Geant4 for brachytherapy

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Why Geant4 for brachytherapy

- Quality assurance
  - Plan checking
Why Monte Carlo For Brachytherapy

- Quality assurance
  - Plan checking
- Source modelling
  - TG-43 data
Why Monte Carlo For Brachytherapy

• Quality assurance
  • Plan checking

• Source modelling
  • TG-43 data

• Detector optimisation
  • Geometry
  • Materials
AAPM Task Group 43 Report

- The TG43 report recommends the dose rate for a cylindrical source be expressed in 2D coordinates in terms of separable functions

\[ D^*(r,\theta) = S_k \cdot \lambda \cdot \left[ \frac{G(r,\theta)}{G(r_0,\theta_0)} \right] \cdot g(r) \cdot F(r,\theta) \]

Where
- \( S_k \) is the air kerma strength
- \( \lambda \) is the dose rate constant
- \( G(r,\theta) \) is the geometry function
- \( g(r) \) is the radial dose function
- \( F(r,\theta) \) is the anisotropy function
- \( (r_0,\theta_0) \) is the reference point
TG43 Data Limitations

- TG43 data is limited for this application as
  - The data sets for the anisotropy function begin at 5mm depth
  - Anisotropy function data is available at 0.5, 1, 2, 3, 4 and 5cm radial distance from the seeds

- A more thorough dosimetric dataset at close distances may be desired for close range applications
The Goal

- Use Monte Carlo to develop two dimensional arrays of dosimetric data about brachytherapy seeds
  - Radially every mm from 1 to 25mm
  - Angularly every 5° from 0 to 90°

- Import the arrays into the dosimetric software

- Geant4 was the toolkit of choice to perform a Monte Carlo based dosimetric analysis to produce the array

<table>
<thead>
<tr>
<th>Angle (degrees)</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
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</thead>
<tbody>
<tr>
<td>Radial distance (mm)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>0</td>
<td>x</td>
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</tr>
</tbody>
</table>
Geant4 for Brachytherapy

- Allows for ease of source modelling
- Supports low energy electromagnetic physics models
  - Down to 250 eV

Amersham Health model 6711 I-125
Amersham Health model 6702 I-125
I-125 generated as a radioactive coating on silver core, 1-3 µm depth

The Model

• Seeds placed at centre of 30x30x30 cm³ liquid water phantom

• Seeds located at centre of 25 concentric spherical shells

• Shells from 1mm to 25 mm radius

• Shells of thickness 0.05 mm

• Any energy deposition within a spherical shell is sent to a scoring routine
The Scoring Routine

• Used to tabulate the data in the required format \((r, \theta)\)
  • Scoring array \([25][19]\)
    For 25 shells, 19 angles
• The radius in mm is simply the shell number
• The angle is calculated using the coordinate of deposition
  \[ \theta = \cos^{-1}(\frac{|z|}{r}) \]
  rounded to nearest 5°
Energy deposition added to deposition array at \([r-1][\theta/5]\)
Model Output

• At the end of the simulation
  • Output the dose per particle for each component of the radius-angle array to file

• Calculate TG43 formalism functions from obtained data for correlation with standard values
Model Output

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  - Output the dose per particle for each component of the radius-angle array to file

- Calculate TG43 formalism functions from obtained data for correlation with standard values

\[
G(r, \theta) = \sin^{-1}\left(\frac{L \sin(\tan^{-1} \left[ \frac{r \sin(\theta)}{r \cos(\theta) - L/2} \right])}{\sqrt{\left[r \sin(\theta)\right]^2 + \left[r \cos(\theta) + L/2\right]^2}}\right). \\
\]

Geometry function

\[
g_X(r) = \frac{\dot{D}(r, \theta_0)G_X(r_0, \theta_0)}{\dot{D}(r_0, \theta_0)G_X(r_0, \theta_0)} \\
F(r, \theta) = \frac{\dot{D}(r, \theta)G_L(r, \theta_0)}{\dot{D}(r_0, \theta_0)G_L(r, \theta)}
\]

Radial dose function  Anisotropy Function

Implementation of TG43 functions skipped due to time constraints !!!
Model Commissioning

• To test the validity of the model

• Spherical shells adjusted
  • Radius every 5 mm
  • From 5 mm to 10 cm

• Radial dose function and anisotropy function plotted

Radial dose function
Amersham Health 6711

TG43 – red
Monte Carlo - black
Model Commissioning

Anisotropy function, $F(r, \theta)$
Amersham Health 6711

$r = 1\text{cm}$
TG43 – red
Monte Carlo - black

$r = 2\text{cm}$
TG43 – red
Monte Carlo - black

- Agreement within 5% for angles greater than $45^\circ$
- Under-response at small angles
Model Commissioning

- Radial dose function
  - Agreement within 2.5% for radii up to 25 mm
  - Under-response with depth
- Anisotropy function
  - Agreement within 5% for angles above 45°
  - Under-response for small angles
- The results indicate the titanium capsule walls, 7 µm, may be modelled
  - Too thin on the sides
    - Spectrum too soft, radial dose function low with depth
  - Too thick at the end caps relative to sides
    - Anisotropy function low at small angles
Model Commissioning

- TG43 formalism data obtained using a combination of:
  - TLD measurements – 8.7% uncertainty
  - Monte Carlo: 2.5% uncertainty at 1cm
  - Monte Carlo: 5% uncertainty at 5cm

Where to apply the models

- Eye plaque Brachytherapy
  - I-125 based plaque (ROPES)
  - An artist's impression of an eye plaque during the treatment of an eye

- Prostate brachytherapy dosimetry
Prostate brachytherapy dosimetry

• The Seed Dosimetry Toolkit
  • Allows input of seed plans
  • Constructs
    • Isodose curves
    • DVHs
  • Allows the export of seed coordinates for full plans in portable seed array (.psa) files
Prostate brachytherapy dosimetry

- Brachy_plot
  - Geant4 application
  - Import .psa files
  - Allows plotting of
    - Dose colour maps
    - Isodose curves
  - Allows point dosimetry in desired locations
Brachy_plot

• Imports seed locations
  • Placing full seed geometric models into a detector construction class

• Uses a random number generator to select a seed coordinate for the primary vertex in a primary generator class

• Records dose deposition in 700x700 dose grids of voxel size 0.001mm³ using a sensitive detector class

• 15 dose grids, 5mm apart
Brachy_plot

• Stores all doses in memory during run
  • No writing to hard disk
  • Optimises speed

• Calls an analysis manager class at end of run
  • The ROOT analysis package
  • Takes dose grids from memory
  • Creates histograms for the dose grids on each of the 15 scoring planes
Seed Dosimetry Toolkit generated isodose curves

Brachy_plot generated isodose curves
Applications of Brachy_plot

• Calcification studies
  • Effect of calcifications within the prostate on dosimetry

• Optimisation of detectors
  • For development of in-vivo dosimeters for
    • Urethral dosimetry
    • Rectal dosimetry
The urethral mini-dosimetry system

The urethral mini-dosimetry system is an intraoperative real time dosimetry system for LDR permanent prostate brachytherapy using spectroscopic dosimetry.

- Measures point doses
- Measures dose at any point along the urethra
- Measures dose profiles along the urethra during implantation
- Provide post planning system verification through post implant dosimetry
The urethral mini-dosimetry system

- The design allows us to insert a silicon mini-detector into the urethra
- The probe is small and flexible, which allows it to be placed inside a Foley catheter during a seed implantation
The silicon mini-detector

The Centre of Medical Radiation Physics have developed a silicon mini-detector and preamplifier/amplifier system to satisfy the spectroscopic requirements of the urethral probe.

Silicon detector design featuring a planar $p^+ n n^+$ diode

The detector is designed to provide highly isotropic measurements under full depletion.
Probe construction

- Kapton carrier housing the detector and surface mounted electronics
- A Field Effect Transistor (FET), directly coupled to the detector, provides immediate amplification of pulses
- The Aluminium shields serve to protect the signals from electromagnetic radiation
BrachyView

- New in-body ultra-functional probe:
  - Ultrasound, CT and radiation source imaging captured real-time
- Used in HDR and LDR brachytherapy
- Applications
  - Seed Positioning in tumour
  - Real-time CT imaging
Seed Positioning

- Medipix detector array mounted within ultrasound probe to obtain images of seeds
- Seed configuration obtained through reconstruction

Resolution of seed 3D localisation is 0.1mm
Real-time CT Imaging

- In body CT with rotating X-ray tube
- 80 times less dose than CT
- Diagnostic and screening capability
Thank You