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

Neelam Tyagi, Ph.D.
Joanna E. Cygler, Ph.D.

2 The Ottawa Hospital Cancer Centre, Ottawa, Canada
3 Carleton University Dept. of Physics, Ottawa, Canada
4 University of Ottawa, Dept. of Radiology, Ottawa, Canada

Part II: Electron beams

Joanna E. Cygler, Ph.D., FCCPM, FAAPM

The Ottawa Hospital Cancer Centre, Ottawa, Canada
Carleton University, Dept. of Physics, Ottawa, Canada
University of Ottawa, Dept. of Radiology, Ottawa, Canada
Outline

• Rationale for MC dose calculations for electron beams
• Commercially available Monte Carlo based electron treatment planning systems
• Clinical implementation of MC-based TPS
• Issues to pay attention to when using MC based system
• Timing comparisons of major vendor MC codes in the clinical setting.

Rationale for Monte Carlo dose calculation for electron beams

• Difficulties of commercial pencil beam based algorithms
  - Monitor unit calculations for arbitrary SSD values - large errors*
  - Dose distribution in inhomogeneous media has large errors for complex geometries

* can be circumvented by entering separate virtual machines for each SSD - labour consuming
Rationale for Monte Carlo dose calculation for electron beams


![Graph showing measured, pencil beam, and Monte Carlo doses for different depths and horizontal positions.]

- **Commercial implementations**
  - **MDS Nordion (now Nucletron) 2001**
    - First commercial Monte Carlo treatment planning for electron beams
    - Kawrakow's VMC++ Monte Carlo dose calculation algorithm (2000)
    - Handles electron beams from all clinical linacs
  - **Varian Eclipse eMC 2004**
    - Neuenschwander's MMC dose calculation algorithm (1992)
    - Handles electron beams from Varian linacs only (23EX)
    - Work in progress to include linacs from other vendors
  - **CMS XiO eMC for electron beams 2010**
    - Based on VMC (Kawrakow, Fippel, Friedrich, 1996)
    - Handles electron beams from all clinical linacs
Nucletron Electron Monte Carlo

Dose Calculation Module

- Originally released as part of Theraplan Plus
- Currently sold as part of Oncentra Master Plan
- Fixed applicators with optional, arbitrary inserts, or variable size fields defined by the applicator like DEVA
- Calculates absolute dose per monitor unit (Gy/MU)
- User can change the number of particle histories used in calculation (in terms of particle #/cm²)
- Data base of 22 materials
- Dose-to-water is calculated in Oncentra
- Dose-to-water or dose-to-medium can be calculated in Theraplan Plus MC DCM
- Nucletron performs beam modeling

Varian Macro Monte Carlo

transport model in Eclipse

- An implementation of Local-to-Global (LTG) Monte Carlo:
  - Local: Conventional MC simulations of electron transport performed in well defined local geometries ("kugels" or spheres).
    - Monte Carlo with EGSnrc Code System - PDF for "kugels"
    - 5 sphere sizes (0.5-3.0 mm)
    - 5 materials (air, lung, water, Lucite and solid bone)
    - 30 incident energy values (0.2-25 MeV)
    - PDF table look-up for "kugels"
  - Global: Particle transport through patient modeled as a series of macroscopic steps, each consisting of one local geometry ("kugel")

This step is performed off-line.

C. Zankowski et al "Fast Electron Monte Carlo for Eclipse"
Varian Macro Monte Carlo
transport model in Eclipse

- Global geometry calculations
  - CT images are pre-processed to user defined calculation grid
  - HU in CT image are converted to mass density
  - The maximum sphere radius and material at the center of each voxel is determined
    - Homogenous areas → large spheres
    - In/near heterogeneous areas → small spheres

C. Zankowski et al "Fast Electron Monte Carlo for Eclipse"

Varian Eclipse Monte Carlo

- User can control
  - Total number of particles per simulation
  - Required statistical uncertainty
  - Random number generator seed
  - Calculation voxel size
  - Isodose smoothing on / off
    - Methods: 2-D Median, 3-D Gaussian
    - Levels: Low, Medium, Strong
  - Dose-to-medium is calculated
CMS XiO Monte Carlo system

- XiO eMC module is based on VMC*
  - simulates electron (or photon) transport through voxelized media
- The beam model and electron air scatter functions were developed by CMS
- The user can specify
  - voxel size
  - dose-to-medium or dose-to-water
  - random seed
  - total number of particle histories per simulation
  - or the goal Mean Relative Statistical Uncertainty (MRSU)
- CMS performs the beam modeling


Software commissioning tests

- Criteria for acceptability
- Homogeneous water phantom
- Inhomogeneous phantoms (1D, 2D, 3D, complex)
  - Ding G.X.et al, Med. Phys., 26, 2571-2580, 1999
- Measurements, especially in heterogeneous phantoms, should done with a high (1 mm) resolution
User input data for MC based TPS

Treatment unit specifications:
• Position and thickness of jaw collimators and MLC

• For each applicator scraper layer:
  Thickness
  Position
  Shape (perimeter and edge)
  Composition

• For inserts:
  Thickness
  Shape
  Composition

No head geometry details required for Eclipse, since at this time it only works for Varian linac configuration

User input data for MC TPS cont

Dosimetric data for beam characterization, as specified in User Manual

• Beam profiles without applicators:
  - in-air profiles for various field sizes
  - in-water profiles
    - central axis depth dose for various field sizes
    - some lateral profiles

• Beam profiles with applicators:
  - Central axis depth dose and profiles in water
  - Absolute dose at the calibration point

Dosimetric data for verification
  - Central axis depth doses and profiles for various field sizes
Clinical implementation of MC treatment planning software

• Beam data acquisition and fitting
• Software commissioning tests
• Clinical implementation
  - procedures for clinical use
  - possible restrictions
  - staff training

*should include tests specific to Monte Carlo

A physicist responsible for TPS implementation should have a thorough understanding of how the system works.

Software commissioning tests: goals

• Setting user control parameters in the TPS to achieve optimum results (acceptable statistical noise, accuracy vs. speed of calculations)
  - Number of particle histories
  - Required statistical uncertainty
  - Voxel size
  - Smoothing
• Understand differences between water tank and real patient anatomy based monitor unit values
XiO: 9 MeV - Trachea and spine

Vandervoort and Cygler, COMP 56th Annual Scientific Meeting, Ottawa, June 2010

Lateral profiles at various depths, SSD=100cm, Nucletron TPS

9 MeV, 10x10cm$^2$ applicator, SSD=100cm. Homogeneous water phantom, cross-plane profiles at various depths. MC with 10k/cm$^2$.

20 MeV, 10x10cm$^2$ applicator, SSD=100cm. Homogeneous water phantom. Cross-plane profiles at various depths. MC with 10k and 50k/cm$^2$. 
Monte Carlo Settings: Noise in the distributions

Varying MRSU, voxel size=2.5×2.5×2.5 mm³, dose-to-medium, 6 MeV beam, 10×10 cm² applicator

CMS eMC: Cut-out factors

Vandervoort and Cygler, COMP 56th Annual Scientific Meeting, Ottawa, June 2010
**Eclipse eMC no smoothing**

Voxel size = 2 mm


**Eclipse eMC**

Effect of voxel size and smoothing

Dose-to-water vs. dose-to-medium

D_{w} - energy absorbed in a small cavity of water divided by the mass of that cavity.

D_{m} - energy absorbed in a medium voxel divided by the mass of the medium element.

\[ D_{w} = D_{m} \left( \frac{S}{\rho} \right)_{m}^{w} \]

Dose-to-water vs. dose-to-medium, MRSU=2%, voxel size=4×4×4 mm³, 6 MeV beam, 15x15 cm² applicator, both 602 MU
### Good clinical practice

- Murphy’s Law of computer software (including Monte Carlo)
  
  "All software contains at least one bug"

- Independent checks

### MU MC vs. hand calculations

<table>
<thead>
<tr>
<th>Monte Carlo</th>
<th>Hand Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real physical dose calculated on a patient anatomy</td>
<td>Rectangular water tank</td>
</tr>
<tr>
<td>Inhomogeneity correction included</td>
<td>No inhomogeneity correction</td>
</tr>
<tr>
<td>Arbitrary beam angle</td>
<td>Perpendicularly beam incidence only</td>
</tr>
</tbody>
</table>
9 MeV, full scatter phantom (water tank)

RDR=1 cGy/MU

Lateral scatter missing

Real contour / Water tank =
= 234MU / 200MU = 1.17
**MU real patient vs. water tank**

MC / Water tank = 292 / 256 = 1.14

**MU-real patient vs. water tank: Impact on DVH**

![Graph showing dose vs. % volume for different regions](image)
Posterior cervical lymph node irradiation - impact on DVH

![Graph showing dose vs. PTV volume for conventional and customized irradiation.](image)

Jankowska et al, Radiotherapy & Oncology, 2007

Internal mammary nodes

MC / Water tank= 210 / 206=1.019
How long does it take?

- MC gives entire distribution, not just a few points
- time for N beams is the same as for 1 beam
- timing is a complex question since it depends on
  - statistical uncertainty and how defined
  - voxel size
  - field size
  - beam energy and whether photons or electron
  - accuracy sought
  - speed of CPU and optimization of compiler
  - complexity of patient specific beam modifiers

Monte-Carlo Settings: Effect on computation time

Timing Results XiO:

For 9 and 17 MeV beams, 10x10 cm² applicator and the trachea and spine phantom, timing tests were performed for a clinical XiO Linux workstation, which employs 8 processors, 3 GHz each, with 8.29 GB of RAM.
### Timing – Pinnacle³

dual processor 1.6 GHz Sun workstation, 16 GB RAM.

<table>
<thead>
<tr>
<th>Patient</th>
<th># histories</th>
<th>CPU time (min)</th>
<th># histories</th>
<th>CPU time (min)</th>
<th># histories</th>
<th>CPU time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (cheek)</td>
<td>3.4x10⁶</td>
<td>4.8</td>
<td>1.4x10⁷</td>
<td>20</td>
<td>1.6x10⁸</td>
<td>3.9</td>
</tr>
<tr>
<td>2 (ear)</td>
<td>1.7x10⁶</td>
<td>2.1</td>
<td>6.5x10⁵</td>
<td>8.1</td>
<td>7.1x10⁷</td>
<td>1.5</td>
</tr>
<tr>
<td>3 (breast)</td>
<td>3.3x10⁶</td>
<td>7.1</td>
<td>1.4x10⁷</td>
<td>29.9</td>
<td>1.5x10⁸</td>
<td>5.4</td>
</tr>
<tr>
<td>4 (face)</td>
<td>1.1x10⁷</td>
<td>32.1</td>
<td>4.7x10⁸</td>
<td>134.5</td>
<td>5.2x10⁸</td>
<td>24.5</td>
</tr>
</tbody>
</table>


### Timing – Nucletron TPS

Oncentra 4.0

- Anatomy: 201 CT slices
- Voxels: 3 mm³
- 10x10 cm² applicator
- 50k histories/cm²

**4 MeV Timer Results:**
- Init = 0.321443 seconds
- Calc = 42.188 seconds
- Fini = 0.00158201 seconds
- Sum = 42.5111 seconds

**20 MeV Timer Results:**
- Init = 0.311014 seconds
- Calc = 110.492 seconds
- Fini = 0.00122603 seconds
- Sum = 110.805 seconds

Faster than pencil beam!
Timing – Varian Eclipse

Eclipse MMC, Varian single CPU Pentium IV
XEON, 2.4 GHz
10x10 cm², applicator, water phantom,
cubic voxels of 5.0 mm sides
6, 12, 18 MeV electrons,
3, 4, 4 minutes, respectively


Summary - electron beams

• Commercial MC based TP systems are available
  - fairly easy to implement and use
  - MC specific testing required
• Fast and accurate 3-D dose calculations
• Single virtual machine for all SSDs
• Large impact on clinical practice
  - Accuracy of dose calculation improved
  - More attention to technical issues needed
  - Dose-to-medium is calculated, although some systems calculate dose-to-water as well
  - MU based on real patient anatomy (including contour irregularities and tissue heterogeneities)

Requirement for well educated physics staff
New clinical dilemma

• Accurate dose calculation systems
  – at last we know what dose we are giving to tumors and OAR
• How are we to incorporate this knowledge into clinical practice?
  – Will we change the dose prescription?
  – We have done it for photon beams and inhomogeneity corrections in lungs…

Discussion: dose prescription issues

• MC-calculated doses can in some instances be significantly different (10-20%) from conventional algorithms, such as radiological pathlength, and convolution-based methods or pencil beam in case of electron beams

• In light of these differences:
  – should dose prescriptions change with MC-based calculations?
  – How?
Dose prescription - AAPM TG-105 perspective

- MC method is just a more accurate dose algorithm
- Dose prescription issues are not specific to MC-based dose calculation
- As with other changes to the therapy treatment process, users should correlate doses and prescriptions with respect to previous clinical experience

Conclusions

- Clinical implementation of MC-based systems must be performed thoughtfully and users, especially physicists, must understand the differences between MC-based and conventional dose algorithms
- Successful implementation of clinical MC algorithms requires strong support from the clinical team and an understanding of the paradigm shift with MC algorithms
- A properly commissioned MC-based dose algorithm will improve dose calculation accuracy for electron and photon beams
- More accurate dose calculations may improve dose-biological effect correlations
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