Successes and challenges associated with MC treatment planning in the clinic

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Outline

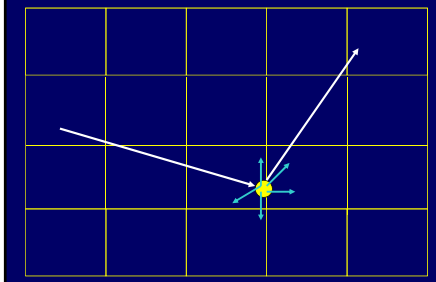
A. Introduction to the Monte Carlo Method as applied to radiation transport

B. Beam modeling: A review of available methods and examples of vendor implementations

C. Clinical Challenges: statistical uncertainties, reporting of dose in tissues (medium and water), and IMRT optimization

Monte Carlo transport of radiation
Photon transport

Photons don't interact much - The mean collision distance for a 2 MeV photon in water is ~ 20 cm



Analog Transport

Fundamental Interaction Types:

- compton
- photo-electric
- pair production
- Coherent (Rayleigh)

Interaction probabilities depend on energy, atomic no., density

Monte Carlo transport of radiation
Electron transport

Electron interactions are numerous – A 2 MeV electron will lose energy at a rate of ~ 2 MeV per cm interacting in water and undergo ~ 10^6 collisions (excitations + ionizations)

For external photon beam radiation, electron transport is the bottle neck!

Interaction Types

- Collisions
- Elastic (multiple) scattering
- Radiative processes (bremsstrahlung)

The Condensed History Technique (CHT)

The vast majority of electron interactions lead to very small changes in the electron energy and/or direction

Berger (1963) proposed the CHT, which groups e' interactions into single "steps" that account for aggregate effects of scattering along the path

The CHT is the single most important development in the application of MC calculations in the radiotherapy setting; without the CHT MC calculations in RT would be prohibitively long

The Condensed History Technique (CHT)

The CHT introduces an artificial parameter, the "step size"; the electron step algorithm (transport mechanics) can strongly influence speed and accuracy

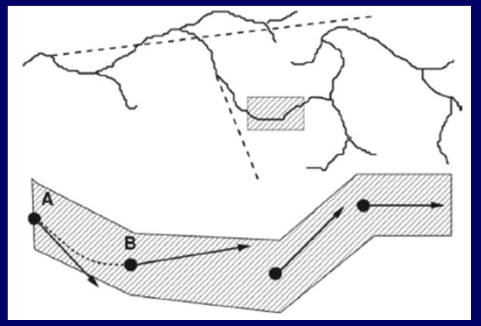


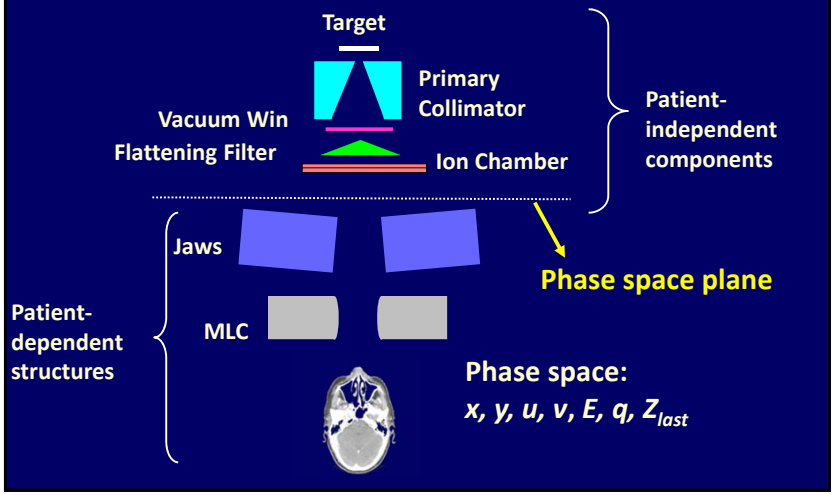
Illustration of a class II condensed history scheme: From AAPM TG-105: Med Phys 34: 2007

The Condensed History Technique (CHT)

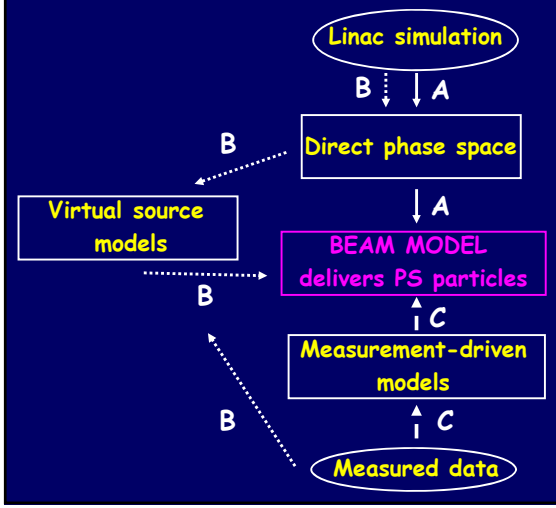
The significant improvements in efficiency with "second generation" codes (e.g. VMC++, XVMC, EGSnrc, DPM, MMC, etc.) are mainly a result of differences in the transport mechanics and boundary crossing implementations, relative to "first generation codes" (EGS4/Presta, MCNP, Penelope, Geant4, etc.)

In general, "second generation" codes employ e-step algorithms that converge faster, i.e. you are able to take fewer CH steps for the same precision

Treatment head simulations and beam modeling



The possible options for specifying a beam model



From *AAPM TG-105: Med Phys 34: 2007*

***AAPM Task Group Report No. 157*: Source modeling and beam commissioning for Monte Carlo dose calculation based radiation therapy treatment planning**

C-M Ma (Chair), IJ Chetty, J Deng, B Faddegon, SB Jiang, J Li, J Seuntjens, JV Siebers, E Traneus

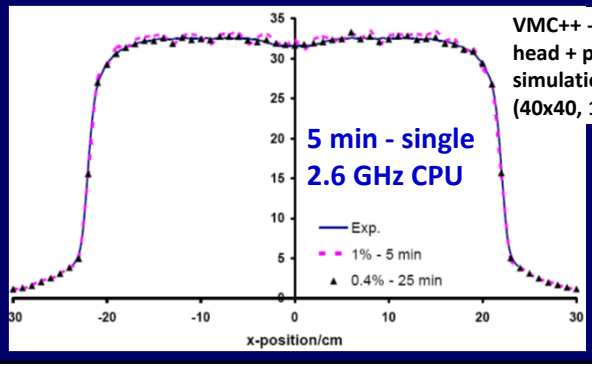
A. Direct Phase Space Simulation

A phase space file can be generated at a plane above the patient-dependent components (jaws and MLC) and is used as input for the patient-dependent simulation; full simulation without storing PS information can be performed

Methods for simulation through the patient-dependent components include: direct simulation with or without approximations

Direct simulation: VMC++

VMC++ (Kawrakow) has incorporated aggressive variance reduction techniques (e.g. Directional Bremss Splitting) for "real-time) treatment head simulations



VMC++ - Full Tx head + phantom simulation (40x40, 10 cm)

Fragoso, Kawrakow *et al.* Med Phys 36: 2009

B. Multiple Source Models

Motivation: Virtual source models provide a more concise characterization of the PS file – they do not require GB of disk space, and are possibly more efficient

Fluence distributions for individual treatment head components (sub-sources) are reconstructed from the phase space file acquired in a plane above the patient-dependent components

Distributions for particle fluence, mean energy and angle for sub-sources are correlated

Beam Model Representation

$$\Phi(x,y,u,v,E) = \sum_{j=1}^{m} \phi_j f_j(E) g_j(x,y,x_s,y_s)$$

From C-M Ma *et al.*: Med Phys 1997

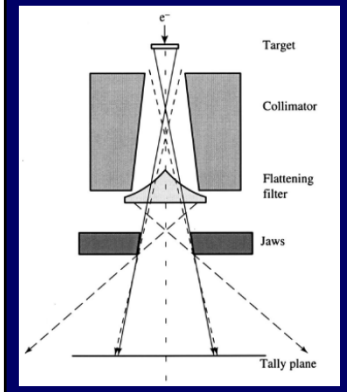
ϕ_j **is the relative source intensity for sub-source *j***

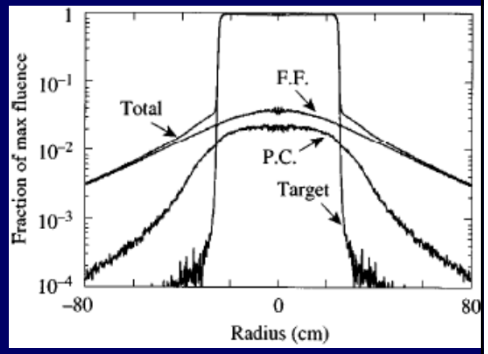
x_s, y_s **are the x-and y-coordinates in the source plane**

$g_j(x, y, x_s, y_s)$ **is the sub-source fluence distribution**

$f_j(E)$ **is the sub-source energy distribution**

Example Photon Fluence Distributions





Schach von Wittenau *et al.*: Med Phys 1999

C. Measurement Driven Models

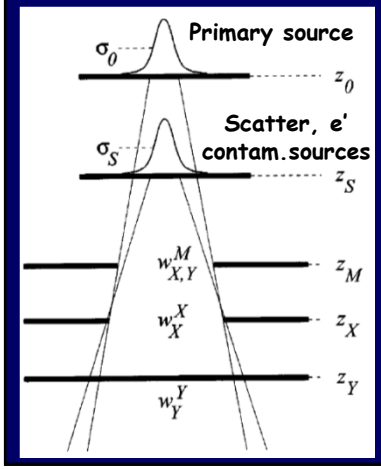
Analytical representations or parameterized forms describing the fluence distributions and returning the phase space for calculations within the patient

Optimal model parameters are derived from fitting procedures comparing calculations and measurements

Beam modifiers may also be modeled using analytical approaches and parameters to account for primary and scatter photons

Measurement Driven Models: Examples

Virtual Energy Fluence Model (XVMC): Fippel *et al.* Med Phys (2003)



FWHMs and relative weights of the sources are iteratively adjusted to produce the best agreement between calculations of the energy fluence and measured profiles in air

Energy spectrum is derived by minimizing the differences between measurements and the superposition of the calculated doses – includes an off-axis softening term

Commercial MC system implementations

The majority of commercially available MC systems employ measurement-driven models

Measurement-driven models do not require detailed knowledge of the treatment head and are very similar to the analytical models used over the years with conventional algorithms

Using these models one may not be utilizing the full potential of the MC technique in simulating complicated delivery techniques, such as IMRT

Commissioning and Experimental Verification

The MC method should be subjected to testing as reported in articles on commissioning of dose algorithms, such as AAPM TG-53 and IAEA TRS-430

Experiments should be performed to test the beam model accuracy and the transport accuracy within patient-like geometries, and in complex in complex configurations designed to verify the improved accuracy expected with the use of the MC method

Accurate measurements are a requirement for accurate simulations: AAPM TG 155 Small Fields and Non-Equilibrium Condition Photon Beam Dosimetry (Das *et al.*)

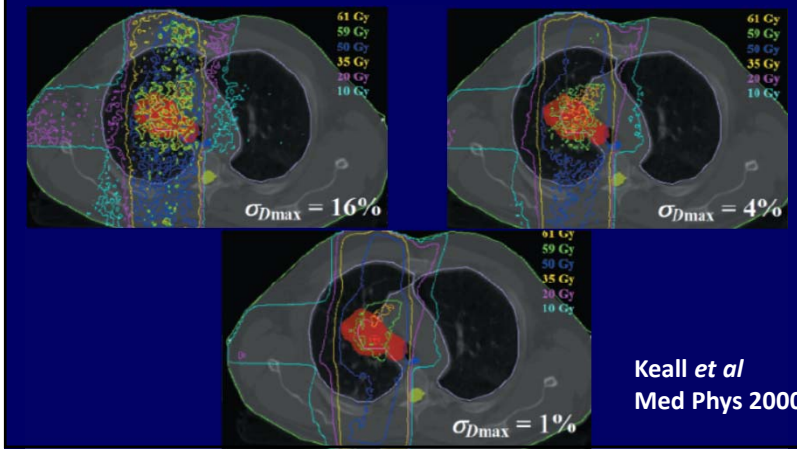
Statistical Uncertainties in MC-computed dose

How many physicists does it take to perform a Monte Carlo simulation?

Answer: 1-3, sigma = .05

Adapted from http://www.ahajokes.com/

MC patient dose calculation and statistical uncertainties

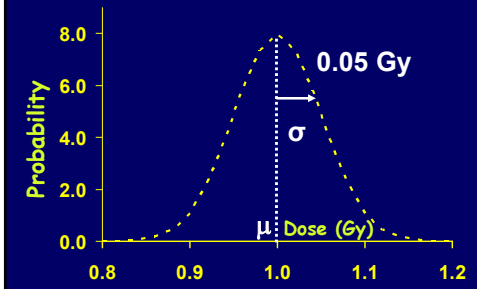


Keall *et al*
Med Phys 2000

Statistical uncertainties

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

$\sigma \sim 1/\sqrt{N}$ [N= total no. of particles simulated]



In Tx planning, the relative uncertainty $= \sigma / \mu$

$\sigma / \mu \sim 1/\sqrt{\text{dose}}$

Questions / Challenges: Statistical Uncertainties

To what level of uncertainty do I need to run the calculation to feel confident with the results, and where should I specify that point?

MC-based dose prescriptions should be volume-based (e.g. to the PTV); doses should not be prescribed to the max. or min. dose points (AAPM TG-105)

In a region of uniform dose (e.g. the PTV), the statistical outliers (e.g. max. or min. dose points) can deviate from the mean dose by many standard deviations

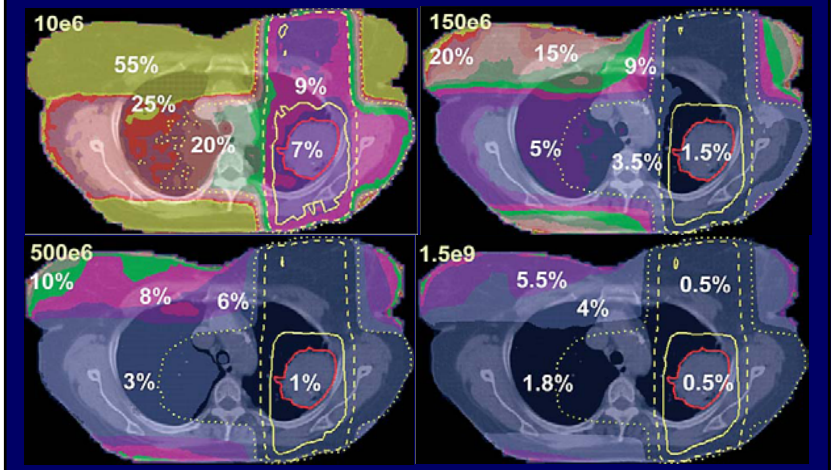
Statistical uncertainties: Recommendations (AAPM TG-105)

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

Dose volume indices for parallel organs like the lung (e.g. the mean lung dose) are minimally impacted by statistical noise

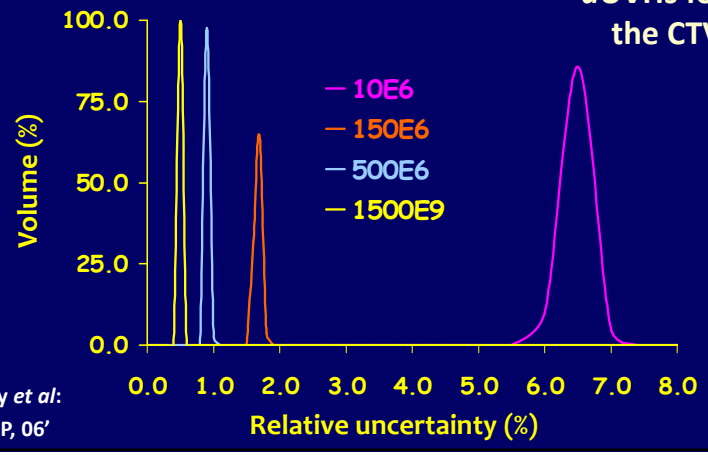
For serial organs, where point doses are important, (e.g. the max. cord dose) higher statistical precision may be necessary; volume-based uncertainties will be more reliable

Tools for evaluating uncertainties in planning: UMPlan



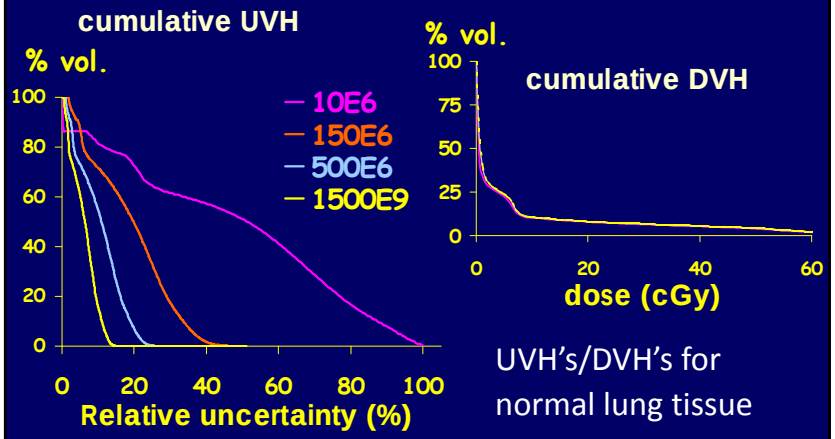
Chetty, Fraass, McShan *et al*: IJROBP, 06'

Tools for evaluating uncertainties in planning: Uncertainty volume histograms (UVHs)



Chetty *et al*: IJROBP, 06'

Tools for evaluating uncertainties in planning: UVHs

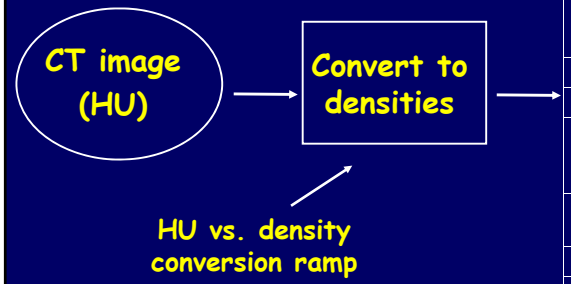


UVH's/DVH's for normal lung tissue

MC-based treatment planning: CT number to material conversions

Methods for CT-to-material conversions

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

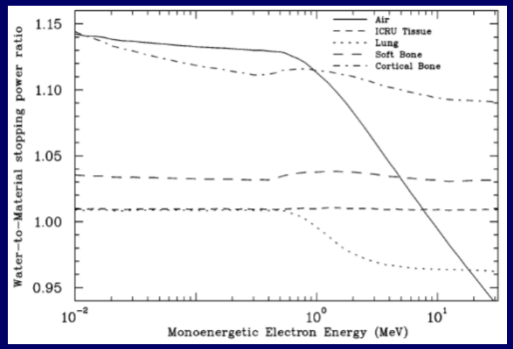


Tissue	Relative Electron Density
air	0.0
lung	0.2 (0.1-0.5)
Soft tissue, water	1.0
spongy bone	1.2
skull	1.65
compact bone	1.85

CT-to-material conversions: Recommendations

Both mass density and material compositions (atomic no.) are needed for accurate MC calculation

Failure to incorporate atomic no. compositions can result in notable errors at higher tissue densities (Verhaegen and Devic, PMB, 50:937, '05)



From Siebers *et al* PMB: 45: 983 (2000)

Converting dose-to-medium (D_m) to dose-to-water (D_w)

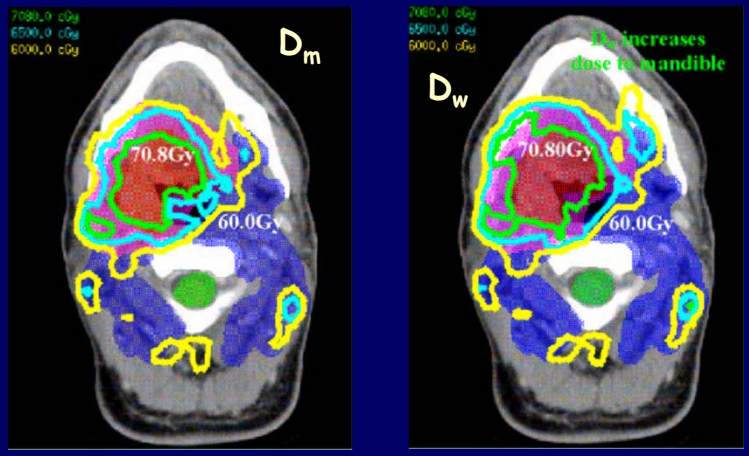
The conversion can be accomplished using the Bragg-Gray formalism:

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

$\left(\frac{S}{\rho} \right)_m^w$ Unrestricted wat-to-med mass collision stopping power averaged over the energy spectrum of electrons at the pt. of interest

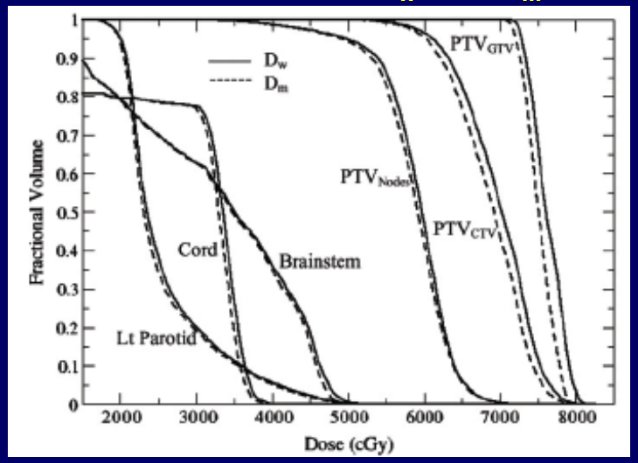
This can be applied either as a post-processing step or as a multiplication factor to the energy loss step

Clinical Examples: D_w and D_m



Dogan, Siebers, Keall: Phys Med Biol 51: 4967-4980 (2006)

Clinical Examples: D_w and D_m

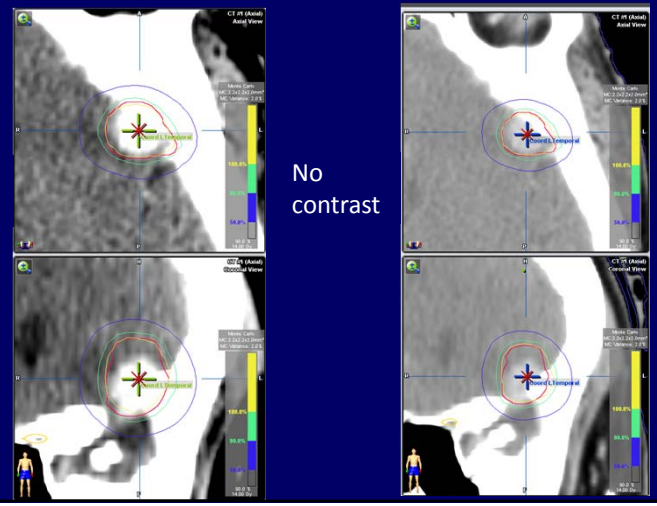


Dogan, Siebers, Keall: Phys Med Biol 51: 4967-4980 (2006)

Challenge: impact of contrast on D_w and D_m : brain tumor

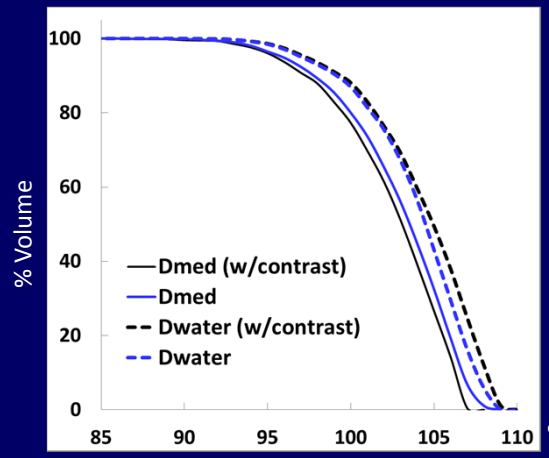
w/ contrast

No contrast



Courtesy:
H. Li (HFHS)

Challenge: impact of contrast on D_w and D_m : brain tumor



Courtesy: H. Li (HFHS)

IMRT Optimization

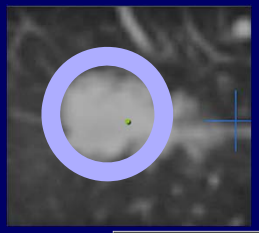
SABR for early stage lung cancers and the increased use of IMRT: Videtic *et al.* "Intensity-modulated radiotherapy-based stereotactic body radiotherapy for medically inoperable early-stage lung cancer: excellent local control."
Int J Radiat Oncol Biol Phys. 77(2):344-9 (2010)

In some commercial implementations, MC-calculations are used for the final dose only – pencil beam algorithms are used for optimization

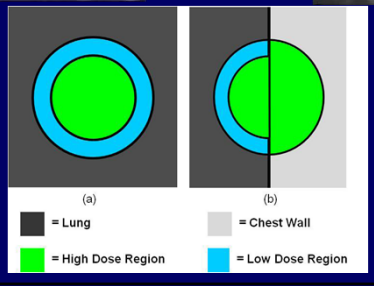
"Optimized" converges based on the inaccurate, pencil-beam-based beamlet calculations

Implications for PB-based beamlet calculations in MC planning

"island" tumor

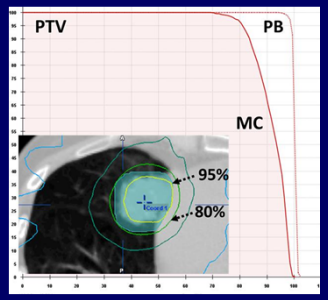


"lung-wall" tumor



Altman *et al.* "Practical IMRT, MC-based SBRT planning", *JACMP,* 13 (6) 2012

How do we mitigate the "cold" spot at the periphery?

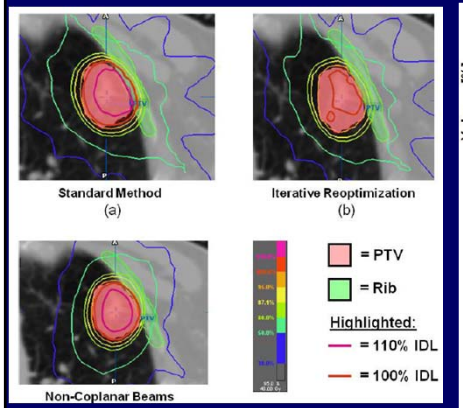


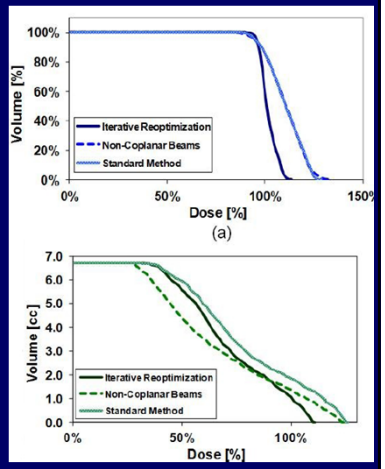
Normalize the dose to the cold spot – may work well for island tumors but not so well for tumors situated near OARs (e.g. rib-cage)

Iterative Optimization – define the cold spot and "boost" it in the second iteration

Non-coplanar beams – increases DOF to shape the dose distribution

How do we improve the dose distributions?





Altman *et al.* "Practical IMRT, MC-based SBRT planning", *JACMP,* 13 (6) 2012

Summary

Modeling and commissioning of the accelerator models: development of accurate models for characterizing linacs from different manufacturers and commissioning of these models is challenging - AAPM TG-157: Commissioning of beam models in Monte Carlo-based clinical treatment planning, Charlie Ma *et al*.

Experimental verification: Verification of complex beam configurations; transport in patient tissues under situations of charged-particle disequilibrium will be important, but challenging

Summary

Tools for MC-based Tx planning: issues such as statistical uncertainties in dose must be addressed by the clinical team; proper tools for display and evaluation of statistical uncertainties will be necessary in MC-based Tx planning

Reporting of dose to tissues: More guidance is needed on reporting of Dw or Dm particularly in situations where high Z structures are present

IMRT optimization: Vendors should implement MC-based beamlet calculations or perform automatic iterative optimization using MC dose distributions

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Monte Carlo treatment planning in radiation therapy

Part II-electron beams

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Objectives – electron beams

- To discuss currently available commercial MC-based treatment planning systems for electron beams.
- To describe commissioning of such systems in terms of beam models and dose calculation modules.
- To discuss the factors associated with MC dose calculation within the patient-specific geometry, such as statistical uncertainties, CT-number to material density assignments, and reporting of dose-to-medium versus dose-to-water.
- Evaluation of the possible clinical impact of MC-based electron beam dose calculations

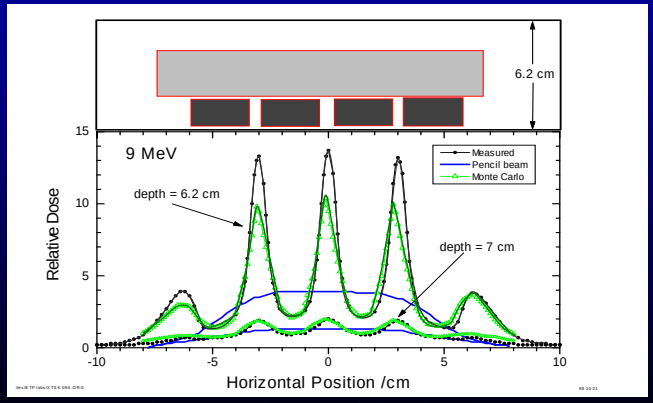
Rationale for Monte Carlo dose calculation for electron beams

- 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*

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

Rationale for Monte Carlo dose calculation for electron beams



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

Monte Carlo based Treatment Planning Systems

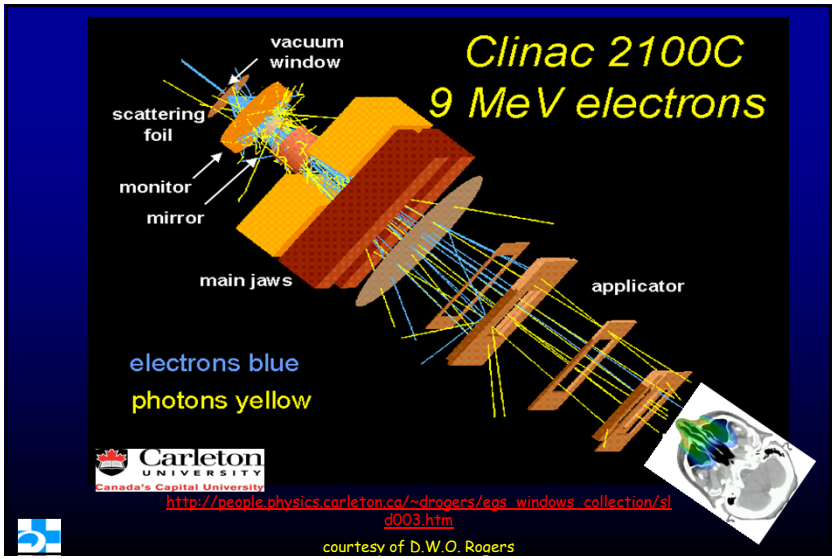
M C dose calculations give in general the right answer

- 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 heterogeneities can be properly handled
- There are many experimental benchmarks showing M C calculations can be very accurate (see the references)

Components of Monte Carlo based dose calculation system

There are two basic components of MC dose calculation, see the next slide:

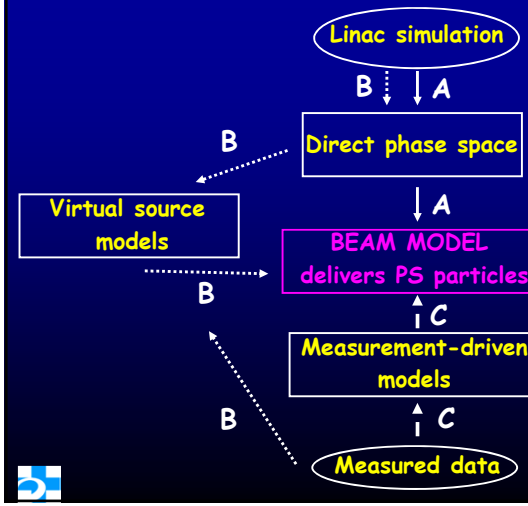
1. Particle transport through the accelerator head
   - Explicit transport (e.g. BEAM code)
   - Accelerator head model (parameterization of primary and scattered beam components)
2. Dose calculation in the patient



Particle transport through the machine head - beam models

- Direct MC simulation of the accelerator head
  - beam simulations can be done accurately if all the parameters are known - but they often are not
- Beam models provide a solution to the above problem
  - is any algorithm that delivers the location, direction and energy of particles to the patient dose-calculating algorithm.

Possible options for specifying a beam model



AAPM TG-105: Med Phys 34: 2007
courtesy of I. Chetty

Example of a beam model

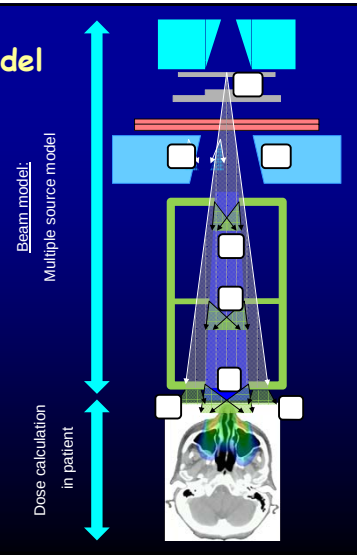
Sub-sources

1 - the main diverging source of electrons and photons;

2 - edge source of electrons;

3 - transmission source of photons;

4 - line source of electrons and photons.

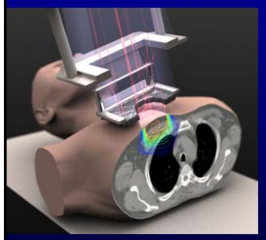


M.K. Fix et al,
Phys. Med. Biol. 58 (2013) 2841-2859

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 beam models for linacs from other vendors (*M.K. Fix et al, Phys. Med. Biol. 58 (2013) 2841-2859)*
- CMS XiO eMC for electron beams 2010
  - Based on VMC (Kawrakow, Fippel, Friedrich, 1996)

Nucletron Electron Monte Carlo Dose Calculation Module

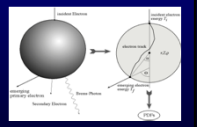


510(k) clearance (June 2002)

- 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"

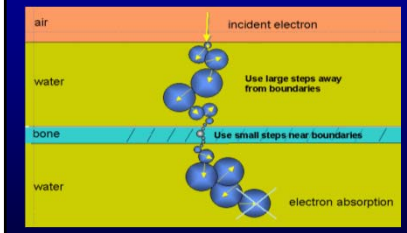


This step is performed off-line.

  - 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 (several sizes available)
  - 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 the early VMC* code
  - 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)
  - minimum value of dose voxel for MRSU specification
- CMS performs the beam modeling

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

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 model), as specified in User Manual, for example:

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

Clinical implementation of MC treatment planning software

- Beam data acquisition and fitting
- Software commissioning tests*
  - Beam model verification
    - Dose profiles and MU calculations in a homogeneous water tank
  - In-patient dose calculations
- Clinical implementation
  - procedures for clinical use
  - possible restrictions
  - staff training

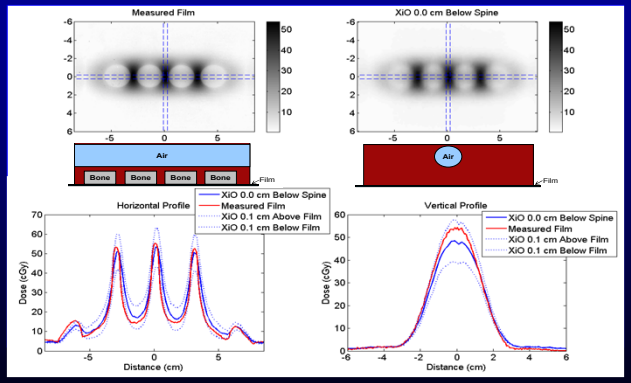
should include tests specific to Monte Carlo

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

Software commissioning tests: goals

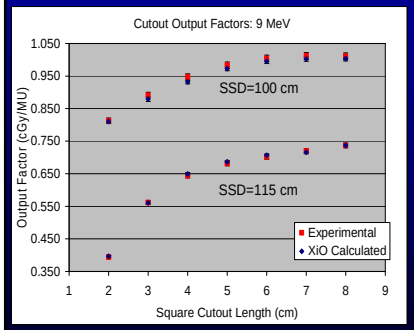
- Setting user control parameters in the TPS to achieve optimum results (acceptable statistical noise, accuracy vs. speed of calculations)
  - Number of particle histories
  - Required statistical uncertainty
  - Voxel size
  - Smoothing
- Understand differences between water tank and real patient anatomy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

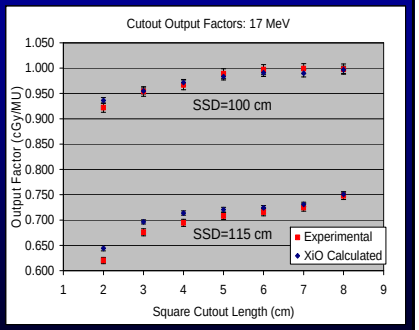
XiO: 9 MeV - Trachea and spine
importance of high quality data



SU-E-T-669

Example of beam model verification
CMS eMC: cutout factors



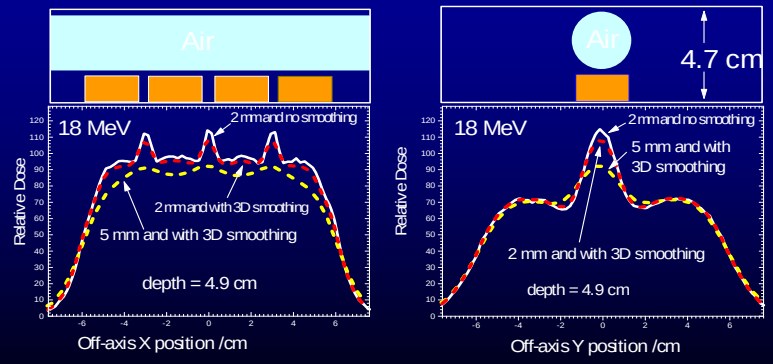


Monte Carlo Settings: Noise in the dose distributions

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

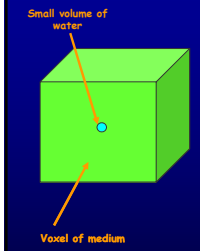
MRSU=10% MRSU=5% MRSU=2%

Eclipse eMC
Effect of voxel size and smoothing



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

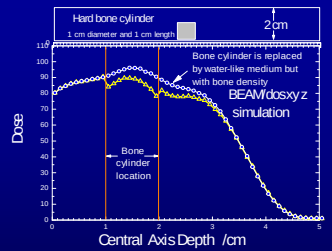
Dose-to-water vs. dose-to-medium

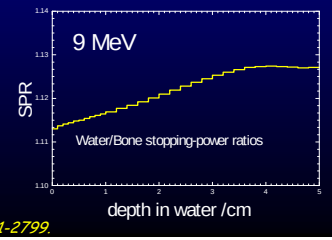


D_m - energy absorbed in a medium voxel divided by the mass of the medium element.

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

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

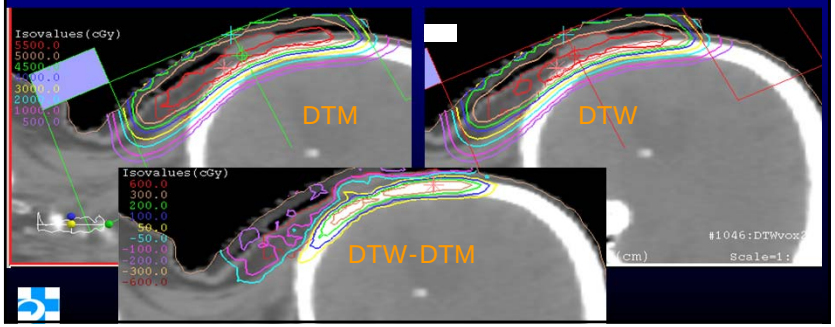




Ding, G X., et al Phys. Med. Biol. 51 (2006) 2781-2799.

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

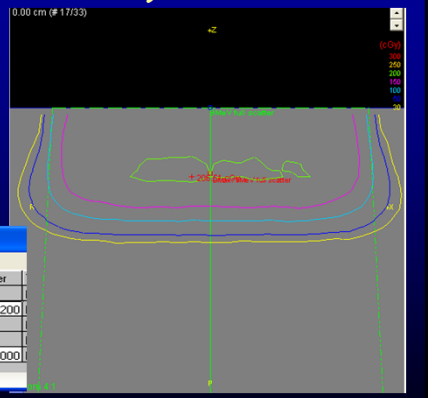


MU MC vs. hand calculations

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



Lateral scatter missing

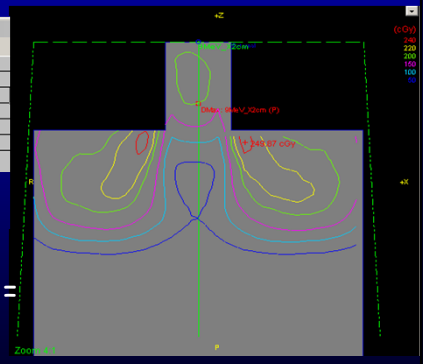
Point Dose Data

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

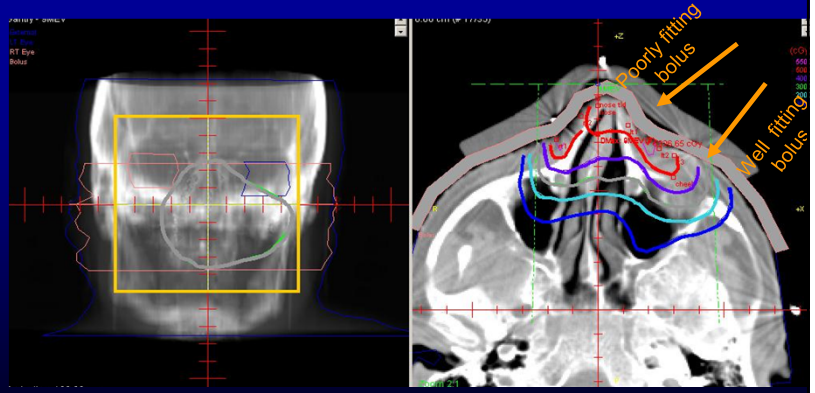


Real contour / Water tank =

=234MU / 200MU=1.17

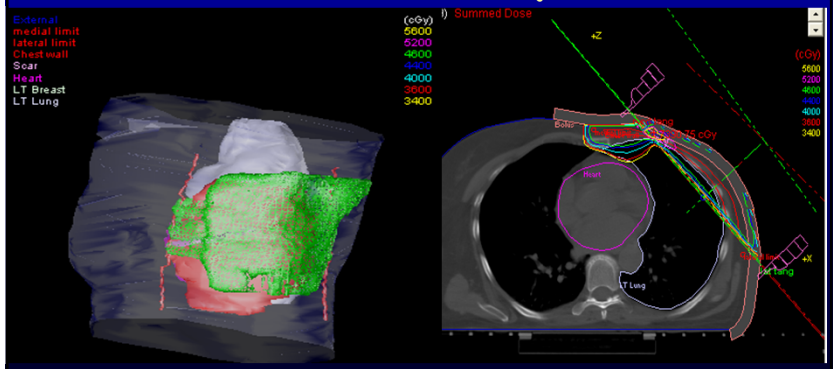
Reason for more MU: % isodose at the nominal (reference) d_{max} depth < 100%

MU real patient vs.water tank



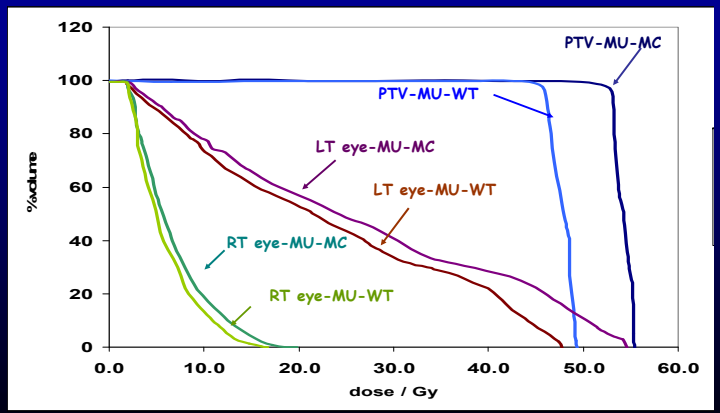
MC / Water tank= 292 / 256=1.14

Internal mammary nodes

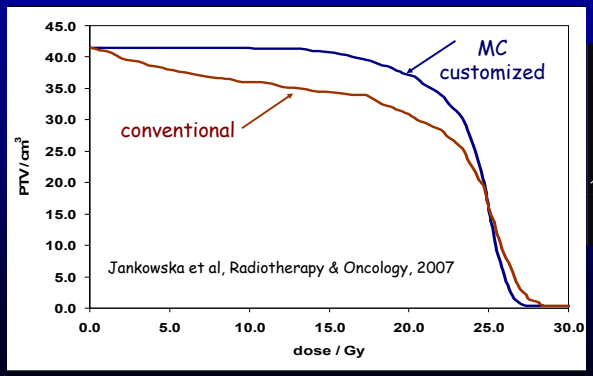


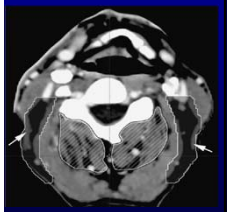
MC / Water tank= 210 / 206=1.019

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



Posterior cervical lymph node irradiation - impact on DVH

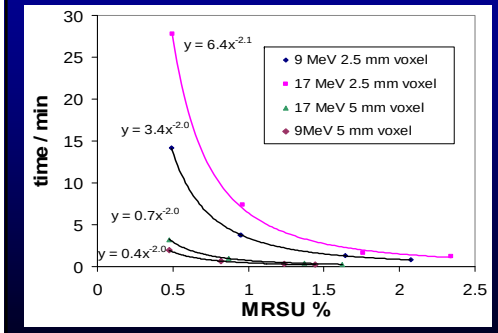




How long does it take?

- MC gives entire dose distribution in the irradiated volume, 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
  - speed of CPU and optimization of compiler
  - complexity of patient specific beam modifiers

Monte-Carlo Settings: Effect on computation time



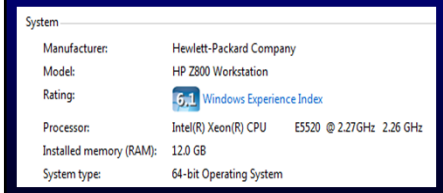
Timing Results XiO TPS:

For 9 and 17 MeV beams, 10x10 cm² 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.

J.E. Cygler and G.X. Ding, in Monte Carlo Techniques in Radiation Therapy, ISBN-10: 1466507926, Taylor & Francis (CRC Press INC) Boca Raton 2013, p 155-166

Timing – Nucletron TPS Oncentra 4.0

Anatomy - 201 CT slices
Voxels 3 mm³
10x10 cm² applicator
50k histories/cm²



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 (minutes) 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)

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