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

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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...

Interfraction Variability

Setup Error

- Patient positioning
  - Rotation
  - Weight change
  - Skin mark shifts
  - Volume changes
    - Deformation
    - Bladder/rectum volumes
    - Bowel gas motion
    - Peristalsis
    - Respiration
    - Cardiac motion

Intrafraction Variability

Organ Motion

Dosimetric Challenges

Volumetric Dosimeters

Moving Forward
Background

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Dosimetric Challenges

Volumetric Dosimeters

Moving Forward
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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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
Dosimetric Challenges

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Raaijmakers et al. PMB 53 (2008) p913
Electron Return Effect (ERE)

Background

Dosimetric Challenges

Volumetric Dosimeters

Moving Forward

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

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

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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\[
\begin{align*}
    H \cdot + O_2 & \rightarrow HO_2 \cdot \\
    HO_2 \cdot + Fe^{2+} & \rightarrow HO_2^- + Fe^{3+} \\
    HO_2^- + H^+ & \rightleftharpoons H_2O_2 \\
    Fe^{2+} + H_2O_2 & \rightarrow Fe^{3+} + HO^- + HO \cdot \\
    Fe^{2+} + HO \cdot & \rightarrow Fe^{3+} + HO^- \\
        G(Fe^{3+}) & = 3G(H \cdot) + G(HO \cdot) + 2G(H_2O_2) \\
    D & = \frac{N_A \cdot e}{\rho \cdot l \cdot G(Fe^{3+})} \cdot \frac{OD(D) - OD(0)}{\varepsilon_m} \\
    D & = \frac{N_A \cdot e}{10 \rho \cdot G(Fe^{3+})} \cdot \frac{R_1(D) - R_1(0)}{r_{eff}^{3+} - r_2^{2+}}
\end{align*}
\]
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**
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  - Easily created in any shape and minimally toxic chemicals
  - Optical edge artifacts and non-MR-visible signal change
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Electron Return Effect (ERE)
Electron Return Effect (ERE)

PRESAGE – Radiochromic Plastic

FOX – Radiochromic Gel

Normalized Signal vs. Depth (cm)
Real-time 3D Dose Acquisition

Radiochromic Gel

![Graph showing signal intensity over time for 0° and 270° gantry beam on. The graph indicates linear relationships with equations y = 0.17x + 124.71 (R² = 0.97) for 0° and y = 0.16x + 125.78 (R² = 0.99) for 270°. The graph also shows a comparison between un-irradiated and irradiated regions.]
Real-time 3D Dose Acquisition

Polymer Gel

Difference in Signal Intensities between inside and outside of radiation field
Right field edge

Beam on: 2 min 44 sec

Time [s]
MR and Radiation Isocenter Registration

Radiochromic Gel

Background
Dosimetric Challenges
Volumetric Dosimeters
Moving Forward
End-to-end Testing Workflow

CT → TPS Plan → MRI → Deliver plan and MRI → Compare delivered dose to planned dose
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
End-to-end Testing
End-to-end Testing

Monaco dose
End-to-end Testing
End-to-end Testing
End-to-end Testing
End-to-end Testing: TG-119

MC dose

Gel dose

ArcCHECK-MR dose

### Dosimetric Challenges

- **AP PA**
  - Monaco dose: [Image]
  - Gel dose: [Image]
  - ArcCHECK-MR dose: [Image]

- **Multi Target**
  - Monaco dose: [Image]
  - Gel dose: [Image]
  - ArcCHECK-MR dose: [Image]

- **Prostate**
  - Monaco dose: [Image]
  - Gel dose: [Image]
  - ArcCHECK-MR dose: [Image]

- **Head/Neck**
  - Monaco dose: [Image]
  - Gel dose: [Image]
  - ArcCHECK-MR dose: [Image]

- **C-Shape**
  - Monaco dose: [Image]
  - Gel dose: [Image]
  - ArcCHECK-MR dose: [Image]

### Volumetric Dosimeters

- **99.1%**
- **96.7%**
- **97.9%**
- **94.3%**
- **94.8%**
- **100.0%**
- **91.6%**
- **94.5%**
- **93.8%**
- **86.8%**

- **7%/4mm**
- **3%/3mm**
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!

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