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

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Part II: Electron beams

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Outline

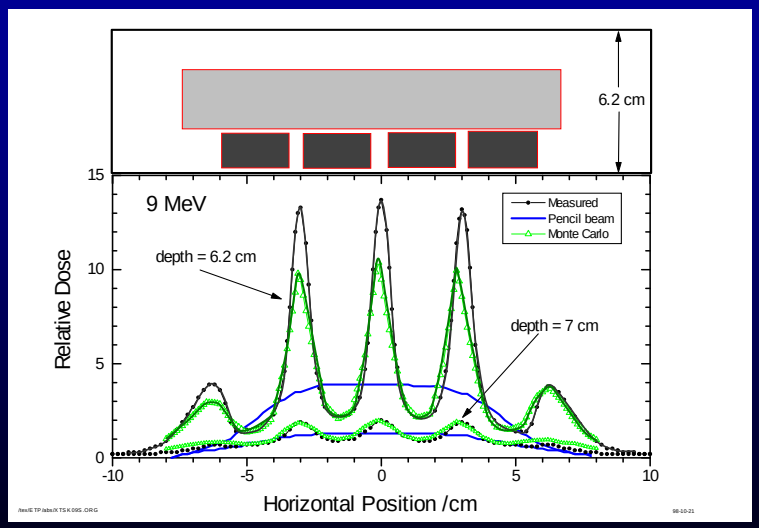
- Rationale for MC dose calculations for electron beams
- Commercially available Monte Carlo based electron treatment planning systems
- Clinical implementation of MC-based TPS
- Issues to pay attention to when using MC based system
- Timing comparisons of major vendor MC codes in the clinical setting.

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

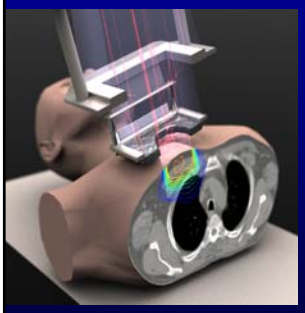


Ding, G. X., et al, Int. J. Rad. Onc. Biol Phys. (2005) 63:622-633

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

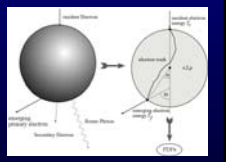


510(k) clearance (June 2002)

- 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 #/cm^2)
- 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"

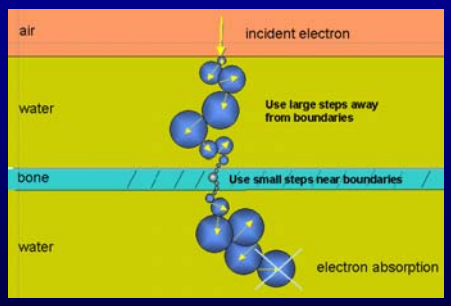


This step is performed off-line.

  - Global: Particle transport through patient modeled as a series of macroscopic steps, each consisting of one local geometry ("kugel")

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

*Kawrakow, Fippel, Friedrich, Med. Phys. 23 (1996) 445-457
*Fippel, Med. Phys. 26 (1999) 1466–1475

Software commissioning tests

- Criteria for acceptability
  - *Van Dyk et al, Int. J. Rad. Oncol. Biol. Phys., **26**, 261-273,1993;*
  - *Fraass, et al, AAPM TG 53: Quality assurance for clinical radiotherapy treatment planning," Med. Phys. 25, 1773–1829 1998*
- Homogeneous water phantom
- Inhomogeneous phantoms (1D, 2D, 3D, complex)
  - Cygler et al, Phys. Med. Biol., *32*, 1073, 1987
  - *Ding G.X.et al, Med. Phys., 26, 2571-2580, 1999*
  - Shiu *et al*, Med.Phys. 19, 623—36, 1992;
  - Boyd *et al, Med. Phys., 28, 950-8, 2001*
- 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

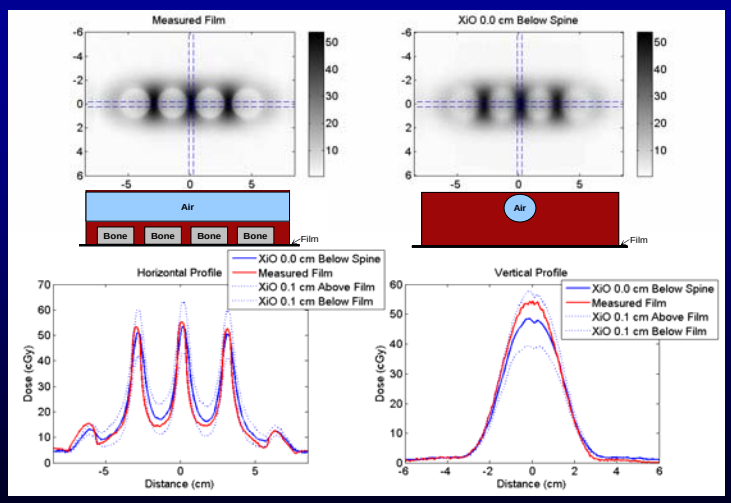
**should include tests specific to Monte Carlo*

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

Software commissioning tests: goals

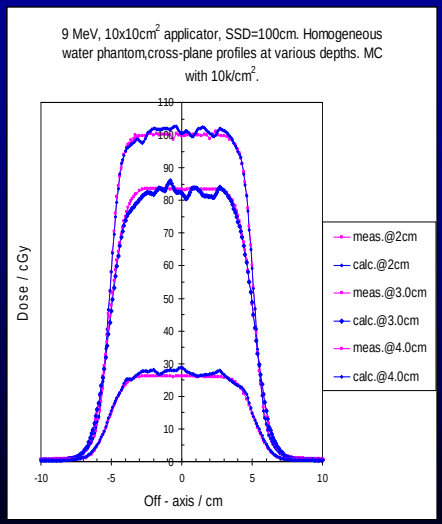
- Setting user control parameters in the TPS to achieve optimum results (acceptable statistical noise, accuracy vs. speed of calculations)
  - Number of particle histories
  - Required statistical uncertainty
  - Voxel size
  - Smoothing
- Understand differences between water tank and real patient anatomy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

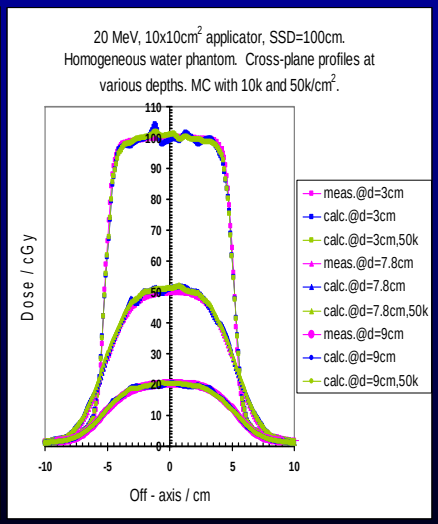
XiO: 9 MeV - Trachea and spine



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

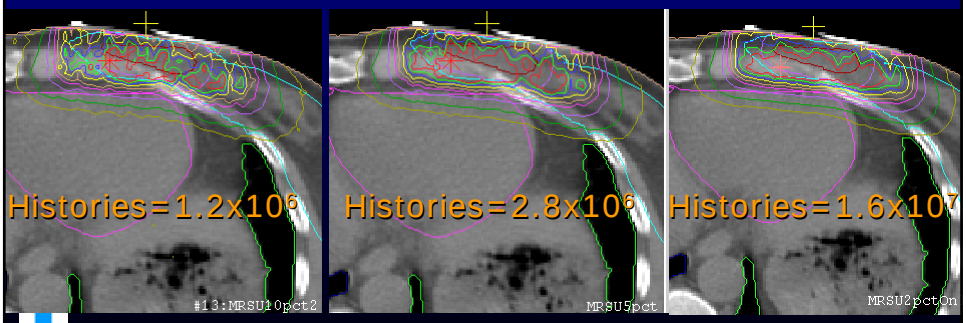
Lateral profiles at various depths, SSD=100cm, Nucletron TPS



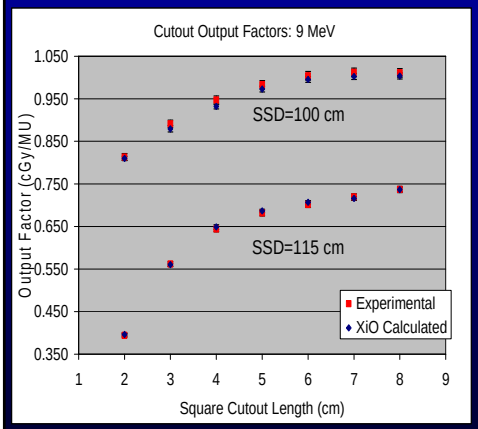


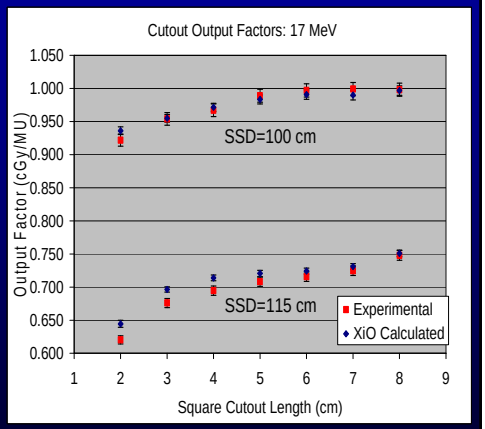
Monte Carlo Settings: Noise in the distributions

Varying MRSU, voxel size=2.5×2.5×2.5 mm^3, dose-to-medium, 6 MeV beam, 10x10 cm^2 applicator



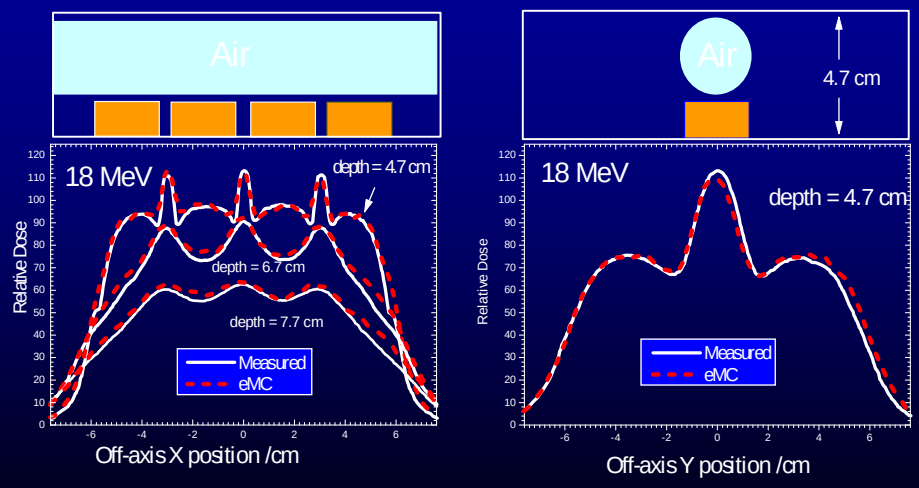
CMS eMC: Cut-out factors





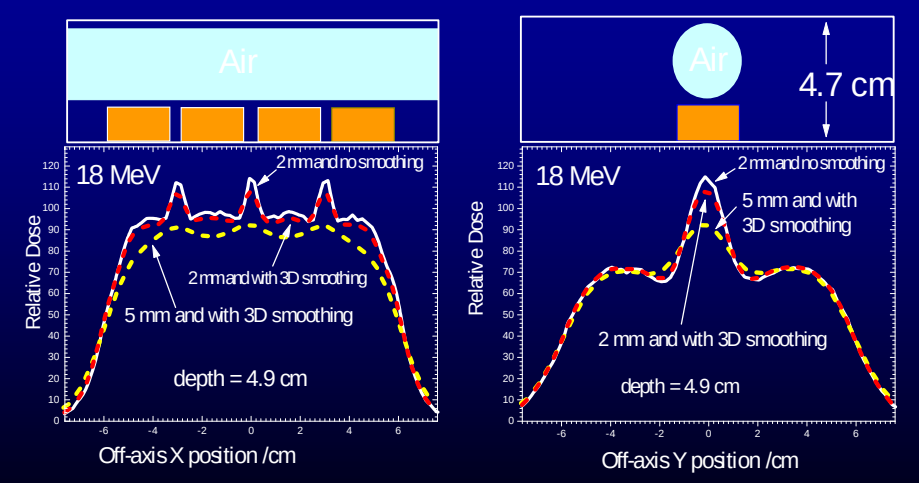
Vandervoort and Cygler, COMP 56th Annual Scientific Meeting, Ottawa ,June 2010

Eclipse eMC no smoothing
Voxel size = 2 mm



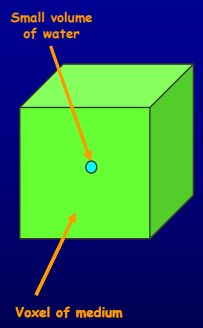
Ding, G X., et al (2006). Phys. Med. Biol. 51 (2006) 2781-2799.

Eclipse eMC
Effect of voxel size and smoothing



Ding, G X., et al (2006). Phys. Med. Biol. 51 (2006) 2781-2799.

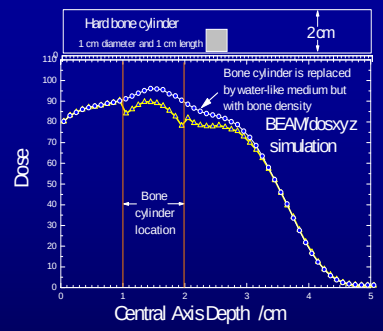
Dose-to-water vs. dose-to-medium

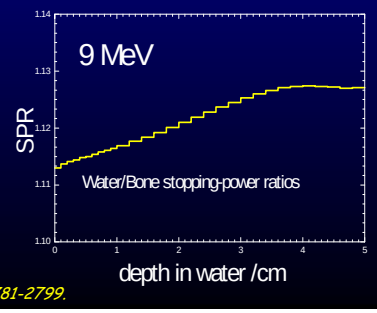


D_m - energy absorbed in a medium voxel divided by the mass of the medium element.

D_w - energy absorbed in a small cavity of water divided by the mass of that cavity.

$$D_w = D_m \left(\frac{S}{\rho}\right)_m^w$$

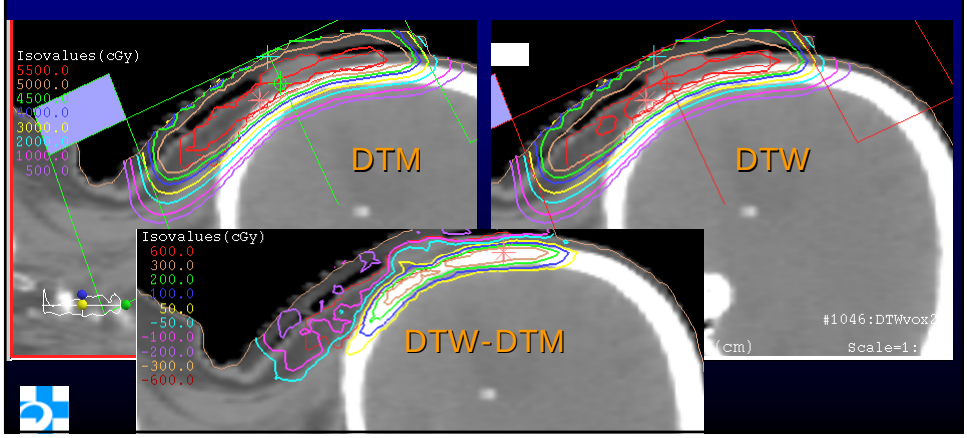




Ding, G X., et al Phys. Med. Biol. 51 (2006) 2781-2799.

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

Dose-to-water vs. dose-to-medium, MRSU=2%, voxel size=4×4×4 mm^3, 6 MeV beam, 15x15 cm^2 applicator, both 602 MU



Good clinical practice

- Murphy's Law of computer software (including Monte Carlo)

"All software contains at least one bug"

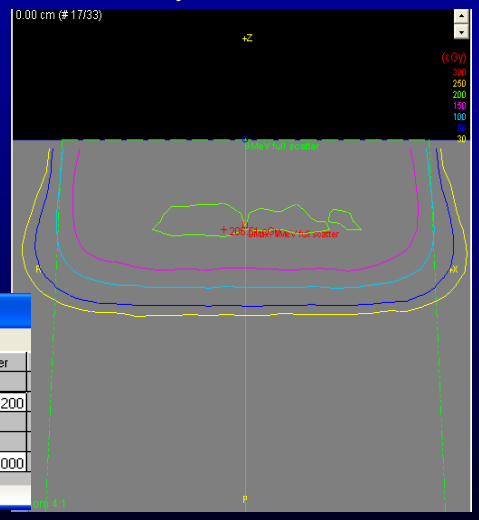
- Independent checks

MU MC vs. hand calculations

Monte Carlo	Hand Calculations
Real physical dose calculated on a patient anatomy	Rectangular water tank
Inhomogeneity correction included	No inhomogeneity correction
Arbitrary beam angle	Perpendicular beam incidence only

9 MeV, full scatter phantom (water tank)

RDR=1 cGy/MU



Point Dose Data

File Edit

	9MeV full scatter
Weight	N/A
MU or min	200
Iso: 9MeV full scatter	N/A
dMax: 9MeV full scatter	N/A
DMax: 9MeV full scatter (0.00,0.00,-2.10)	200.000

Lateral scatter missing

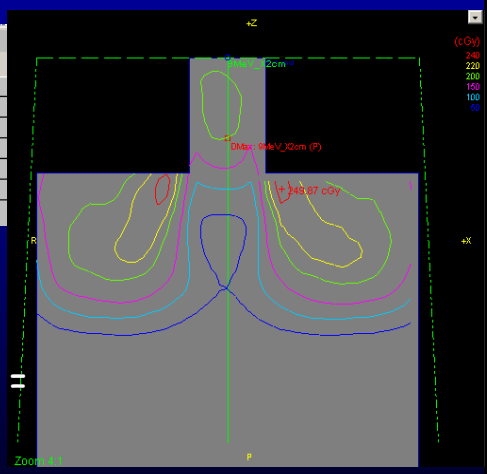
Point Dose Data

File Edit

	9MeV_X2cm	Total Rel. Dose
Weight	N/A	N/A
MU or min	234	N/A
Iso: 9MeV_X2cm	N/A	N/A
dMax: 9MeV_X2cm	N/A	N/A
DMax: 9MeV_X2cm (P) (0.00,0.00,-2.10)	200.000	N/A

Plan Data - Norm: 100.00

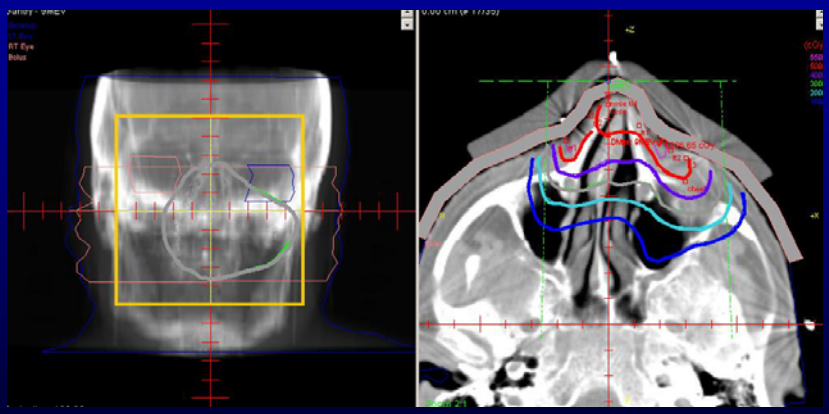
Number of Fractions	1
MU or min / Fraction	234



Real contour / Water tank =

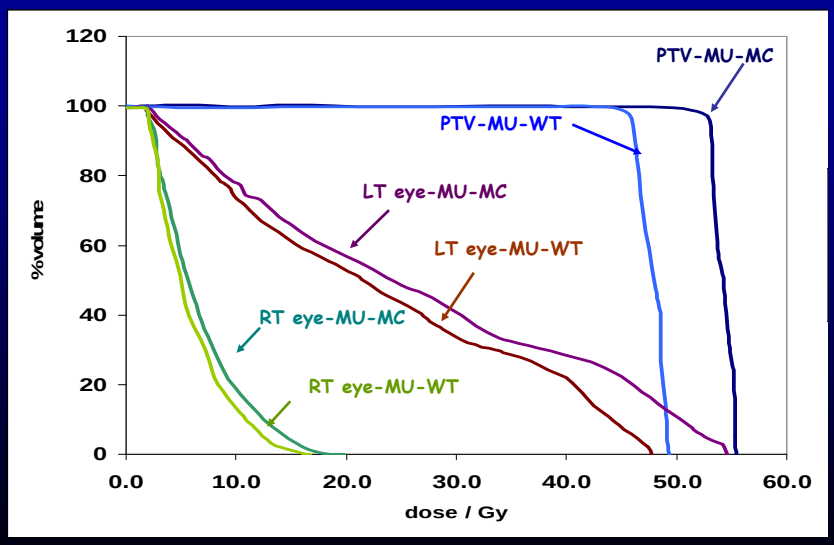
=234MU / 200MU=1.17

MU real patient vs.water tank

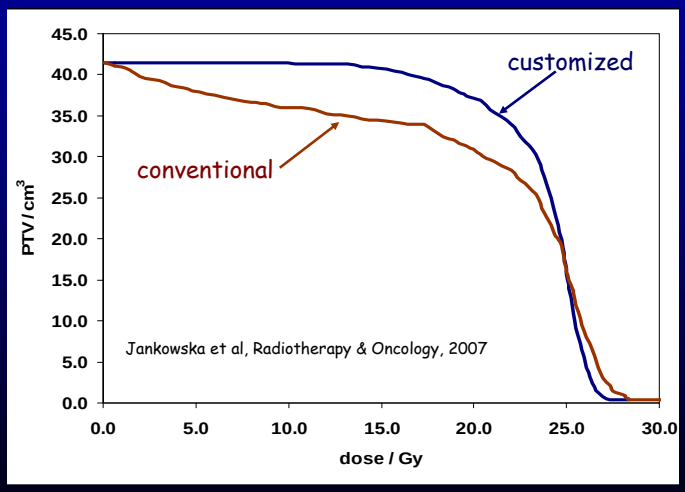


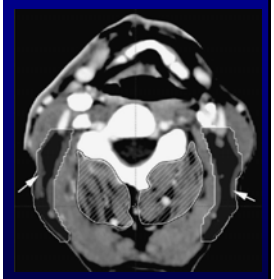
MC / Water tank= 292 / 256=1.14

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

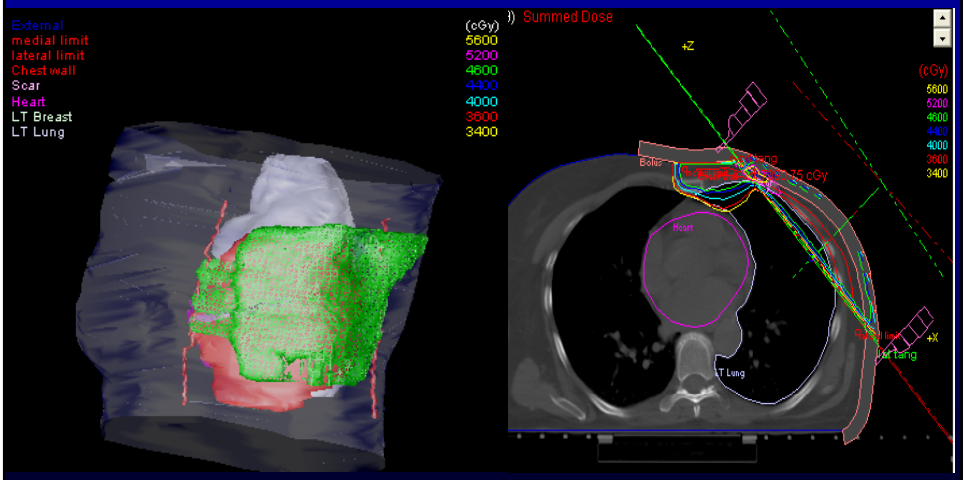


Posterior cervical lymph node irradiation - impact on DVH





Internal mammary nodes

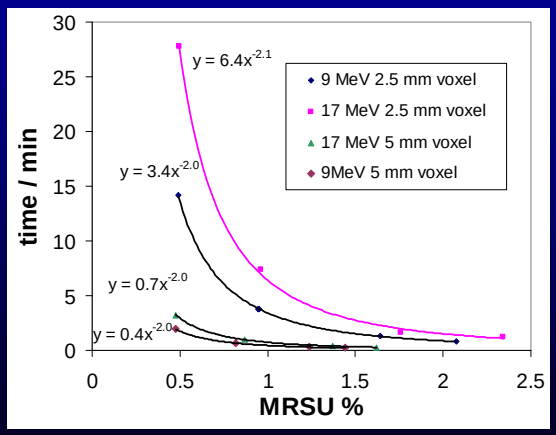


MC / Water tank= 210 / 206=1.019

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 cm^2 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 – Pinnacle^3

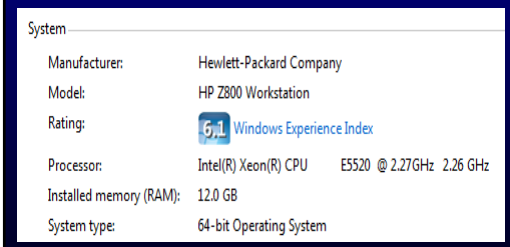
dual processor 1.6 GHz Sun workstation, 16 GB RAM.

Overall uncertainty						
	2%		1%		0.5%	
Patient	# histories	CPU time (min)	# histories	CPU time (min)	# histories	CPU time (h)
1(cheek)	3.4×10^6	4.8	1.4×10^7	20	1.6×10^8	3.9
2 (ear)	1.7×10^6	2.1	6.5×10^6	8.1	7.1×10^7	1.5
3 (breast)	3.3×10^6	7.1	1.4×10^7	29.9	1.5×10^8	5.4
4 (face)	1.1×10^7	32.1	4.7×10^8	134.5	5.2×10^8	24.5

Fragoso et al.: Med. Phys. 35, 1028-1038, 2008

Timing – Nucletron TPS Oncentra 4.0

Anatomy - 201 CT slices
Voxels 3 mm^3
10x10 cm^2 applicator
50k histories/cm^2



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

Chetty et al.: AAPM Task Group Report No. 105: Monte Carlo-based treatment planning, Med. Phys. 34, 4818-4853, 2007

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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