Developing a model of an electronic portal imaging device using Geant4

SAM BLAKE | Ph.D. Candidate
INSTITUTE OF MEDICAL PHYSICS | SCHOOL OF PHYSICS
THE UNIVERSITY OF SYDNEY
Introduction

Portal imaging in radiotherapy

- Electronic Portal Imaging Devices (EPIDs)

- High-resolution $a$-$Si$ flat panel used for real time:
  - MV imaging (indirect detection; phosphor scintillator)
  - Dosimetry (direct detection; no phosphor)
Introduction

Portal imaging in radiotherapy

- EPIDs used clinically for\(^1\):
  - IGRT
  - Patient setup verification
  - *In vivo* dosimetry\(^2\)

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Introduction

Geant4

- Monte Carlo toolkit for radiation transport
- OOD, C++
- Spans multiple energy scales:
  - High energy
  - Low energy extensions
  - Optical
Motivation

• Long term development of dual-mode EPID
  • Currently, commercial EPIDs optimized for imaging
  • Removing the phosphor improves response for dosimetry, but worsens image quality
  • Accurate EPID model would allow for investigation of configuration optimized for imaging and dosimetry

• Self-consistent approach to modelling high energy and optical transport within EPIDs not previously studied
  • Conflicting views in literature regarding importance of modelling optical transport
### Table 1. Summary of optical studies in previous Monte Carlo EPID simulations.

<table>
<thead>
<tr>
<th>Study</th>
<th>Optical transport scored?</th>
<th>Noteworthy conclusions</th>
</tr>
</thead>
</table>
| 1 Siebers et al.       | no                        | • Estimate optical blurring should be significantly less than 1mm.  
                          |                           | • Able to reproduce field size dependence of EPID response without optical correction but with empirically derived backscatter correction.                        |
| 2 Kirkby et al.        | yes                       | • Incorporating optical spreading noticeably broadens overall PSF kernel compared to scoring energy deposition in phosphor alone  
                          |                           | • Use separate code for modelling optical transport                                                                                                   |
| 3 Cremers et al.       | yes                       | • Since energy deposition in phosphor depends on incident x-ray energy, optical transport must be considered.  
                          |                           | • Use separate code for modelling optical transport                                                                                                   |
| 4 Schach von Wittenau et al. | no                        | • Estimate optical blurring should be ~1mm or ~1 pixel in their notional detector.                                                                 |
| 5 Kausch et al.        | yes                       | • It is mandatory to simulate optical transport within phosphor to make quantitative predictions for MTF, NPS, DQE  
                          |                           | • Use separate code for modelling optical transport                                                                                                   |


Project Goals

1. Develop a comprehensive MC model of a linac beam and EPID using Geant4

2. Investigate the optical physics processes operating within the phosphor and photodiode

3. Validate this model by comparing with experimental data
Model Overview

2 main components:
1. Linac source
   - Previous work
   - To be revisited...
2. EPID detector
   - Current work
- IAEA published phase-space files
  - Store physical data (e.g. $E$, $x$, $p$) as particles pass through scoring plane
  - 5 square field sizes
- Simulated energy deposited in water, compared to measured data
- Benchmarked uncertainties
Model Overview - Linac

Relative dose profiles in water at $d_{\text{max}}$

- 20x20 Ref
- 20x20 Sim
- 15x15 Ref
- 15x15 Sim
- 10x10 Ref
- 10x10 Sim
- 5x5 Ref
- 5x5 Sim
- 3x3 Ref
- 3x3 Sim
Model Overview - Linac

PDDs in water along CAX

![Graph showing PDDs in water along CAX with depth on the x-axis and relative dose on the y-axis.](graph.png)
Model Overview - EPID

- Series of uniform slabs
- Define material & geometry for each layer
- Specify physical properties for each material
Processes involving optical photons:
- Reflection & refraction at medium boundaries
  - Specify surface/boundary properties: G4OpticalSurface
- Bulk absorption
- Rayleigh and Mie scattering

Processes generating optical photons:
- Cerenkov radiation
- Transition radiation
- Scintillation
• Scintillation invoked via G4Scintillation class

• Required parameters:
  • Scintillation yield (photons/MeV)
  • Resolution scale
  • Optical photon emission spectra, \( I(E) \):
    • Fast component & time decay constant
    • Slow component & time decay constant
    • Yield ratio
Optical Physics in Geant4

const G4int nEntries3 = 9;
G4double ScntE[nEntries3] = { 6.6*eV, 6.7*eV, 6.8*eV, 6.9*eV, 
                              7.0*eV, 7.1*eV, 7.2*eV, 7.3*eV, 7.4*eV };

G4double RI3[nEntries3] = { 2.4, 2.4, 2.4, 2.4, 2.4, 2.4, 2.4, 2.4, 2.4 };

G4double Absorption3[nEntries3] = { 4.0*cm, 4.0*cm, 4.0*cm, 4.0*cm, 4.0*cm, 
                                   4.0*cm, 4.0*cm, 4.0*cm, 4.0*cm };

G4double ScntFast[nEntries3] = { 0.000134, 0.004432, 0.053991, 0.241971, 
                                0.398942, 0.000134, 0.004432, 0.053991, 0.241971 };

G4double ScntSlow[nEntries3] = { 0.00001, 0.00002, 0.00003, 0.004, 
                               0.008, 0.005, 0.02, 0.001, 0.00001 };

G4MaterialPropertiesTable* myMPT3 = new G4MaterialPropertiesTable();
myMPT3->AddProperty("RINDEX", ScntE, RI3, nEntries3);
myMPT3->AddProperty("ABSLENGTH", ScntE, Absorption3, nEntries3);
myMPT3->AddProperty("FASTCOMPONENT", ScntE, ScntFast, nEntries3);
myMPT3->AddProperty("SLOWCOMPONENT", ScntE, ScntSlow, nEntries3);
myMPT3->AddConstProperty("SCINTILLATIONYIELD", 1000./MeV);
myMPT3->AddConstProperty("RESOLUTIONSCALE",2.0);
myMPT3->AddConstProperty("FASTTIMECONSTANT", 1.*ns);
myMPT3->AddConstProperty("SLOWTIMECONSTANT",10.*ns);
myMPT3->AddConstProperty("YIELDRATIO", 0.8);
Sci->SetMaterialPropertiesTable(myMPT3);
How can we validate all this?

Currently focusing on scoring:
1. Energy deposited in phosphor
2. Optical photon hits in $a$-Si photodiode

Observing effects of varying backscatter thickness
- Clinical sources of BS (e.g. EPID support arm)
- Uniform BS used in previous modelling\(^1\)

Total energy deposited in phosphor layer by 1 MeV monoenergetic broad beam for various BS thicknesses
Narrow beam (width = 0.4 mm) used to generate line of incident radiation.

- Allows measurement of Line Spread Function (LSF) in detector layers.
- LSF gives spatial resolution of an imaging system.
Narrow Beam Simulations

Total energy deposited in phosphor layer by 1 MeV monoenergetic narrow beam for various BS thicknesses

Energy Deposited (keV)

Distance from Central Axis (mm)
Narrow Beam Simulations

LSF of total optical photon hits in the a-Si photodiode from a narrow 1MeV monoenergetic beam for various BS thicknesses

Number of optical photon hits vs Distance from central axis (mm) for various BS thicknesses:
- 50mmBS
- 40mmBS
- 30mmBS
- 20mmBS
- 10mmBS
- 0mmBS
• Primary A:
  • Non-BS
  • trackingStatus = 0

• Primary B:
  • BS
  • trackingStatus = 1
    (after backscattering)

• trackingStatus label inherited by secondaries
Non-backscattered Hits

LSF of non-BS optical photon hits in the a-Si photodiode from a narrow 1MeV monoenergetic beam for various BS thicknesses

Number of optical photon hits vs Distance from central axis (mm) for various BS thicknesses (50mmBS, 40mmBS, 30mmBS, 20mmBS, 10mmBS, 0mmBS).
Backscattered Hits

LSF of BS optical photon hits in the a-Si photodiode from a narrow 1MeV monoenergetic beam for various BS thicknesses.

Number of optical photon hits

Distance from central axis (mm)
Conclusions

- Preliminary model of an EPID has been developed using Geant4
- Optical photon transport has been modelled and is currently being refined
- Backscattered contributions to EPID signal may be tracked independently
- Initial LSF simulations demonstrate noticeable signal blur due to scattered optical photons
Future Work

- Validation of optical modelling
  - Particularly important for phosphor

- Comparison of LSF simulations with experimental LSF measurements

- Use of phase-space linac source model in conjunction with EPID detector model
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