Clinical Implementation and Application of Monte Carlo for Electron Beam Therapy

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June 3rd, 2016
Educational Objectives

- To understand the need for Monte Carlo for electron therapy
- To learn the principles of the two electron Monte Carlo algorithms used in commercial TPS
- To learn how to commission a clinical electron Monte Carlo algorithm and to review key results in literature
Pencil Beam Algorithms

- Pencil beam algorithms are used for electron dose calculation since early 1980s.
- Point dose calculated as integral of contributions from Gaussian pencil beam distributions obtained using Fermi-Eyges multiple scattering theory.

\[
D_{(x,y,z)} = \int \int d_p(x - x', y - y', z) \, dx' \, dy'
\]

\[
d_p(r,z) = d_p(o,z) e^{-r^2/\sigma_r^2(z)}
\]

\[
\sigma_{x}^2(z) = \frac{1}{2} \int \left( \frac{\theta^2}{\rho l(z')} \right) \rho(z') (z - z')^2 \, dz'
\]

Mass angular stopping power
Limitations of Pencil Beam Algorithm

- Fermi-Eyges theory is strictly valid for slab geometry
- The pencil beam algorithm is bound to fail where
  - The cross section of the inhomogeneity is smaller than the pencil beam spread
  - The pencil beam pass through different inhomogeneity

Experimental verification of Hogstrom algorithm:
13 MeV, 8×8 cm² field, SSD = 100 cm
TLD dose compared to calculate isodose
Error up to 13%
Monte Carlo Algorithms

- Simulate transport of millions of particles through matter
- Fundamental laws of physics are used to determine probability distribution of individual particle interactions
- Each particle is followed in medium and deposits energy by interactions.
- 2 key components
  - random number generator and phase space
- It is the most accurate dose calculation method, but requires longer calculation time
- The accuracy is not limited by tissue heterogeneity or interface, but is limited by the statistical uncertainty
Commercial eMC Algorithms

- Marco MC (MMC) algorithm by Neuenschwander (1992)
  - Varian Eclipse (2004)

- Voxel based MC (VMC++) algorithm by Kawrakow (2000)
  - Nucletron Oncentra MasterPlan (2001)
    - First commercial eMC algorithm
  - CMS (now Elekta) XiO (2010)
  - RayStation (2013)
MMC in Varian Eclipse

Steps of implementation in Eclipse:
1. Initial phase space model
2. Local simulation
3. Geometric pre-processing
4. Global simulation
Step 1. Initial Phase Space Model

- A four-source model
  1. Primary source of electrons and photons at scattering foil
  2. Secondary virtual electron source near MU chamber
  3. Scattering electron source from applicator and cutout edge
  4. Transmission photons

- Compute PDFs of position, direction and energy of electrons and photons for each source at phase space plane.
Primary Source

- A point source for the electrons and photons coming from the scattering foil, 10 cm below the nominal target.
- The particles are sampled on a plane located 95 cm below the nominal target, inside the shape defined by the cutout.
- The directions of the photons and electrons are determined as follows:
  - The direction of the photons is given by the sampled position on the plane and the Z-position of the focus (10 cm below the nominal target).
  - The mean direction of the electrons is given by the sampled position in the plane and the position of the nominal target. The direction is then varied according to a Gaussian distribution with an energy dependent variance.
Jaw Source

- Describes electrons and photons scattered at jaws.
- The origin of the particles is sampled uniformly from 4 horizontal line segments located along the center of the inner side of the jaws.
- The particles are sampled on a plane at 95 cm below the nominal target inside cutout.
- The direction of the photons and electrons:
  - Photons: given by the sampled position in the plane and the sampled origin position.
  - Electrons: given by the sampled position in the plane and the sampled origin position. The direction is then varied according to a Gaussian distribution with an energy dependent variance.
Scattering Electron Sources

- **Scraper sources**: One for each upper applicator scraper, a line source long the edge of scraper opening
  - Electrons from the upper rim of the cutout. They are produced by main electrons entering the *scraper material* on the upper plane.
  - Electrons from the inner side of the cutout. They are produced by main electrons entering the *scraper material* on the inner side.

- **Edge electrons**: a line source along the edges of the opening of the cutout
  - Electrons from the upper rim of the cutout, and produced by main electrons entering the *cutout material* on the upper plane.
  - Electrons from the inner side of the cutout, and produced by main electrons entering the *cutout material* on the inner plane.

- **Scraper and edge electrons** electrons are sampled using pre-calculated scatter kernels.
Transmission Photons

- Sampled using pre-calculated kernels. They exit from the outer rim of the applicator and from the insert material.
- The following three types of transmission photons are taken into account:
  - Main photons passing through the insert material without interaction.
    - They have the same direction as the main photons but a different energy distribution.
  - Scattered photons produced by main photons in the insert material
    - They are sampled by using a pre-calculated kernel.
Step 2. Local Simulation

- MMC uses spheres for local simulation
  - The transport of monoenergetic electrons through a spherical volume element (kugel) is precalculated in EGSnrc.
  - The probability of an emerging electron is tabulated as a function of its exit position, direction and energy.
  - Probability distribution functions (PDFs) for kugels of different materials and radii, and for a range of electron energies are stored in database.

![Diagram of electron transport through a kugel](attachment:image.png)
MMC Database

- MMC database for local simulation
  - 5 materials: air, lung phantom, water, Lucite, and solid bone phantom
  - 5 sphere diameters: 1, 2, 3, 4, and 6 mm

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>4</th>
<th>5</th>
<th>7</th>
<th>&gt;7.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max diameter (mm)</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

- 30 incident energies: 0.2, 0.4, 0.6, 0.8, 1, 1.5, 2, 3, ..., 24, 25 MeV

- Info stored for each combination of the above three parameters:
  - Exit energy, exit position and exit direction of primary electrons
  - Energy, direction and probability of secondary electrons
  - Energy and probability of secondary photons
Step 3: Geometric Pre-processing

- Goal: to determine sphere sizes and mean sphere densities at each position in the whole CT, prior to the simulation.
- CT volume is converted to mass density volume
  - with 1 to 5 mm resolution,
  - using HU-mass density conversion factor.
- Mass density volume scanned for heterogeneity.
- Sphere index is assigned to each voxel in the volume
  - Sphere index: max sphere radius that can be used from the current voxel center without the corresponding sphere reaching into the other material.
  - Max allowed sphere size depends on the electron energy.
  - Large changes in adjacent sphere sizes are prevented.
  - Small spheres near interface.
  - Large spheres at greater distance from interface.
Heterogeneity Management

- A voxel is considered part of a heterogeneous volume if the density ratio with its neighbors is >1.5.
- If densities in both voxels are <0.05 g/cm³, the ratio is not evaluated.

- The material assigned to each sphere depends on the average mass density within the sphere.
  1. If average density of a sphere = the density of a preset materials:
     - That preset material is selected for the sphere.
  2. If average density of a sphere is between two preset materials:
     - The material is randomly selected from these two materials each time a particle enters the sphere. The probability for a material to be selected is proportional to the closeness of a sphere’s average density to the density of the material.
  3. If density of a voxel exceeds the max density in the database (1.84 g/cm³):
     - the maximum density will be used and scattering may not be based on the correct material.
Result of a Pre-processed CT Slice

- Sphere diameter size (in mm) in each voxel
- 1 mm grid size
- 3 Heterogeneity

Eclipse Photon and Electron Algorithms
13.7 Reference Guide
Step 4: Global Simulation

- **Primary electron transport**
  - PDF of an electron exiting a sphere is used as input to neighboring sphere.
  - Step size reduced near interface with density ratio >1.5.
  - Algorithm stops a particle at interface and restarts with a new sphere in the new material.
  - Energy of the primary electron is deposited along a straight line from the point where it enters the sphere to the point where it leaves.

\[
T_{\text{vox}} = T_{\text{dep}} \frac{S_{\text{vox}}}{S_{\text{dep}}} \frac{l_{\text{vox}}}{l_{\text{dep}}}
\]

- **Linear stopping power of the voxel**
- **Energy deposited in voxel**
- **Energy deposited in current step**
- **Length inside voxel**
- **Length of current step**
- **Linear stopping power of the sphere**
- **Boundary crossing between materials**
- **Inhomogeneity**
- **Step size reduction near boundary**
- **Stop at interface**
- **Electron direction and stepsize from previous sphere**

Eclipse Photon and Electron Algorithms
13.7 Reference Guide
Step 4: Global Simulation

- **Primary photon interactions**
  - Compton scatter, pair production, and photoelectric effect.
  - During the interactions, the direction of the primary photon may change.

- **Distance between the subsequent primary photon interactions** is chosen randomly based on
  - the photon’s mean free path,
  - the attenuation coefficient at the given density,
  - the photon’s remaining energy.

- The primary photon is traced until it has lost all its energy.
Step 4: Global Simulation

- Secondary electron transport
  - Each macro step generates one secondary electron and one secondary photon (or only one secondary photon) with associated weight $w(T_i)$, which is the probability that the secondary particle occurs in the local simulation of the incident electron of energy $T_i$.
  - The energy and the direction of the secondary electrons are sampled from the distributions obtained from the local simulations.
  - Secondary electron energy deposited along its direction in each voxel

$$\Delta E_e = w(T_i) \times 2\frac{MeV}{cm} \times \Delta l \times \frac{S_{vox}}{S_{water}}$$

- $\Delta E_e$ = Energy deposited to voxel from the secondary electron.
- $w(T_i)$ = Weight of the secondary particle emerging from incident electron of energy $T_i$.
- $\Delta l$ = Length of the line inside the voxel.
- $S_{vox}$ = Linear stopping power of the voxel material.
- $S_{water}$ = Linear stopping power of water.
Step 4: Global Simulation

- Secondary photon transport
  - Only energy is sampled, direction is taken from the incident electron.
  - The distance to the next interaction is determined using local mass attenuation and applying ray tracing from the sampled starting position along the direction of the incoming primary electron.
  - At the interaction position, the energy which is transferred from the photon to the electron is sampled from a PDF depending on the photon energy using data from XCOM.
  - The weight of the electron is set to the weight of the photon.
  - While the photon is no longer tracked, the energy of the electron is deposited along the photon’s direction.
Overall statistical accuracy is defined as

the average relative statistical uncertainty of all voxels in the region of interest (which contains all voxels within the body structure with a dose larger than the user-defined value P% of the maximum dose.

\[ S_P = \frac{1}{N_P} \sum_{D_{ijk} > P\%D_{\text{max}}} \Delta D_{ijk} \]

- \( P \) = Value of the Dose threshold for uncertainty set in calculation options.
- \( N_P \) = Number of voxels satisfying the condition \( D_{ijk} > P\%D_{\text{max}} \).
- \( D_{ijk} \) = Dose at point \((i, j, k)\) within the body structure.
- \( D_{\text{max}} \) = Maximum dose within the body structure.
- \( \Delta D_{ijk} \) = Relative standard deviation of the dose deposited to point \((i, j, k)\)
Dose Smoothing

- Eclipse supports two methods to smooth the final dose distribution to reduce statistical noise.

- **Gaussian dose smoothing**
  - A 3D convolution smoothing method that uses a kernel representing the shape of a Gaussian curve.
  - The degree of smoothing is determined by the standard deviation of the Gaussian distribution.
  - It produces a weighted average of each pixel’s neighborhood, with the average weighted more towards the value of the central pixels.

- **Median dose smoothing**
  - The value of a pixel determined by examining the pixel values in its neighborhood on a slice and taking the median of these values.
  - The median smoothing is performed slice by slice.
  - Fairly small window sizes are used to minimize the error.
Clinical Evaluation

Comprehensive evaluation of a commercial macro Monte Carlo electron dose calculation implementation using a standard verification data set

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(Received 13 October 2005; revised 23 March 2006; accepted for publication 24 March 2006; published 9 May 2006)
Isodose Comparison

- 20 MeV, 100-cm SSD, homogeneous water configuration.
Commercial VMC

Masterplan

XiO

RayStation
Commercial Implementation of VMC

- **VMC algorithm**
  - Initially developed by Kawrakow and Fippel in 1996

- **XVMC algorithm**
  - Extended from VMC by Fippel in 2000 to include photons
  - First commercialized by CMS (now Elekta) XiO in 2010

- **VMC++ algorithm**
  - C++ implementation of VMC and XVMC, with improvements in modeling of physical process and incorporation of new variance reduction techniques
  - Commercial TPS:
    - Nucletron Oncentra MasterPlan in 2001
    - RayStation in 2013 (to be used as example in this lecture)

- **Two independent components in commercial TPS**
  - Treatment independent: phase space engine
  - Treatment dependent: dose engine based on XVMC or VMC++
RayStation Electron Beam Line

- Coupled multi-source beam model
- Simulate treatment head by Monte Carlo
- Linac geometry input
  - Jaws and MLC: position and thickness
  - Applicator scraper layers: position, thickness, shape and composition
  - Cutout: thickness and composition
- Effective source parameters
  - Compensate for effects of incident beam characteristics and additional components (ion chamber, mirror ...)
  - No need for detailed specs of upper treatment head geometry
Input Data Requirements

- Open air fluence profiles and fluence factor \((OF_{\text{air}})\)
  - At two SDD separated by 20 cm: 70 and 90 cm or 75 and 95 cm
  - \(8\times8, 8\times20, 8\times30\) and \(30\times30\) cm\(^2\)
  - \(OF_{\text{air}}\) normalized to \(8\times20\) field at the shorter SDD

- Open water depth dose (largest field size for photon)

- Applicator water dose (with open cutout)
  - cGy/MU at \(d_{\text{max}}\) or a reference depth for each applicator at each energy

- Applicator water depth dose

- Applicator crossline profiles at a shallow and a deep depth

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Shallow depth (cm)</th>
<th>Deep depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4 \leq E \leq 6)</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>(6 &lt; E \leq 15)</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>(15 &lt; E \leq 25)</td>
<td>3</td>
<td>15</td>
</tr>
</tbody>
</table>
Electron Beam Components

- Three components
  - Direct electrons
  - Indirect electrons
  - Bremsstrahlung photons

- Source phase space
  \[ \Phi_S = \varphi_E(E) \times \varphi_S(x,y,u,v) \]
  - Energy spectrum
  - Spatial-angular distribution
Electron Energy Spectrum

- Direct electrons are sampled from parameterized effective energy and spatial-angular distributions.
- Energy spectrum is determined from open field PDD, which only direct electrons and scattering foil bremsstrahlung photons contribute to.
Spatial-angular Distribution

- Spatial-angular distribution $\varphi_S(x,y,u,v)$ in a plane near the secondary scattering foil.

![Diagram showing spatial-angular distribution](image)

### Parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluence distribution width [cm]</td>
<td>1.6500</td>
</tr>
<tr>
<td>Fluence cut-off radius [cm]</td>
<td>1.3000</td>
</tr>
<tr>
<td>Distance to virtual source [cm]</td>
<td>6.0000</td>
</tr>
<tr>
<td>Angular spread on axis [deg]</td>
<td>7.9985</td>
</tr>
<tr>
<td>Angular spread at cut-off radius [deg]</td>
<td>2.6000</td>
</tr>
<tr>
<td>Angular spread curvature</td>
<td>0.95</td>
</tr>
</tbody>
</table>

![Graph showing fluence and angular spread](image)
Contamination Photons

- Photon contamination mainly from bremsstrahlung in the scattering foils
- A simplified energy fluence model is used where the energy spectrum is deduced from depth dose curves according to.
- Laterally a rotational symmetric Gaussian distribution is applied with attenuation to account for the cutout aperture and the geometry of the most downstream scraper layer.
Exit Phase Space

- **Direct fluence**
  - 1. Electrons that have not interacted with any collimating elements

- **Indirect fluence**
  - 2. Electrons emitted from collimating element edges
  - 3. Bremsstrahlung photons

- The amplitudes of the indirect fluence are coupled to that of the direct fluence
VMC++ Algorithm: Scheme

- **VMC++ vs. VMC & XVMC**
  - VMC++ is a C++ implementation of VMC and XVMC, with
    - improvements in the modeling of underlying physical process
    - incorporation of new variance reduction techniques

- **VMC++ use a Class II condensed history (CH) scheme for charge particle transport, the same as EGS4.**

- **VMC++ vs. EGS4**
  - VMC++ employs boundary crossing algorithm, with steps not terminated at interface, but continue until criterion determining step length satisfied.
  - Particles can pass several regions in a single CH step, resulting in improved calculation efficiency.
  - CH step lengths in VMC++ are determined by the maximum first elastic scattering moment per step, the maximum energy loss per step and delta particle production threshold energy.

VMC++ Algorithm: Cross Sections

- Each physical process is treated as a separate object.
- After initialization with a given material composition, each object can:
  - calculate the total cross section
  - calculate moments of the cross section
  - sample energy direction changes
  - prepare cumulative sampling table
- Each process is simulated using its physics principal, e.g.,
  - Inelastic electron/photon scattering
    - Bethe theory with density effect corrections
  - Bremsstrahlung production
    - Bethe-Heitler cross section with empirical correction factor

VMC++ Performance

- 50 to 100 times faster than EGS4/PRESTA due to:
  - Improved boundary crossing algorithm (5 to 20)
  - Quasi-random numbers (2)
  - VMC++ use refined “history repetition” technique (STOPS), compared to the original VMC (2 to 5)

VMC++ Accuracy for High-Z Materials

Figure 1: Dose distribution from a $10 \times 10 \text{ cm}^2$ 20 MeV electron beam in a lead phantom.
VMC++ ICCR 20 MeV Benchmark

VMC++ to EGSnrc dose differences (in % of the maximum dose) along the central axis of a 1.5 × 1.5 cm², 20 MeV electron incident on water/aluminum/lung phantom.

Statistical uncertainties are of the order of 0.2% of $D_{max}$.

VMC++ Material Management

- Each voxel is characterized by a material identifier and a voxel specific density.
- The material identifier points to a discrete material with known composition.
- The list of materials includes the following materials:
  - Materials generated from HU to density/material map. A HU value maps to a mass density which in turn maps to one of 57 interpolated materials.
  - Standard materials available in RayStation with fixed densities equal to the nominal density of each material.

Physics Commissioning

- **Metrics**
  - 1D: cone ratio and distance factor
  - 2D: PDD and profile

- **Fields**
  - Open: e.g., 10×10
  - Regular: square, rectangle and circle
  - Irregular: concave, convex, triangle, C-shape, elongated
  - Small field: 4×4, 2×2

- **Distance**
  - SSD: 98, 100, 105 and 110 cm
Physics Commissioning

- Oblique incidence
  - A middle size open field at 15 and 30°

- Inhomogeneity
  - EBT3 film with inhomogeneous phantom consisting of tissue, air, lung, and bone materials

- End-to-end test
  - EBT3 film sandwiched between a breast phantom and underlying solid water

Y. Wang, Y. Park and K. P. Doppke, AAPM 2015
Results: Inhomogeneity

- An inhomogeneous layer sandwiched between solid water
  - Lung tissue phantom on left
  - Bone air phantom on right
  - Vertical junction of inhomogeneous materials aligned to CAX
- One ETB3 film at posterior interface, and another 0.5 or 1.0 cm below.

Y. Wang, Y. Park and K. P. Doppke, AAPM 2015
Results: End-to-End Test

- EBT3 film sandwiched between a breast phantom and underlying solid water.
- End-to-end processes:
  - Phantom scanned on CT with BBs, data transferred to RayStation, eMC plan created, plan export to RadCalc then to MOSAIQ, phantom setup on couch using laser on BBs, plan delivered to phantom, dose measured in film and compared to TPS
- Absolute dose comparison without normalization

Y. Wang, Y. Park and K. P. Doppke, AAPM 2015
MGH Clinical Experiences

- MGH implemented RayStation eMC in 2012 (version 4.0)
- Commissioned Varian and Elekta eMC model
  - Treated a large number of breast patients on Varian and Elekta
  - Treated scalp, extremity sarcoma and H&N on Elekta
- Change in prescription method
  - In pencil-beam, prescribe to percentage of a nominal $d_{\text{max}}$
  - In eMC, prescribe to depth, since a nominal no longer exist
- More accurate MU due to more accurate calculations with
  - Surface curvature, tissue deficit, inhomogeneity
  - Caveat: decades of clinical outcome based on pencil-beam MU
  - Challenge on 2nd calc based on cubic water-equivalent phantom
- Customized bolus contoured in RayStation can be accurately produced by 3D printing
Summary

- Given sufficient statistics, Monte Carlo is the most accurate dose calculation method for photons and charged particles.
- Many major commercial TPS now offer eMC algorithm.
- Recent advances on computer speed have made clinical implementation of eMC feasible.
- Commercial eMC systems have two independent engines: beam phase space and patient dose calculation.
- The creation of an accurate beam phase space model is a very challenging duty.
- The patient dose calculation engines have been validated by various clinical groups.
References


