Reference dosimetry protocols and their application in radiotherapy environments with strong magnetic fields.

CIRMS 2018

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MRI-guided Radiotherapy

- New treatment modality that combines MR-imaging with radiotherapy linacs
- Introduces magnetic fields to the radiotherapy environment
- Current range from 0.35 T to 1.5 T
Standard Reference Dosimetry Protocols
Formalism

Standard Reference Dosimetry Protocols

All major dosimetry protocols use some variation of the following formalisms

Direct Calibration

\[ D_{w}^{Q} = M \cdot N_{D,w}^{Q} \]  (e.g. NPL)

Corrected Calibration

\[ D_{w}^{Q} = M \cdot N_{D,w}^{60Co} \cdot k_{Q} \]  (e.g. AAPM, IAEA)
Beam Quality

Standard Reference Dosimetry Protocols

• Some measurable metric (or beam quality specifier) must be used to determine the radiation quality of the beam.

• Two most common beam quality specifiers are:
  - $\%dd(10)_x$ Used by AAPM TG-51 protocol
    The percentage depth dose at 10 cm depth for a pure photon beam (*no electron contamination*). Must be measured at 100 cm SSD.

  - $TPR_{10}^{20}$ Used by IAEA TRS-398 protocol
    Ratio of the dose at isocenter at a depth of 20 cm to the dose at isocenter at a depth of 10 cm. *Independent of SSD*. Potential for the relationship with $k_Q$ to change for FFF beams.
Beam Quality Correction
Standard Reference Dosimetry Protocols

AAPM TG-51

IAEA TRS-398

\[ k_Q \]

\[ 55 \ 60 \ 65 \ 70 \ 75 \ 80 \ 85 \ 90 \]

\[ 0.94 \ 0.95 \ 0.96 \ 0.97 \ 0.98 \ 0.99 \ 1.00 \ 1.01 \]

\[ \%dd(10)_x \]

\[ k_O \]

\[ 0.50 \ 0.55 \ 0.60 \ 0.65 \ 0.70 \ 0.75 \ 0.80 \ 0.85 \]

\[ Photon \ beam \ quality, \ Q \ (TPR_{20,10}) \]
Complications in Magnetic Fields
Focus where it matters

Lorentz Force

No Magnetic Field

1.5 T Magnetic Field

Electrons (in red) continue to scatter.

However, their trajectory in water/tissue is heavily influenced by the Lorentz force.

Note: Positrons (in blue) are deflected in the opposite direction.
Electron Return Effect

- No Magnetic Field
- 1.5 T Magnetic Field
Beam Quality Determination

Complications in Magnetic Fields

Source to surface distance (SSD) restrictions due to the cryostat
Beam Quality Determination

Complications in Magnetic Fields

• Magnetic field alters the effective point of measurement of ionization chambers.

• Must be accounted for when measuring percentage depth doses (PDDs)

Beam Quality Determination

Complications in Magnetic Fields

Magnetic field alters the depth dose distribution.

- Changes the value of the $\%dd(10)_x$ beam quality specifier

$TPR_{10}^{20}$ effectively independent of magnetic field strength

<table>
<thead>
<tr>
<th>Pure Photon Beam</th>
<th>$d_{\text{max}}$</th>
<th>$%dd(10)_x$</th>
<th>$TPR_{10}^{20}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No magnetic field</td>
<td>1.85</td>
<td>71.4</td>
<td>0.697</td>
</tr>
<tr>
<td>1.5 T magnetic field</td>
<td>1.30</td>
<td>69.7</td>
<td>0.695</td>
</tr>
</tbody>
</table>

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Air Gap Effect
Complications in Magnetic Fields


**Calibration Phantoms**

Complications in Magnetic Fields

* PTW Stationary Water Phantom

* Photo courtesy of Nikolas Marinos, Elekta
Ion Chamber Response

Complications in Magnetic Fields

Adaptation Strategies
Code of Practices?

Adaptation Strategies

THERE ARE CURRENTLY NO PUBLISHED CODES OF PRACTICE FOR DOSIMETRY IN MAGNETIC FIELDS BY ANY MAJOR STANDARDS AUTHORITY.

New facility supports development of MRI-guided radiotherapy

A new electromagnet at the National Physical Laboratory’s (NPL) Theratron radiation facility will enable research supporting MRI-guided radiotherapy - a state-of-the-art cancer treatment.

Radiotherapy treats cancer by focusing beams of ionising radiation on a tumour, killing cancerous cells by damaging their DNA. Radiation delivery must be tightly controlled to minimise damage to the surrounding healthy tissue.

Typically, X-ray based techniques are used to image a patient immediately before treatment to direct the radiation. But tumours move and deform inside a patient’s body with bodily functions such as breathing, and can shift and change in size over the course of treatment.

MRI-guided radiotherapy provides real-time images during a patient’s treatment, and offers more detailed and higher contrast images for the identification of tumours and soft tissues. This boosts tumour targeting accuracy, reducing side-effects and increasing survival rates.

Currently, incurable cancers, such as kidney and pancreatic tumours, which can’t be accurately tracked during treatment, may become treatable.

FIRST WATER CALORIMETER MEASUREMENTS IN AN MRI-LINAC

A leap towards traceable dosimetry for MR-guided radiotherapy

A team of researchers from VSL Dutch Metrology institute and the University Medical Centre Utrecht have, for the first time ever, carried out calorimetric absorbed dose to water measurements in a 1.5 T magnetic field of an Elekta Atlas MR-linac. The measurements that
Formalism

Adaptation Strategies

Current dosimetry formalisms do not account for the effect of the magnet field on the ionization chamber response:

Original Formalism

$$D^Q_w = M \cdot N^{60}_D \cdot k_Q$$

Adapted Formalism

$$D^Q_w = M \cdot N^{60}_D \cdot k_Q \cdot k^Q_B$$

$k^Q_B$ (or $k_B$) is difficult to measure. Monte Carlo difficult to validate empirically.
Ion Chamber Orientation

Adaptation Strategies

$k_B$ vs Beam Quality

Adaptation Strategies

Electromagnet Setups

Adaptation Strategies

• Range of magnetic fields

• Requires small volume water phantom – limited phantom scatter / field size

• Chamber is restricted to an orientation perpendicular to the magnetic field and the beam


Dose to Water
Adaptation Strategies

- NPL using Alanine
- Calorimetry
  - Water calorimetry (VSL)
  - Graphite calorimetry (see next presentation)

Published values of $k_B$

Adaptation Strategies

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Challenges</th>
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<tbody>
<tr>
<td>High accuracy</td>
<td>Low availability</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$k_B (1.5 \text{ T})$</th>
<th>$\l_A$</th>
<th>$\l_A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A12 (0.65)</td>
<td>0.9993</td>
<td>0.9940</td>
</tr>
<tr>
<td>A19 (0.62)</td>
<td>1.0007</td>
<td>0.9964</td>
</tr>
<tr>
<td>A2 (0.54)</td>
<td>0.9989</td>
<td>0.9952</td>
</tr>
<tr>
<td>T2 (0.54)</td>
<td>1.0004</td>
<td>0.9990</td>
</tr>
<tr>
<td>A12S (0.25)</td>
<td>0.9984</td>
<td>0.9962</td>
</tr>
<tr>
<td>A18 (0.125)</td>
<td>0.9981</td>
<td>0.9971</td>
</tr>
<tr>
<td>T1 (0.057)</td>
<td>0.9962</td>
<td>0.9983</td>
</tr>
<tr>
<td>A1SL (0.057)</td>
<td>0.9966</td>
<td>0.9983</td>
</tr>
<tr>
<td>A14* (0.016)</td>
<td>0.9718</td>
<td>0.9827</td>
</tr>
<tr>
<td>T14* (0.016)</td>
<td>0.9696</td>
<td>0.9837</td>
</tr>
<tr>
<td>A10* (0.016)</td>
<td>0.9725</td>
<td>0.9823</td>
</tr>
<tr>
<td>A16* (0.016)</td>
<td>0.9600</td>
<td>0.9830</td>
</tr>
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</table>


Currently published values are Monte Carlo based. Most studied chamber is the waterproof PTW 30013 Farmer chamber.


23 | Focus where it matters
Need for standards
Need for standards

• Current protocols do not explicitly account for magnetic fields

• Adapting existing protocols in a clinic means deviating from the protocols (Legal implications? Accreditation implications?)

• Limited published data – need for consensus and standardization
Thank you

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