Monte Carlo Treatment Planning: Implementation of Clinical Systems

Richard Popple1 and Joanna E. Cygler2,3,4
1Department of Radiation Oncology, The University of Alabama at Birmingham
2The Ottawa Hospital Regional Cancer Centre, Ottawa, Canada
3Carleton University Dept. of Physics, Ottawa, Canada
4University of Ottawa, Dept. of Radiology, Ottawa, Canada

Outline
1. Educational review of the physics of the MC method.
2. Factors associated with MC dose calculation within the patient-specific geometry, such as statistical uncertainties, approximations of the underlying physics model, CT-number to material density assignments, and reporting of dose-to-medium versus dose-to-water.
3. Review the vendor transport codes currently used for clinical treatment planning.
4. Experimental verification of MC algorithms.
5. Potential clinical implications of MC calculated dose distributions.
6. Example timing comparisons of the major vendor MC codes in the clinical setting.

Disclosure and Acknowledgements
• UAB has a RapidArc evaluation agreement with Varian Medical Systems
• Author has a research grant with Varian Medical Systems
• Some slides courtesy of
  - Indrin Chetty, Ph.D.
  - D.W.O. Rogers, Ph.D.

Outline/Objectives Part I
• Educational review of the physics of the MC method
• Factors associated with MC dose calculation within the patient-specific geometry
  - statistical uncertainties
  - approximations of the underlying physics model
  - CT-number to material density assignments
  - dose-to-medium versus dose-to-water
Monte Carlo method overview

"The Monte Carlo technique for the simulation of the transport of electrons and photons through bulk media consists of using knowledge of the probability distributions governing the individual interactions of electrons and photons in materials to simulate the random trajectories of individual particles. One keeps track of physical quantities of interest for a large number of histories to provide the required information about the average quantities."

D.W.O. Rogers and A.F. Bielajew
Condensed history method


Variance Reduction Techniques (VRT)

- Efficiency $\varepsilon = 1 / s^2 T$
  - $T \propto N$
- Variance Reduction Techniques increase $\varepsilon$ by reducing $s^2$ for a given number of particles.
  - Range rejection
  - Bremsstrahlung splitting
  - Russian roulette
  - And more...
- Inappropriate application of VRT can result in inaccurate results and/or reduced efficiency.

Process overview
Accelerator beam model

- Direct simulation
- Stored phase space
- Virtual source model

CT-number to material density

- Patient tissues (via imaging data) need to be converted into cross sections required for MC simulation.

CT image (HU)

HU vs. density conversion ramp

Convert to densities

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Relative Electron Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>0.0</td>
</tr>
<tr>
<td>lung</td>
<td>0.2 (0.1-0.5)</td>
</tr>
<tr>
<td>soft tissue, water</td>
<td>1.0</td>
</tr>
<tr>
<td>spongy bone</td>
<td>1.2</td>
</tr>
<tr>
<td>skull</td>
<td>1.65</td>
</tr>
<tr>
<td>compact bone</td>
<td>1.85</td>
</tr>
</tbody>
</table>

Both mass density ($\rho$) and material compositions (atomic number, $Z$) are needed for accurate MC calculation. Failure to incorporate compositions, $Z_{\text{eff}}$, can result in notable errors at higher tissue densities (Verhaegen and Devic, PMB, 50:937, '05).
Dose-to-medium versus dose-to-water

- Historical clinical experience is based on dose-to-water, \( D_w \)
  - therapeutic doses and normal tissue tolerance doses are based on \( D_w \)
  - possible need for revision, since more accurate dose calculation available now?
- Dose-to-medium (\( D_m \)) is inherently computed by MC dose algorithms.
  - may be of more clinical relevance than \( D_w \)
- TG-105 recommends that a method be available in MC code to convert \( D_m \) to \( D_w \) and that both values are reported.

Converting \( D_m \) to \( D_w \)
The conversion can be accomplished using the Bragg-Gray formalism:

\[
D_w = D_m \left( \frac{S}{\rho} \right)_m
\]

Unrestricted wat-to-med mass collision stopping power averaged over the energy spectrum of electrons at the pt. of interest

This can be applied either as a post-processing step or as a multiplication factor to the energy loss step

Clinical Examples: \( D_w \) and \( D_m \)

Clinical Examples: Dw and Dm

Statistical uncertainty

- Two sources
  - Treatment head simulation
  - Patient simulation
- Statistical uncertainty in dose will approach the latent uncertainty associated with the phase space

Reporting of statistical uncertainty

\[ R_{D>0.5D_{\text{max}}} = \frac{1}{K_{D>0.5D_{\text{max}}}} \sum_{D>0.5D_{\text{max}}} \left( \frac{S_D}{D} \right)^2 \]

Effect on dose prescriptions

- Statistical outliers (max. or min. dose points) can deviate from the mean dose by many standard deviations
- MC-based dose prescriptions should be volume-based
- Do not prescribe to max or min dose points
Statistical uncertainties: Recommendations

- DVHs and dose indices, such as TCP and NTCP are not highly sensitive to statistical noise
  - Calculations with statistical precision of <2% are sufficient to accurately predict these values
- For serial organs, where point doses are important, (e.g., the max. cord dose) higher statistical precision may be necessary

Approximations of the underlying physics model

- Systematic uncertainties can be introduced by approximations
  - Source model
  - Efficiency enhancing techniques
  - Macro Monte Carlo methods
  - Etc....

Monte Carlo Treatment Planning: Implementation of Clinical Systems
Part II: Clinical Implementation

Joanna E. Cygler, Ph.D., FCCPM, FAAPM
The Ottawa Hospital Regional Cancer Centre, Ottawa, Canada
Carleton University Dept. of Physics, Ottawa, Canada
University of Ottawa, Dept. of Radiology, Ottawa, Canada

Outline Part II

- Monte Carlo based commercial TP systems
- Experimental verification of MC algorithms
  - homogeneous water phantom
  - heterogeneous phantoms
  - setting user control parameters in the TPS to achieve optimum results (minimum statistical noise, minimum distortion of real dose distribution)
- Brief review of potential clinical implications of MC calculated dose distributions
  - Use of bolus, lead wires etc.
  - Water tank vs. real patient MU
- Timing comparisons of major vendor MC codes in the clinical setting.
Why do we need Monte Carlo based Treatment Planning Systems?

Rationale for Monte Carlo based Treatment Planning Systems

- Traditional dose calculation algorithms fail in many cases
- MC gives us in general the right answer
- There are no significant approximations
  - no approximate scaling of kernels is needed
  - electron transport is fully modelled
  - geometry can be modelled as exactly as we know it
  - All types of inhomogeneities are properly handled
- There are many experimental benchmarks showing MC calculations can be very accurate

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

Commercial implementations

- **MDS Nordion 2001**
  - First commercial Monte Carlo treatment planning for electron beams
  - Implementation of Kawrakow's VMC+ Monte Carlo dose calculation algorithm (2000)
  - Handles electron beams from all clinical linacs
- **Varian Eclipse eMC 2004**
  - Based on Neuenschwander's MMC dose calculation algorithm (1992)
  - Handles electron beams from Varian linacs only
- **CMS Monaco for photon beams – IMRT only**

*presently Nucletron

Description of Nucletron Electron Monte Carlo DCM

- Fixed applicator with optional, arbitrary inserts
- Calculates absolute dose per monitor unit (Gy/MU)
- 510(k) clearance (June 2002)

Varian Macro Monte Carlo

- PDF table look-up for "kugels" or spheres instead of analytical and numerical calculation
- CT images pre-processes
  - Homogenous areas → large spheres
  - In/near heterogeneous areas → small spheres
- Database with probable outcome for every combination of:
  - 30 incident energy values (0.2-25 MeV)
  - 5 materials (air, lung, water, Lucite and solid bone)
  - 5 sphere sizes (0.5-3.0 mm)

EGSnrc used to create beam data

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

- Beam profiles without applicators:
  - in-air profiles for various field sizes
  - in-water profiles
    - Central axis depth dose for various field sizes
    - Some off-axis 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 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 (minimum statistical noise, accuracy vs. speed of calculations)
  - Number of histories
  - Voxel size
  - Smoothing
- Understand differences between water tank and real patient anatomy based monitor unit values

User controlled MC calculation parameters

- **Nucletron**
  - User can define number of histories used in calculation (in terms of particle #/cm²)
- **Varian**
  - User can define:
    - Maximum number of histories used in calculation >/=0
    - Statistical uncertainty (within the high dose volume)
    - Calculation grid size (voxel size)
    - Smoothing method and level
    - Random number generator seed
Software commissioning tests

- Criteria for acceptability
- Homogeneous water phantom
- Inhomogeneous phantoms
- Measurements, especially in heterogeneous phantoms, should be done with a high (1 mm) resolution

Homogeneous water phantom tests

- Standard SSD 100 cm and extended SSD
- Open applicators - PDD and profiles
- Square and circular cut-outs
- Oblique incidence
  - $\gamma = 15^\circ$ and $30^\circ$
- MU tests - SSD 100 and extended SSD
  - All open applicators
  - Square, rectangular, circular, some irregular cutouts

Typical Experimental setup

- Electron applicator
- Water tank
- Diode detector
- RFA300 (Scanditronix) dosimetry system
- $\gamma$-type electron diode
- Scan resolution = 1mm

Homogeneous water phantom tests

- Open applicators - PDD and profiles
- Square and circular cut-outs

In-air or in water beam profiles

Typical Experimental setup

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

- 10 MeV, 10x10 cm$^2$ applicator, SSD=100 cm. Homogeneous water phantom, cross-plane profiles at various depths. Nucletron TPS with Nucletron TPS.
- 20 MeV, 10x10 cm$^2$ applicator, SSD=100 cm. Homogeneous water phantom. Cross-plane profiles at various depths. MC with Nucletron TPS.
Overall mean and variance of MC/hand monitor unit deviation, Nucletron TPS


Inhomogeneous phantoms

- Low and high density inhomogeneities
- 1 D (slab) geometry
- 2 D (ribs) geometry
- 3 D (small cylindrical) geometry
- Complex (trachea and spine) geometry

Inhomogeneous phantoms

- Low and high density inhomogeneities
- 1 D (slab) geometry
- 2 D (ribs) geometry
- 3 D (small cylindrical) geometry
- Complex (trachea and spine) geometry

Air cylinder

Voxel size 0.39 cm, 47 slices

900 MHz, CPU time for 50k/cm²

14:01 - 20 MeV, 9:31 – 9 MeV

Voxel size 0.39 cm, 47 slices

20 MeV, Air cylinder, 10x10 cm² applicator, SSD=100 cm. Cross-plane profiles. MC with 10k/cm².

Results MC tests: voxel size 9 MeV

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

9 MeV - clinical hard bone

Results: clinical – soft bone

- The maximum difference in dose is 1.8%, in agreement with soft bone phantom study and consistent with stopping power ratio.

Clinical implementation issues

- Bolus fitting (no air gaps)
- Lead markers (wires, lead shots) used in simulation
- Monitor unit calculations
  - Water tank or real patient anatomy
  - Dose to water or dose to medium
- Workload

Example of poorly fitting bolus
How to correct poorly fitting bolus

**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**

**Monte Carlo**
Real physical dose calculated on a patient anatomy
Inhomogeneity correction included
Arbitrary beam angle

**Hand Calculations**
Rectangular water tank
No inhomogeneity correction
Perpendicular beam incidence only

---

**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

Impact on DVH

Jankowska et al, Radiotherapy & Oncology, 2007
**Timing – Nucletron TPS Theraplan Plus**

- 10x10 cm² applicator
- 50k histories/cm²
- Anatomy - 41 CT slices
- Voxel size 3 mm³
- Pentium 4 Xenon 2.2 GHz
- Calculation time
  - 1.5 min. for 6 MeV beam
  - 8.5 minutes for 20 MeV beam

*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

---

**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>3.4x10⁸</td>
<td>4.8</td>
<td>1.4x10⁹</td>
<td>20</td>
<td>1.6x10⁴</td>
<td>3.9</td>
</tr>
<tr>
<td>2 (ear)</td>
<td>1.7x10⁹</td>
<td>2.1</td>
<td>5.9x10⁹</td>
<td>8.1</td>
<td>7.1x10⁷</td>
<td>1.5</td>
</tr>
<tr>
<td>3 (breast)</td>
<td>3.3x10⁹</td>
<td>7.1</td>
<td>1.4x10⁹</td>
<td>29.9</td>
<td>1.5x10⁴</td>
<td>5.4</td>
</tr>
<tr>
<td>4 (face)</td>
<td>1.1x10¹⁰</td>
<td>32.1</td>
<td>4.7x10¹⁰</td>
<td>114.5</td>
<td>5.2x10⁷</td>
<td>24.5</td>
</tr>
</tbody>
</table>

**Conclusions**

- Commercial MC based TP system are available
  - 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 improved
  - More attention to technical issues needed
  - Dose-to-medium calculated
  - MU based on real patient anatomy (including contour irregularities and tissue heterogeneities)
- Requirement for well educated physics staff
Acknowledgements

George X. Ding  Indrin Chetty
George Daskalov  Margarida Fragoso
Gordon Chan  Richard Popple
Robert Zohr  Charlie Ma
Elena Gil  David W.O. Rogers

In the past I have received research support from Nucletron and Varian.

TOHCC has a research agreement with Elekta.