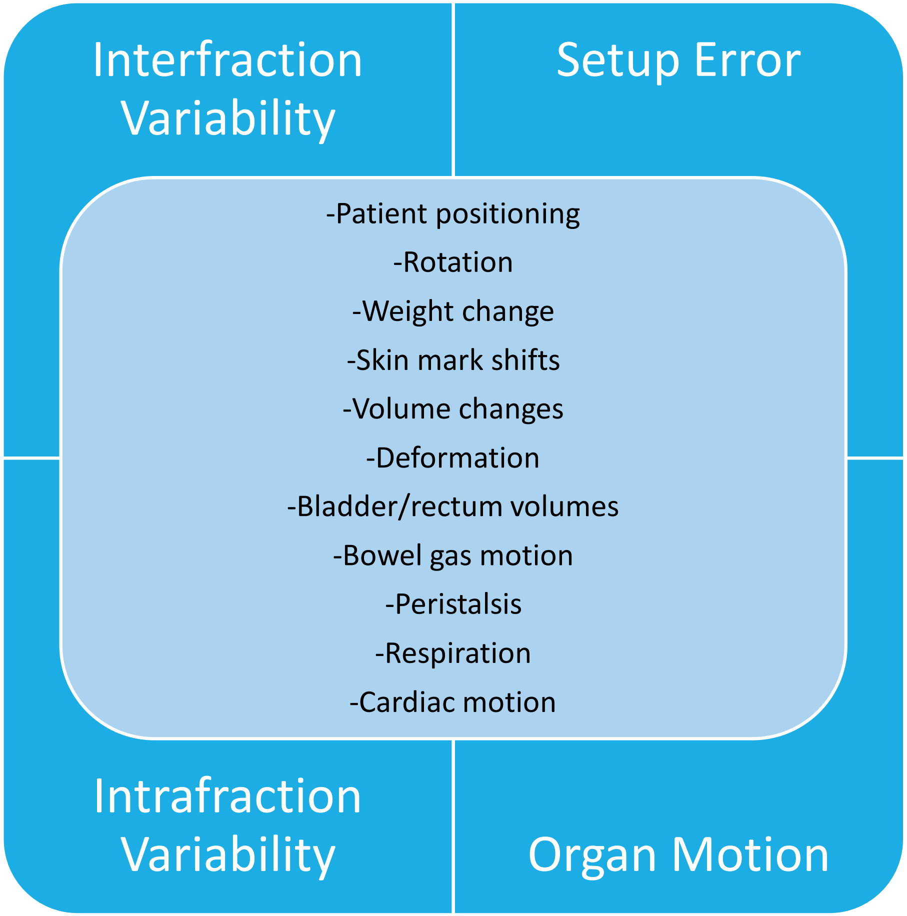
ICRU 50 and 62





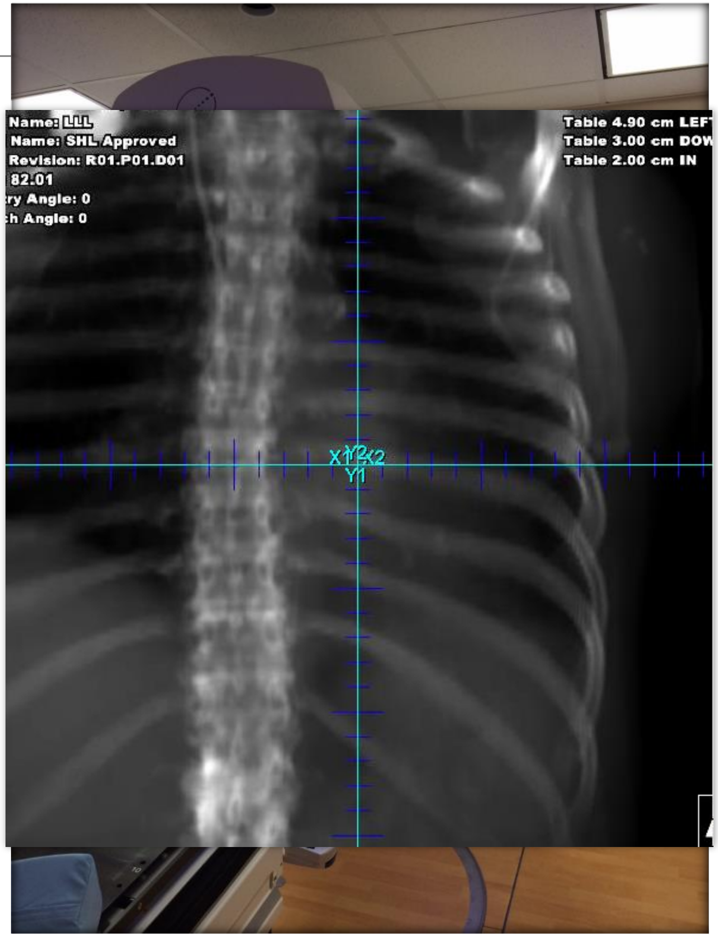
Background

- Image-guided radiation therapy (IGRT):
  - Accurate positioning of patients for precise treatments
  - Decrease radiation side effects and improve patient outcomes

Background

- Image-guided radiation therapy (IGRT):
  - kV and MV on-board imagers
  - Cone beam CT (CBCT)
  - Tomotherapy
  - Surface tracking

  - However: Internal anatomy not always correlated to bony or surface anatomy



Images courtesy of Ibbott

Background

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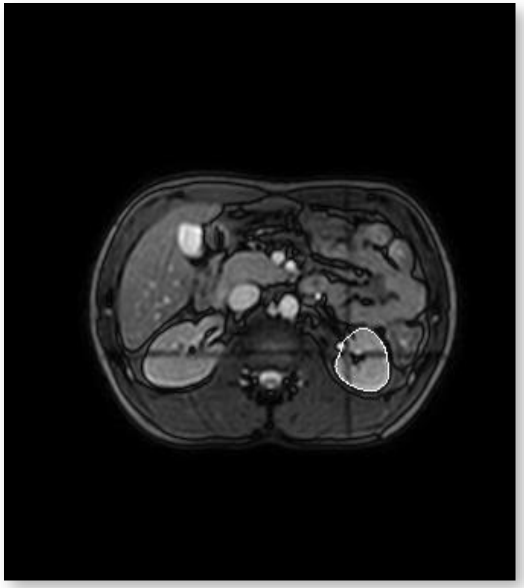
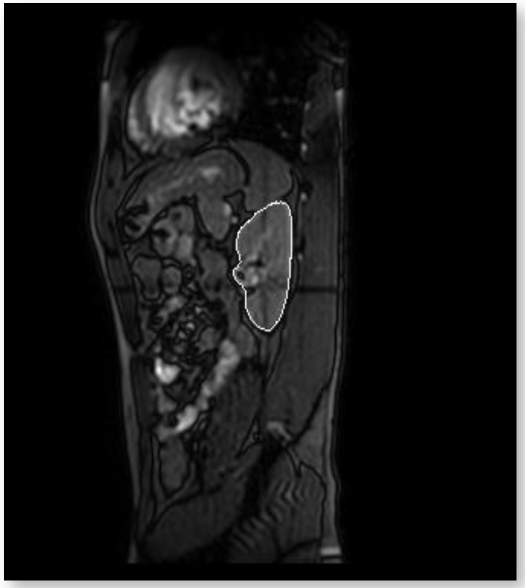


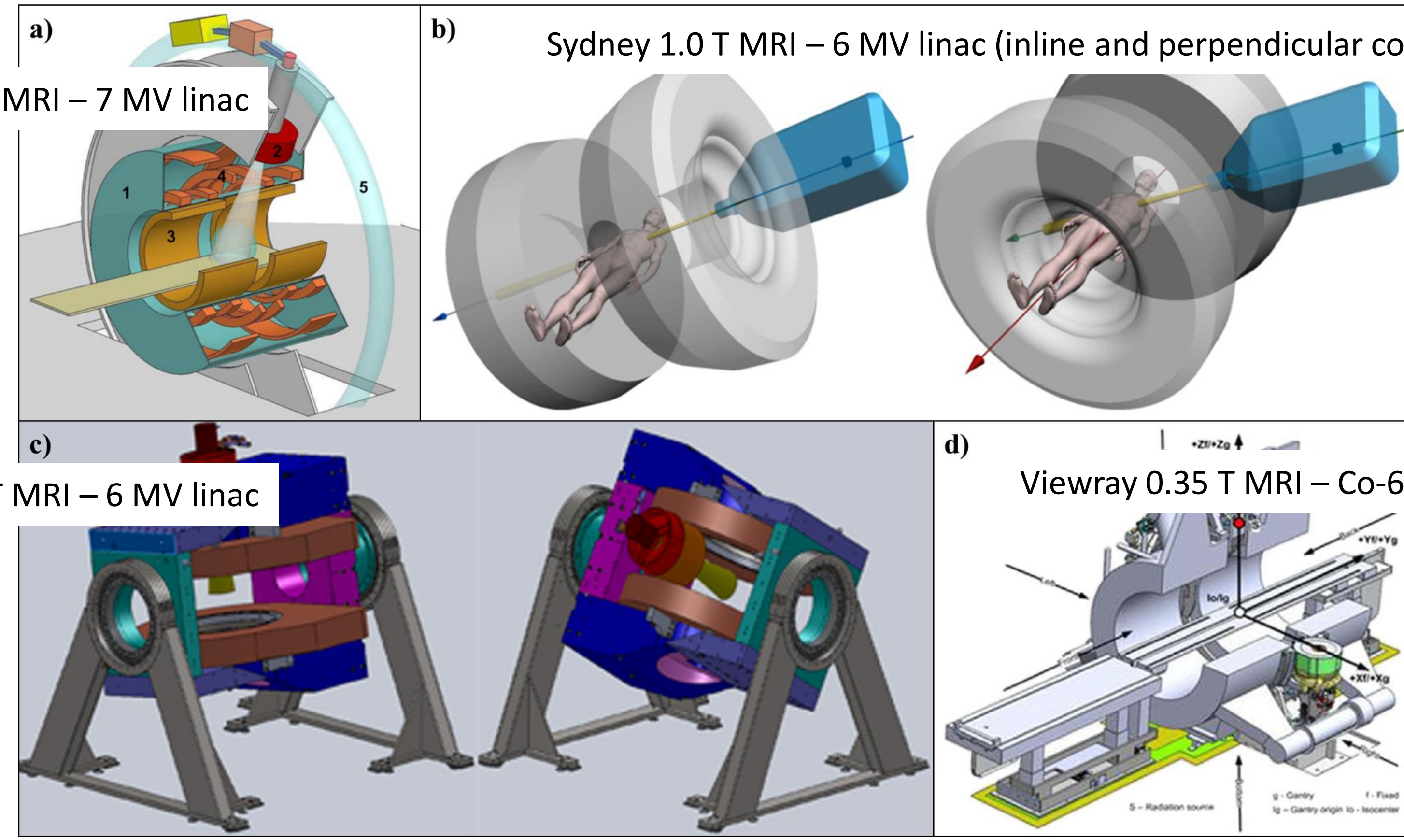


Images courtesy of Elekta

Background

Elekta 1.5 T MRI – 7 MV linac

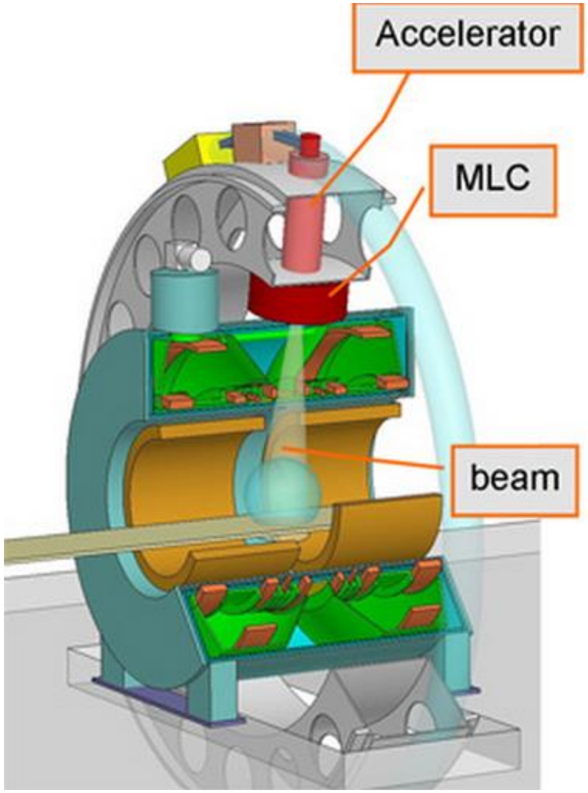
Sydney 1.0 T MRI – 6 MV linac (inline and perpendicular configurations)



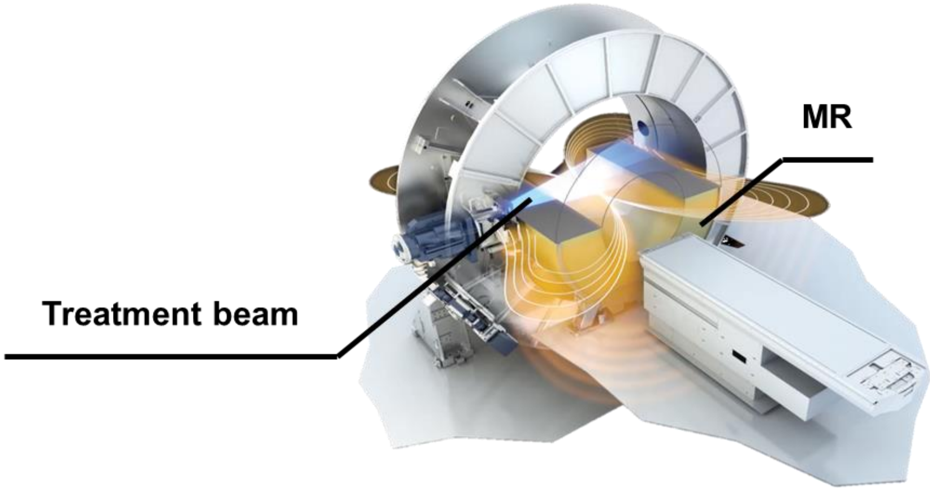
Aurora 0.5 T MRI – 6 MV linac

Viewray 0.35 T MRI – Co-60/6 MV linac

Background



- Integrated 1.5 T Philips MRI – 7 MV Elekta linear accelerator (MR-Linac) system
- Magnetic field (B_0-field) is perpendicular to radiation beam



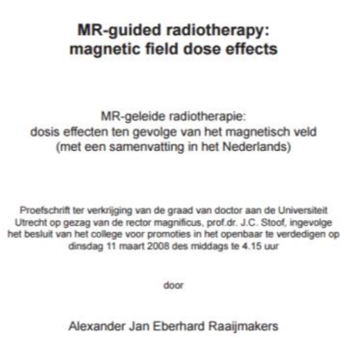
Images courtesy of University Medical Center Utrecht and Elekta

Background

Images courtesy of Elekta and Ibbott

Dosimetric Challenges

- Magnetic field is perpendicular to radiation beam
- Lorentz force acts on traveling charged particles
- Trajectories of secondary electrons are altered changing the dose distribution


MR-guided radiotherapy:
magnetic field dose effects

MR-geleide radiotherapie:
dosis effecten ten gevolge van het magnetisch veld
(met een samenvatting in het Nederlands)

Proefschrift ter verkrijging van de graad van doctor aan de Universiteit Utrecht op gezag van de rector magnificus, prof.dr. J.C. Stoof, ingevolge het besluit van het college voor promoties in het openbaar te verdedigen op dinsdag 11 maart 2008 des middags te 4.15 uur

door

Alexander Jan Eberhard Raaijmakers

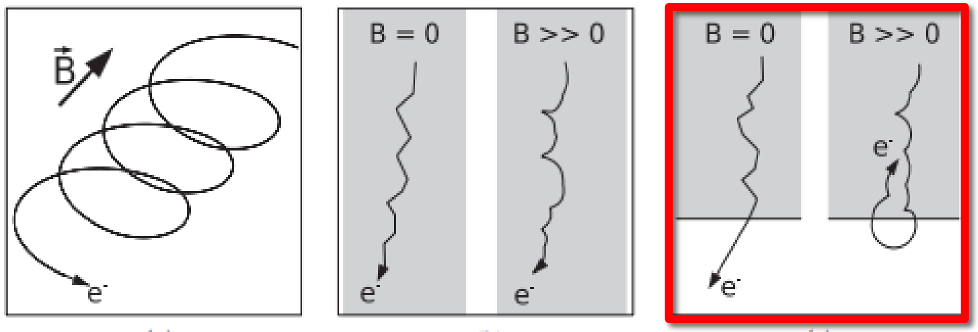


Figure 1.3: Electron trajectory examples. (a) electron trajectory in vacuum at B >> 0. (b) electron trajectories in tissue. (c) electron return effect (ERE)

Dosimetric Challenges

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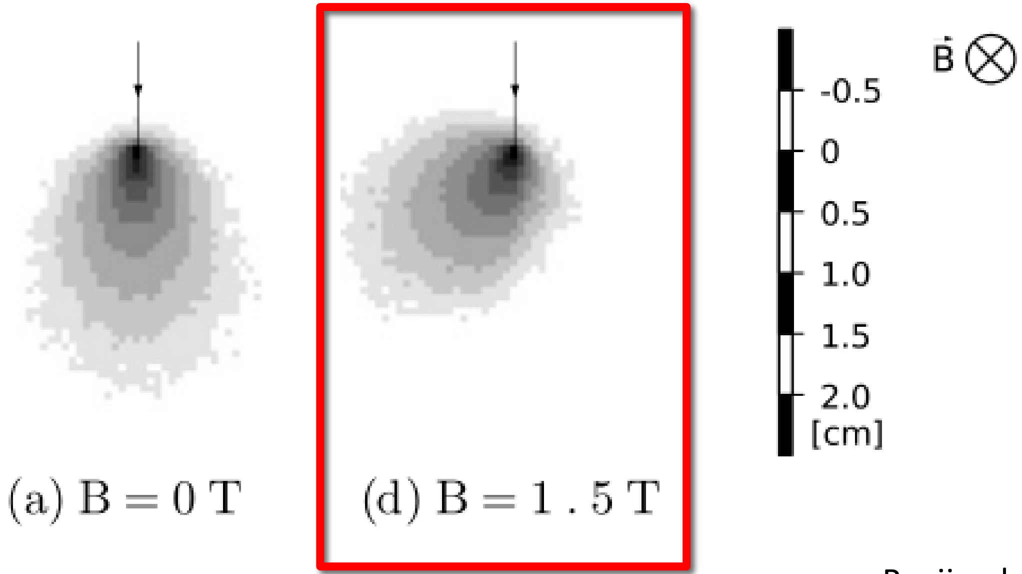


Raaijmakers et al. PMB 53 (2008) p913

Electron Return Effect (ERE)

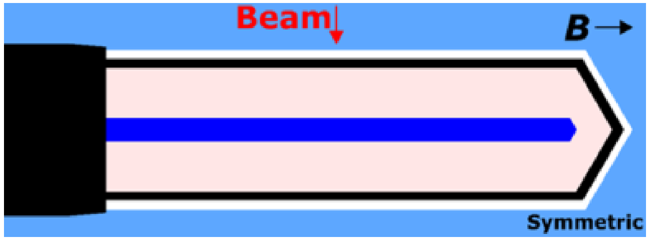
INSTITUTE OF PHYSICS PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. **50** (2005) 1363–1376 doi:10.1088/0031-9155/50/7/002

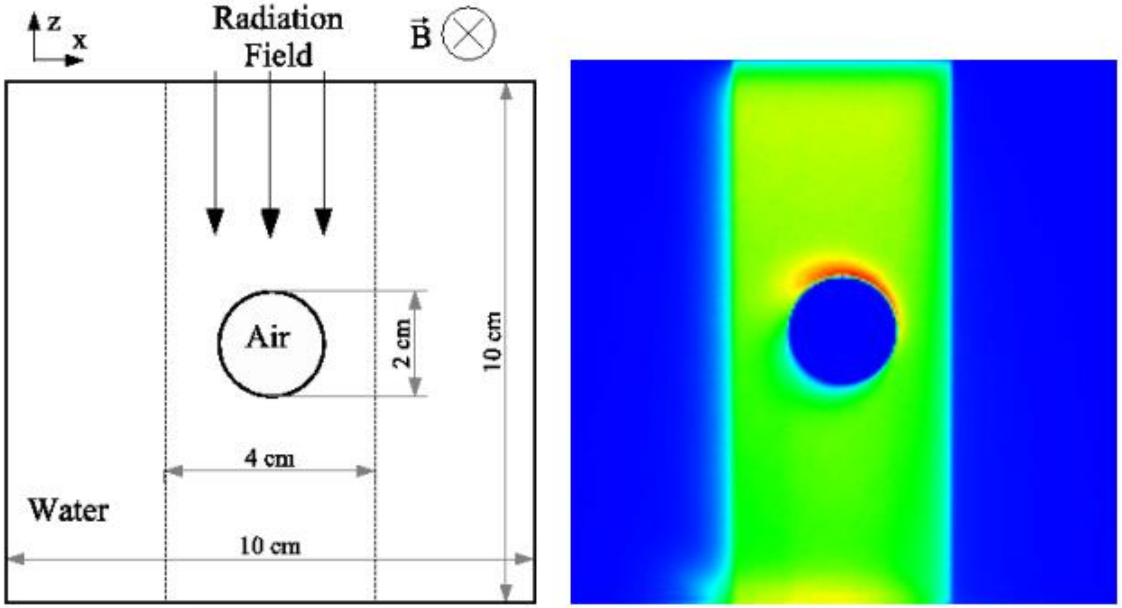
Integrating a MRI scanner with a 6 MV radiotherapy accelerator: dose increase at tissue–air interfaces in a lateral magnetic field due to returning electrons

A J E Raaijmakers, B W Raaymakers and J J W Lagendijk

Department of Radiotherapy, University Medical Center Utrecht, Heidelberglaan 100, 3584 CX, Utrecht, The Netherlands



O'Brien et al 2017: Monte Carlo study of the chamber-phantom air gap effect in a magnetic field



(a) Simulation Setup. (b) Central x–z plane

Figure 6. Schematic simulation setup (a) and energy deposition in the central plane perpendicular to the magnetic field direction for a phantom with an air tube (b).

Challenges

- Practical challenges:
  - No light field
  - Only a sagittal laser

- Use film or onboard EPID (MV Imager) to position devices (sometimes with addition of BBs)
- Some sort of rigid platform/holder for daily/weekly/monthly QA measurements

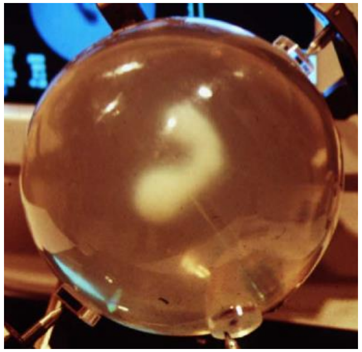
Dosimetric Challenges

- Conventional quality assurance tools provide limited information
  - Point measurements: ion chambers, diodes, TLDs, OSLDs, and etc.
  - Planar measurements: 2D arrays and film
- 1D and 2D measurements can miss dose information occurring in 3D (or 4D including motion and/or time)
- Air-filled detectors and air gaps in solid water and other tools susceptible to electron return effect (ERE)
- Dosimeter arrays are not usually MR compatible
  - Vendors have started to provide MR compatible ion chambers, ArcCheck, Starcheck, and IC Profiler
  - But these devices only provide 1D, 2D, and at best quasi-3D dose information

- **3D dosimeters can address all of these concerns**

3D Dosimeter Types

- Radiochromic gel
  - Fricke xylenol orange
  - FOX and rFOX – my gel
  - TruView™ and etc.
- Polymer gel
  - BANANA
  - BANG
  - PAGAT and etc.
- Radiochromic plastic/silicone
  - PRESAGE® and Presage-Def
  - Leuco dye in silicone
  - FlexyDos3D and etc.



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  - Leuco dye in silicone
  - FlexyDos3D and etc.

$$\mathrm{H}\cdot + \mathrm{O_2} \rightarrow \mathrm{HO_2}\cdot$$

$$\mathrm{HO_2}\cdot + \mathrm{Fe^{2+}} \rightarrow \mathrm{HO_2^-} + \mathrm{Fe^{3+}}$$

$$\mathrm{HO_2^-} + \mathrm{H^+} \rightleftharpoons \mathrm{H_2O_2}$$

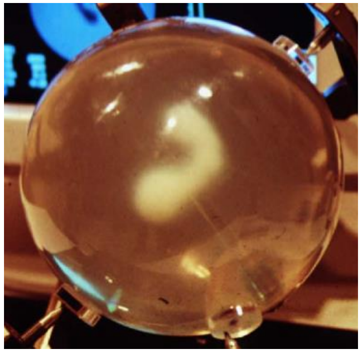
$$\mathrm{Fe^{2+}} + \mathrm{H_2O_2} \rightarrow \mathrm{Fe^{3+}} + \mathrm{HO^-} + \mathrm{HO}\cdot$$

$$\mathrm{Fe^{2+}} + \mathrm{HO}\cdot \rightarrow \mathrm{Fe^{3+}} + \mathrm{HO^-}$$

$$G(\mathrm{Fe^{3+}}) = 3G(\mathrm{H}\cdot) + G(\mathrm{HO}\cdot) + 2G(\mathrm{H_2O_2})$$

$$D = \frac{N_A \cdot e}{\rho \cdot l \cdot G(Fe^{3+})} \cdot \frac{OD(D) - OD(0)}{\varepsilon_m}$$

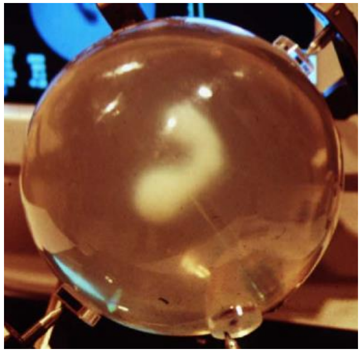
$$D = \frac{N_A \cdot e}{10\rho \cdot G(Fe^{3+})} \cdot \frac{R_1(D) - R_1(0)}{r_{eff}^{3+} - r^{2+}}$$



3D Dosimeter Types

- Radiochromic gel
  - Easily created in-house and non-toxic chemicals
  - MR visible changes with irradiation and reusable formulations are possible
  - Diffusion of signal –no longer a major concern with MR-guided systems?

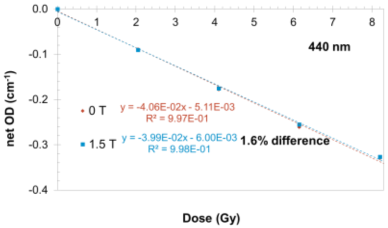
- Polymer gel
  - Minimal diffusion within 24 hours of irradiation
  - MR visible changes with irradiation
  - Oxygen sensitivity and toxic components

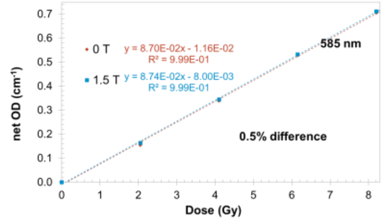


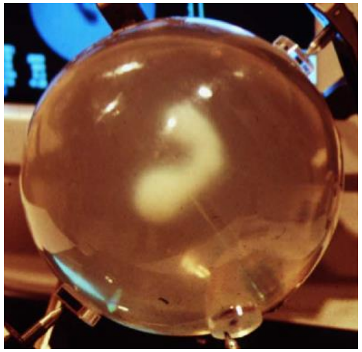
- Radiochromic plastic/silicone
  - Minimal diffusion within 24 hours of irradiation
  - Easily created in any shape and minimally toxic chemicals
  - Optical edge artifacts and non-MR-visible signal change

3D Dosimeter Types

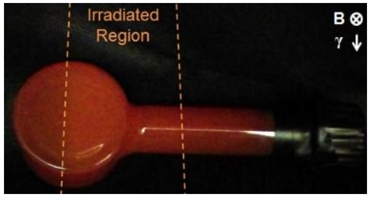
- Radiochromic gel

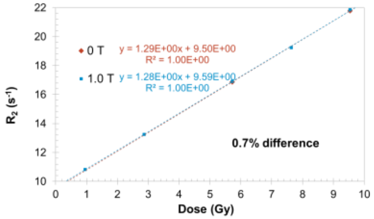






- Polymer gel





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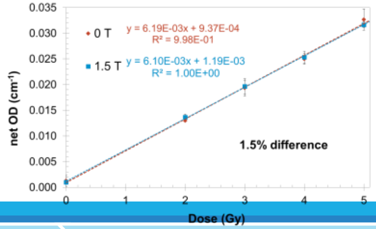

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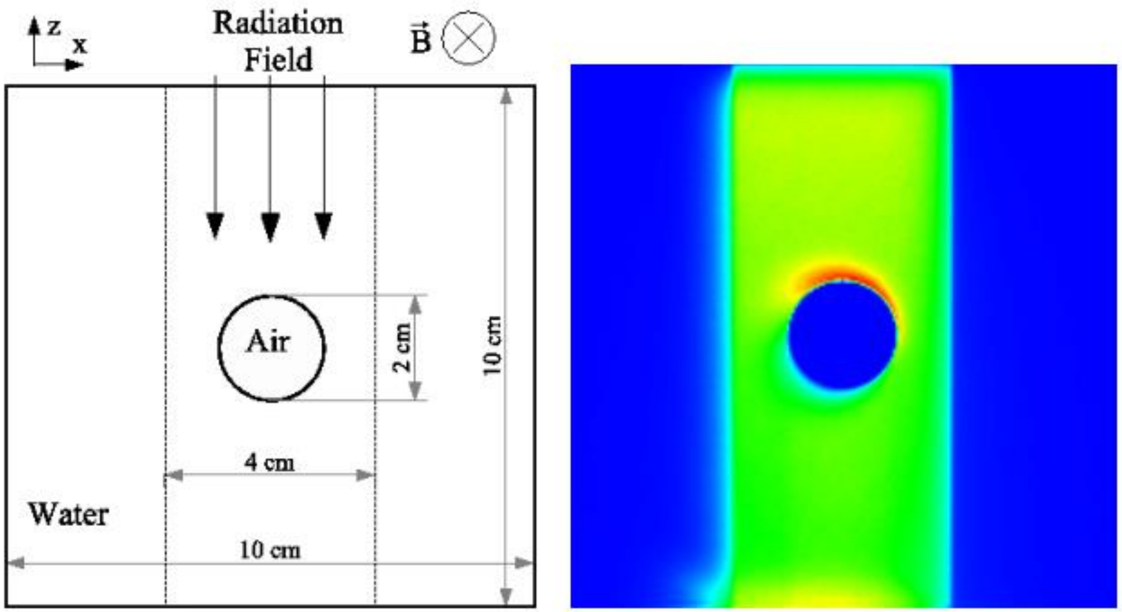

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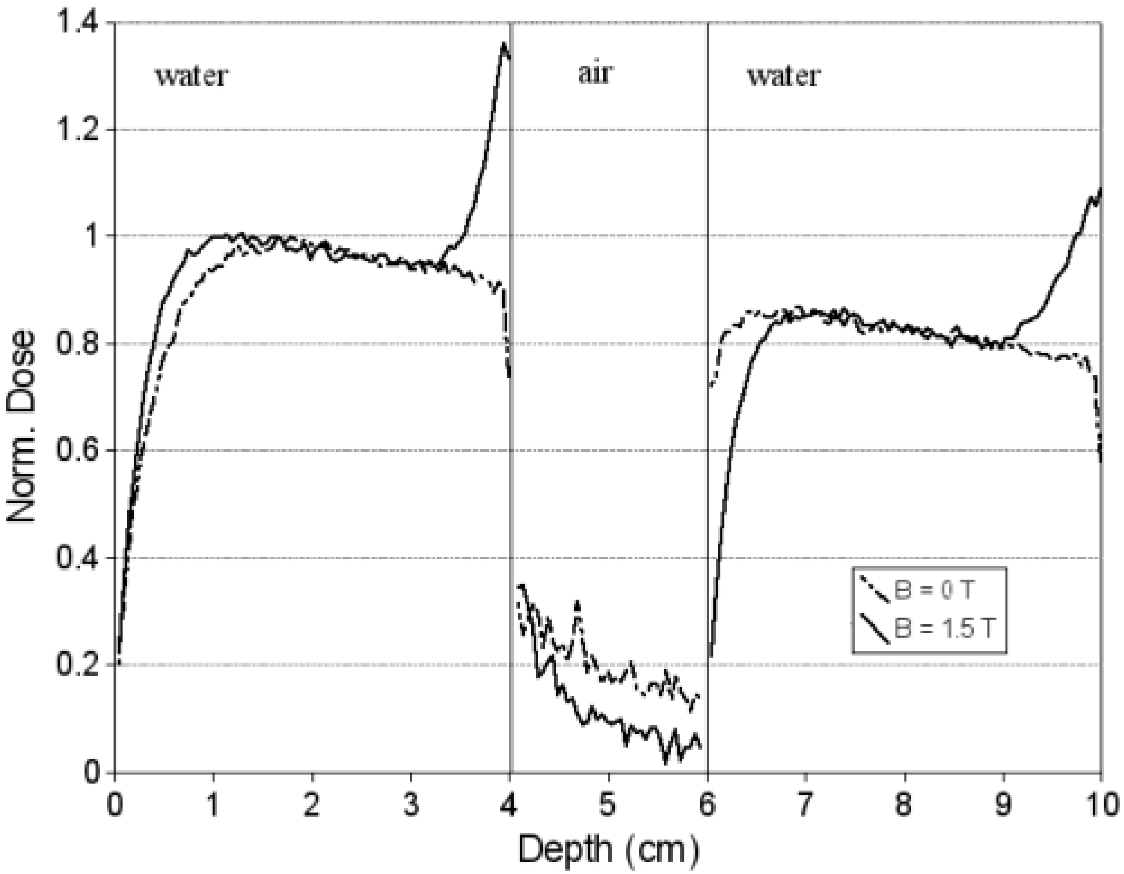

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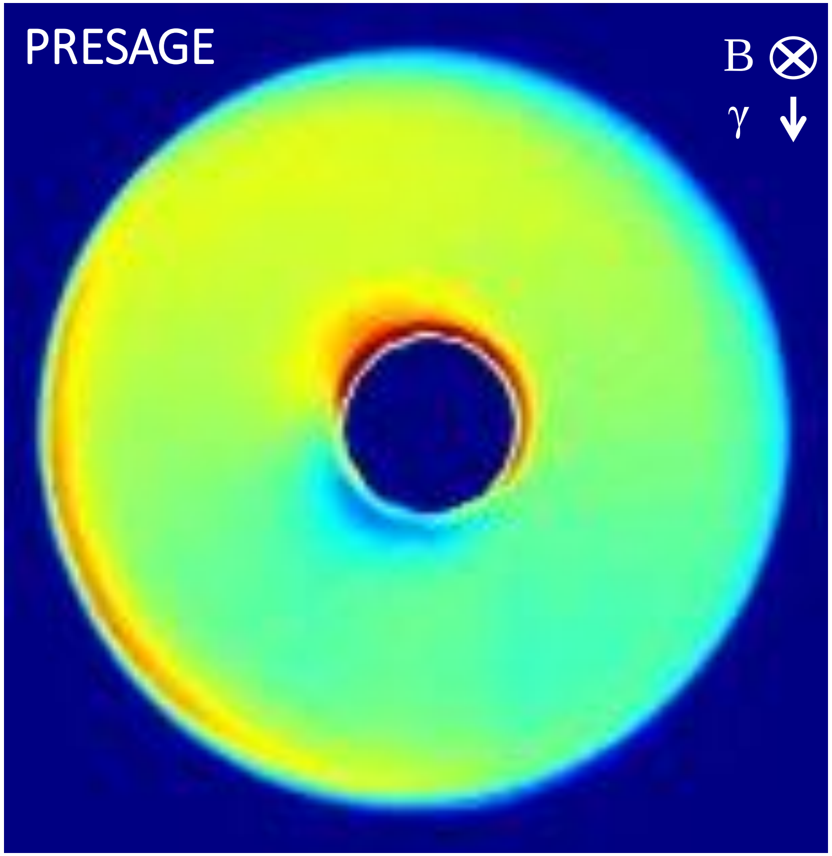
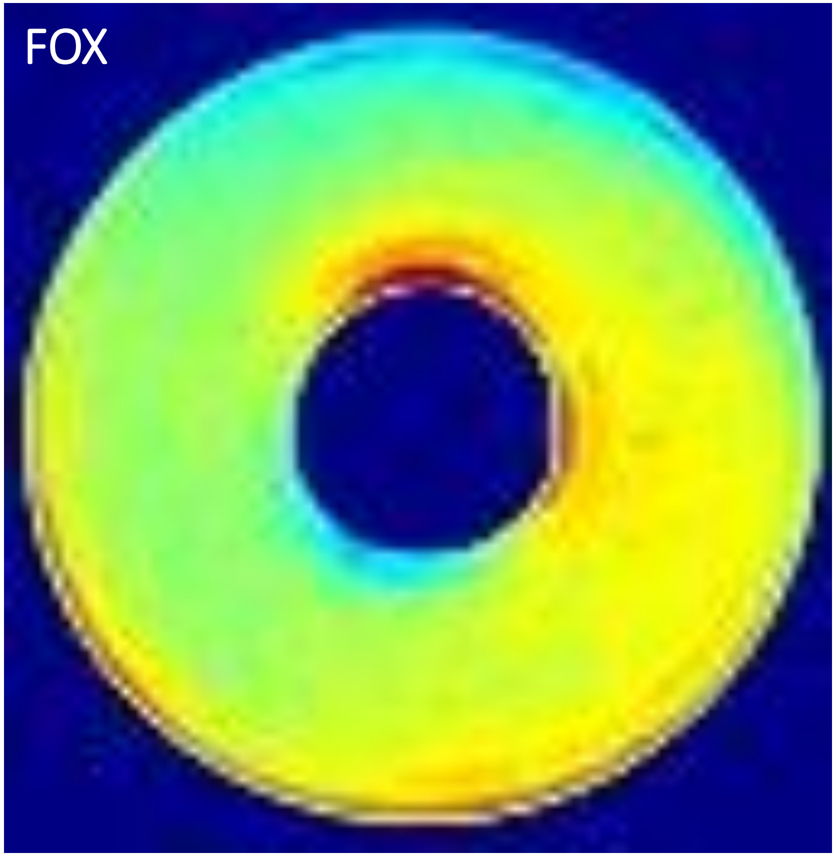
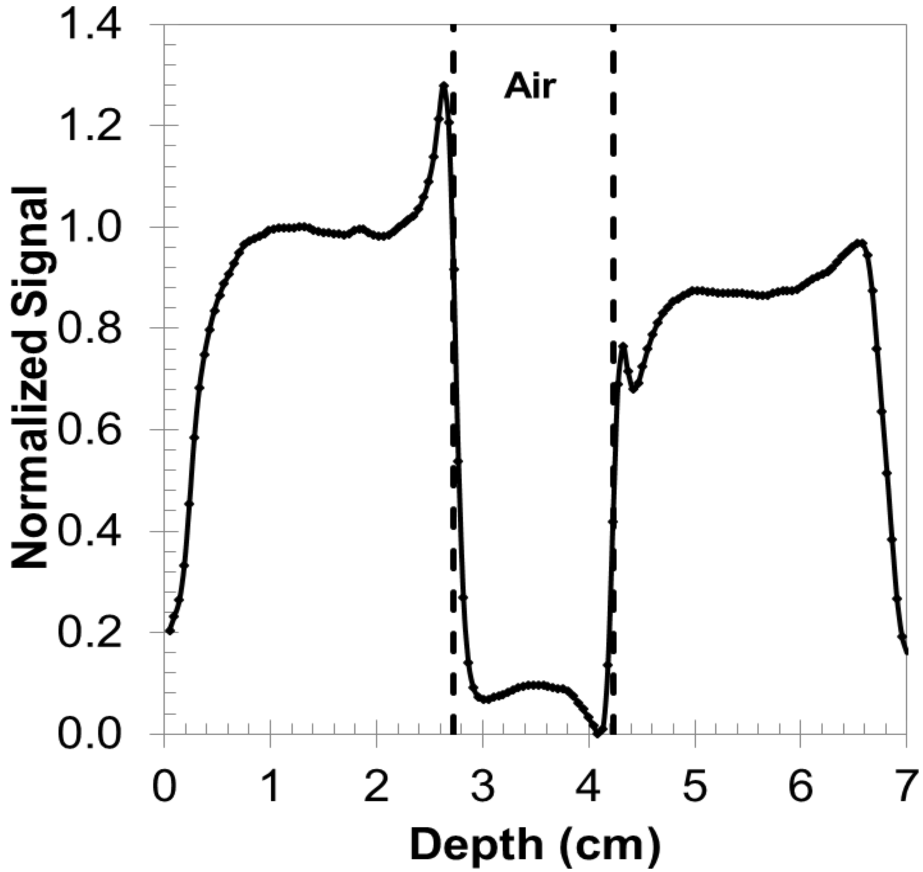


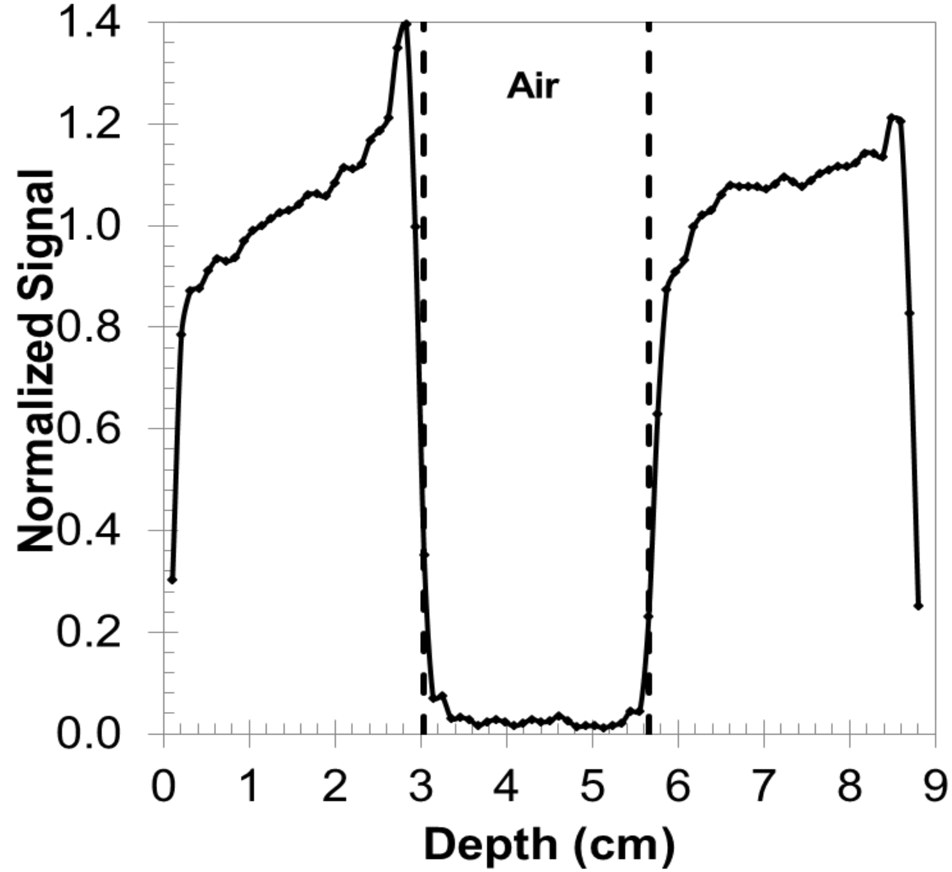


Electron Return Effect (ERE)

PRESAGE – Radiochromic Plastic

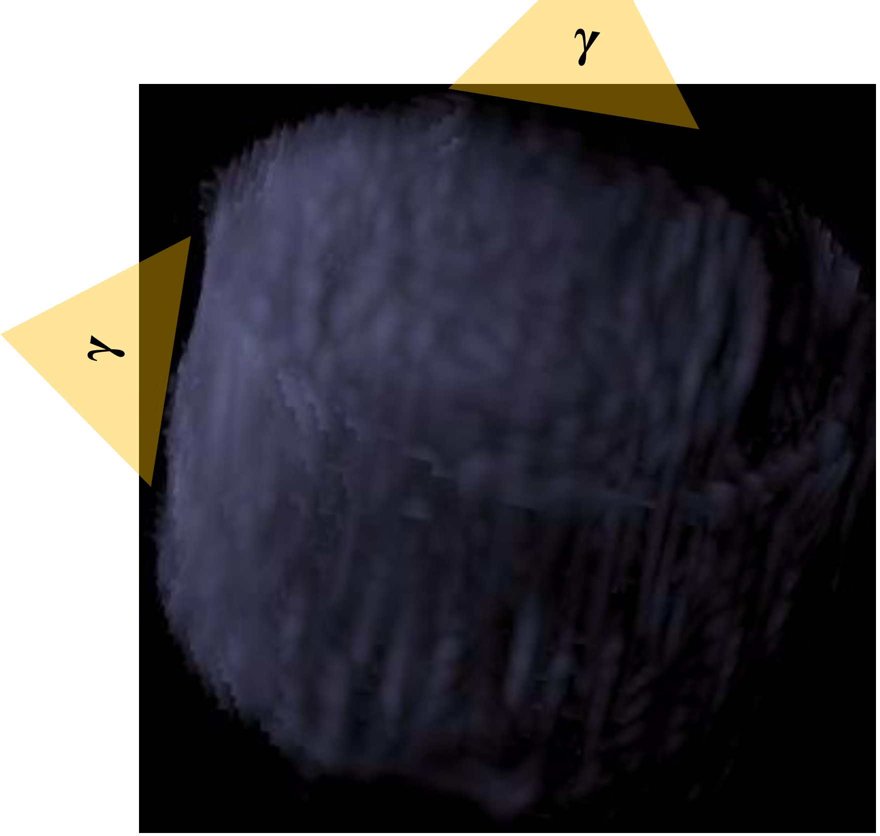


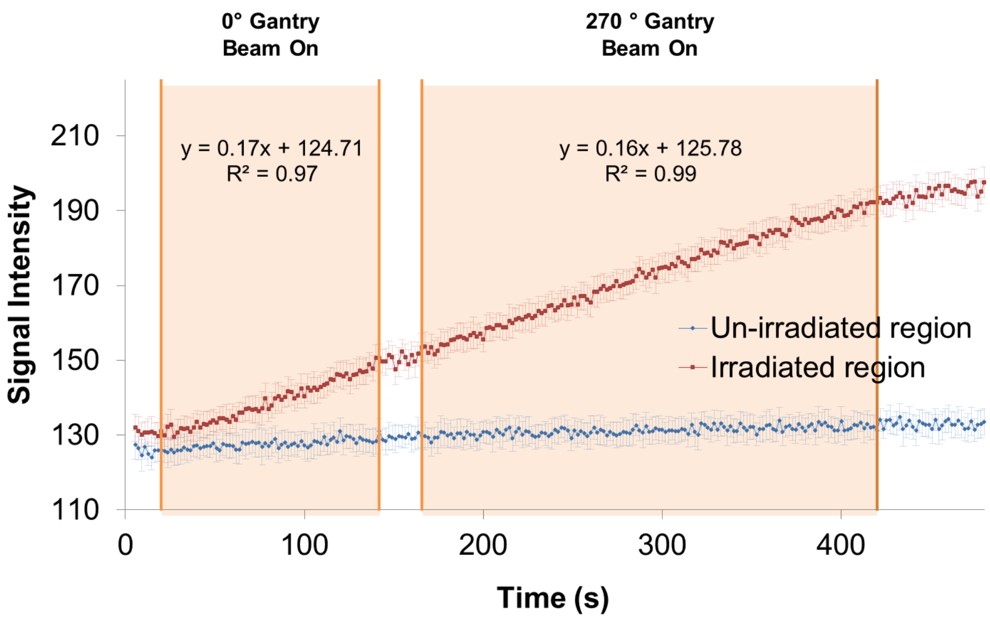
FOX – Radiochromic Gel



Real-time 3D Dose Acquisition

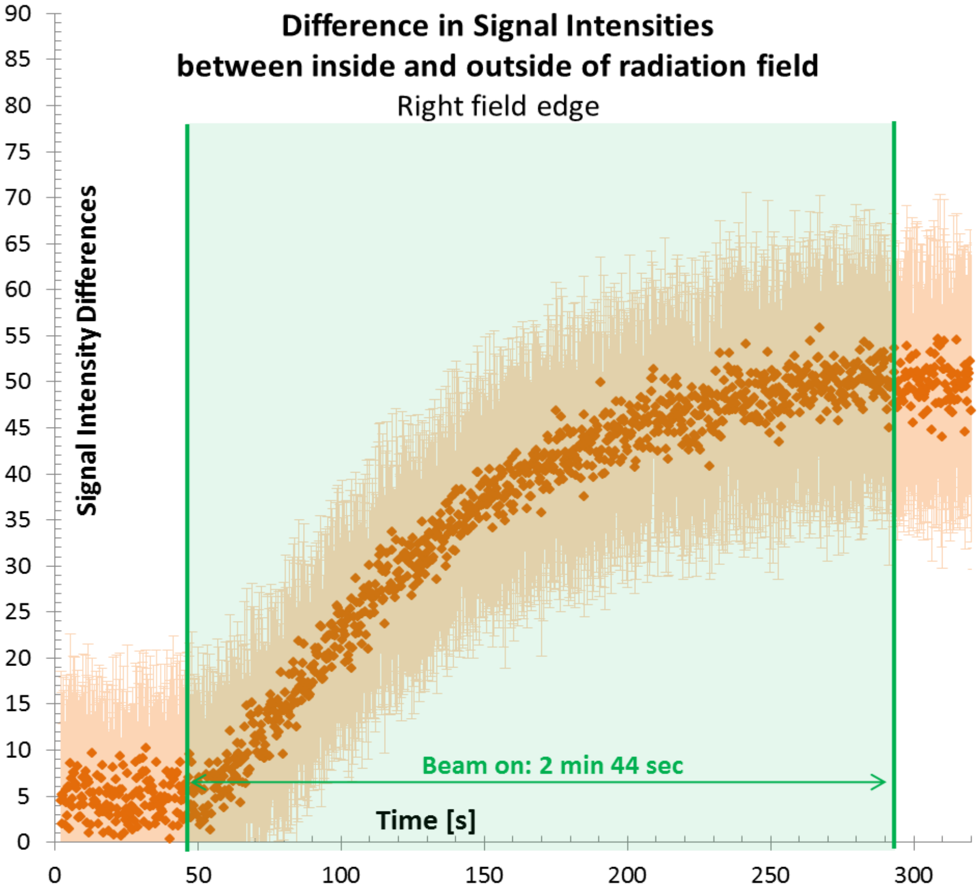
Radiochromic Gel





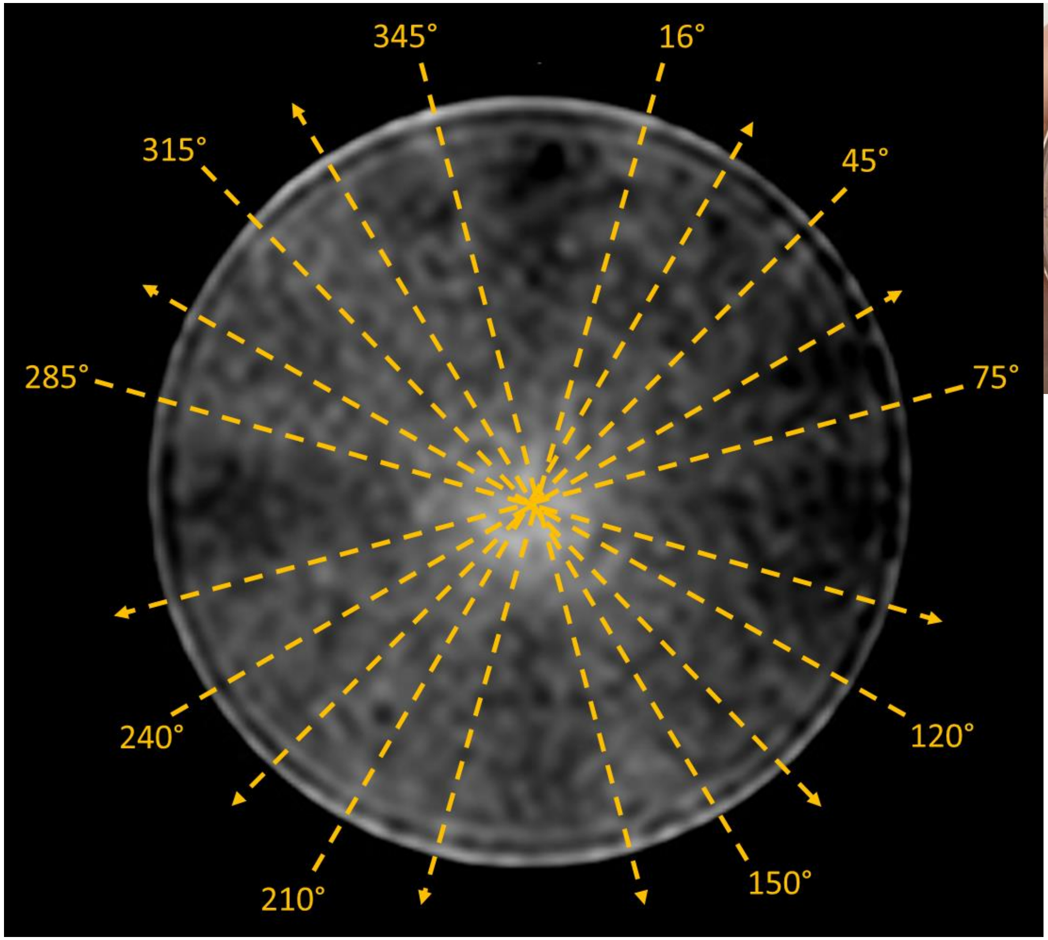
Real-time 3D Dose Acquisition

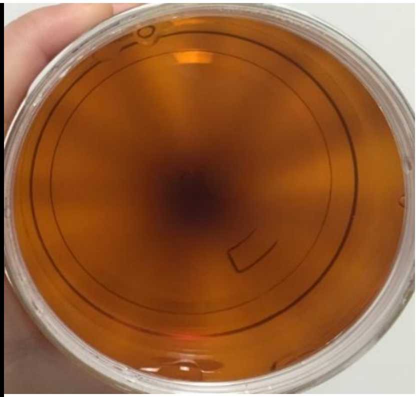
Polymer Gel



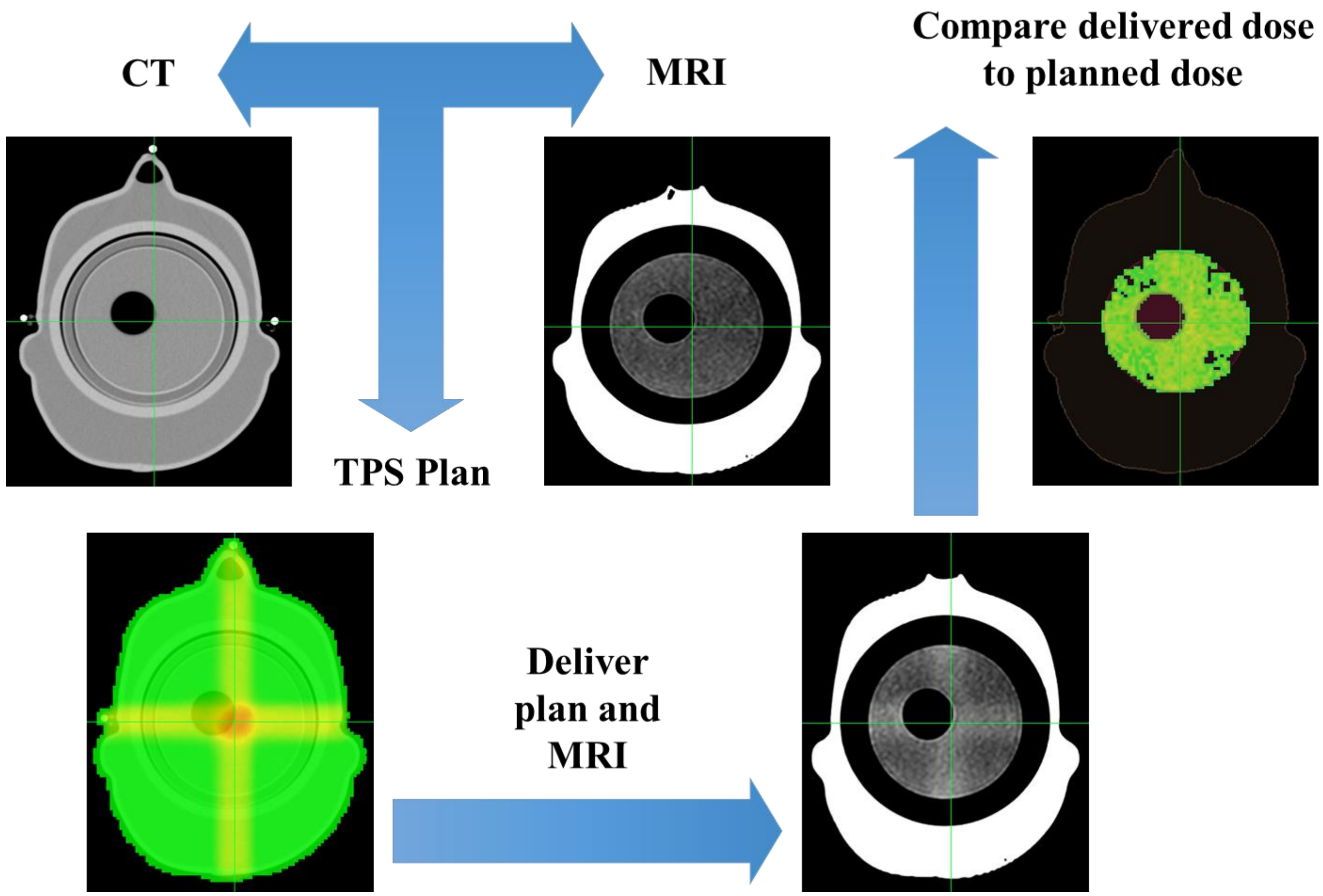
MR and Radiation Isocenter Registration

Radiochromic Gel





End-to-end Testing Workflow



Current Limitations in Testing

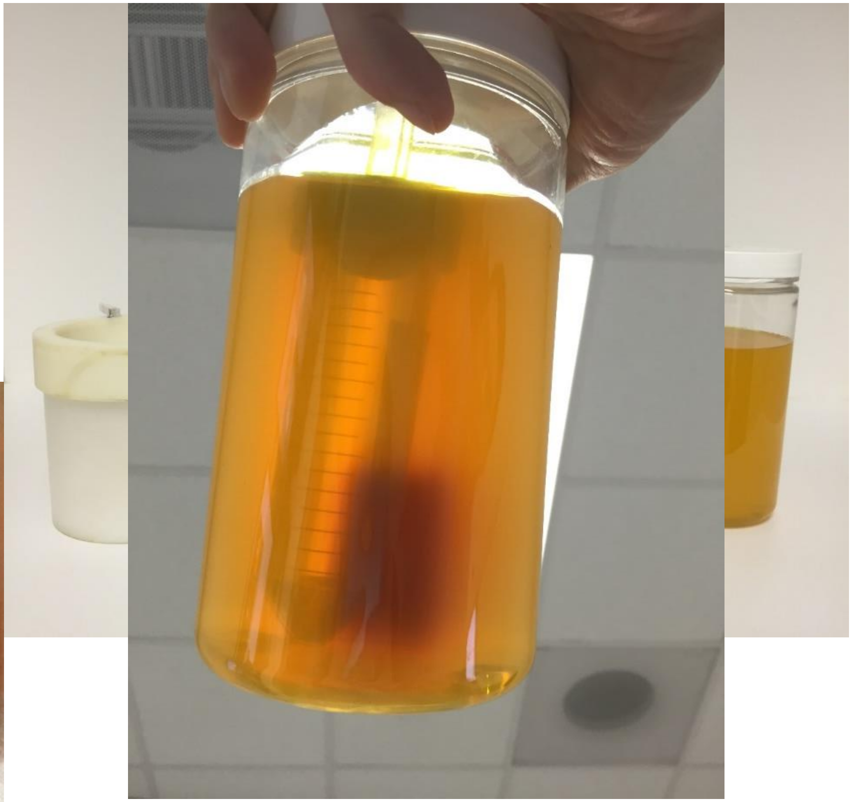
- Limitations: pre-clinical system
  - MR and MV isocenter registration
  - MLC calibration

- Currently undergoing upgrades
  - New couch and anterior coil
  - Re-commissioning of MRI and linac components
    - New beam model and cryostat correction for Monaco TPS

End-to-end Testing

- Heterogeneous phantom: retired IROC-Houston head and neck credentialing phantom (mostly water filled)

- Homogeneous phantom: 2 L gel for TG-119 plan testing



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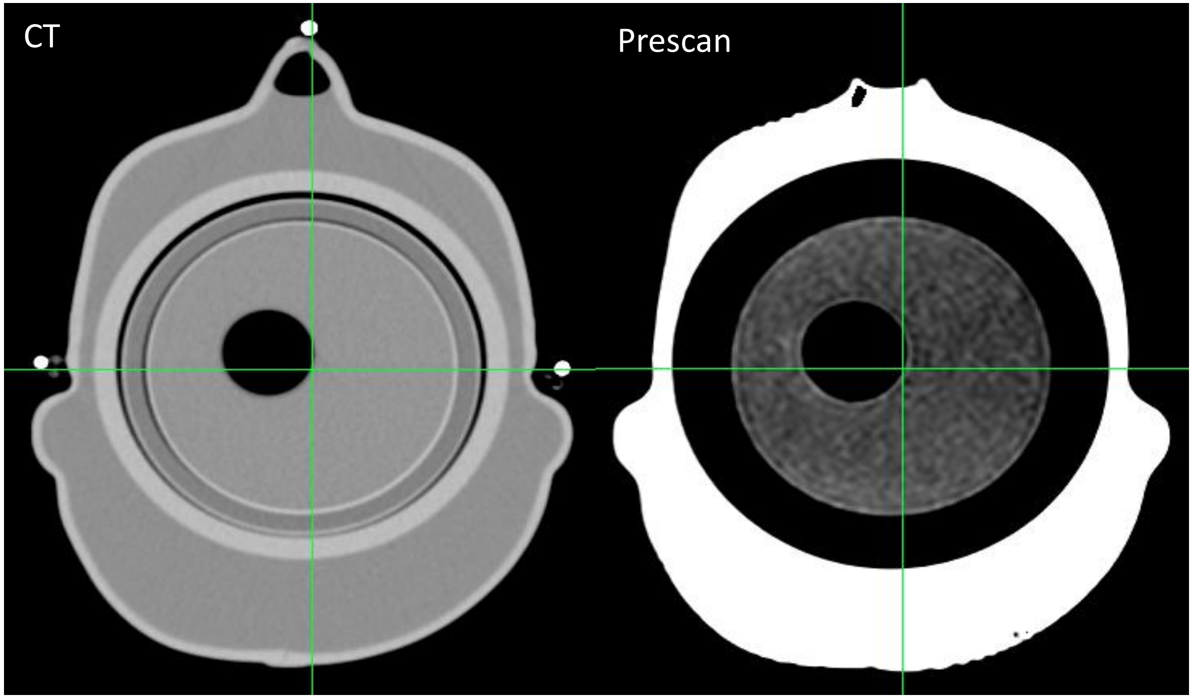

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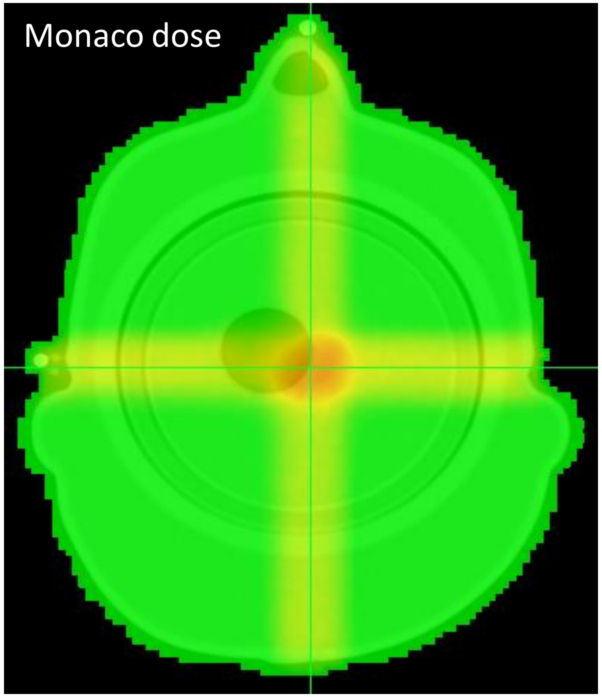

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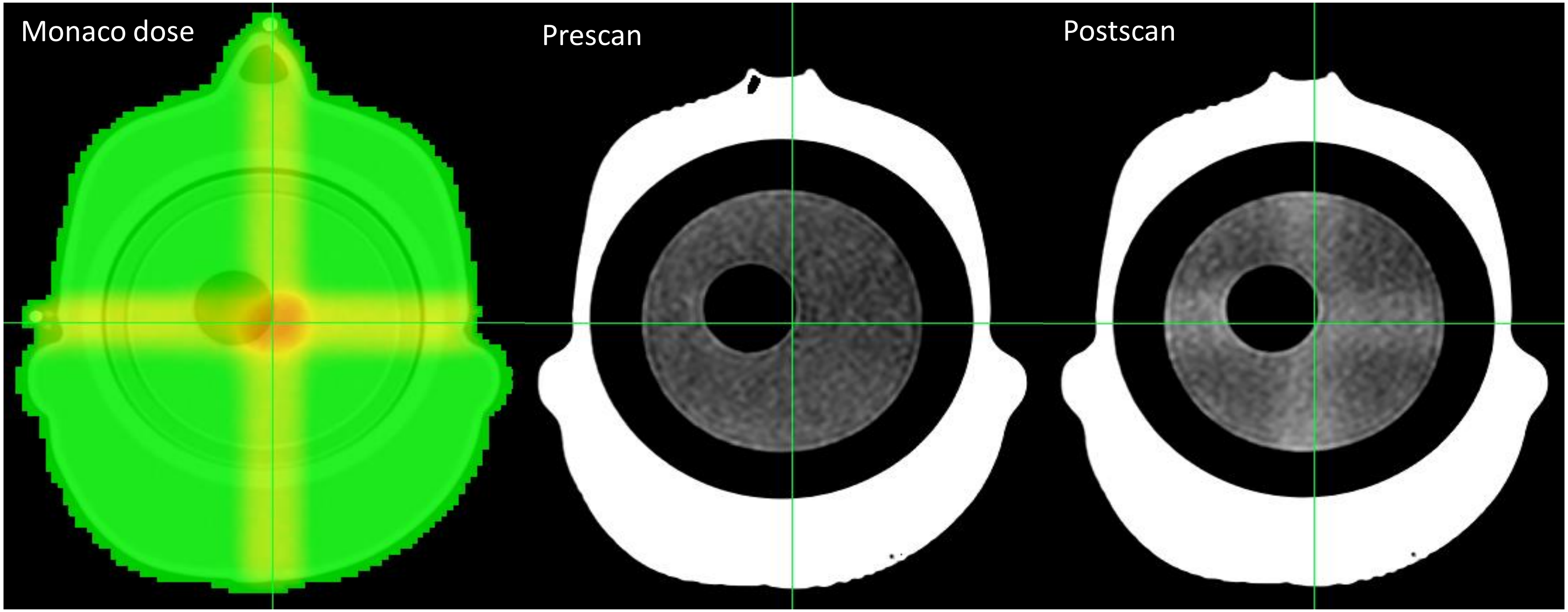

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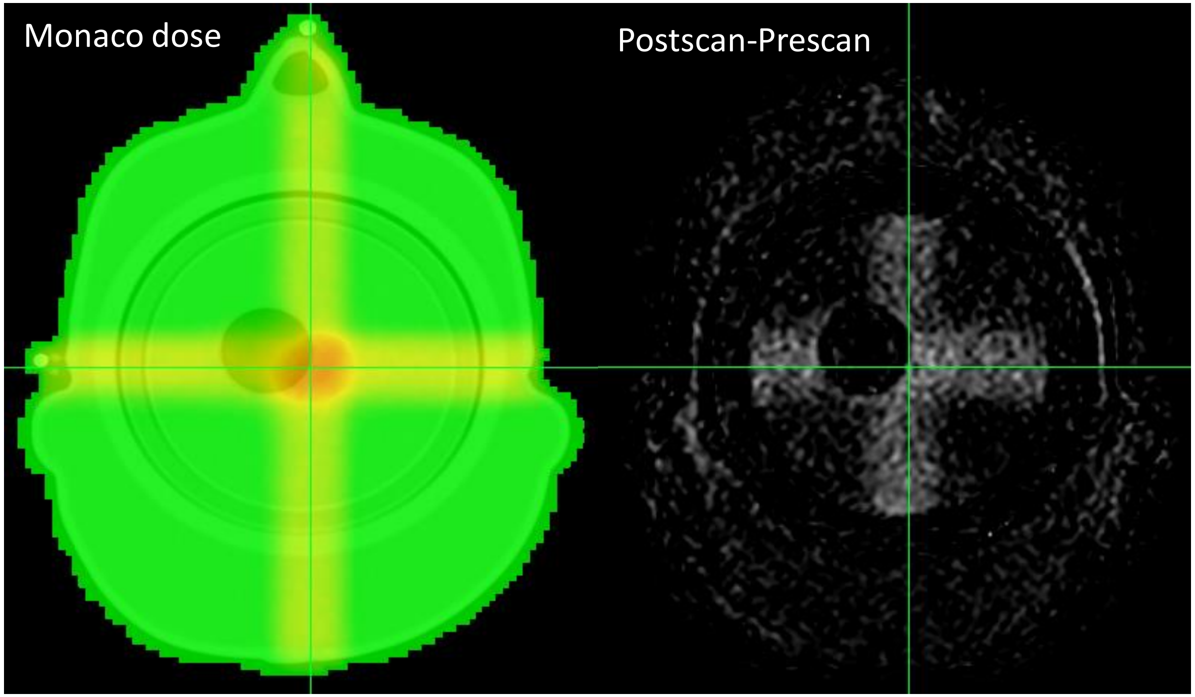
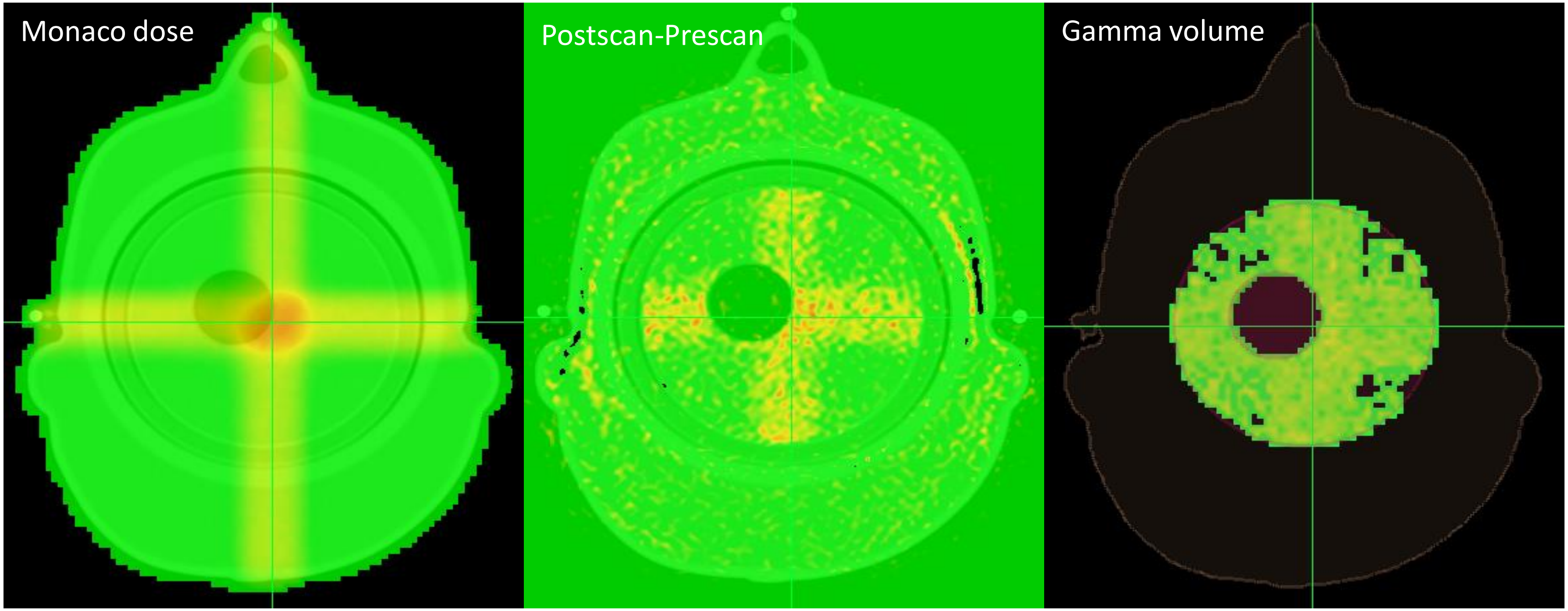
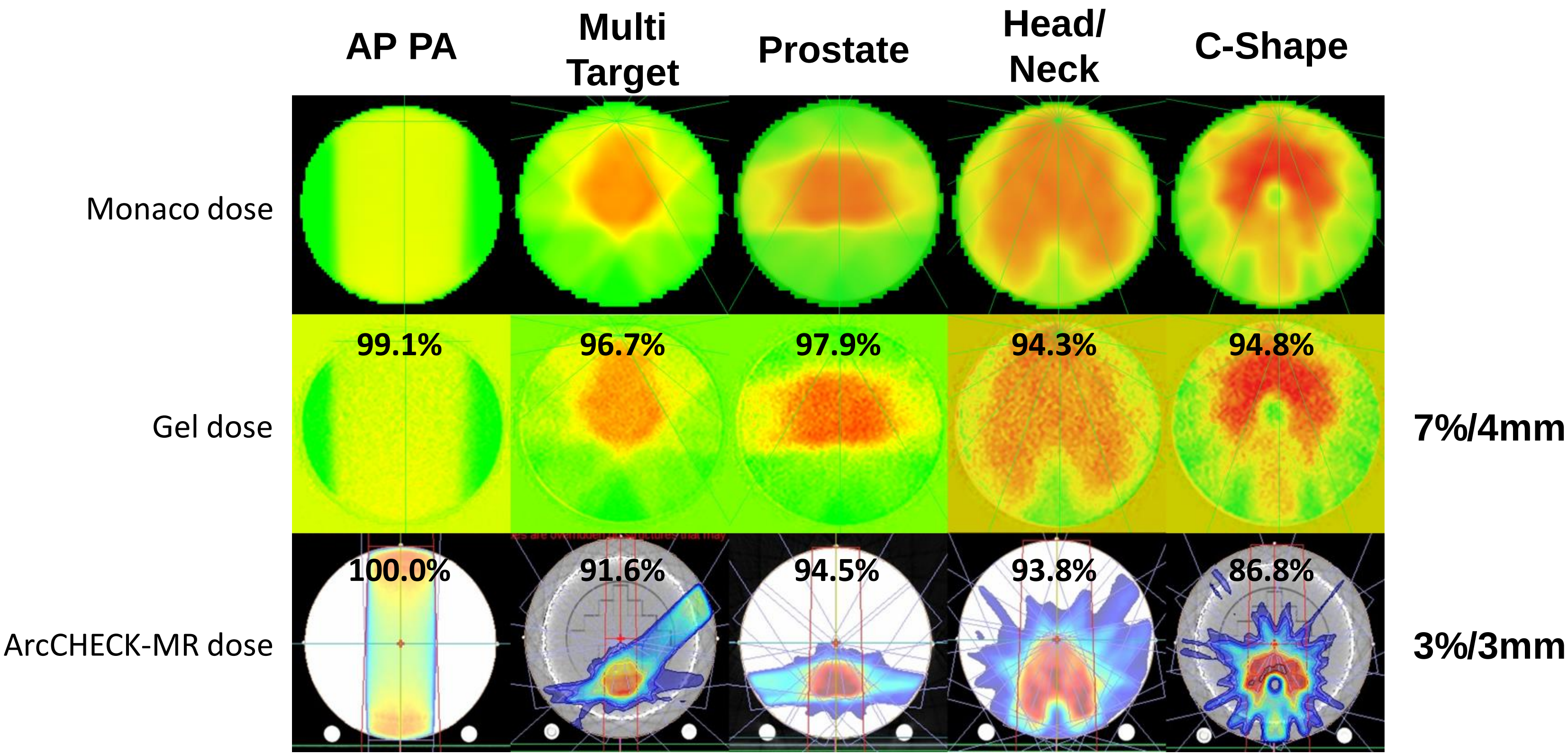


End-to-end Testing



End-to-end Testing: TG-119



Moving Forward

- Motion phantom with deformable gel
  - 4D MRI vs 4D CT
  - Deformable image registration and dose accumulation
- Other tissue-equivalent gels (lung, bone, etc) to create anthropomorphic heterogeneous phantoms
- Post-processing methods to de-noise subtraction MR images for improving dose quantification

Summary

Dosimetric Challenges

- Have to think outside of the box: single laser and no light field
- Devices that are being tested: Ionization chambers, IC Profiler, Starcheck, onboard EPID, ArcCheck, and etc.

Volumetric Dosimeters

- Gel dosimeters can provide valuable 3D dose information and are the only phantoms that can be used for full end-to-end workflow testing
- May be valuable as a training tool prior to patient treatments

Moving Forward

- Continued dosimetry and phantom development including deformation and motion

Thank you!

- Contact: HJLee1@mdanderson.org

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MR-Linac

Investigation of magnetic field effects on the dose–response of 3D dosimeters for magnetic resonance – image guided radiation therapy applications

Hannah J. Lee [a,b,*], Yvonne Roed [a,c], Sara Venkataraman [a], Mitchell Carroll [a,b], Geoffrey S. Ibbott [a,*]

[a] Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, Houston; [b] The University of Texas MD Anderson Cancer Center UTHealth Graduate School of Biomedical Sciences; and [c] Department of Physics, University of Houston, USA

9th International Conference on 3D Radiation Dosimetry IOP Publishing

IOP Conf. Series: Journal of Physics: Conf. Series **847** (2017) 012057 doi:10.1088/1742-6596/847/1/012057

Using 3D dosimetry to quantify the Electron Return Effect (ERE) for MR-image-guided radiation therapy (MR-IGRT) applications

Hannah J Lee[1,2], Gye Won Choi[1,2], Mamdooh Alqathami[1], Mo Kadbi[3], Geoffrey Ibbott[1]

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[2]UT at Houston Graduate School of Biomedical Sciences, Houston, TX

[3]MR Therapy, Philips healthTech, Cleveland, OH

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Physics in Medicine & Biology

IPEM Institute of Physics and Engineering in Medicine

PAPER

Real-time volumetric relative dosimetry for magnetic resonance—image-guided radiation therapy (MR-IGRT)

Hannah J Lee[1,2,5], Mo Kadbi[3], Gary Bosco[4] and Geoffrey S Ibbott[1,5]

[1] Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, Houston, TX, United States of America

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[3] MR Therapy, Philips HealthTech, Cleveland, OH, United States of America

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[5] The University of Texas MD Anderson Cancer Center, 1400 Pressler Street, Houston, TX 77030, United States of America