Clinical Implementation and Application of Monte Carlo Methods in Photon & Electron Dose Calculation – New Issues to Consider in Clinical Practice

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Outline

❖ Introduction to Monte Carlo methods
❖ Commissioning and clinical implementation of Monte Carlo based system
❖ Implementation, Operational and Physics related issues
❖ Clinical significance of Monte Carlo based system
Photon Monte Carlo
Neelam Tyagi, Ph.D.

What are Monte Carlo methods?

- Use probability distributions governing the individual interactions of electrons and photons to simulate the random trajectories of individual particles (Rogers and Bielajew)

- The process is simulated a number of times to obtain the average quantity
**Monte Carlo transport of radiation**

**photon transport**

At each interaction Point:
- Compton
- photo-electric
- pair production

Interaction probabilities depend on energy, atomic no., density

**Analog Transport**

![Image of analog transport diagram]

Courtesy I.J. Chetty

**Phonon transport schemes**

**Conventional Photon Tracking**

- The probability distribution function for photons interacting in a homogeneous medium is given by:
  
  $$ P(R) = \mu e^{-\mu R} $$

  where $\mu$ is the mass attenuation coefficient, and $R$ the distance to next collision

  $$ P'(R) = \int_0^R \mu e^{-\mu R} = R = -\ln(\xi)/\mu $$

  The mean collision distance for a 2 MeV photon in water is $\sim 20$ cm

![Image of conventional photon tracking diagram]

Courtesy I.J. Chetty
Rationale for Monte Carlo dose calculation for photon beams

Aarup et al, Radiotherapy & Oncology 2009

ρ\text{lung} = 0.1 \text{ g/cc} (Expiration)

ρ\text{lung} = 0.4 \text{ g/cc} (Expiration)

ρ\text{lung} = 0.1 \text{ g/cc} (Deep Inspiration)

ρ\text{lung} = 0.1 \text{ g/cc} (Deep Inspiration)
Radiotherapy specific general purpose codes

Modeling Radiotherapy beams

- BEAMnrc
- MCNP
- GEANT
- Penelope

Optimized for Patient dose calculation only

- Peregrine
- VMC/XVMC
  - DPM
  - MCDose

Commercially available Monte Carlo systems

- CMS Monaco
  - Algorithm: source model
  - 3D conformal, IMRT (SMLC & DMLC)
  - and VMAT capability No wedges

- Brainlab iPlan
  - Algorithm: source model
  - 3D conformal, IMRT (SMLC & DMLC)
  - and VMAT capability No wedges

- Accuray Multiplan
  - Algorithm, source model
  - Radiosurgery specific
Linear accelerator beam modeling

- Patient independent structures
- Patient dependent structures

Phase space - x, y, z (position), u,v,w (direction), energy

Linear Accelerator Beam Modeling:
Three different approaches

- Direct phase space simulation
- Virtual source model derived from phase space simulation
- Virtual source model derived from measurements

Chetty et al. AAPM TG-105
Virtual Source model in Commercial TPS

Commissioning of Monte Carlo based System

Data for beam Characterization specified by the vendor
(Fraass et al, AAPM TG-53, Das et al, AAPM TG 106)
- CAX pdd & profile scans in water: square fields (1x1 to 40x40 cm²), rectangular fields, Diagonal profile scans in water
- Output factors in water
- Absolute dose in water (linac calibration geometry)

Requires two levels of testing:
1. Radiation output from the linear accelerator
   - Beam model (square fields, output factors, electron contamination)
   - Beam modifying devices
2. Dose calculation in homogeneous and heterogeneous geometries
MC validation report: pdds, profiles & output factors

PDDs, and Profiles for various field sizes & depths

Beam model verification: beam modifiers
Beam model verification: build-up dose region, oblique incidence

- Choice of measurement detector
- Electron contamination model
  Important for breast & Head and Neck plans

Panettieri et al, Radiotherapy Oncology, 2009

Dose comparisons in heterogeneous medium

Slab inhomogeneity phantom
Head & Neck phantom

Chetty et al, PMB, 2003
Tyagi et al, PMB, 2006
Implementation and operational issues

Issues addressed in

- **NCI report**
  

- **AAPM Task group 105**
  

- **AAPM Summer School**
  
  “Integrating new technologies into the clinic: Monte Carlo and Image-Guided Radiation Therapy”, AAPM Summer school 2006

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Commercial Treatment Planning System

**User Input**
- Grid/Voxel spacing
- Uncertainty based # of Histories
- Dose reporting (Dose-to-medium vs. Dose-to-water)
Effect of statistical uncertainty

- Sources of statistical uncertainty –
  - treatment head uncertainty (concern for PS based models, not a concern for measurement based source models)
  - patient simulation uncertainty

- Commercial MC systems based on uncertainty based # of histories
  (specify % uncertainty per control point or per plan)

Effect of statistical uncertainty: IDLs & DVHs

5% 3% 0.5%
CT-number to material conversion

- Conventional TPS algorithm are based on HU-to-material density conversion
- Particle interactions in MC simulations require knowledge of both material density and material composition for appropriate cross-section
- Medium and/or mass density mis-assignment could result in dose errors of up to 10% for 6MV and 30% for 18 MeV (Verhaegen and Devic, PMB, 2005)

CT-number to material conversion

- Relating CT # to interaction probabilities (Kawrakov et al, Med Phys, 1996)
- Stoichiometric CT calibration method (Vanderstraeten et al, PMB 2007)
- Dual energy CT based material extraction (Bazalova et al, PMB 2008)
Dose-to-medium vs. Dose-to-water

Dogan et al, PMB 2006

Clinical significance of a Monte Carlo based TPS

- VMAT planning for kernel based method vs. Monte Carlo in terms of planning QA and planning time
- Comparison of Kernel based methods vs. Monte Carlo for clinical sites such as breast, head and neck and lung
- Optimizing prescription based on Monte Carlo dose calculation
- TCP and NTCP or outcome modeling based on MC dose calculation engine
Head and Neck

Paelinck et al, Radiotherapy & Oncology 2006

Spirodovich et al, Radiotherapy & Oncology 2006

Lung SBRT (Pencil Beam vs. Monte Carlo)

Fragoso et al

PMB 2010
Lung SBRT: Effect of Tumor size & location

<table>
<thead>
<tr>
<th>Tumor Type</th>
<th>D95</th>
<th>D99</th>
<th>Dmean</th>
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<tr>
<td>Peripheral</td>
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<tr>
<td>&lt;3 cm</td>
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<tr>
<td>3-5 cm</td>
<td>21±8 (6-33)</td>
<td>12±5 (7-22)</td>
<td>12±5 (7-22)</td>
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<tr>
<td>&gt;5 cm</td>
<td>10±4 (7-18)</td>
<td>8±4 (3-18)</td>
<td>8±4 (3-18)</td>
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<tr>
<td>Central</td>
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<td></td>
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<tr>
<td>&lt;3 cm</td>
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<td></td>
</tr>
<tr>
<td>3-5 cm</td>
<td>14±6 (7-25)</td>
<td>12±6 (4-25)</td>
<td>12±6 (6-16)</td>
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<tr>
<td>&gt;5 cm</td>
<td>8±2 (4-10)</td>
<td>7±3 (3-14)</td>
<td>7±3 (3-14)</td>
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<tr>
<td>Peripheral</td>
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<tr>
<td>&lt;3 cm</td>
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<td></td>
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<tr>
<td>3-5 cm</td>
<td>16±7 (5-33)</td>
<td>11±4 (6-18)</td>
<td>11±4 (6-18)</td>
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<tr>
<td>&gt;5 cm</td>
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<tr>
<td>Central</td>
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<tr>
<td>&lt;3 cm</td>
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<tr>
<td>3-5 cm</td>
<td>15±7 (1.27)</td>
<td>13±7 (4-25)</td>
<td>9±3 (6-15)</td>
</tr>
<tr>
<td>&gt;5 cm</td>
<td>8±2 (6-10)</td>
<td>6±4 (0-13)</td>
<td>6±4 (0-13)</td>
</tr>
</tbody>
</table>

Van der Voort van Zyp et al, Radiotherapy & Oncology 2010

Optimizing prescription for lung SBRT

<table>
<thead>
<tr>
<th>Tumor Type</th>
<th>EPL dose</th>
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<tbody>
<tr>
<td>Peripheral Tumors</td>
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<tr>
<td>&lt; 3 cm</td>
<td>3x16 Gy</td>
<td>3x17 Gy</td>
<td>3x18 Gy</td>
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<tr>
<td>3-5 cm</td>
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<tr>
<td>&gt; 5 cm</td>
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<td></td>
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<tr>
<td>Central Tumors (close to esophegus)</td>
<td>6x7 Gy</td>
<td>6x7,3 Gy</td>
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<tr>
<td>3-5 cm</td>
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<td></td>
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<tr>
<td>&gt; 5 cm</td>
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<td></td>
</tr>
<tr>
<td>Central Tumors</td>
<td>5x10.4 Gy</td>
<td>5x11 Gy</td>
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</tr>
<tr>
<td>3-5 cm</td>
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<tr>
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