Clinical Implementation of Monte Carlo Methods for External Photon Therapy

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Outline

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

B. "Second-generation" MC codes: Factors that render these codes fast enough for clinical treatment planning

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

Outline

D. Commissioning and Experimental Verification of MC-based systems

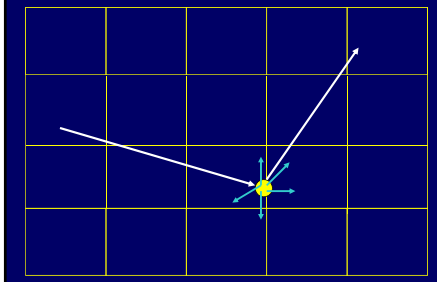
E. Statistical uncertainties in dose

F. Dose-to-water and dose-to-material

G. Clinical Applications: lung SBRT planning

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

Without the CHT MC calculations in RT would be prohibitively long even today!!!

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

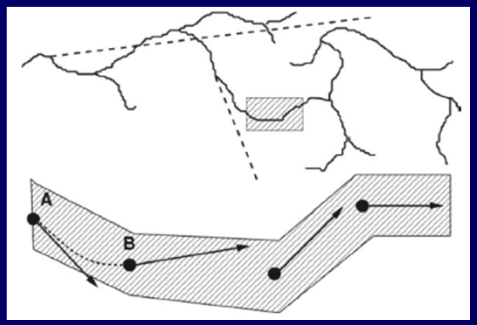


Illustration of a class II condensed history scheme: From AAPM TG-105: Med Phys 34: 2007

Which of the following regarding the condensed history method is *true*?

20%	1.	It is used for the single-scatter (analog) transport of photons
20%	2.	It is used for the single-scatter (analog) transport of electrons
20%	3.	It is based on the observation that the majority of electron interactions lead to very *large* changes in the electron energy and/or direction
20%	4.	It is based on the observation that the majority of electron interactions lead to very *small* changes in the electron energy and/or direction
20%	5.	None of the above

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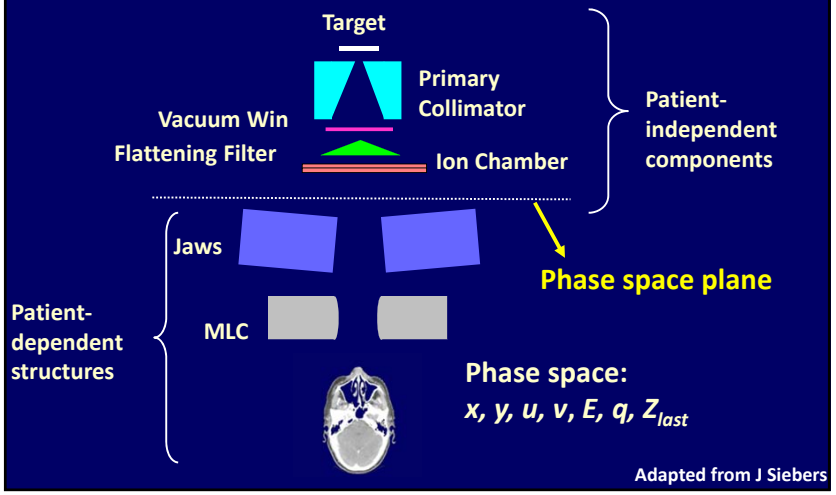
The Condensed History Technique (CHT)

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.)

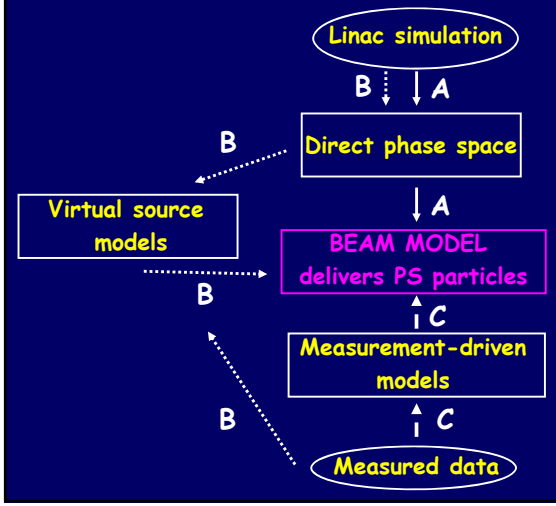
In general, "second generation" codes employ e-step algorithms that converge faster, i.e. you are able to take fewer CH steps for the same precision

Treatment head simulations and beam modeling



Adapted from J Siebers

The possible options for specifying a beam model



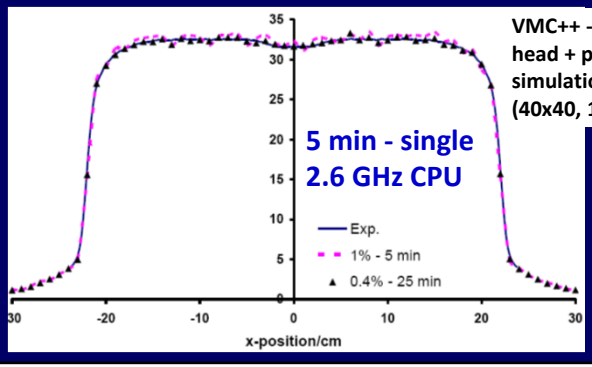
From *AAPM TG-105: Med Phys 34: 2007*

***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 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: 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

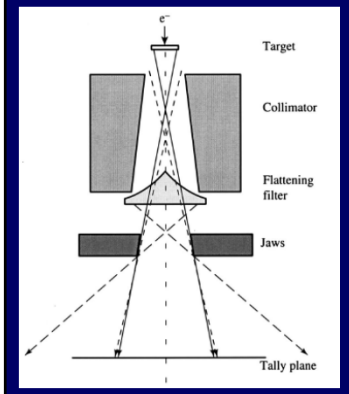
ϕ_j **is the relative source intensity for sub-source *j***

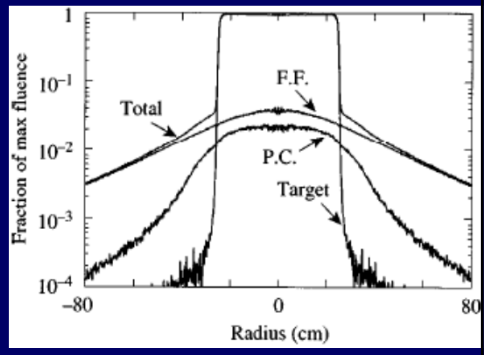
x_s, y_s **are the x-and y-coordinates in the source plane**

$g_j(x,y,x_s,y_s)$ **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

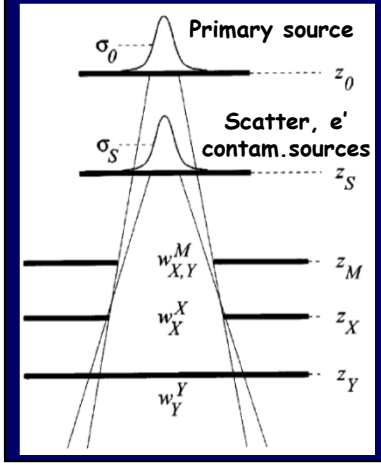
Analytical representations or parameterized forms describing the fluence distributions and returning the phase space for calculations within the patient

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, relative weights are iteratively adjusted to match calculations of the energy fluence with measured profiles in air

Energy spectrum: minimize 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

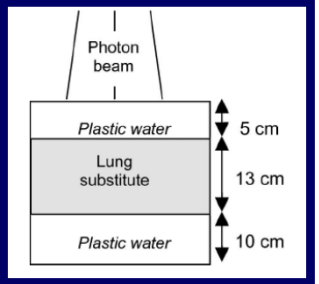
Commissioning and Experimental Verification

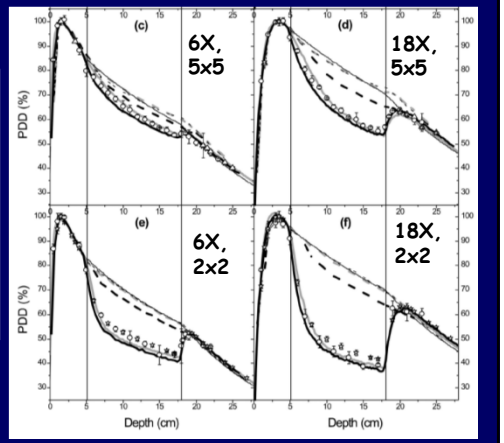
The MC method should be subjected to testing as reported in articles on commissioning of dose algorithms, such as AAPM TG-53 and IAEA TRS-430

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!

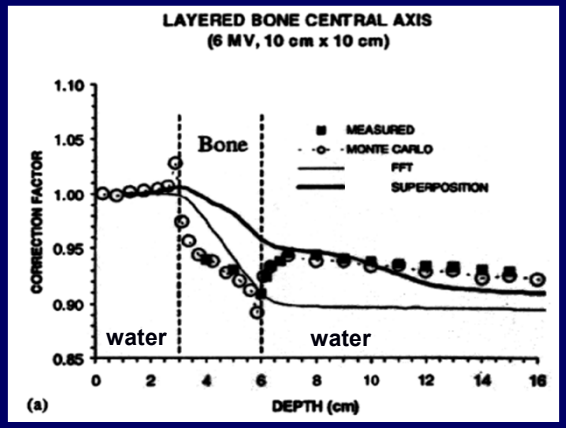
Slab phantoms with heterogeneities: depth doses





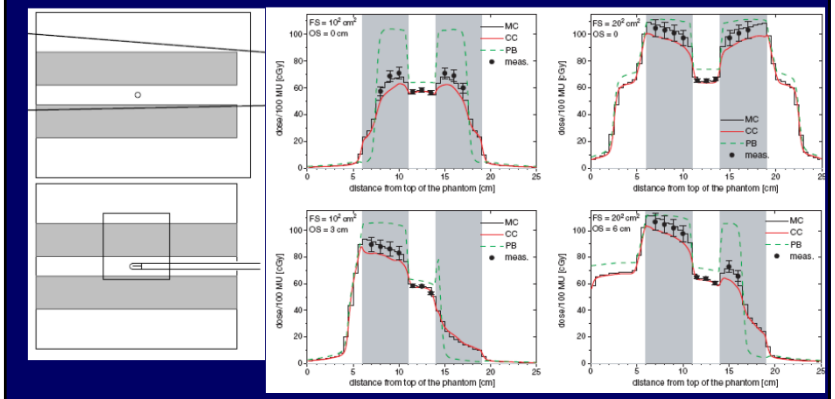
Carrasco and Jornet Med Phys 31: 2899 (2004)

Slab phantoms with high density materials



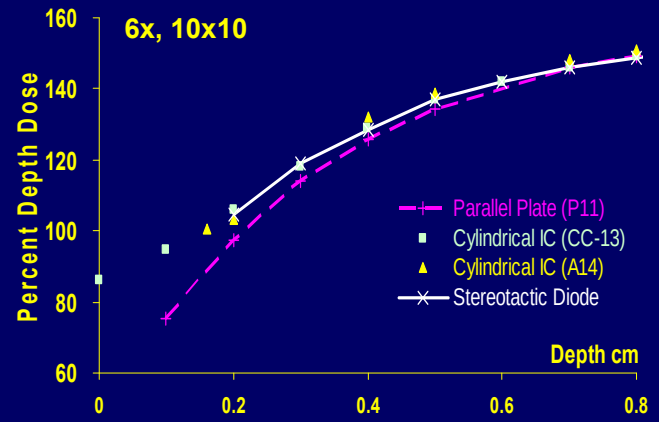
Ma *et. al.* Med. Phys. 26 (1999)

Slab phantoms with heterogeneities: profiles



Krieger and Sauer - Phys Med Biol 50: 859 (2005)

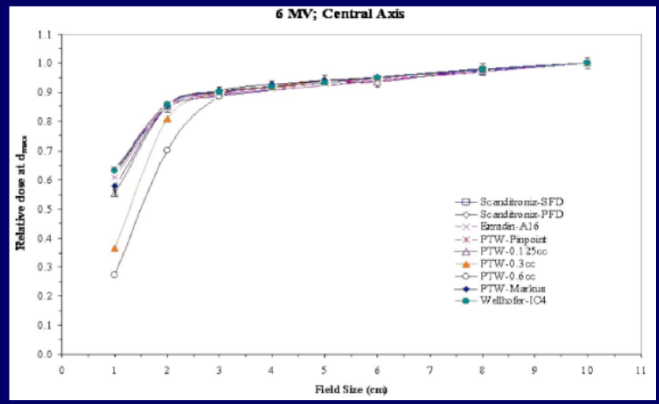
Issues with measurements – buildup region



Courtesy of P. Roberson, S. Yokoyama (UM)

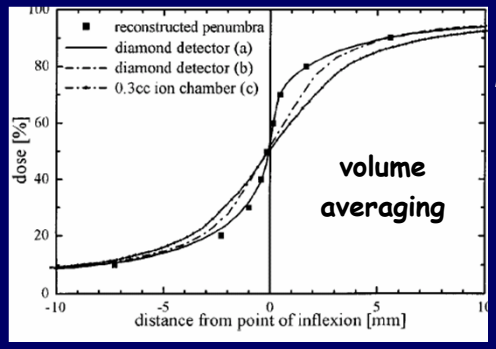
Issues with measurements – small field sizes

Measurements with small field sizes are complicated



Das, Ding, Ahnesjo: *Med Phys* 35:206 (2008)

Issues with measurements – small field sizes



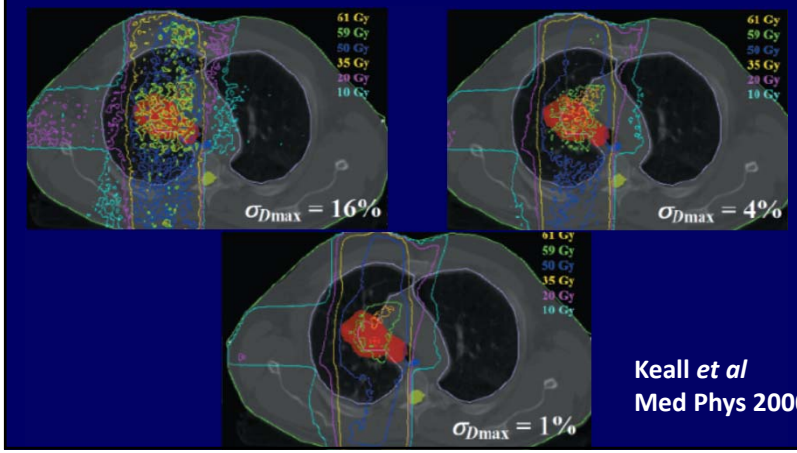
Laub and Wong, *Med Phys* 30:341 (2003)

Das et al. "Small fields: Nonequilibrium radiation dosimetry" *Med Phys* 35: (2008)

AAPM TG No. 155 Small Fields and Non-Equilibrium Condition Photon Beam Dosimetry: Das and Francescon *et al.*

Statistical Uncertainties in MC-computed dose

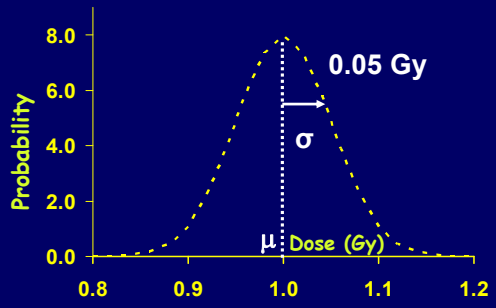
MC patient dose calculation and statistical uncertainties



Keall *et al* Med Phys 2000

Statistical uncertainties

Noisy isodose lines are due to the stochastic nature of the MC method



In Tx planning, the relative uncertainty = σ /μ

σ /μ ~ 1/√dose

σ ~ 1/√N [N= total no. of particles simulated]

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

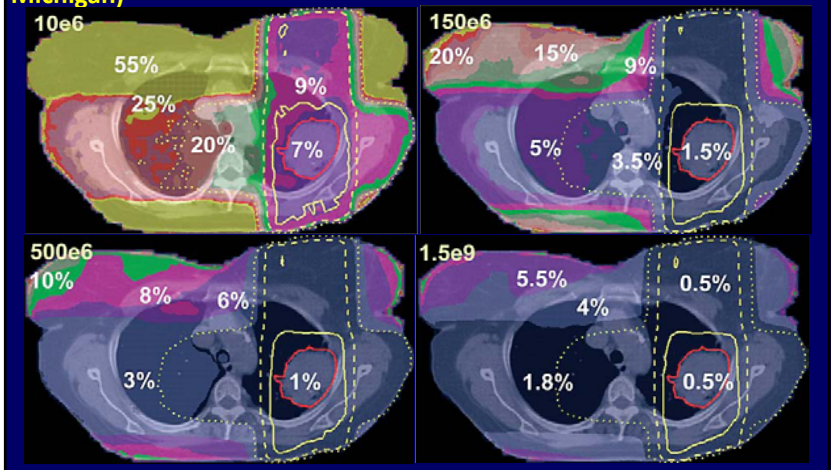
Statistical uncertainties: Recommendations (AAPM TG-105)

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

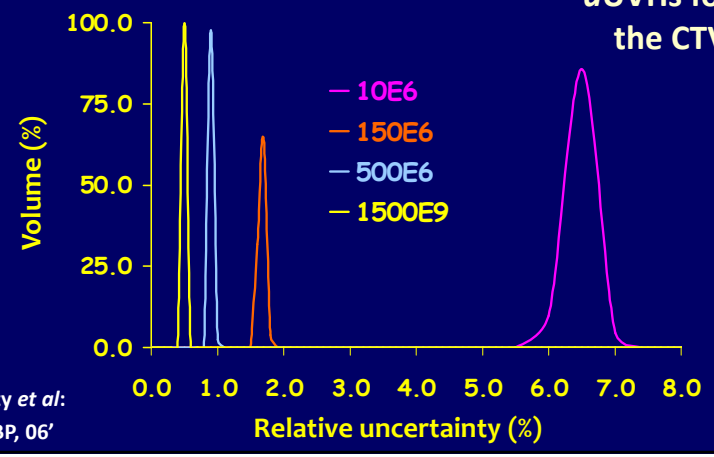
For serial organs, where point doses are important, (e.g. the max. cord dose) higher statistical precision may be necessary; volume-based uncertainties will be more reliable

Tools for evaluating uncertainties in planning: UMPlan (Univ of Michigan)



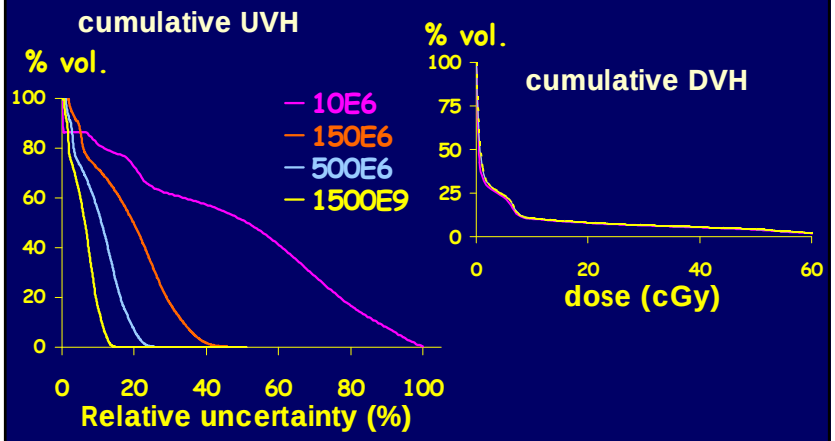
Chetty, Fraass, McShan *et al*: IJROBP, 06'

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



Chetty *et al*: IJROBP, 06'

UVH's/DVH's for normal lung tissue



A MC simulation, run with 1 million (1 M) histories produces an uncertainty in average dose of 4%. If we want the uncertainty to be 1%, how many histories should be run (assuming all other factors are equal)?

20%	1. 1 M
20%	2. 2 M
20%	3. 4 M
20%	4. 8 M
20%	5. 16 M

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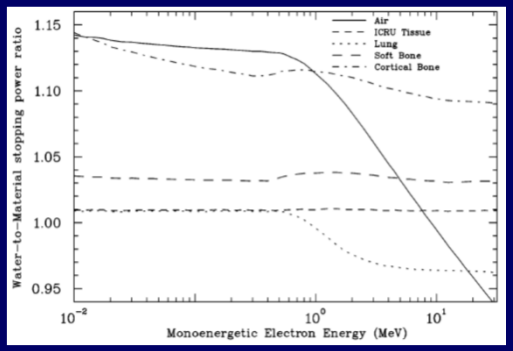
MC-based treatment planning: CT number to material conversions

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)

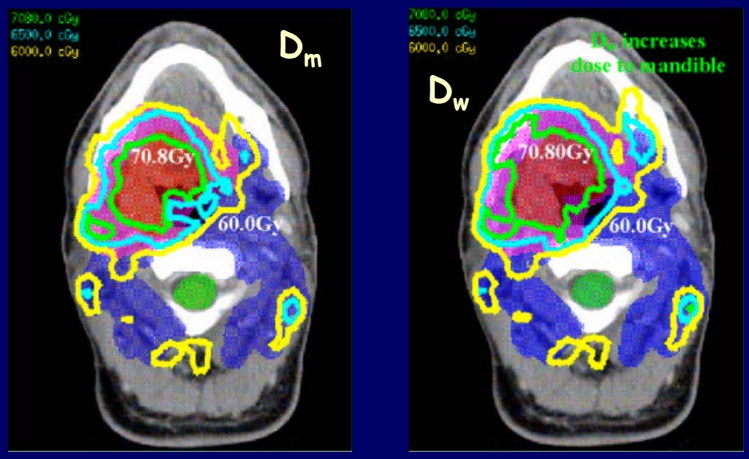
The conversion can be accomplished using the Bragg-Gray formalism:

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

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

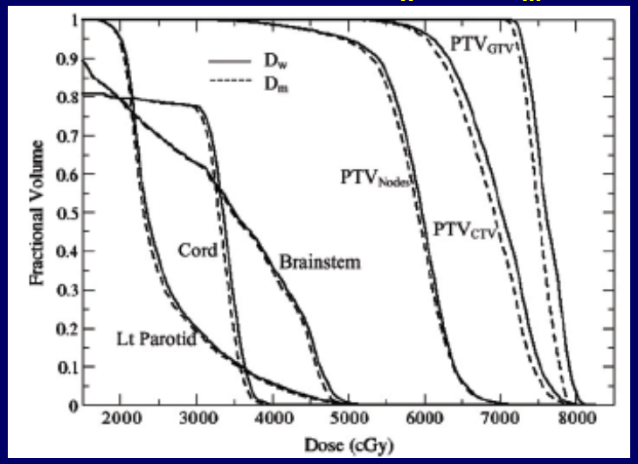
This can be applied either as a post-processing step or as a multiplication factor to the energy loss step

Clinical Examples: D_w and D_m



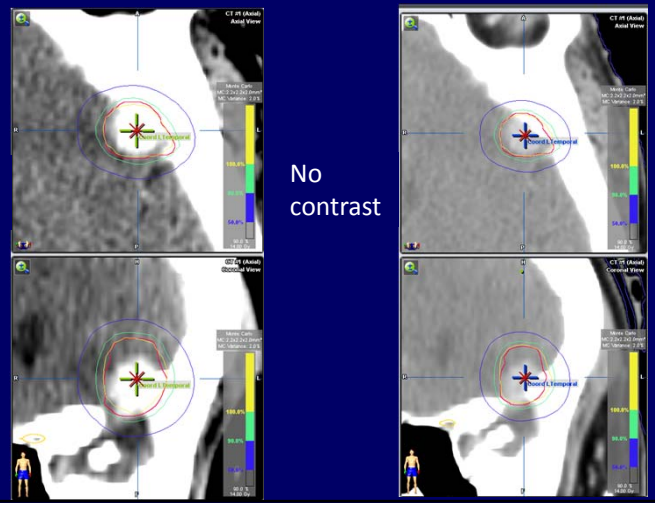
Dogan, Siebers, Keall: Phys Med Biol 51: 4967-4980 (2006)

Clinical Examples: D_w and D_m

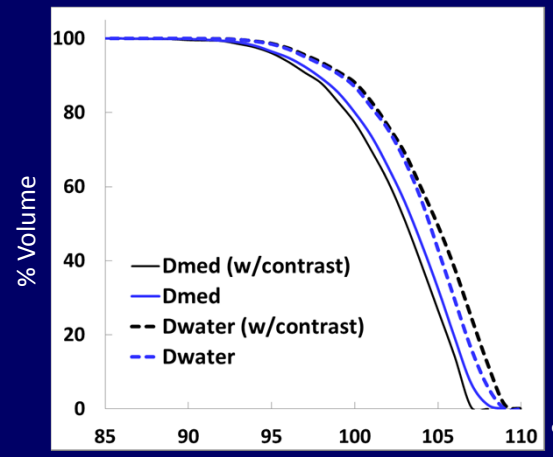


Dogan, Siebers, Keall: Phys Med Biol 51: 4967-4980 (2006)

Challenge: impact of contrast on D_w and D_m



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



Courtesy: H. Li (HFHS)

Dose-to-medium and dose-to-water: Recommendations

The AAPM TG-105 report recommends that vendors report both D_m and D_w as part of their dose calculation output

The method of conversion from D_m to D_w should be clearly documented

Which of the following regarding dose-to-water (D_w) and dose-to-medium (D_m) in the MV energy range is *true*?

20% 1. D_w and D_m are equivalent for all tissues

20% 2. D_m is always higher than D_w for all tissues

20% 3. D_w and D_m differ by greater than 10% for lung tissue

20% 4. D_w and D_m differ by greater than 10% for cortical bone

20% 5. D_w and D_m differ by greater than 10% for soft bone

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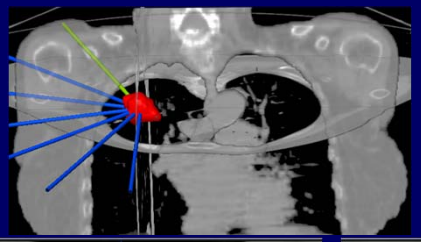
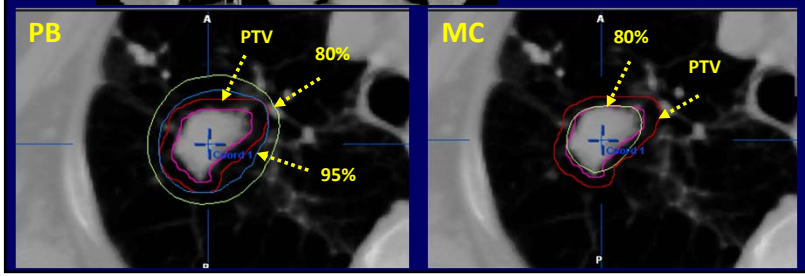
Clinical Application
Lung SBRT treatment planning

Lung SBRT dose calculations



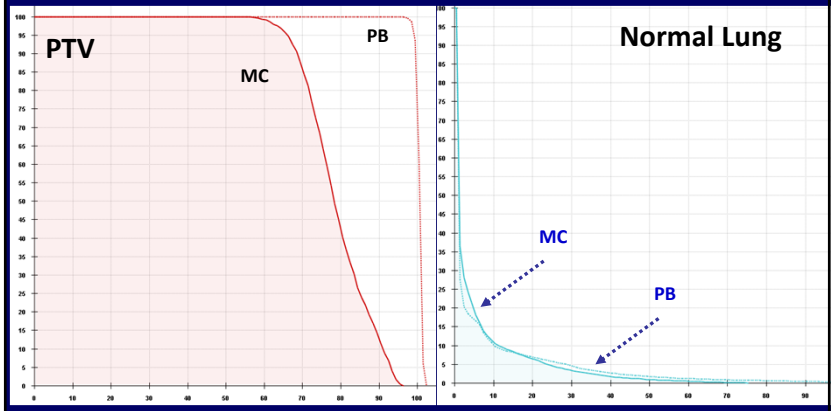
PTV diam. = 3.2 cm

PTV vol. = 14.6 cc

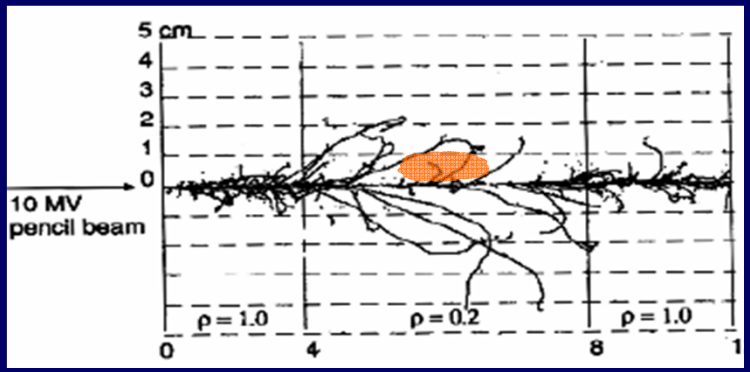


Patient Study: DVHs

PTV diam. = 3.2 cm

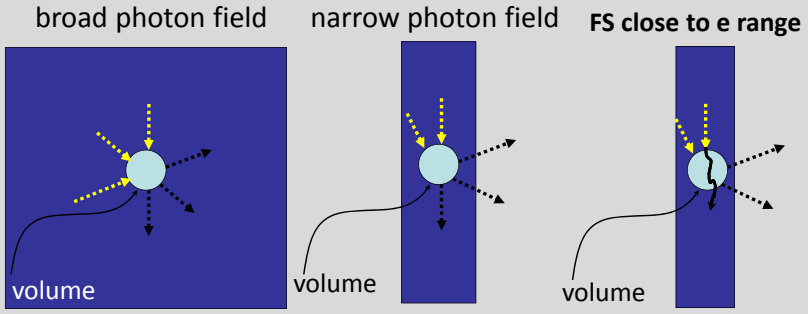


Lateral Scattering of electrons in low density lung tissue carries energy/dose away from the tumor



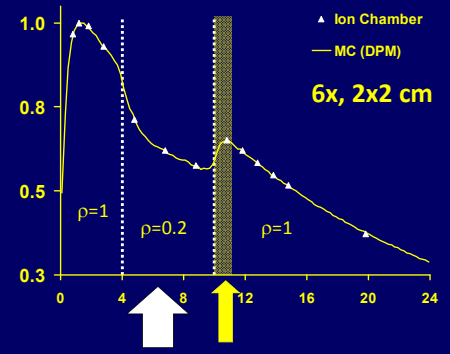
Monte Carlo simulation, 10 MV pencil beam

Small Field Dosimetry: Loss of charged particle equilibrium (CPE)



In narrow field, CPE is lost and dose reduction can be severe

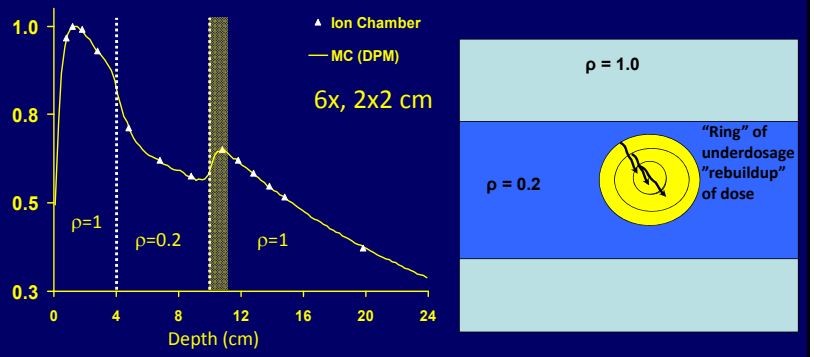
Small field central axis depth dose: slab phantom



"Build down effect" – severe dose reduction caused by scattering of electrons into the lung tissue

Dose builds up in the tumor resulting in underdosage at tumor periphery.

Implications for "island" tumors



"Ring" of underdosage gets larger for smaller tumors (as the tumor size approaches the electron range)

Comparative Dose Study: Methods

Retrospective analysis of 135 patients with NSCLC treated with SABR using 12Gy x 4 (BED=106 Gy) – early stage, peripheral and centrally-located tumors

Treatment planning performed with a 1-D Equilavent path-length-based pencil beam algorithm (1D-EPL) [BrainScan/iPlan, BrainLAB); patients were treated using these dose distributions

Motion mitigated with 4D simulation to form an ITV; PTV margin was 5 mm isotropically

Comparative Dose Study: Methods

1D-EPL patient treatment plans were recomputed using the following algorithms: 3-D EPL (pencil beam 3D-EPL, Anisotropic Analytical Algorithm (AAA), Acuros, Collapsed Cone Convolution (CCC), and Monte Carlo (MC)

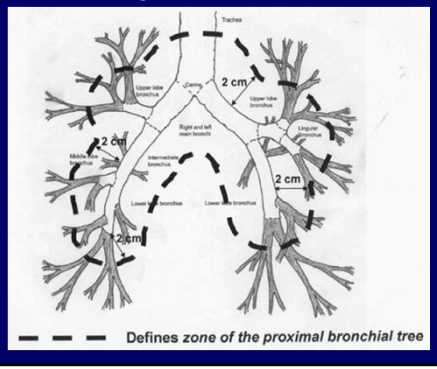
Each of the above algorithms was commissioned using measurements in water phantoms as well as slab-phantoms with low-density, lung-equivalent media

Beam models were within 2%/2 mm agreement vs. measurements in water phantoms and within 3% agreement in slab phantoms with lung-equivalent media for all except the pencil-beam algorithms

Comparative Dose Study: Methods

Location of the lung tumors was categorized as follows: island-type peripheral tumors surrounded by lung tissues (lung-island; N=39), and tumors located in the central area (lung-central; N=52), tumors attached to the chest-wall (lung-wall; N=44)

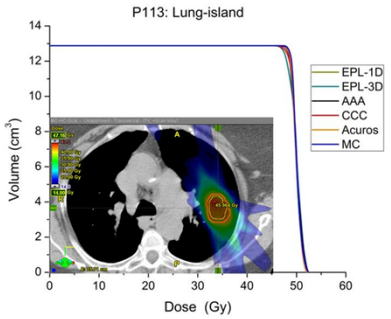
Timmerman *et al*
RTOG 0236



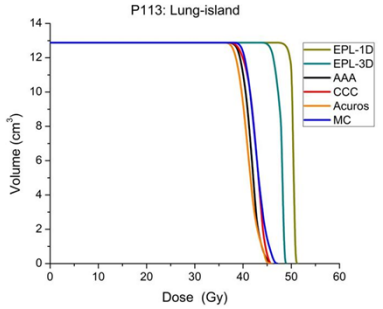
Results: Island Tumors

Planned dose is 48 Gy to the 95% line with the EPL-1D algorithm

Uniform density plans



Heterogeneity corrected plans



Effect of tumor location and size: peripheral, ISLAND-type tumors (N=39)

PTV D95 (%) for EPL-3D, AAA, CCC, AcurosXB, and MC relative to EPL-1D (100%)

FS (cm)	EPL-3D (%)	AAA (%)	CCC (%)	AcurosXB (%)	MC (%)
3≤FS<5	95.1±2.1	80.2±4.3	80.0±6.0	76.6±6.9	79.7±5.9
5≤FS<7	95.7±1.9	83.0±4.3	82.7±5.4	80.0±5.9	83.0±5.1
7≤FS<10	92.8±0.3	84.5±0.8	85.3±0.7	83.5±1.2	85.7±1.4

Devpura *et al.* Proceedings of the 2013 ICCR meeting, Melbourne, Australia

Effect of tumor location and size: CHEST-WALL-seated tumors (N=44)

PTV D95 (%) for EPL-3D, AAA, CCC, AcurosXB, and MC relative to EPL-1D (100%)

FS (cm)	EPL-3D (%)	AAA (%)	CCC (%)	AcurosXB (%)	MC (%)
3≤FS<5	96.2±1.2	84.7±4.4	85.4±5.4	82.1±6.5	84.5±5.3
5≤FS<7	96.4±2.3	86.2±4.8	86.7±5.6	84.0±6.5	86.3±5.6
7≤FS<10	97.1±1.1	91.4±2.8	92.1±3.2	90.5±3.5	91.9±3.2

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Effect of tumor location and size: CENTRAL tumors (N=52)

PTV D95 (%) for EPL-3D, AAA, CCC, AcurosXB, and MC relative to EPL-1D (100%)

FS (cm)	EPL-3D (%)	AAA (%)	CCC (%)	AcurosXB (%)	MC (%)
3≤FS<5	94.8±1.8	83.2±5.5	83.3±6.4	81.7±6.9	83.5±5.9
5≤FS<7	95.3±2.1	86.1±5.8	86.8±6.5	85.0±7.1	86.8±6.1
7≤FS<10	95.4±1.1	90.7±3.7	90.9±3.9	89.8±3.9	91.3±4.0

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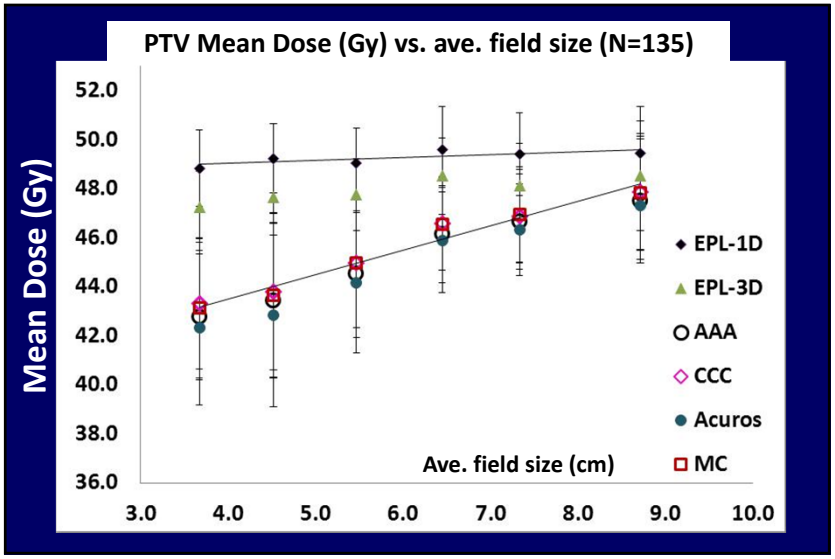
Effect of tumor location and size: All tumors (N=135)
PTV D95 relative to 1D-EPL (100%)

Location	FS (cm)	EPL-3D (%)	AAA (%)	CCC (%)	AcurosXB (%)	MC (%)
Lung-island	3≤FS<5	95.1±2.1	80.2±4.3	80.0±6.0	76.6±6.9	79.7±5.9
	5≤FS<7	95.7±1.9	83.0±4.3	82.7±5.4	80.0±5.9	83.0±5.1
	7≤FS<10	92.8±0.3	84.5±0.8	85.3±0.7	83.5±1.2	85.7±1.4
Lung-wall	3≤FS<5	96.2±1.2	84.7±4.4	85.4±5.4	82.1±6.5	84.5±5.3
	5≤FS<7	96.4±2.3	86.2±4.8	86.7±5.6	84.0±6.5	86.3±5.6
	7≤FS<10	97.1±1.1	91.4±2.8	92.1±3.2	90.5±3.5	91.9±3.2
Lung-central	3≤FS<5	94.8±1.8	83.2±5.5	83.3±6.4	81.7±6.9	83.5±5.9
	5≤FS<7	95.3±2.1	86.1±5.8	86.8±6.5	85.0±7.1	86.8±6.1
	7≤FS<10	95.4±1.1	90.7±3.7	90.9±3.9	89.8±3.9	91.3±4.0

Peripherally located, "island" tumors with small volumes (3≤FS<5 cm) have largest discrepancies



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, D_w vs. D_m must be addressed by the clinical team; proper tools for display and evaluation will be necessary in MC-based Tx planning

Avoid Pencil beam algorithms for lung cancer treatment planning, especially for small field sizes (< 5 cm) and when tumors are located peripherally

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Thank you for your attention