Optical Calorimetry: A novel technique for measuring absorbed dose to water in radiotherapy

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I. Introduction
Introduction

- ADW is the quantity of relevance in radiotherapy
- Calorimetry is the most common technique for ADW standards
  \[ D_w = \Delta T \cdot c_w \]
- The temperature changes of interest are in the sub-mK range

Graphite calorimeter

Water calorimeter

Image source: Agenzia Nazionale per le Nuove Tecnologie, Italy
www.enea.it/produzione-scientifica

Image source: Physikalisch-Technische Bundesanstalt, Germany
www.ptb.de
Problem Statement

• Thermistor drawbacks: self-heating in radiation field due to low heat capacity

• Optical calorimetry uses the temperature dependence of the refractive index of transparent media

• Advantages:
  a) The ability to measure temperature changes without a mechanical probe
  b) The capability to obtain 2D and 3D dose distributions

* EGSnrc-generated simulation for the UWMRRRC linac
The goal of this investigation is to establish accurate and precise interferometric measurements for water calorimetry over a single projection in a 6 MV radiation field.
### Previous Works

<table>
<thead>
<tr>
<th>Author</th>
<th>Detector</th>
<th>Radiation source</th>
<th>Dose range</th>
<th>Resolution / noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hussmann</td>
<td>Holographic plate</td>
<td>Non-clinical electron beam</td>
<td>3000-22000 Gy</td>
<td>100 Gy</td>
</tr>
<tr>
<td>Miller-Hussmann</td>
<td>Photodiode</td>
<td>Non-clinical electron beam</td>
<td>100 Gy</td>
<td>3.5 Gy</td>
</tr>
<tr>
<td>Ackerly</td>
<td>CCD</td>
<td>Synchrotron microbeam</td>
<td>&gt;1000 Gy</td>
<td>Unknown</td>
</tr>
<tr>
<td>Cavan-Meyer</td>
<td>CMOS</td>
<td>HDR brachytherapy source</td>
<td>0-120 Gy</td>
<td>3.5 Gy</td>
</tr>
</tbody>
</table>

Temperature dependence of the refractive index of water \( (dn_w / dT) \)

a) From measurements

b) From models

- International Association for the Properties of Water and Steam formalism:

\[
\frac{n_w^2 - 1}{n_w^2 + 2 \left( \frac{1}{\rho} \right)} = a_0 + a_1 \rho + a_2 \frac{T}{273.15} + a_3 \left( \frac{\lambda}{589} \right)^2 + a_4 \frac{T}{273.15} + a_5 \left( \frac{589}{\lambda} \right)^2 + \frac{a_5}{\lambda^2} - \lambda_{UV}^2 + \frac{a_5}{\lambda_{IR}^2} + a_7 \rho^2
\]

- The International Association for the Properties of Water and Steam. Release on the refractive index of ordinary water, (1997)
II. Methods
Interferometer Setup

He-Ne Laser
Interferometer Setup
ADW Measurements with Interferometry

1. Introduction
2. Methods
3. Results
4. Conclusions

Radiation beam

Temperature (ºC)
Refractive index

Water

ADW \rightarrow \uparrow T \rightarrow \downarrow n \rightarrow PS \rightarrow \Delta I
Three-Phase Protocol

First phase:
Pre-irradiation measurement

Second phase:
Irradiation time

Third phase:
Post-irradiation measurement

ΔPS

τ

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Interferometer-based formalism

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\[ D_w = \frac{1}{1 - k_{\text{HD}}} \cdot c_w \cdot k_a \cdot k_f \cdot \lambda \cdot FS_x \cdot \frac{dn_w}{dT} \cdot \Delta PS \]
Zero-dose measurements

a) Without water along the beampath
b) With water along the beampath

\[ \tau = 20, 30 \text{ and } 40 \text{ s} \]
TPS-based Calculations

1. Introduction
2. Methods
3. Results
4. Conclusions

1. Take CT scan of water phantom
2. Import to Eclipse
3. Calculate
4. Define:
   - Geometry
   - Beam energy
   - Points of interest

1 Virtual Water™ (Med-Cal, Inc, Verona, WI)
2 Eclipse™ (Varian Medical Systems, Inc. Palo Alto, CA)
## Radiation-induced Measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Horizontal beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>6 MV</td>
</tr>
<tr>
<td>Gantry angle</td>
<td>90º</td>
</tr>
<tr>
<td>MUs</td>
<td>200, 300, 400, 500</td>
</tr>
<tr>
<td>Field Size</td>
<td>7.0 x 7.0 cm²</td>
</tr>
<tr>
<td>SSD</td>
<td>100 cm</td>
</tr>
<tr>
<td>Depth of measurement</td>
<td>5 cm</td>
</tr>
</tbody>
</table>

1. Introduction  
2. Methods  
3. Results  
4. Conclusions
III. Results and Analysis
Results

- Zero-Dose Measurements Without Phantom

- Optics-associated contribution (vibrations, intensity and frequency stability)
- No trend observed on mean and median values
- Average SD of 0.12 Gy
Results

- Zero-Dose Measurements With Phantom

With the water phantom

- Optics-associated contribution + thermal effects
- Average 0.06 Gy offset produced by water heating induced by the laser
- Average SD of 0.28 Gy
Results

• ADW measurements vs TPS calculations

Improved accuracy achieved by:

• Reducing vibrations
• Controlling laser and interferometer temperature
• Accounting for temperature drifts
• Minimizing radiation-interferometer interactions
Conclusions

• Designed and characterized an interferometer for optical calorimetry

• Interferometer –based measurements agree within the uncertainty with TPS calculations

• Identified the most significant contribution to the uncertainty

• Measured ADW with a resolution of 0.3 Gy, an order of magnitude better than previous published results
Future Work

- Improving water thermal stability
- Implementing active thermal control
- Correcting for heat transfer
- Controlling and mitigating heat defect
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  • Megan Wood
  • Eric Simiele

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Thanks for your attention!
Questions?