Three-dimensional dosimetry of small fields

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Outline

- 3D dosimeters
  - Fricke gel
  - Polymer gel
  - PRESAGE®

- Small field dosimetry
  - Alfonso formalism
  - Applications for 3D dosimetry

- Radiochromic film stack dosimeter
Radiation-induced conversion of ferrous ions to ferric ions

- Different NMR relaxation rates permit MR readout
- Incorporate ferrous sulphate solution into organic gel matrix to measure spatial dose distribution
  - Postexposure ionic diffusion introduces error
  - High electrical conductivity strongly attenuates RF pulses during MR readout
Numerous variants
  - BANG, MAGIC, PABIG, VIPAR
  - Highly toxic acrylamide monomer

Radiation-induced polymerization
  - Alters NMR relaxation rates
  - Produces optical change
  - Inhibited by oxygen
- Radiochromic plastic
  - Optical contrast due to absorption
  - No container required → Reduced edge artifacts

Courtesy of presage3d.com
Problems with small field dosimetry

- How small is small?
  - Field size
  - Detector size
  - Range of secondary electrons

- Source occlusion
  - Breakdown of FWHM field size definition
  - Reduced source output results in field size overestimation

- Loss of CPE
  - Use of cavity theory
  - Charged particle fluence perturbation
    - Dependent on energy and field size


- 3D dosimeters
- Small field dosimetry
- FSD
Alfonso formalism

- Proposed formalism for dosimetry of small and composite fields
  - Established pathways from conventional reference conditions to nonstandard fields

\[
D_{w,Q}^{\text{msr}} = M_{Q}^{\text{msr}} \cdot N_{D,w,Q_0} \cdot k_{Q,Q_0} \cdot k_{Q,Q_\text{msr}}^{f_{\text{msr}},f_{\text{ref}}}
\]

\[
k_{Q,Q_\text{msr}}^{f_{\text{msr}},f_{\text{ref}}} = \frac{D_{w,Q}^{\text{msr}}/M_{Q}^{\text{msr}}}{D_{w,Q}^{\text{ref}}/M_{Q}^{\text{ref}}}
\]

\[
\Omega_{Q,Q_\text{msr}}^{f_{\text{clin}},f_{\text{msr}}} = \frac{M_{Q}^{\text{clin}}}{M_{Q}^{\text{msr}}} \cdot k_{Q,Q_\text{msr}}^{f_{\text{clin}},f_{\text{msr}}}
\]

\[
D_{w,Q_\text{clin}}^{f_{\text{clin}}} = D_{w,Q}^{f_{\text{msr}}} \cdot \Omega_{Q_\text{clin},Q_\text{msr}}^{f_{\text{clin}},f_{\text{msr}}}
\]

Small-field polymer gel dosimetry

- Compared OF and profiles measured with gel, PinPoint chamber, diode array and diamond detector

- Pros
  - Tissue equivalence
  - No fluence perturbation (gel is phantom and dosimeter)
  - Good resolution
  - No positioning errors due to measurement of full distribution

- Cons
  - High uncertainty in smaller voxels
    - Improves with larger voxels, but volume averaging increases
  - Inconsistencies in preparation
  - Differences in calibration and experimental geometries

Profile measurements

- 3D dosimeters
- Small field dosimetry
- FSD

### Output factor measurements

<table>
<thead>
<tr>
<th>Detector type</th>
<th>5.0 mm</th>
<th>7.5 mm</th>
<th>10 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer gel</td>
<td>0.702 ± 0.029</td>
<td>0.872 ± 0.039</td>
<td>0.929 ± 0.041</td>
</tr>
<tr>
<td>PTW 60008 diode</td>
<td>0.737 ± 0.003</td>
<td>0.899 ± 0.004</td>
<td>0.932 ± 0.004</td>
</tr>
<tr>
<td>(Ref. 18)</td>
<td>0.719 ± 0.015</td>
<td>0.849 ± 0.011</td>
<td>0.892 ± 0.011</td>
</tr>
<tr>
<td>(Ref. 19)</td>
<td>0.706 ± 0.002</td>
<td>0.869 ± 0.002</td>
<td>0.911 ± 0.002</td>
</tr>
<tr>
<td>(Ref. 21)</td>
<td>0.746</td>
<td>0.878</td>
<td>0.916</td>
</tr>
<tr>
<td>PTW PinPoint</td>
<td>0.634 ± 0.003</td>
<td>0.802 ± 0.004</td>
<td>0.857 ± 0.004</td>
</tr>
<tr>
<td>(Ref. 21)</td>
<td>0.642</td>
<td>0.804</td>
<td>0.860</td>
</tr>
<tr>
<td>Gafchromic EBT</td>
<td>0.707 ± 0.005</td>
<td>0.850 ± 0.005</td>
<td>0.903 ± 0.005</td>
</tr>
<tr>
<td>(Ref. 19)</td>
<td>0.701 ± 0.002</td>
<td>0.845 ± 0.002</td>
<td>0.902 ± 0.002</td>
</tr>
<tr>
<td>(Ref. 21)</td>
<td>0.640</td>
<td>0.878</td>
<td>0.916</td>
</tr>
<tr>
<td>PTW diamond</td>
<td>0.672 ± 0.025</td>
<td>0.816 ± 0.026</td>
<td>0.850 ± 0.024</td>
</tr>
<tr>
<td>TLD</td>
<td>0.711 ± 0.021</td>
<td>0.851 ± 0.027</td>
<td>...</td>
</tr>
<tr>
<td>GRD</td>
<td>0.701</td>
<td>0.838</td>
<td>0.877</td>
</tr>
<tr>
<td>Monte Carlo</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Detector**

<table>
<thead>
<tr>
<th>Detector</th>
<th>5 mm</th>
<th>7.5 mm</th>
<th>10 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>A16</td>
<td>0.682 (17)</td>
<td>0.825 (10)</td>
<td>0.874 (7)</td>
</tr>
<tr>
<td>PinPoint</td>
<td>0.683 (18)</td>
<td>0.820 (8)</td>
<td>0.875 (5)</td>
</tr>
<tr>
<td>Diode 60008</td>
<td>0.684 (2)</td>
<td>0.829 (3)</td>
<td>0.879 (3)</td>
</tr>
<tr>
<td>Diode 60012</td>
<td>0.674 (2)</td>
<td>0.818 (3)</td>
<td>0.872 (3)</td>
</tr>
<tr>
<td>EDGE</td>
<td>0.689 (2)</td>
<td>0.825 (3)</td>
<td>0.875 (3)</td>
</tr>
<tr>
<td>Alanine</td>
<td>0.679 (11)</td>
<td>0.831 (13)</td>
<td>0.872 (13)</td>
</tr>
<tr>
<td>TLD</td>
<td>0.668 (4)</td>
<td>0.809 (6)</td>
<td>0.880 (8)</td>
</tr>
<tr>
<td>EBT films</td>
<td>0.659 (17)</td>
<td>0.811 (16)</td>
<td>0.853 (18)</td>
</tr>
<tr>
<td>Polymer gels*</td>
<td>0.702 (21)</td>
<td>0.872 (27)</td>
<td>0.929 (29)</td>
</tr>
<tr>
<td>Weighted mean</td>
<td>0.681 (1)</td>
<td>0.824 (1)</td>
<td>0.875 (1)</td>
</tr>
</tbody>
</table>

Previous investigations of radiochromic film stack dosimetry\cite{1,2}

Considered several characteristics:
  - Water equivalence
  - Energy dependence\cite{3}
  - Orientation dependence\cite{4}
  - Measurement uncertainty

Phantom development

- Film stack dosimeter phantom
- Film and ionization chamber phantom
- TLD phantom
- Cylindrical phantom housing
- 3D dosimeters
- Small field dosimetry
- FSD
Circular films with semicircular tabs on the outer diameter
  - Tabs fix azimuthal orientation of films
- Films were laser cut\(^1\) with a tolerance of 0.08 mm
  - Positioning uncertainty within phantom of 0.19 mm
- 1 mm-thick Virtual Water\(^\text{TM}\)\(^2\) spacers interleaved between films
  - Reduces air gap created by film burr

Film stack dosimeter specifications:
- 3.8 cm diameter
- 2.7 cm height
- 22 films and 21 spacers
- 0.02 mm air gaps

1. Laserage Technology Corporation\(^\text{®}\), Waukegan, IL
2. Med-Cal, Inc., Verona, WI
- MCNP simulations used 6 MV point source
  - Spectrum from BEAMnrc model of UWMRRC linac

- Orientation dependence
  - Simulated dose to cylindrical volume at center of film stack
  - Rotated source about longitudinal axis of tally volume
  - Investigated the impact of air gap size

- Water equivalence
  - Simulated PDD in a cylindrical water phantom for comparison with film stack dosimeter measurements
FSD characterization: Simulations

- Energy dependence
  - EBT2 absorbed-dose energy dependence exceeds 10%\textsuperscript{[1]}
  - Incident spectrum varies with field size
  - Simulated and compared photon energy spectrum in calibration and film stack geometries

FSD characterization: Measurements

- PDD profile measurements
  - Phantoms positioned in cylindrical phantom housing for reproducibility
  - Separate measurements with film stack dosimeter oriented perpendicular and parallel to beam axis
  - Dose at depth measured with Exradin A1SL ionization chamber

- Slit field dose distribution
  - Measured with film stack dosimeter and TLD microcubes

1. Standard Imaging, Middleton, WI
Films were read with Epson® Expression® 10000XL flatbed scanner[1]

- Immediately before and seven days after exposure
- Masks center films in scan bed and reduce extra-film scatter
- Elevated films to eliminate Newton’s ring artifacts
- Monitored scanner stability with neutral-density filters

1. Epson America, Long Beach, CA
Orientation dependence less than 1.5% for smaller air gaps
- Under-response of 3% at parallel incidence for larger air gaps
- Statistical uncertainty of 0.5% \( (k = 1) \)

Results: Water equivalence

- Simulated PDD profile converted to dose using ion chamber measurement
  - Film stack measurements normalized to max simulated dose
- Measurements and simulation agree within 2%

Visibly different photon energy spectra in calibration and film stack geometries

Resulting absorbed-dose energy response less than 0.1%
Slit field measurement geometry

- 3D dosimeters
- Small field dosimetry
- FSD
Results: Slit field profiles

- 3D dosimeters
- Small field dosimetry

Two SBRT lung procedures were prepared using Philips Pinnacle\textsuperscript{3}\textsuperscript{[1]}

- Spherical PTV with 2.5 cm diameter
- Prescription: 50 Gy/5 fractions
- Energy: 6 MV
- Step-and-shoot delivery
CT phantom development

- CT dataset of cylindrical phantom housing was created using MATLAB®[1]
  - 2 mm slice thickness
  - 1.35 1.35 mm² pixel size
  - $\rho_{\text{CPH}} = 1.03 \text{ g/cm}^3$
  - $\rho_{\text{film}} = 1.00 \text{ g/cm}^3$

1. MathWorks, Natick, MA, USA
Reduced prescribed MU by a factor of 5 for a dose at isocenter of ~2-3 Gy

Initial DQA of plans performed with Delta\(^4\) diode array detector\(^{[1]}\)
- 99% passing rate using gamma criteria\(^{[2]}\) of 3% and 3 mm

Two measurements of each plan were made with the film stack dosimeter
- Seven-field plan also measured with TLD phantom

 Compared measured and calculated dose distributions
- 1 \(\times\) 1 \(\times\) 1 mm\(^3\) calculated dose grid resolution

1. ScandiDos, Uppsala, Sweden
Seven-field results

Gamma analysis of film stack measurements using criteria of 3%/3 mm
- Greater than 97% agreement with calculation
- Consistent with TLD and Delta^4 measurements

Repeatability
- Five-field plan: 96% of points agree within 5%
- Seven-field plan: 93% of points agree within 5%
- Overall film measurement uncertainty is 5.3% ($k = 2$)

Polymer gel has strengths and weaknesses for small field dosimetry
- Tissue equivalence, good resolution, no fluence perturbation
- Poor reproducibility, high uncertainty

Radiochromic film stack dosimeter provides an alternative 3D dosimeter
- Maintains strengths of gel dosimeter
- Improved reproducibility and uncertainty
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