Commissioning and clinical implementation of Monte Carlo treatment planning system for electron beams

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Educational Objectives

- Appreciate the need for MC based treatment planning systems
- Understand the effect of different types of heterogeneities (geometry and density) on dose distribution
- Understand how to set user control parameters in the TPS to achieve optimum results (minimum statistical noise, minimum distortion of real dose distribution)
- Learn and understand differences between water tank and real patient anatomy based monitor unit values
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

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

*presently Nucletron*
Monte Carlo calculations in commercial TPS

- Divide the beam into treatment-independent and treatment-dependent components
- Simulate treatment-independent components
  - characterize phase space distribution with a beam model
- Simulate transport through the patient anatomy - dose distribution

Courtesy of Varian after Janssen et al.
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)
User input data Nucletron 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
User input data Nucletron TPS cont

Dosimetric data for beam characterization

• Without applicators:
  - X and Y in-air profiles (8x8, 8x20, 8x35, 35x35, SDD = 70 & 90 cm)
  - Central axis Depth Dose in water for various field sizes

• 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
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
Open field measurements (no applicator)

- Depth-dose curves in water at the source-to-phantom distance (SPD) = 100 cm
- Absolute dose, expressed in [cGy/MU], at a specified point on the depth dose curve
- Profile in air at source-detector distance, SDD = 95 cm for the wide open field without an applicator, e.g. 40x40 cm².
For each energy/applicator combination:

- PDD in water at SSD = 100 cm
- Absolute dose, expressed in [cGy/MU], at a specified point on the depth dose curve

No head geometry details required, since at this time Eclipse works only for Varian linac configuration
Clinical implementation of treatment planning software

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

A physicist responsible for TPS implementation should have a thorough understanding of how the system works.
User controlled 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: 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
Software commissioning tests

- Homogeneous water phantom


- All scans done with a high (1 mm) resolution

Typical Experimental setup

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

In-air or in water beam profiles
Homogeneous water phantom tests

- Standard SSD 100 cm and extended SSD
  - Open applicators - PDD and profiles
  - Square and circular cut-outs
- Oblique incidence
  - $GA = 15^0$ and $30^0$
- MU tests - SSD 100 and extended SSD
  - All open applicators
  - Square, rectangular, circular, some irregular cutouts
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
Effect of statistical uncertainty on MC calculations

20 MeV, SSD=100 cm, homogeneous water phantom. Central axis PDD measured and eMC (Eclipse) calculated for 1% and 3% statistical precision, 2.5 mm voxel size, no smoothing.

Courtesy of R. Popple, Med Phys. 33, 1540-51, 2006
Lateral profiles at various depths, SSD=100 cm, Nucletron TPS

9 MeV, 10x10 cm² applicator, SSD=100 cm. Homogeneous water phantom, cross-plane profiles at various depths. MC with 10k/cm².

20 MeV, 10x10 cm² applicator, SSD=100 cm. Homogeneous water phantom. Cross-plane profiles at various depths. MC with 10k and 50k/cm².
Overall mean and variance of MC/hand monitor unit deviation, Nucletron TPS

Mean = -0.003
Variance = 0.0129

Air cylinder

Voxel size 0.39 cm, 47 slices

900 MHz, CPU time for 50k/cm²
14:01-20 MeV , 9:31 – 9MeV

9 MeV, Air cylinder, 10x10cm² applicator, SSD=100cm. Cross-plane profiles.
MC with 10k/cm².

20 MeV, Air cylinder, 10x10cm² applicator, SSD=100cm. Cross-plane profiles.
MC with 10k/cm².
Results MC tests: voxel size 9 MeV


J.E. Cygler, ACMP 2009
Eclipse eMC no smoothing
Voxel size = 2 mm

18 MeV

depth = 4.7 cm

18 MeV

depth = 6.7 cm

depth = 7.7 cm


J.E. Cygler, ACMP 2009
Eclipse eMC
Effect of voxel size and smoothing

Bone cylinder is replaced by water-like medium but with bone density.

Water/Bone stopping-power ratios

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

Ding, G.X., et al

J.E. Cygler, ACMP 2009
9 MeV – hard bone $D_m$ vs. $D_w$
9 MeV - clinical hard bone
D_{m} vs. D_{w}
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.
Results: Clinical – soft bone

- The maximum difference in dose is 1.8%, which is in agreement with the phantom studies
**Treatment Planning Procedure**

The physician:

- outlines CTV and/or GTV

The dosimetrist / physicist:

- models the beam (energy, custom cutout)
  - CTV covered by 90% isodose line

The software calculates:

- absolute dose distribution in cGy
- number of monitor units, MU
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
  
  “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
MU-real patient vs. water tank Impact on DVH
Posterior cervical lymph node irradiation – impact on DVH

Jankowska et al, Radiotherapy & Oncology, 2007
Internal mammary nodes

MC / Water tank $= 210 / 206 = 1.019$
Timing - Nucletron TPS
Theraplan Plus

- 10x10 cm² applicator
- 50k histories/cm²
- Anatomy - 41 CT slices
- Voxels 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 - Nucletron TPS
Oncentra MasterPlan

Anatomy - 41 CT slices
Voxels 3 mm³
10x10 cm² applicator
50k histories/cm²

9 MeV Timer Results:
Init = 0.586793 seconds
Calc = 204.069 seconds
Fini = 0.262845 seconds
Sum = 204.919 seconds

20 MeV Timer Results:
Init = 0.628385 seconds
Calc = 331.551 seconds
Fini = 0.232272 seconds
Sum = 332.412 seconds

Dell Inspiron 16000
Intel(R) Pentium(R) M processor 1.60GHz
1.60 GHz, 2.00 GB of RAM
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.

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<th>CPU time (min)</th>
<th># histories</th>
<th>CPU time (min)</th>
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<td>4.8</td>
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<td>1.6x10⁸</td>
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<tr>
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<td>7.1</td>
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New developments
Energy modulated electron radiation therapy

- IMRT using photon beams is a widely used treatment modality and has become feasible with the introduction of the MLC.

- Energy modulated electron therapy (EMET) using Monte Carlo dose calculations is a promising new technique that enhances the treatment planning and delivery of dose to superficially located tumors.
MLC for electron beams


Pictures courtesy of C. Ma
MLC for electron beams
EMET with FLEC

• Medical Physics Group at McGill University (Al-Yahiya, Verhaegen and Seuntjens) recently proposed and studied the feasibility of a practical “few-leaf electron collimator” (FLEC) for delivering energy modulated electron therapy (EMET).

The compact design of the FLEC makes it suitable to be attached to a clinical electron applicator. FLEC can be automated and remotely controlled.


J.E. Cygler, ACMP 2009
MERT -dose distributions

Ma et al. PMB 48 (2003) 909-924

patient planned using
a) wedged tangential photon beams
b) IMRTtangential beams
c) four field IMRT
d) eight field MERT

Isodose lines shown: 55, 52.5, 50, 45, 40, 25, 15 and 5 Gy.
Dose Volume Histograms
Ma et al. PMB 48 (2003) 909–924

DVH for the target, lung and heart for:

a) the three photon beam plans
b) the three IMRT plans for the chest wall patient

- Healthy tissues (non-target volumes) receive the least dose with MERT high dose regions are significantly reduced in normal tissues
- MERT reduces both max cardiac and lung doses by >20 Gy relative to tangents
- Almost no volume receives dose greater than 20 Gy in MERT.
- Electron range increases low lung dose
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
  - CT based planning for most sites - workload increase; 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
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References


