Monte Carlo Particle Transport in Medical Physics

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Outline

- Examples of Monte Carlo Applications in Medical Physics
- Monte Carlo for Accurate Dose Calculations
  - Dose Calculation in Treatment Planning Systems
    - Experiment-based Algorithms
    - Analytical Algorithms
    - The Problem of Interfaces
    - Monte Carlo Dose Calculation
- Examples of Monte Carlo Treatment Head/Beam Modeling
- Monte Carlo Modeling in Magnetic Field – MR-guided Radiotherapy
- Monte Carlo-based Treatment Planning
  - Calculation Time vs Statistical Noise
- Monte Carlo Modelling of Radiation Quality
Examples of Applications in Medical Physics

- Treatment head modeling
- Beam delivery/beam characteristics
- Dosimetry
- Correction factors for ionization chambers
- Calculation of dose kernels
- Patient dose calculation
- Estimation of photoneutron/electron contamination/nuclear fragmentation
- Imaging (x-ray, CT, PET, prompt-gamma)
- Radiobiology, RBE modeling
Reference Literature

Monte Carlo Transport of Electrons and Photons
Edited by Theodore M. Jenkins, Walter R. Nelson, and Alessandro Rindi

1986

Monte Carlo Techniques in Radiation Therapy
Edited by João Seco and Frank Verhaegen

2014
Monte Carlo Method in Medical Physics

By courtesy of Emiliano Spezi
Monte Carlo for accurate dose calculation
Radiotherapy and the Problem of Dose Calculation

Radiotherapy requires **accurate and precise dose calculation** to patients.
The accurate transport of radiation through matter is described by the Linear Boltzmann Transport Equation:

\[
\frac{\partial}{\partial s} + \frac{p}{|p|} \cdot \frac{\partial}{\partial x} + \mu(x, p) \psi(x, p, s) = \int dx' \int dp' \mu(x, p, p') \psi(x', p', s)
\]

But
- there is **no general solution in closed form**.
- analytical solutions are possible for only very simple and highly idealized situations.

**Solution techniques:**
- analytical approximations
  - very fast but **limited accuracy**
- implicit Monte Carlo simulation
  - slow but **simple and accurate**
Past: 1970s

Table 1.1. The performance of various computers. The number of million floating point operations per second (MFLOPS) and relative speeds were obtained from a benchmarking study by Dongarra21; the vector capabilities of vector machines were not exploited.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>MACHINE</th>
<th>MFLOPS</th>
<th>RELATIVE SPEED</th>
<th>APPROX. TIME FOR PHOTON BEAM DOSE DISTRIBUTION (Hours)</th>
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<tr>
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<td>microVAX II</td>
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<td>1.0</td>
<td>500</td>
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<td>25</td>
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<tr>
<td>Super</td>
<td>CRAY-2</td>
<td>15</td>
<td>115</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Monte Carlo dose calculation could not be performed for patient treatments back then!

Analytical models had to be used.
Standard Dose Calculation in Clinical Treatment Planning Systems

PAST: 1970s until mid 1990s
Correction-based or Experiment-based Algorithms
TAR, TMR or TPR methods
Depth-Dose for Photon Beams

The photon beam is attenuated when traversing the patient and the absorbed dose in the medium varies with depth.

The variation depends on the beam geometry, quality, and the medium composition.

SAD: Source-Axis-Distance
SSD: Source-Surface-Distance
Depth-Dose for Photon Beams

The photon beam is attenuated when traversing the patient and the absorbed dose in the medium varies with depth.

The variation depends on the beam geometry, quality, and the medium composition.

Energy | $d_{\text{max}}$
---|---
$^{60}\text{Co}$ | 0.5 cm
6 MV | 1.5 cm
18 MV | 3.3 cm

\[ PDD(d, f, SSD) = \frac{D(SSD + d, f)}{D(SSD + d_{\text{max}}, f)} \times 100\% \]

SAD: Source-Axis-Distance
SSD: Source-Surface-Distance

Build-up
Past: 1970s

Phenomenological dose calculation – TAR

Method based on the parameterisation of the dose distribution using measured data sets in water phantom and in air (so-called dosimetric base data).

\[
\text{Tissue Air Ratio (TAR)}
\]

\[
\text{TAR} = \frac{D_{\text{tissue}}}{D_{\text{air}}}
\]

The TAR is affected by the field size and beam energy as well as the depth in the phantom.

Does not account for the build-up in the air measurement.

Not appropriate for modern high energy photons beams.
Past: 1970s

Phenomenological dose calculation – TPR and TMR

The TPR is a variation of the TAR that makes it suitable for use at high energy photon beams. It allows correction of MUs to account for changes in dose at depths other than the reference.

Tissue Phantom Ratio (TPR)

\[ TPR = \frac{D_{\text{phantom}}}{D_{\text{ref}}} \]

Fixed reference depth \( d_{\text{ref}} \) usually 5 cm. Accounts for the build-up of dose in water.

Tissue Maximum Ratio (TMR)

Similar to TPR, but \( d_{\text{ref}} \) is taken as the depth of maximum dose.
Past: 1970s

Correction-based Algorithms

Limitation: Does not handle electronic disequilibrium

Photon source

Standard SSD

Measurements

Calculations (correction factors)

Patient SSD, thickness

Patient composition
Standard Dose Calculation in Clinical Treatment Planning Systems

PAST: 1970s until mid 1990s
Correction-based or Experiment-based Algorithms
TAR, TMR or TPR methods

PRESENT: mid 1990s until 2010-15
Model-based or Superposition/Convolution-based Algorithms
Present: mid 1990s until 2010-15

Convolution methods: Kernels and pencil beams

Method based on calculating microscopic particle interactions of the energy deposition in water for a defined “elementary-photon-beam”.

Point Kernel (calculated with Monte Carlo)

Air

Water

Source

Beam direction

Phantom

Dose grid voxel

\[ D_s(r) = \sum_s T(s, \ldots) A(r - s, \ldots) \]
Present: mid 1990s until 2010-15

Convolution methods: Kernels and pencil beams

Method based on calculating microscopic particle interactions of the energy deposition in water for a defined “elementary-photon-beam”.

Point Kernel (calculated with Monte Carlo)

Multiple Point Kernel

Pencils Kernel
Present: mid 1990s until 2010-15

Analytical models compute the dose in the patient by contribution of several components: **primary dose**, direct beam **phantom scatter** dose, **contaminant** charged particle dose and **head scatter** dose.
The Problem of Interfaces

PBC, PB, FFTC models: based on equivalent path length (electron transport not separately modeled)

AAA and CC algorithms: approximate electron and photon transport

The Problem of Interfaces

Superposition models can handle electronic disequilibrium
But, limitation regarding material interface (different stopping power/scattering)

Proton/ion beam delivery: Passive scattering

Proton/Ion beam delivery: Pencil beam/spot scanning

Analytical Algorithms for Dose Calculation of Ion Beams

Depth-dose profile $Z(z,E_0)$  
Radial-dose profile $L(z,E_0,r)$  
Scattering in medium

TPS for ion beams are mostly based on pencil beam algorithms

$$d = L(z,E_0,r) \cdot Z(z,E_0)$$
The Problem of Tissue Inhomogeneity

Standard Dose Calculation in Clinical Treatment Planning Systems

PAST: 1970s until mid 1990s
Correction-based or Experiment-based Algorithms
TAR, TMR or TPR methods

PRESENT: mid 1990s until 2010-15
Model-based or Superposition/Convolution-based Algorithms

FUTURE: from ~2015 onwards
Stochastic-based or Monte Carlo-based Algorithms
(Review) Monte Carlo Particle Transport Simulation in a Nutshell

Particles are transported **step-by-step** accounting for the stochastic nature of their microscopic interactions.

1. The **distance to the next step** is sampled from the total cross section.

2. The type of interaction is sampled and the scattering event modeled.

3. The transport continues with the next step/or secondary particles.

Monte Carlo can easily handle interfaces of different materials and complex geometries → Scattering and non-equilibrium is accounted for
Analytical vs Monte Carlo Dose Calculation (Photons)

Irradiation of highly heterogeneous geometry.

Pencil Beam Algorithm

Pencil beam algorithm fails to predicts dose inhomogeneity.

Monte Carlo
Analytical vs Monte Carlo Dose Calculation (Photons)

By courtesy of João Seco
Analytical vs Monte Carlo Dose Calculation (Protons)
Para-spinal tumor

Paganetti et al., PMB 53 (17) 2008
Analytical vs Monte Carlo Dose Calculation (Protons)
Para-spinal tumor

Paganetti et al., PMB 53 (17) 2008
Analytical vs Monte Carlo Dose Calculation (Protons)

Para-spinal tumor, total treatment plan

Paganetti et al., PMB 53 (17) 2008

Gamma 2%/2mm
Analytical vs Monte Carlo Dose Calculation (Protons)

Lung case

Monte Carlo  Pencil Beam  Difference

Grassberger et al., PMB 60 (17) 2015
Monte Carlo for modeling of treatment devices
Radiotherapy Treatment Devices: Photon and Electron Beams

TrueBeam

Tomotherapy

CyberKnife
X-ray Treatment Head

Sources of scattered photons

Window
Target/Back/Stopper
Primary Collimator
Flattener
Monitor Chamber

Seco and Verhaegen
Proton and Ion-Beam Radiotherapy

Source: GSI/HIT

Source: Philips/IBA
Proton beam simulation at MGH
Monte Carlo for simulation of radiation transport in magnetic fields
MR-guided Radiotherapy

Source: https://mrrt.elekta.com/elekta-mr-linac/

Source: https://viewray.com/
High effect of magnetic field on dose deposition in lung

\[ \vec{B}_{0T} \]

\[ \perp \vec{B}_{1T} \]

\[ \parallel \vec{B}_{1T} \]

By courtesy of Oliver Schrenk
The Physics of Charged Particle Therapy

Transverse magnetic field leads to asymmetrical point-spread kernel
→ shift of build-up distance
→ electron-return effect (ERE) affecting surface dose (skin, cavities)

Photon beam in transverse B-field

(a) $B = 0 \, \text{T}$  (b) $B = 0.2 \, \text{T}$  (c) $B = 0.75 \, \text{T}$  (d) $B = 1.5 \, \text{T}$  (e) $B = 3 \, \text{T}$


(a) $5 \times 5 \, \text{cm}^2$, central axis
Chamber response in MR-guided RT

Monte Carlo plays a key role in understanding and estimating the effect of magnetic field

Estimation of Electron Contamination in In-line B-field

Proton beam delivery in fringe field (I)

Perpendicular B-field

- The main MRI field and near fringe field act as the strongest to deflect the protons in a consistent direction.
- Off-axis protons are slightly deflected toward or away from the central axis in the direction perpendicular to the main deflection direction
  → distortion of the phase space pattern

Proton beam delivery in fringe field (II)

In-line B-field

- Radial symmetry of the solenoidal style fringe field acts to rotate the protons around the beam’s central axis.
- A minor focusing toward the beam's central axis is also present.

Proton dose distribution in B-field

Distortions on dose distribution in perpendicular B-field

Deflection of proton beam results in shift of the Bragg peak position laterally and in depth with lateral spectral separation of protons.

Fuchs et al., Med Phys 44 2017

Padilla-Cabal et al Med Phys 45 (5), May 2018
For complex geometrical problems as the transport of radiation through a patient, Monte Carlo provides a faster solution than analytical methods.
Extremely difficult to solve analytically, but a trivial task for Monte Carlo!

Adapted from Paganetti, PMB 57 (11) 2012
Advantage of Monte Carlo

Accurately transport radiation through the treatment head and patient

Disadvantages of Monte Carlo

Calculation time
Statistical noise

But...

Monte Carlo codes are getting faster
Computers are getting faster
Noise reduction methods are improving

By courtesy of João Seco
Patient MC Example 1: Head and Neck

By courtesy of João Seco
Patient MC Example 2: Head and Neck

By courtesy of João Seco
Effect of uncertainties on the 95% IDL

10 million

50 million

150 million

1.5 billion
Statistical uncertainties

“Jittery” isodose lines due to the stochastic nature of the MC method are quite different from dose distributions computed with conventional (deterministic) algorithms.

\[ \sigma \sim \frac{1}{\sqrt{N}}, \]

\( N = \text{total no. of particles simulated} \)

In tx planning, Relative uncertainty = \( \frac{\sigma}{\mu} \)
3F lung plan (RT_DPM): relative uncert.

10 million particles

rel. uncert. = $(1\sigma/\mu) \times 100\%$

Clinical plan: one sigma % uncertainty

150 million particles

20% 15% 9%

5% 3.5% 1.5%

rel. uncert. = $(1\sigma/\mu) \times 100\%$

Clinical plan: one sigma % uncertainty

1.5 billion particles

5.5% 4% 0.5%

1.8% 0.5%

rel. uncert. = $(1\sigma/\mu) \times 100\%$
Monte Carlo and the Problem of Statistical Uncertainty

- **Con:** Computationally inefficient, requires long computational time
- **Pro:** Monte Carlo simulations can be made arbitrarily precise
  Monte Carlo simulations can be parallelized

Linux Beowulf cluster built for parallel Monte Carlo simulations
(Prof Seco)
Monte Carlo Particle Transport in Parallel Architectures

Modern Monte Carlo simulations make use of:
- High Performance Computers
- Graphics Processing Units
Monte Carlo for more than just dose calculation...
Radiotherapy with ion beams: Physical aspects

**Energy Deposition (MeV/mm/ion) vs. Depth in Water (mm)**

- $^{16}$O 345 MeV/u
- $^{12}$C 290 MeV/u
- $^{4}$He 152 MeV/u
- $^{1}$H 152 MeV

**Width of lateral dose fall-off (mm) vs. Depth in Water (mm)**

- $^{16}$O
- $^{12}$C
- $^{4}$He
- $^{1}$H

**Dose [arbitrary units] vs. Depth [mm]**

- Proton beam

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The Physics of Charged Particle Therapy
Nuclear fragmentation

Nuclear collisions of the primary ions with the nuclei of atoms in the medium attenuates the beam particles and creates a zoo of new particles.

The fragments are produced in a broad energy and angular distribution.

The impact of nuclear fragmentation is larger for heavier ions and increases with the ion range.

Burigo et al. (2013)
Radiation quality

The LET and dose contribution of fragments changes with the position → variation in RBE

Larger variability of RBE in the tumor and healthy tissues is expected for heavier ions.

The radiation quality as a function of position in the patient can be reliably calculated with Monte Carlo.

Burigo et al. (2014)
LET and Biological Effect

LET has been widely used to characterize the biological effect.

Weyrather et al. 1999

Scholz 2003

Tommasino et al. (2015)
LET-painting in the target

(Top) Dose and dose-average LET for a carbon-ion plan with four fields. (Bottom) LET redistribution in the target volume.

The LET-painting (Bassler et al. 2014) was shown to allow modifying the LET distribution inside the target without impairing the physical dose distribution.

Optimizing the RBE-weighted dose and radiation quality in the target could improve tumor response.

Bassler et al. 2014 Acta Oncol 53: 25
LET-guided optimization

Dose and dose-average LET distributions for base plans for a case of pediatric chordoma irradiated with protons.

At a different study, Giantsoudi and co-authors have presented a LET-guided optimization approach. The results indicated that the LET distribution in the organs-at-risk could be modified at a cost on the dose distribution in the corresponding organ. A reduction of the dose to the organ-at-risk resulted in the increase of the dose-average LET.

Giantsoudi et al. 2013 *Int J Radiat Oncol Biol Phys* 87:216
LET-guided optimization

Grassenberger et al., IJROBP 80 (5) 2011
LET-guided optimization/reoptimization

Plan comparison for a ependymoma patient irradiated with protons.

LET-guided optimization (Giantsoudi et al. 2013) and LET-based reoptimization (Unkelbach et al. 2016) have been successfully applied to modify the LET distribution in the OARs.

Modifying the radiation quality at critical structures could reduce the risks of complications.

Alternatives to LET (I): microdosimetry

At the level of the cell nucleus (micrometer size), the energy deposition fluctuates significantly and cannot be characterized by the LET.

Microdosimetry spectra can be used to specify the radiation quality at this level. This is the base of MKM used at NIRS for the RBE modeling of carbon ions.

Example of tissue-equivalent proportional counter (TEPC) used in microdosimetry

Burigo et al. 2014 *Nucl Instr Meth Phys B* 320: 89
Simulation of Radiation-Induced DNA Damage

Monte Carlo simulations can be used to model the \textit{radiation-induced DNA damages} caused by impact ionizations and radical species.

Alternatives to LET (II): nanodosimetry

At the level of DNA structures (nanometer size), it is appropriate to specify the radiation quality by the **number of ionizations** (nanodosimetry spectrum) taking place in the volume of interest.

Electron-counting nanodosimeter

Ion tracks randomly crossing a cell nucleus.

Burigo et al. 2016 Phys Med Biol **61**: 3698
Take home message: Why Monte Carlo in Medical Physics?

In Physics: More accurate transport of particles in the medium

• More accurate modelling of dose deposition (dosimetry)
• Better understanding of spectrum effects in dosimetry and imaging

In Biology: Better understanding of radiation induced DNA damage

• Accurate dosimetry allows better biological understanding of radiation effects
• Better understanding of particles interacting with DNA

In Oncology: Improvements in physics and biology means improvements in cancer survival rates

• Targeted radiotherapy needs both physics and biology to work together in order to accurately target the tumor.

By courtesy of João Seco
Thank you for your attention!