AAPM Task Group Report No. 105: Issues associated with clinical implementation of Monte Carlo-based treatment planning

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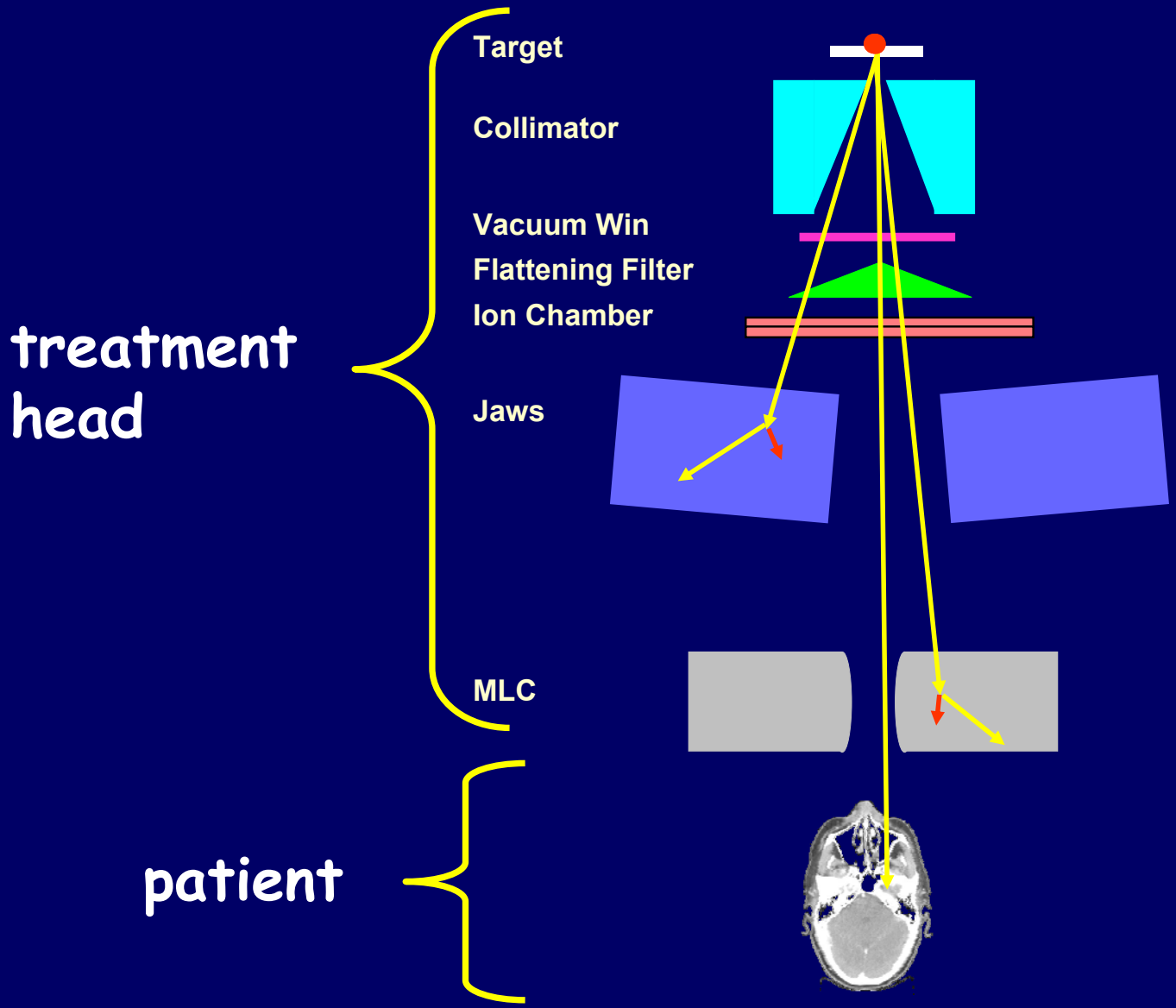
Outline

A. Experimental verification of MC-based algorithms
B. Clinical treatment planning examples
C. Factors associated with MC dose calculation in the patient geometry: statistical uncertainties, CT-to-material conversions, dose-to-water and dose-to-medium
D. Clinical implications: dose prescription issues and outcome studies
E. Current status of MC dose algorithms: clinical vendor system implementations

Monte Carlo simulation in radiotherapy planning



A.1. Experimental Verification

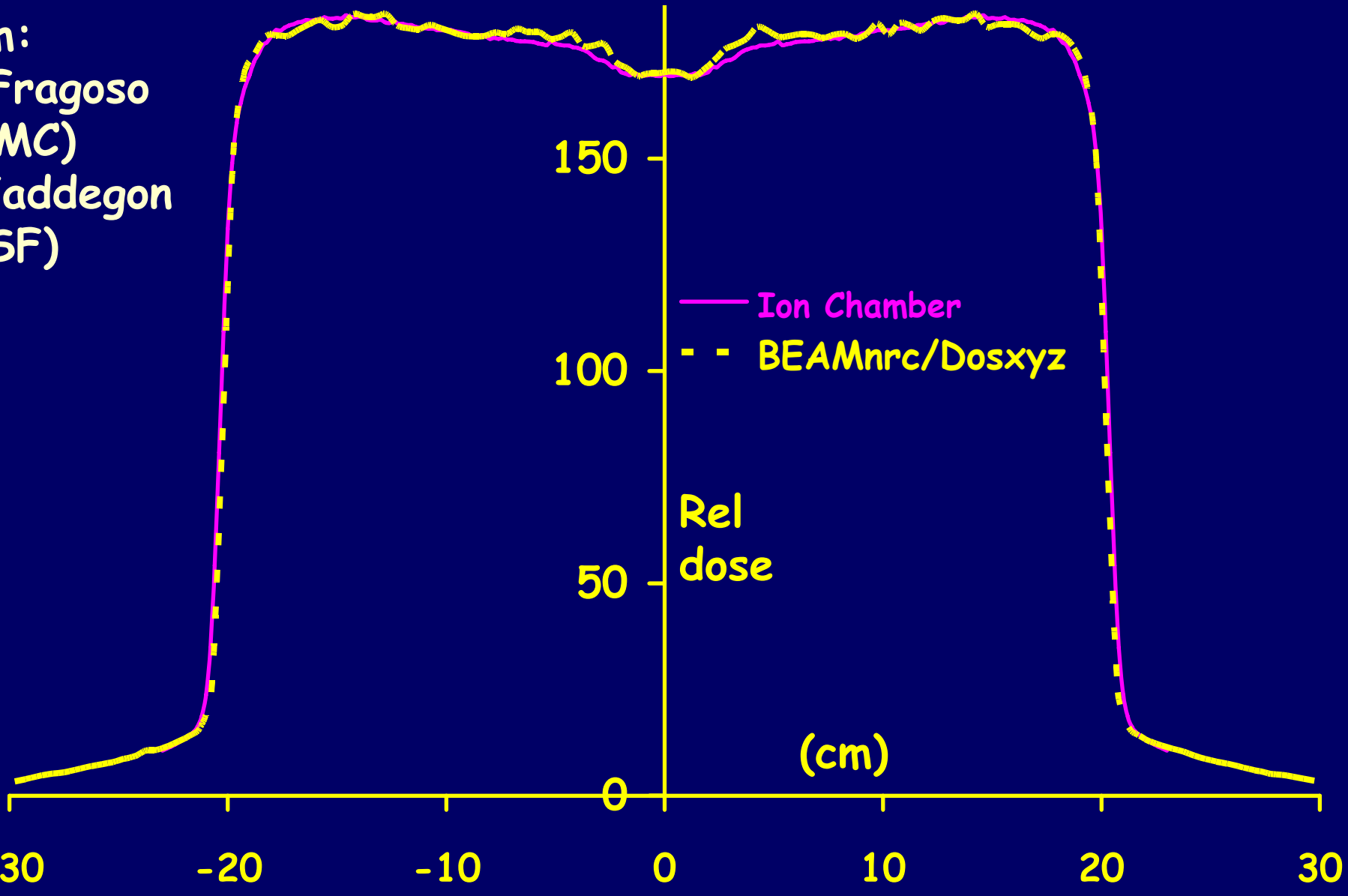
One strategy is to design measurements to test the algorithm performance with emphasis on:

(a) simulation of the linac treatment head components: homogeneous phantoms testing the beam energy, components such as the flattening filter, MLC, etc.

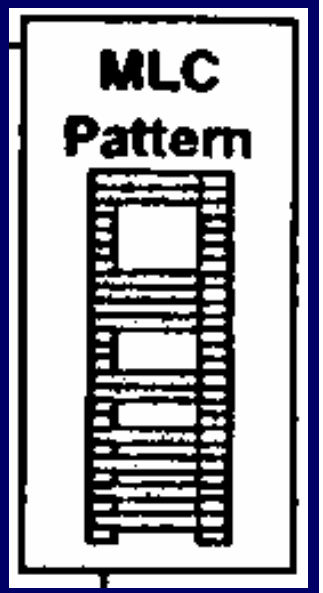
(b) radiation transport accuracy in the patient: heterogeneous phantoms, small field sizes, under non-equilibrium conditions

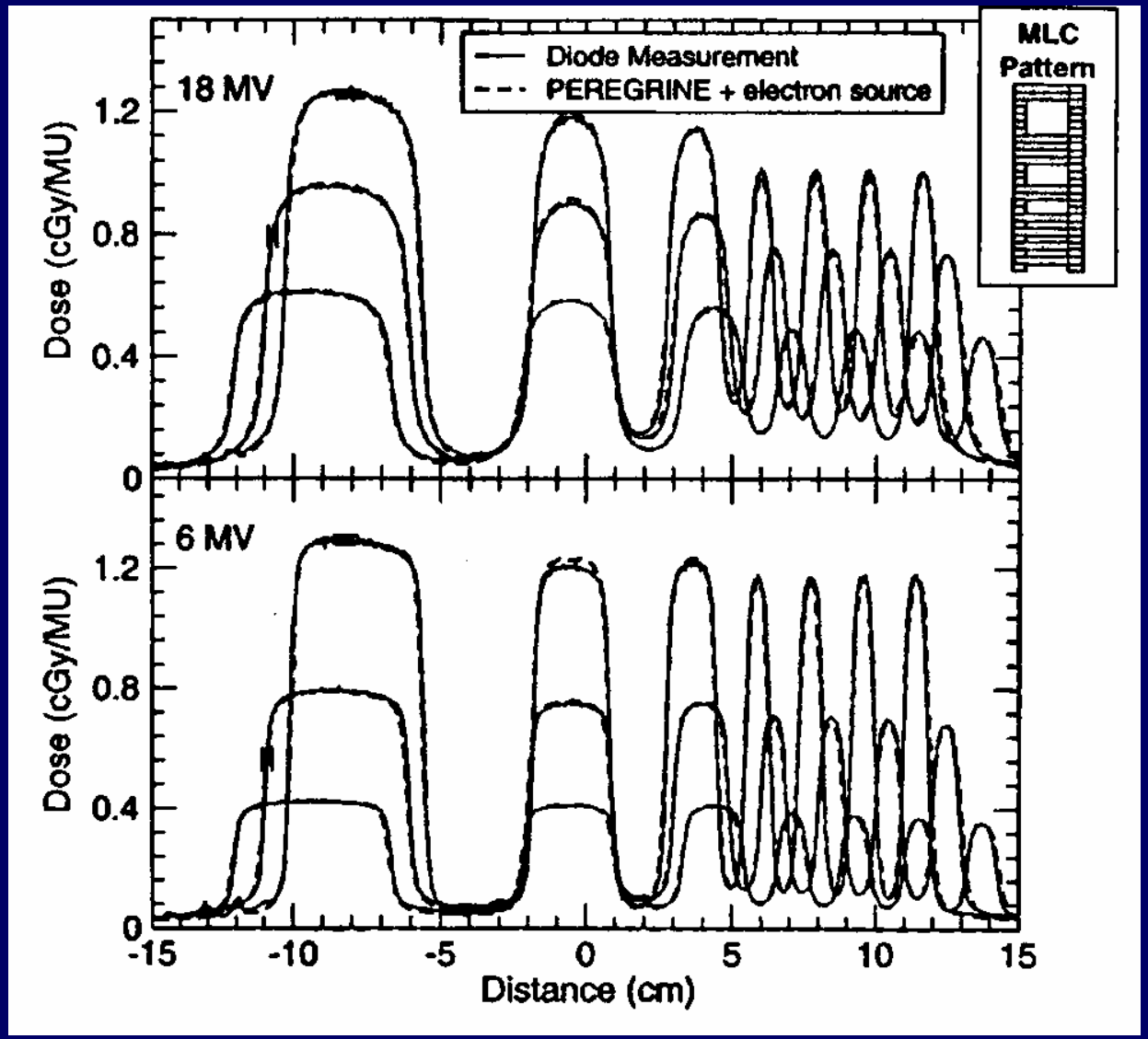
6 MV, 40x40 profile, 1.5 cm d in water
(Siemens, Primus)

From:
M. Fragoso
(UNMC)
B. Faddegon
(UCSF)



MLC transport verification: Picket fence field

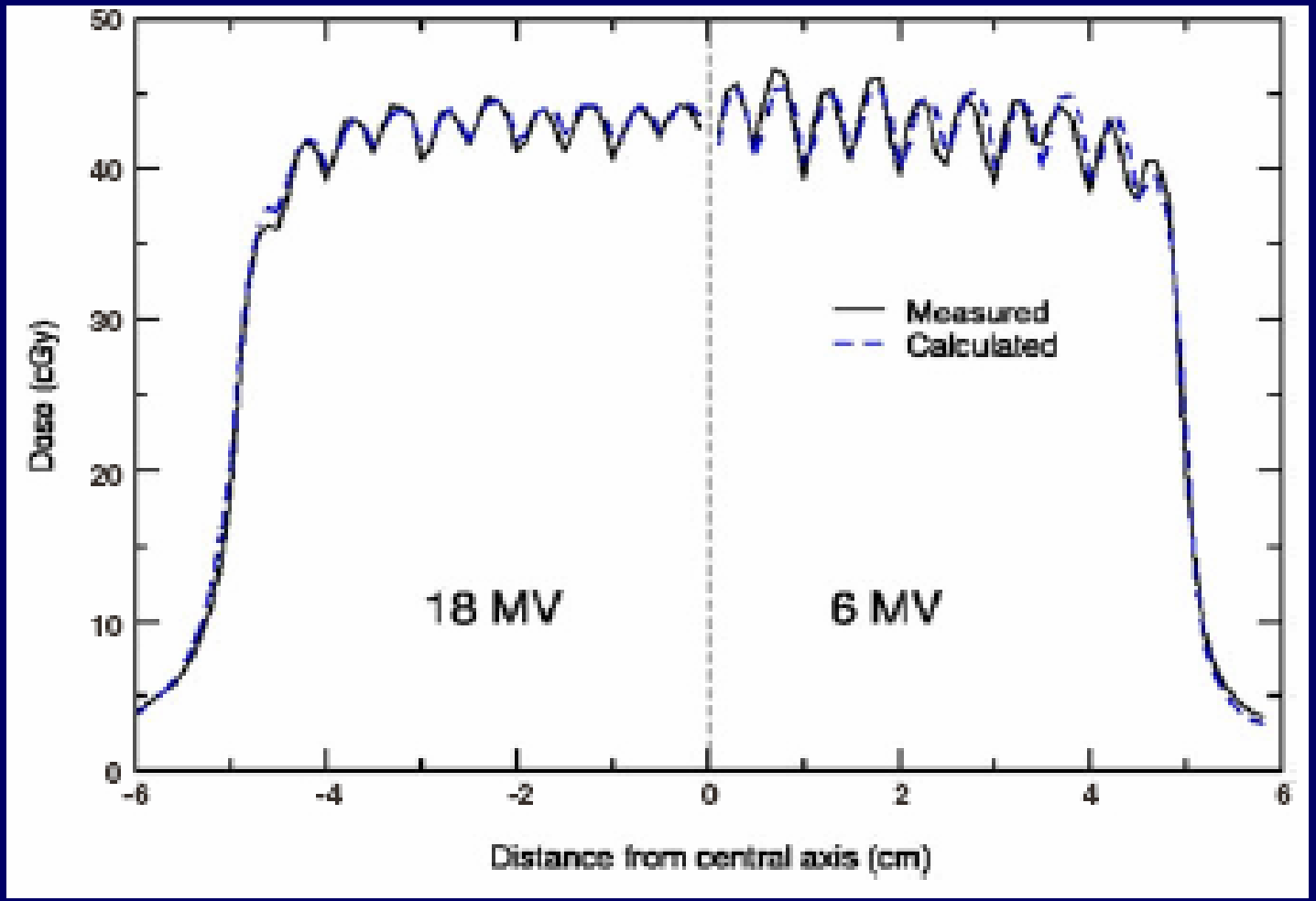




"psuedo-explicit" transport in PEREGRINE

Hartmann Siantar *et. al.* Med. Phys. 28 (2001)

MLC transport verification: Tongue and Groove Effect



Delivered with even/odd leaves closed half the time, resp.

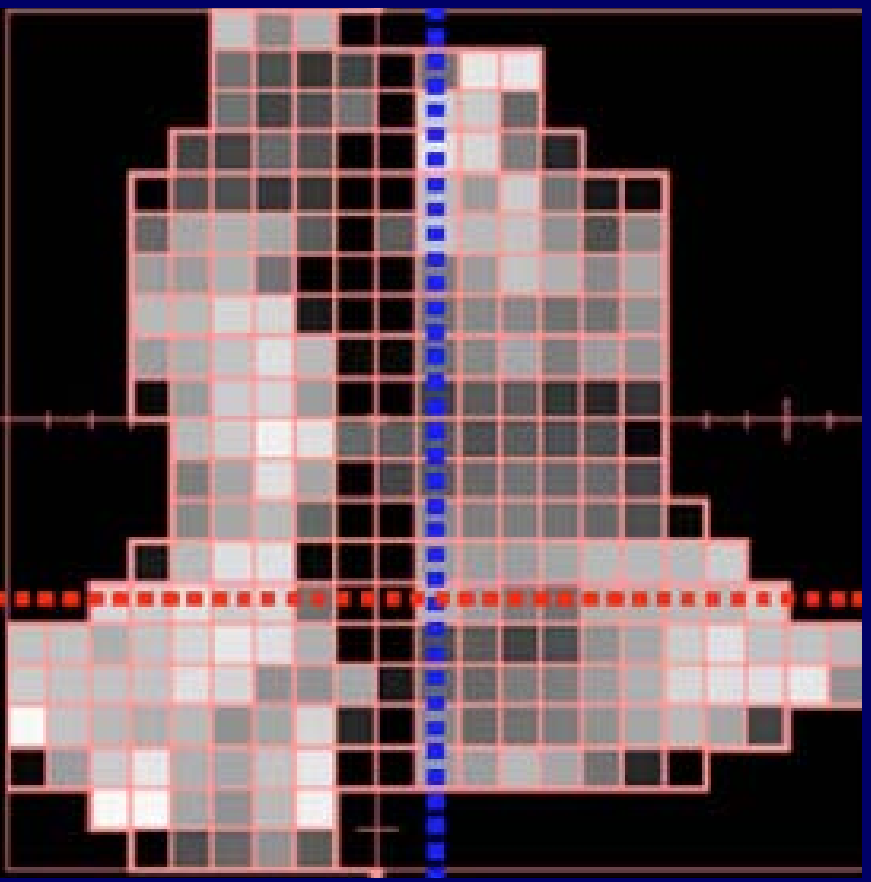
Photon transport (first compton scatter) only in the MLC

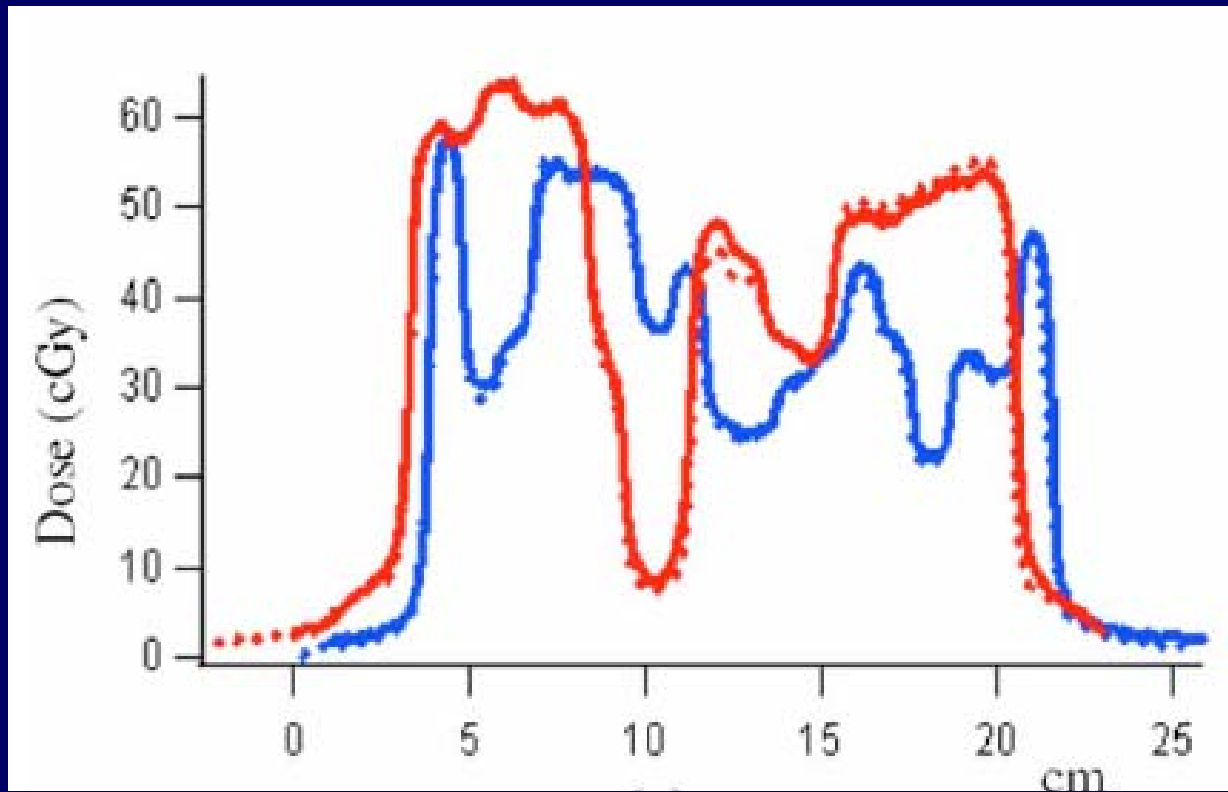
Siebers *et al.* (PMB 47:3225-49, 2002)

MLC transport verification: Patient plan comparison

Split field head/neck SMLC: Film (solid) vs. MC (dashed)

Photon transport (multiple compton scatter) only in the MLC



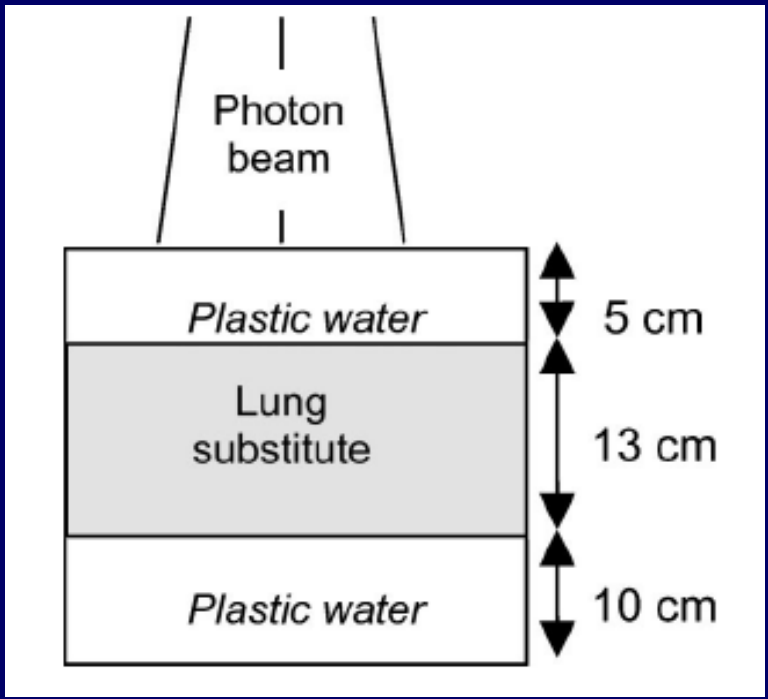


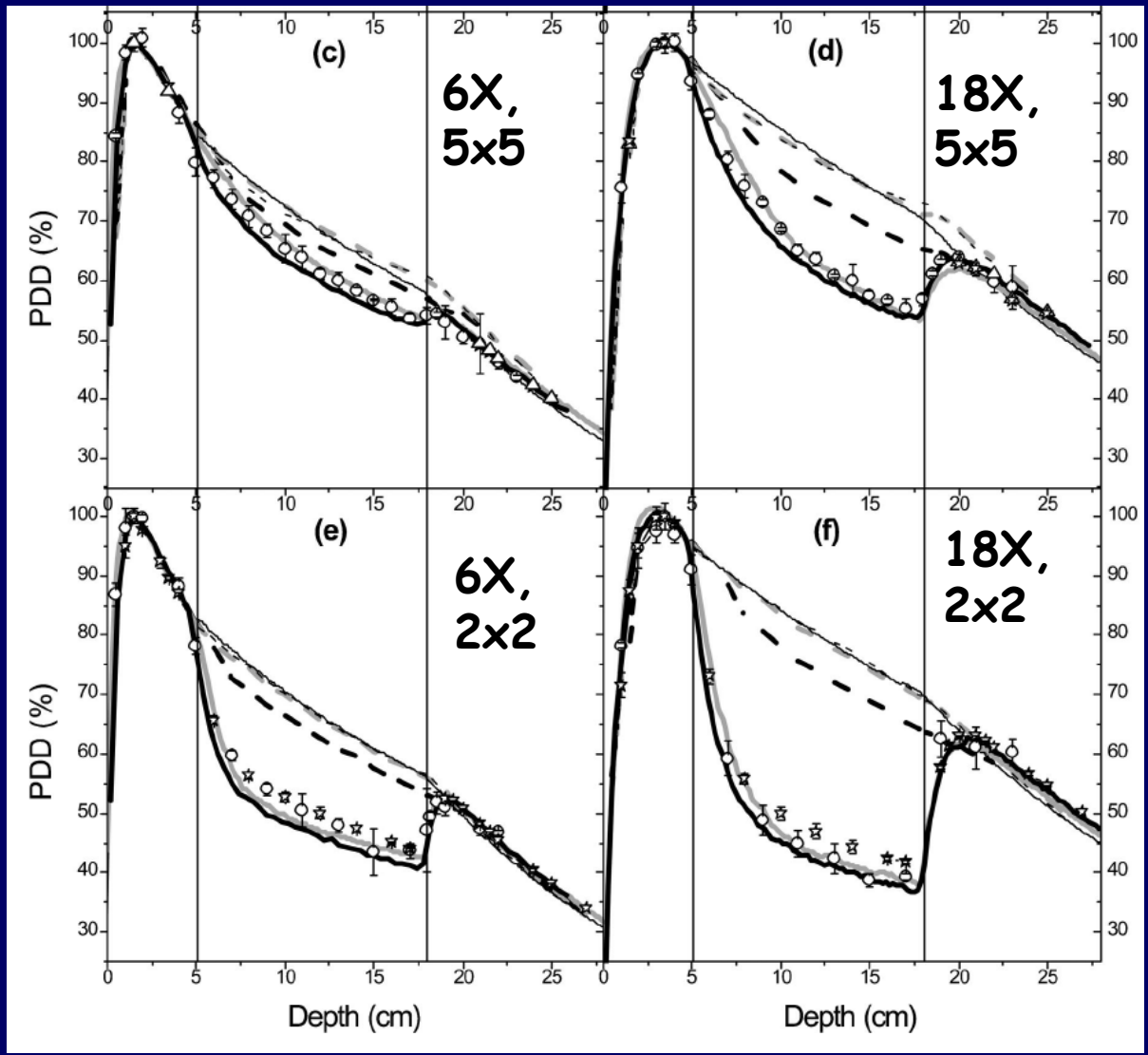
Tyagi *et al.* (PMB 47:3225-49, 2002)

A.2. Patient Transport

Experimental verification in phantom geometries

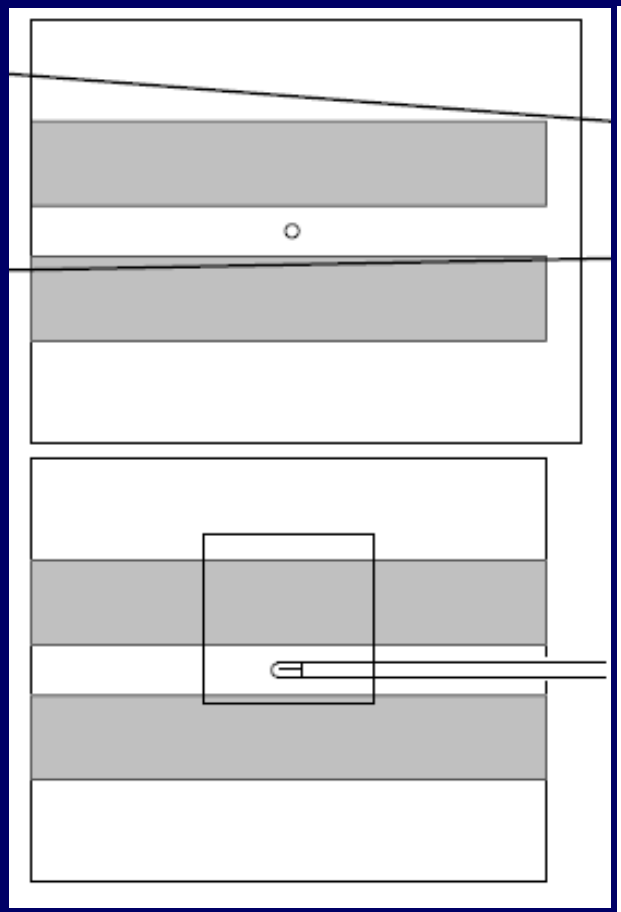
Slab phantoms with heterogeneities: depth doses

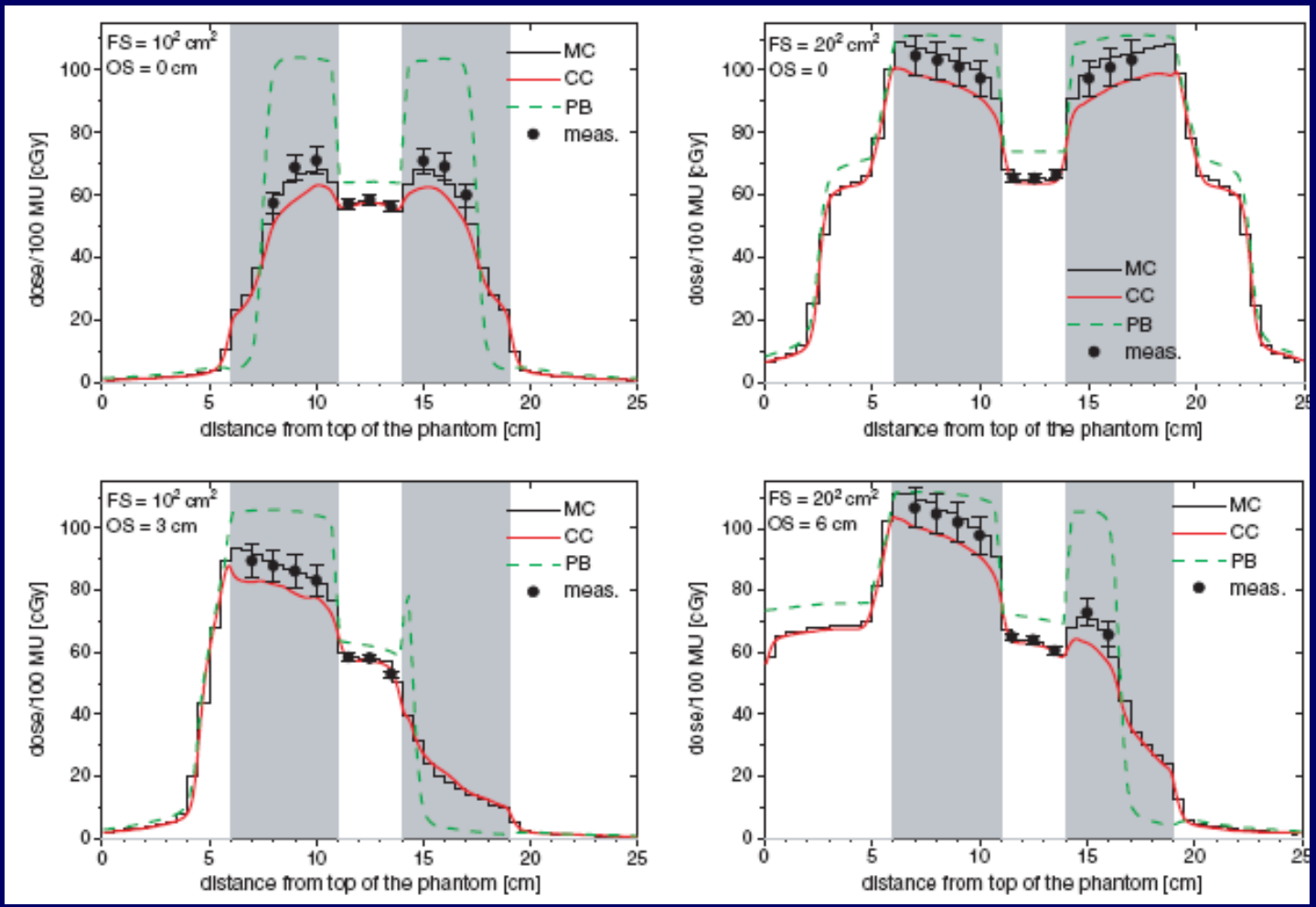




Carrasco and Jornet
Med Phys 31: 2899-2911 (2004)

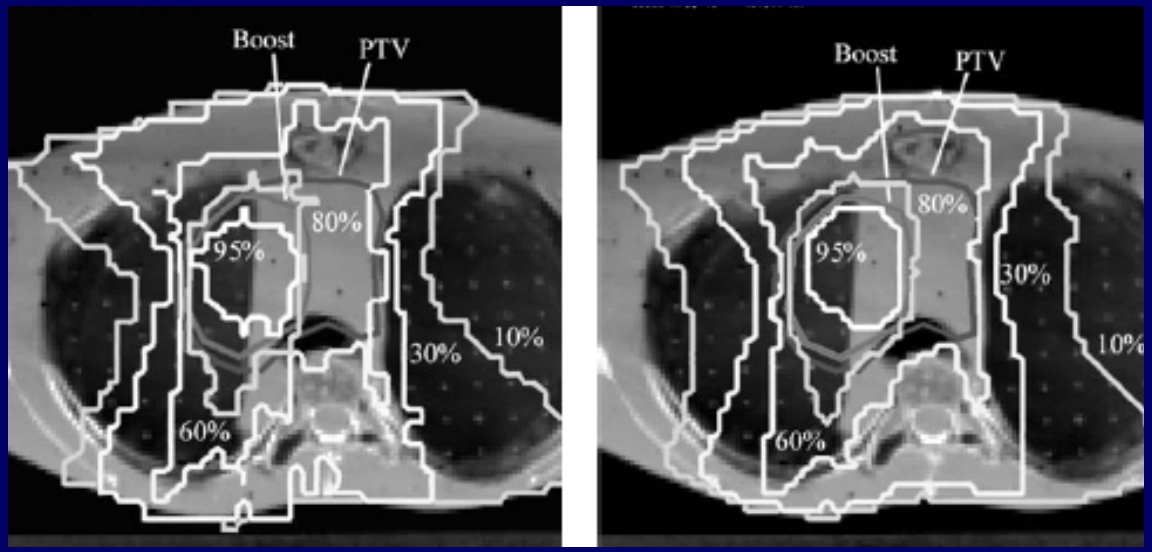
Slab phantoms with heterogeneities: profiles





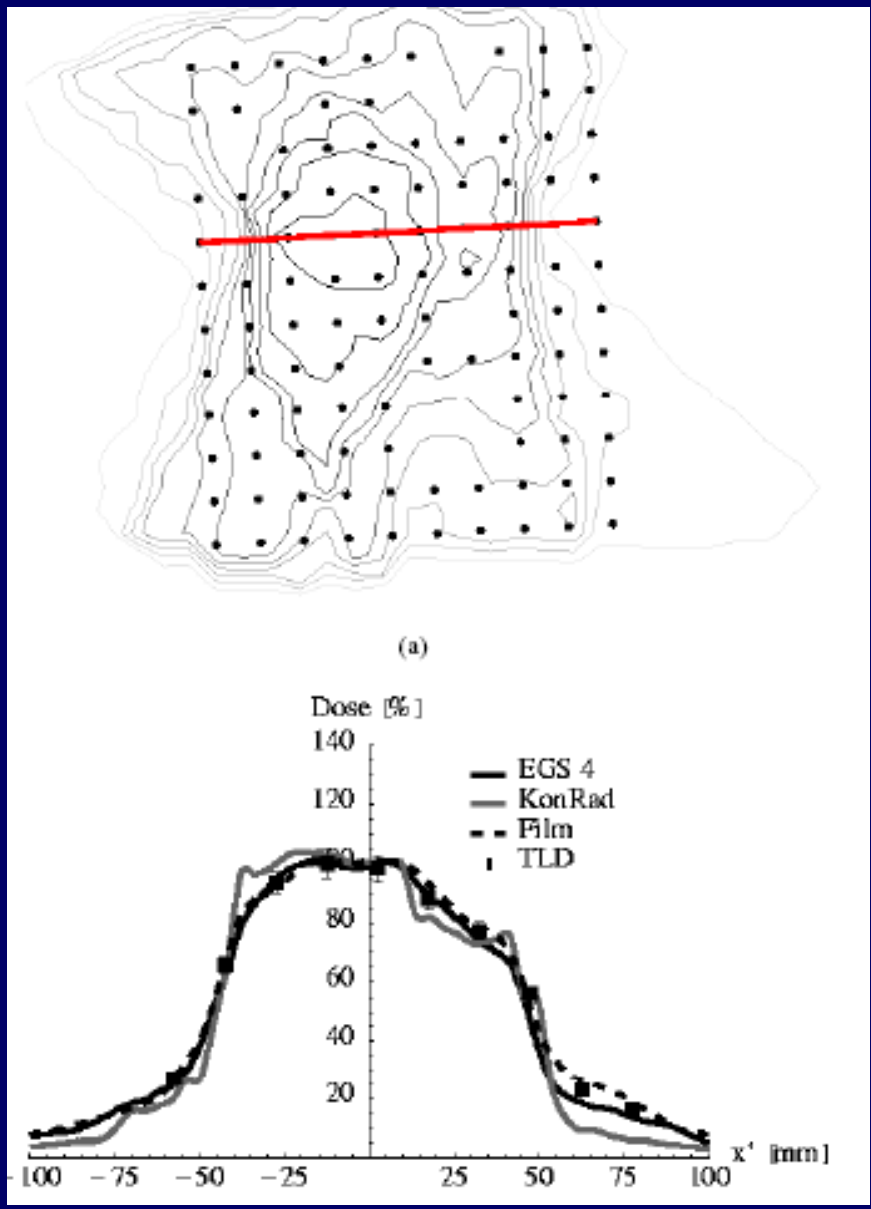
Krieger and Sauer
Phys Med Biol 50: 859-868 (2005)

Experimental verification: anthropomorphic phantoms



Pencil beam (Konrad)

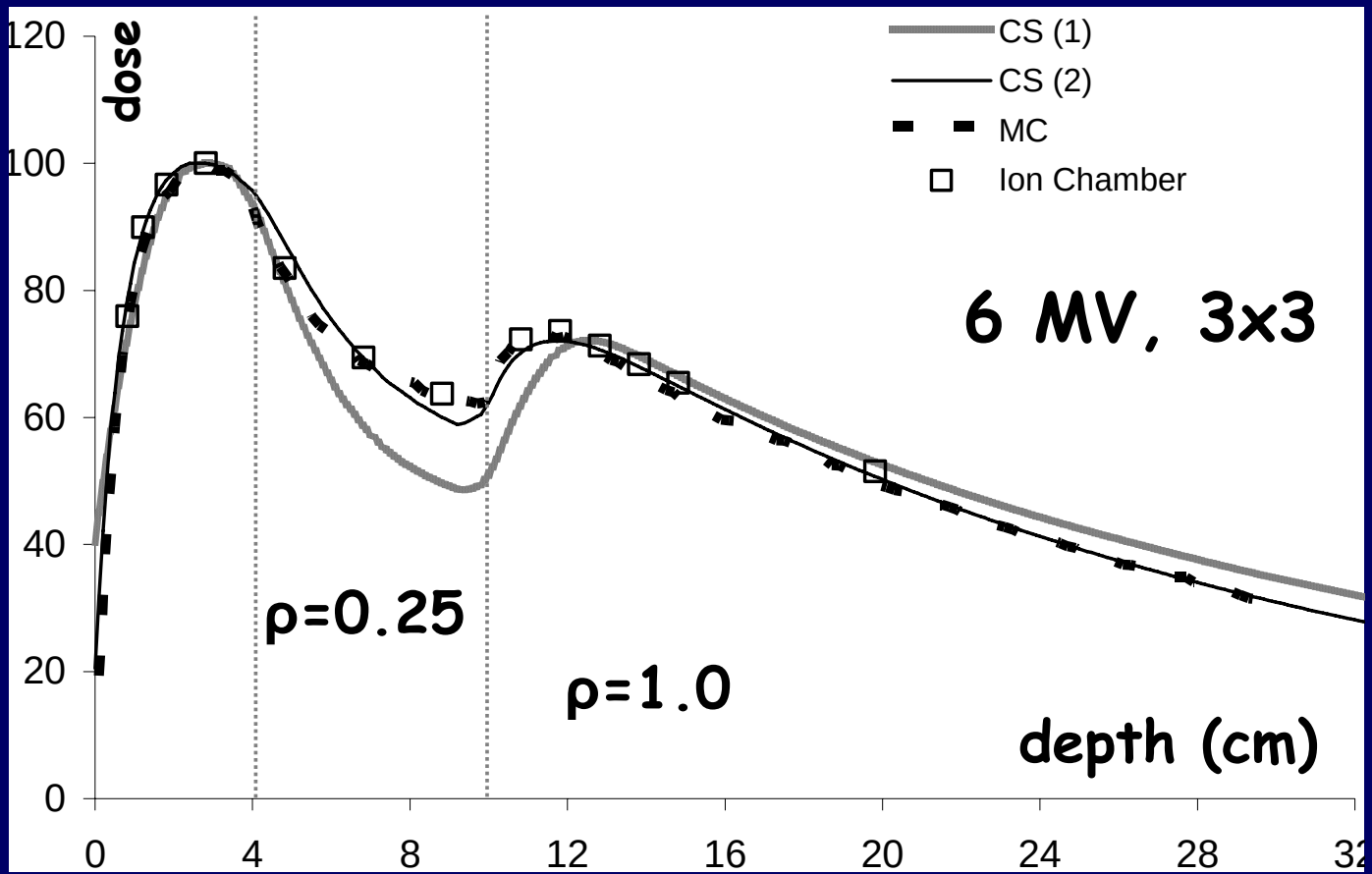
EGS4



Laub, Bakai and Nusslin
Phys Med Biol 46: 1695-1706 (2005)

Algorithmic implementation is important!

The agreement between the MC and other model-based methods (e.g. CS) will strongly depend on the particular implementation of the algorithm



CS (1): 2 rep. component energies

CS (2): 1 rep. energy averaged over spectrum

Both CS (1) and (2) agree in water-based tests

Experimental Verification: Summary

In addition to testing proposed in reports, such as TG-53 (Fraass *et* al), experimental testing should include complex configurations designed to verify the improved accuracy expected with the use of the Monte Carlo method

Measurements at the 2% level of accuracy in clinically realistic geometries are difficult

Measurements under conditions of charged particle disequilibrium are even more difficult and will require detector perturbation corrections

Measurement Issues in Commissioning and Benchmarking of Monte Carlo Treatment Planning Systems, J Seuntjens: Proceedings of the AAPM 2006 Summer School

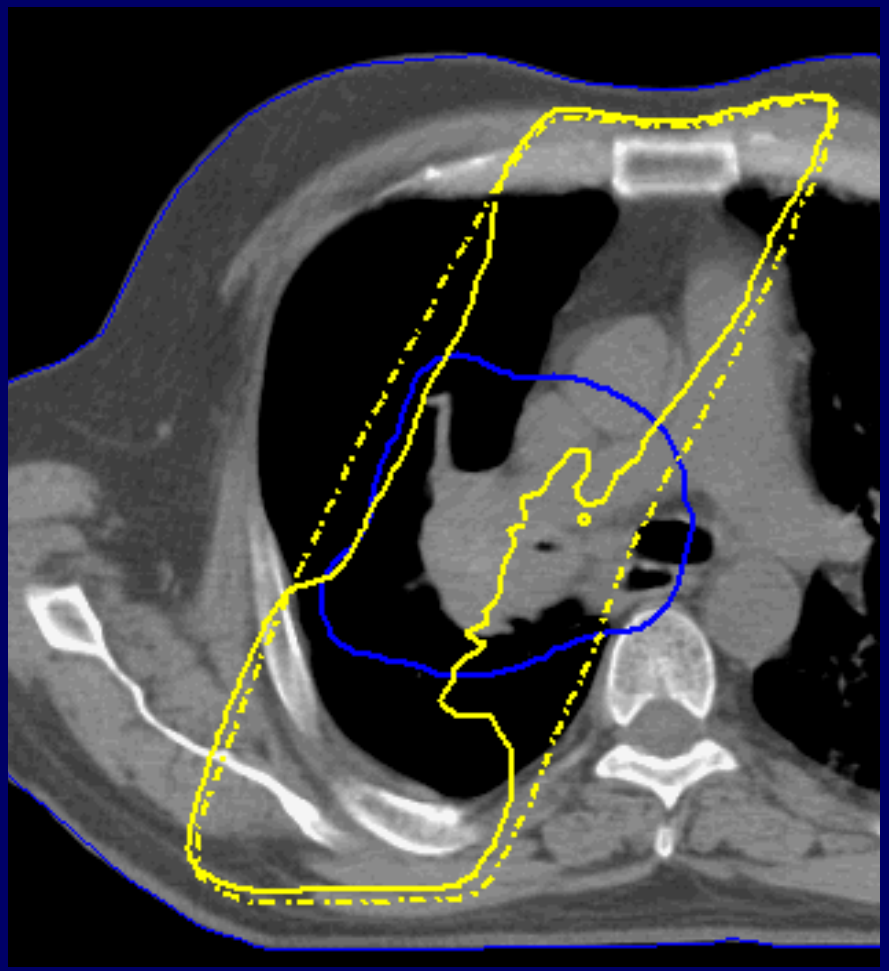
B. Monte Carlo-based calculations: clinical planning examples

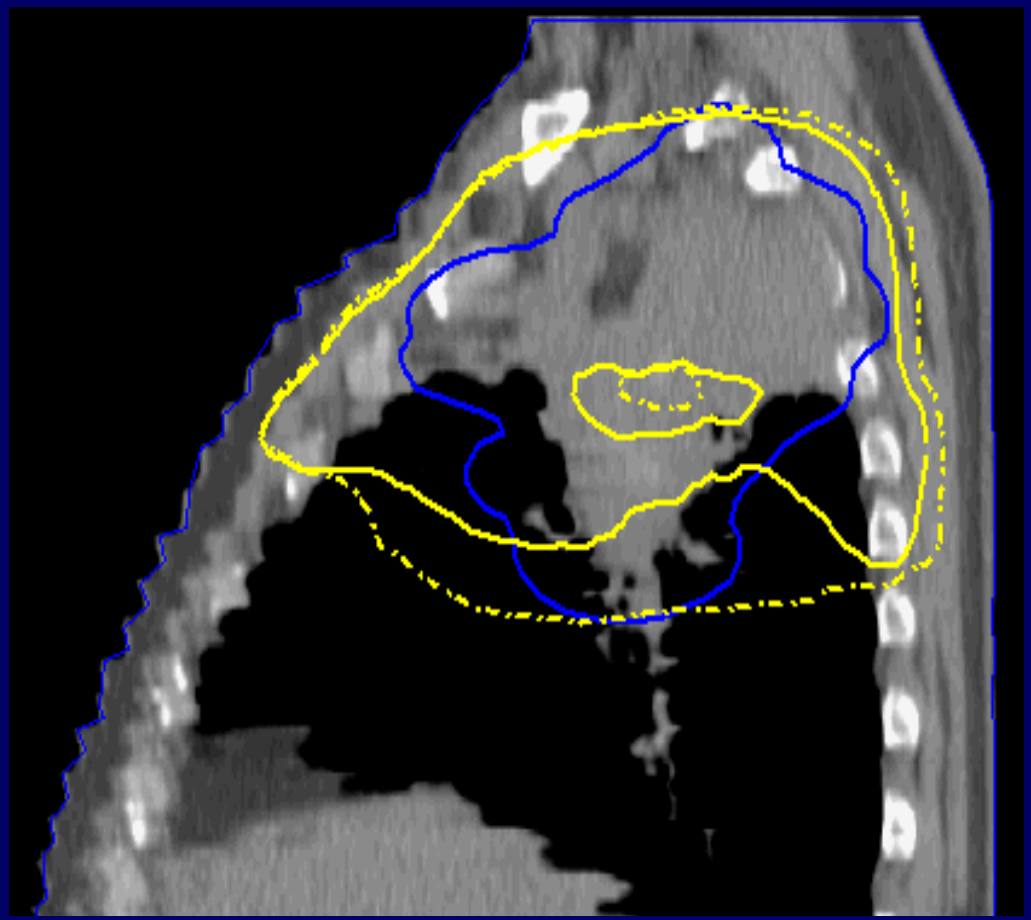
Comparison of MC vs. simple (EPL) and sophisticated heterogeneity correction methods (CS) in the lung for photon and electron beams

MC and equivalent path length (EPL)

15 MV, 2 field lung
95% IDL

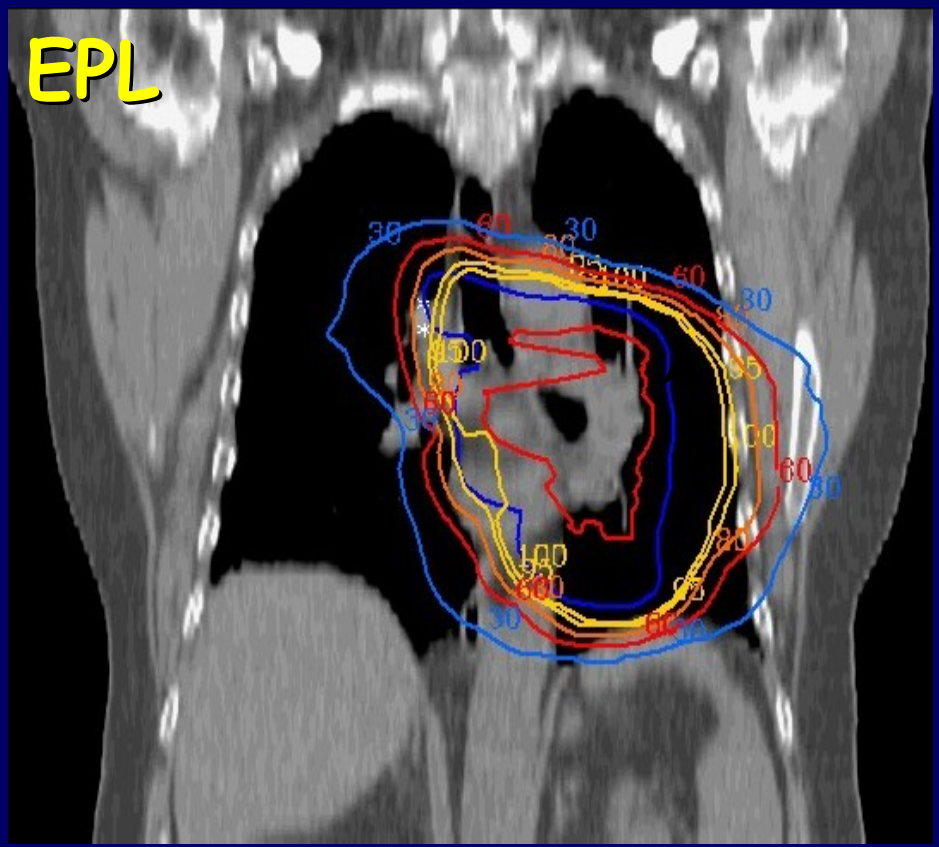
Solid = MC
Dashed = EPL
Blue = PTV

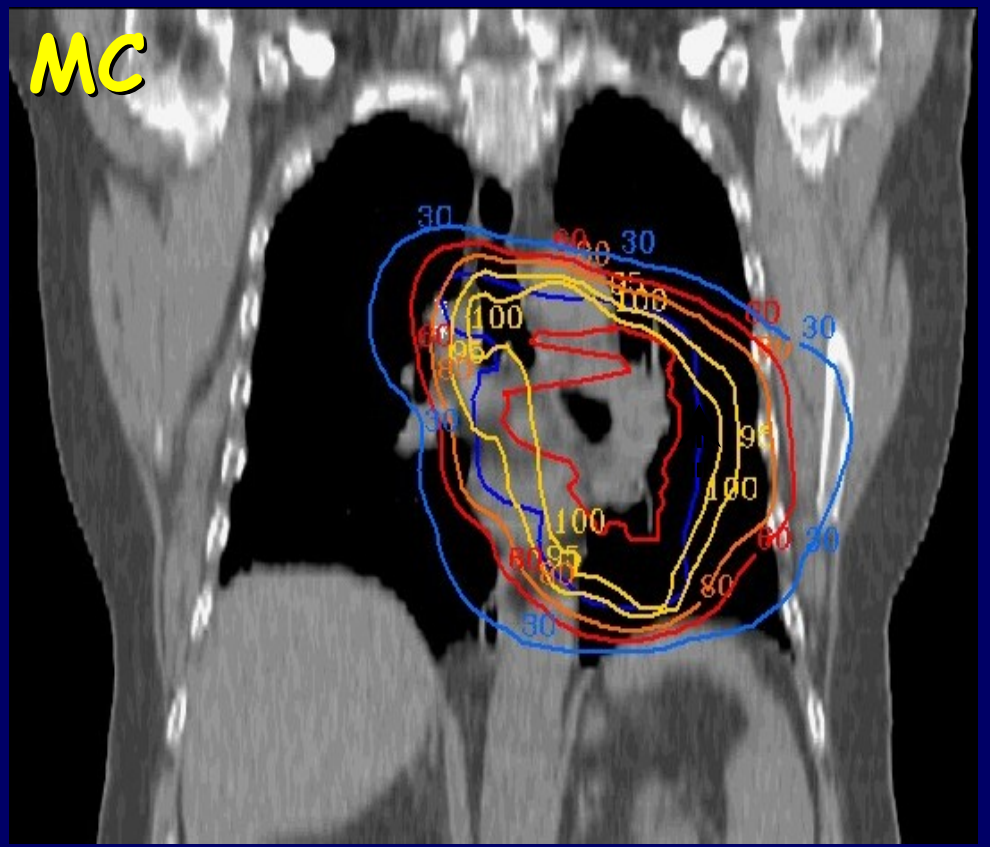




15 MV conformal lung plan

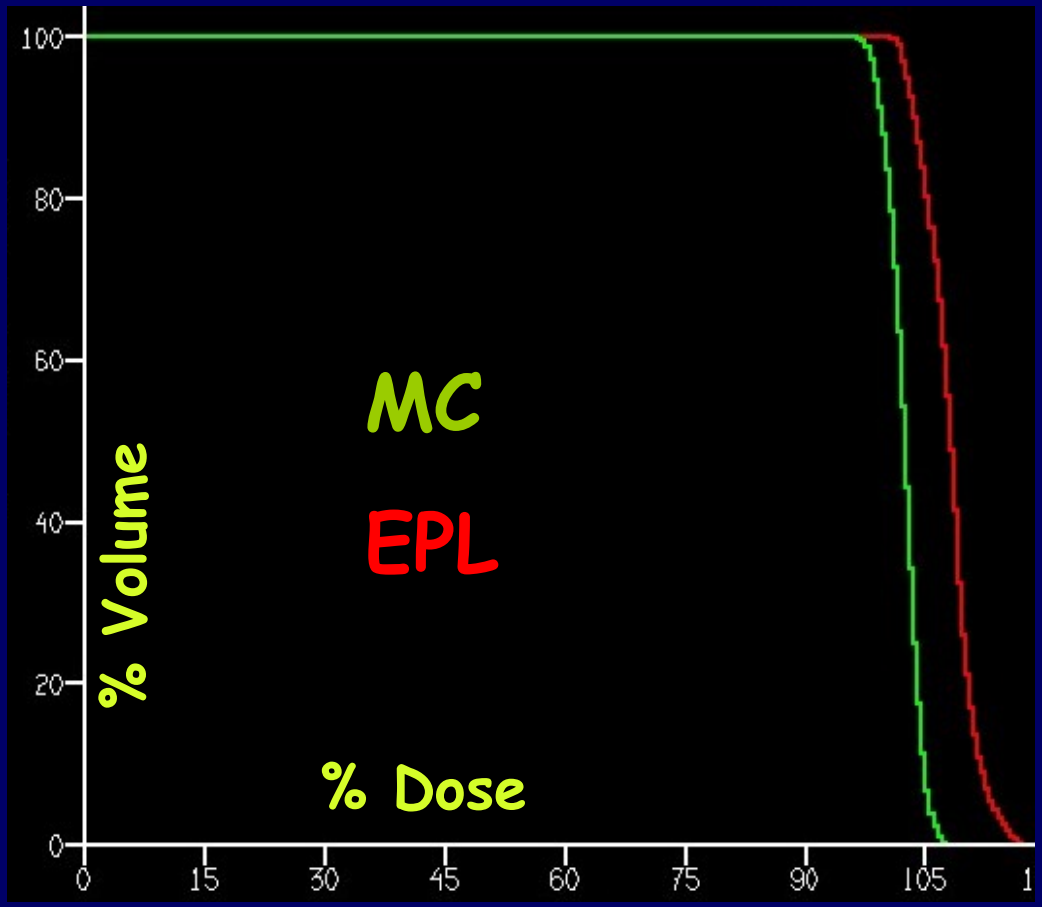
Note the differences in the spatial dose and dose gradient due to penumbral broadening



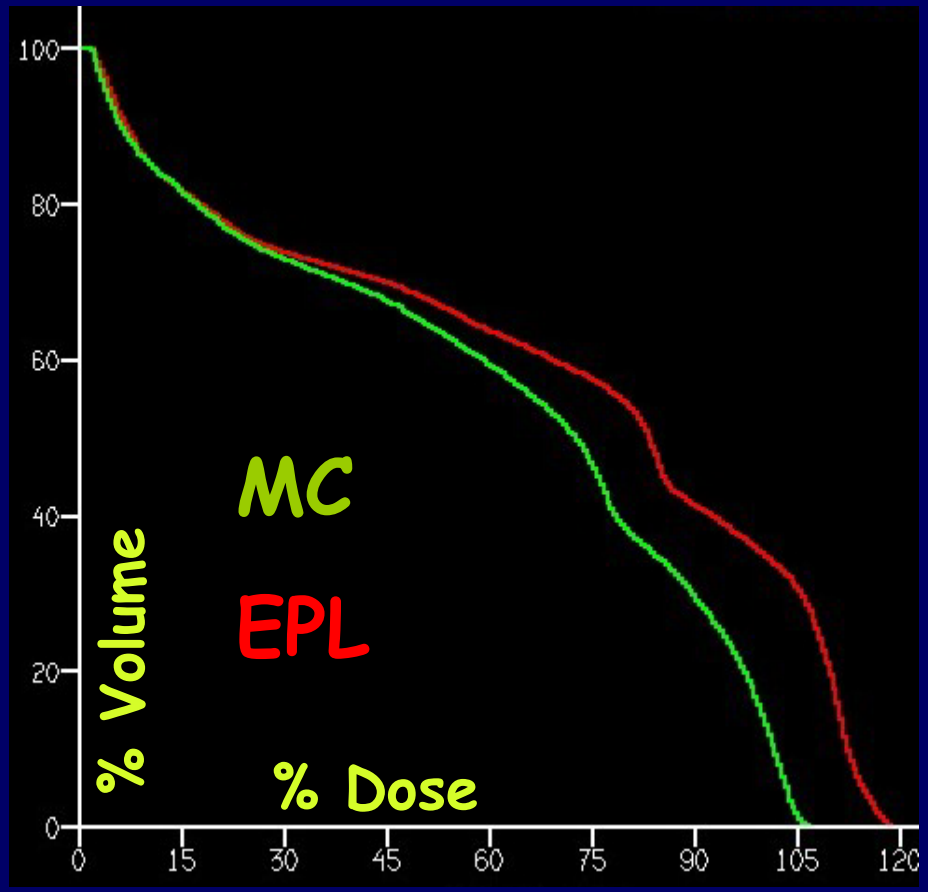


15 MV conformal lung plan

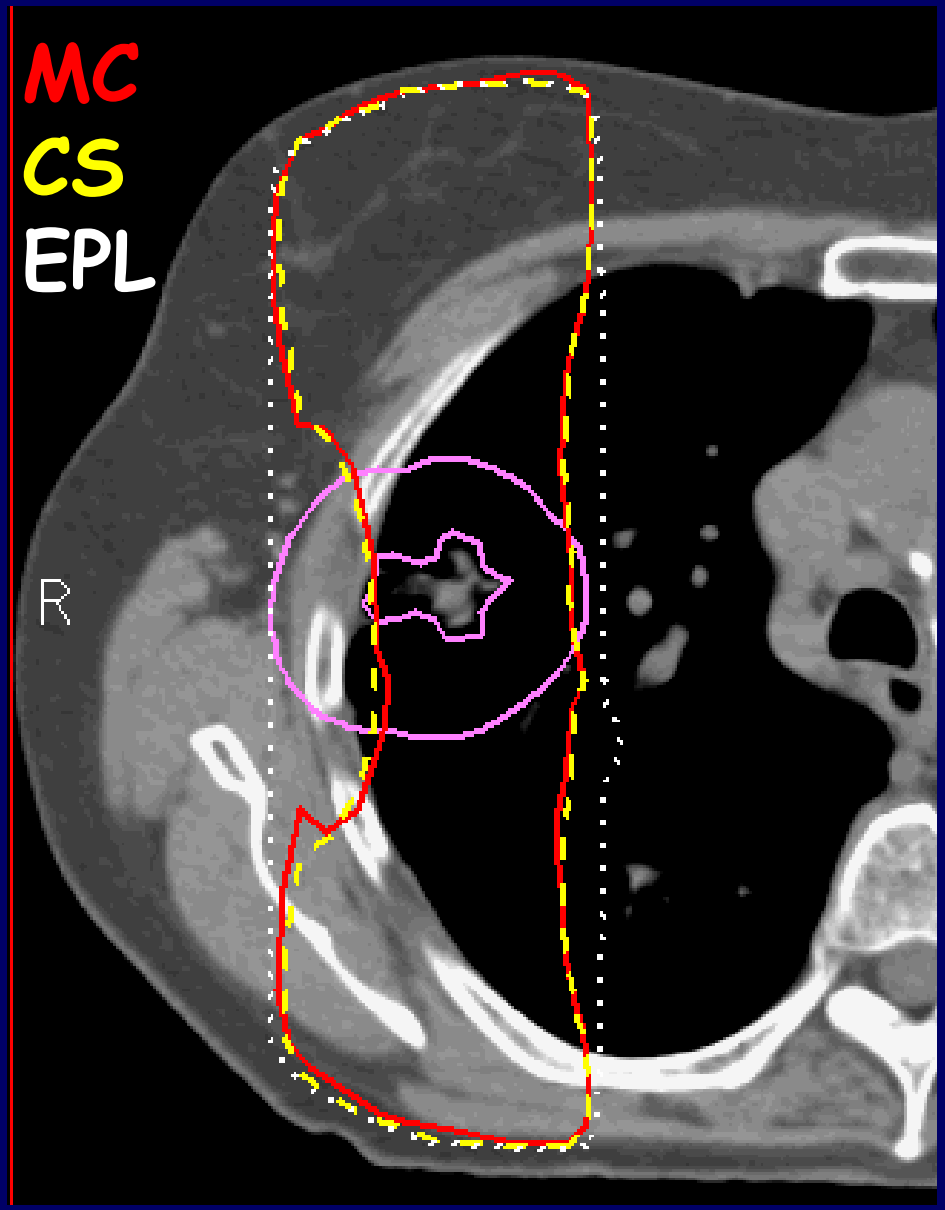
DVH - CTV

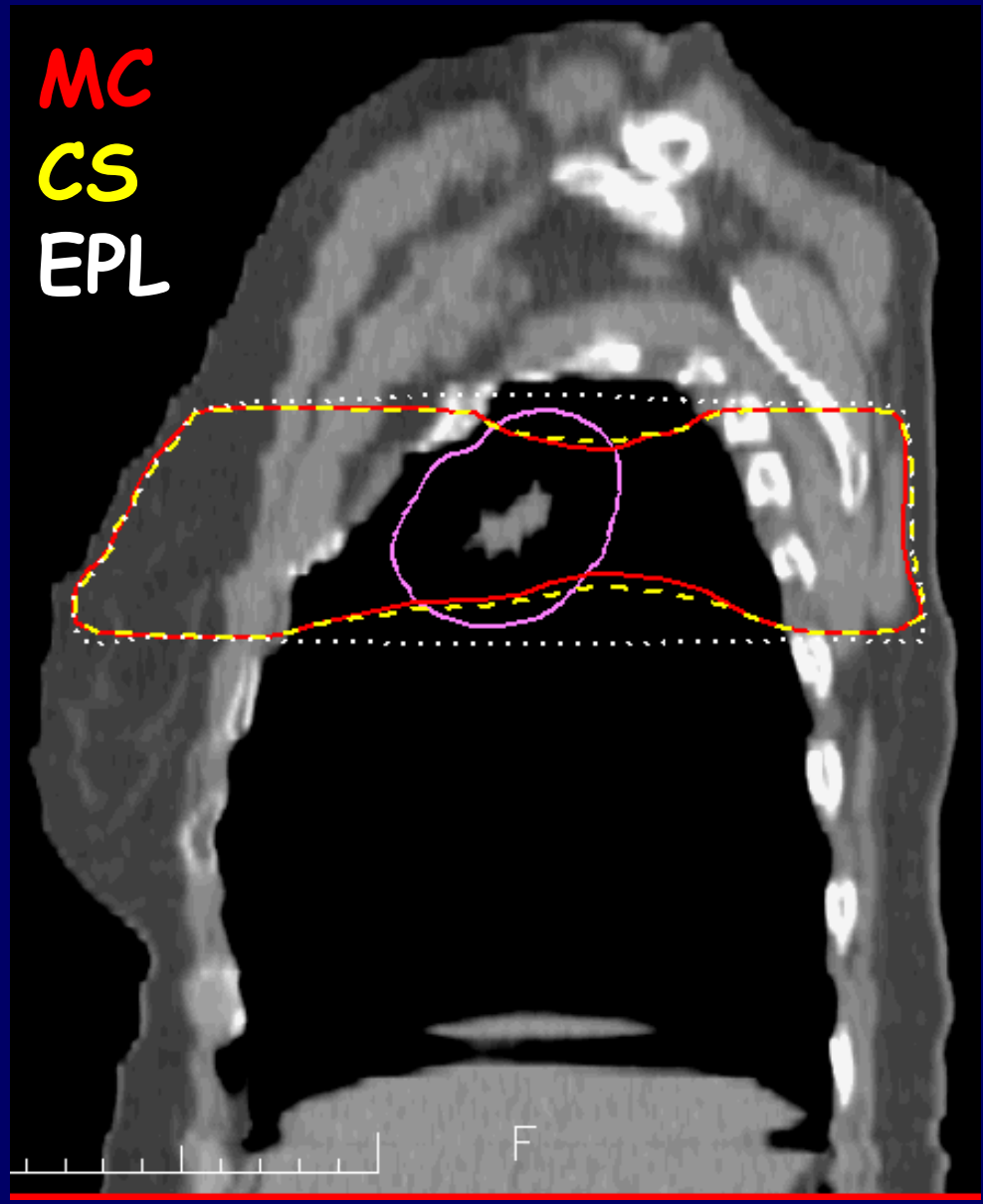


DVH - left lung



6 MV (6x6) AP/PA lung plan: 95% IDL

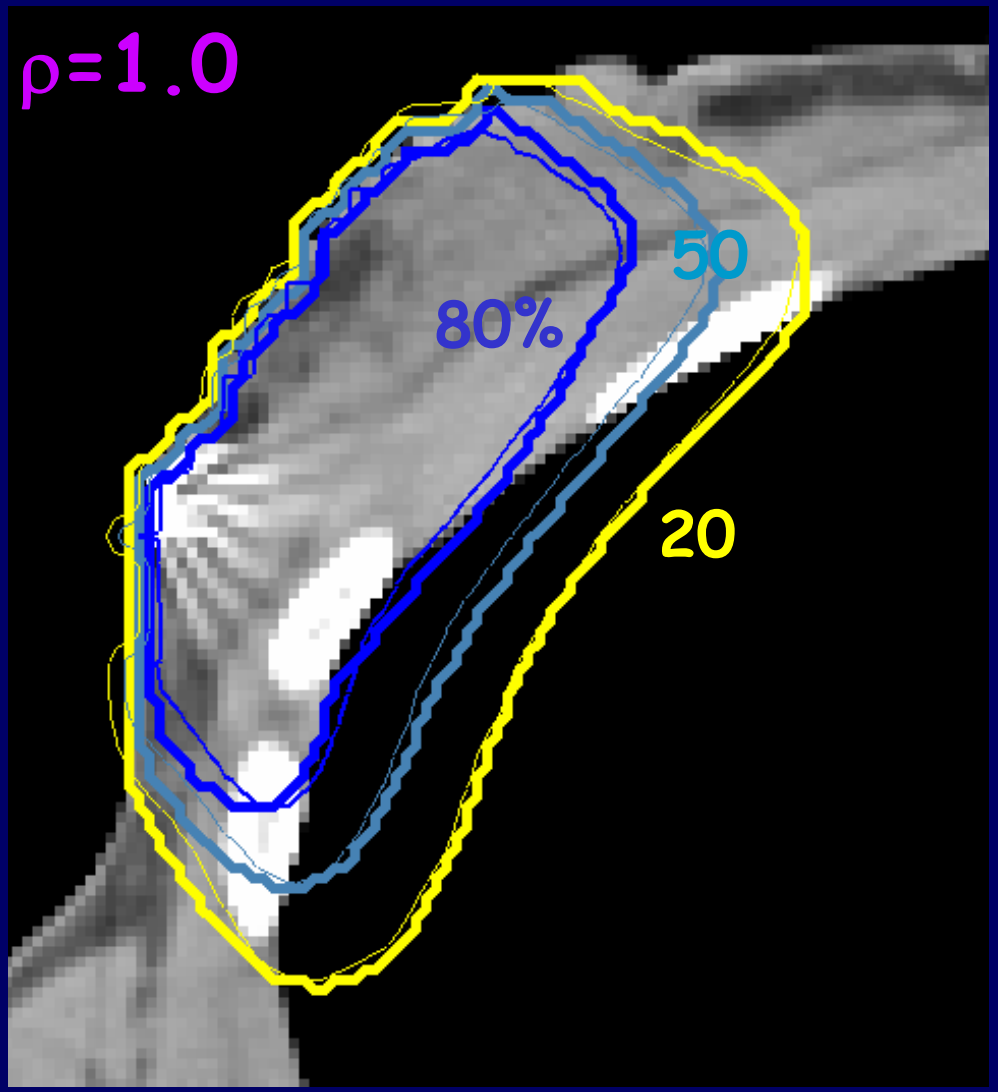


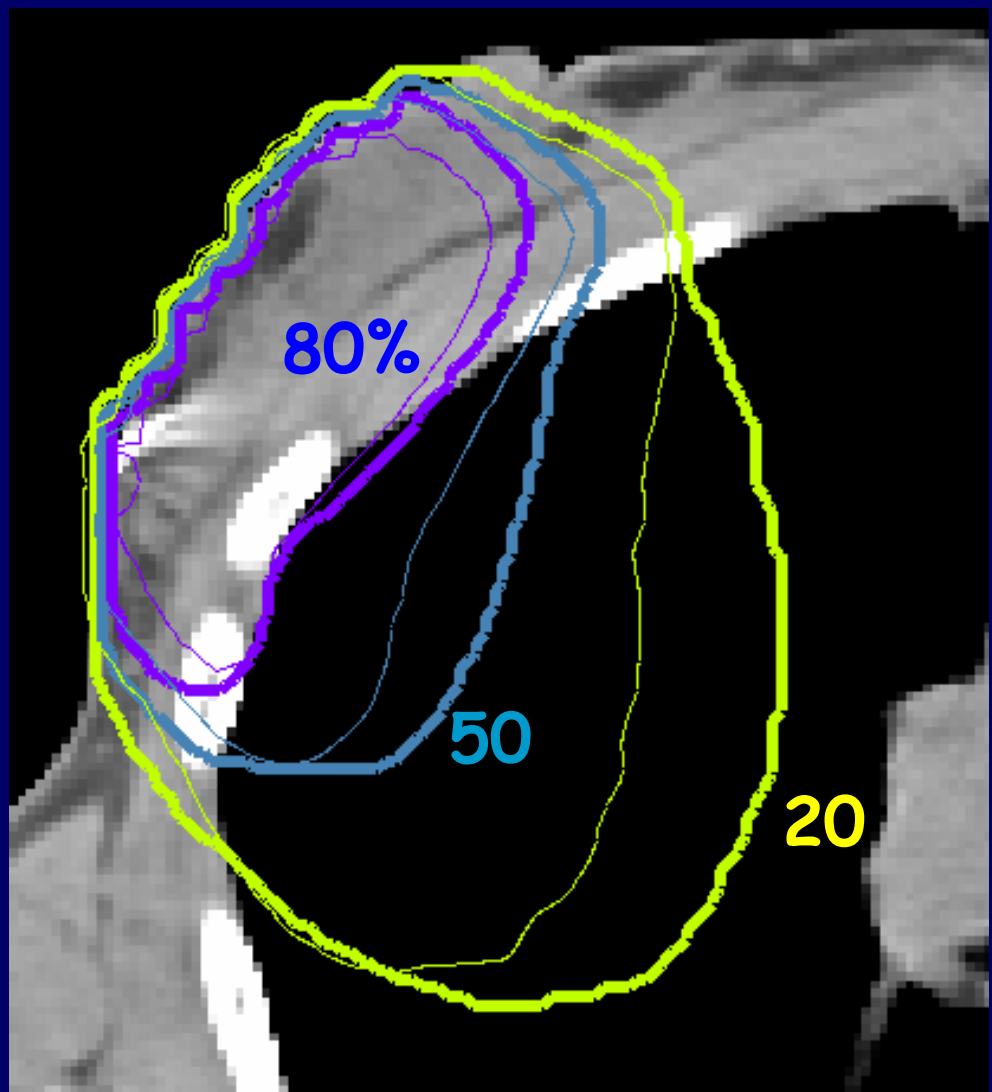


Electron beams: 9 MeV, 10x10 w/ custom block

Pinnacle (Philips) planning system v 8.1 s

MC= thick line, pencil beam= thin line





C. Statistical Uncertainties

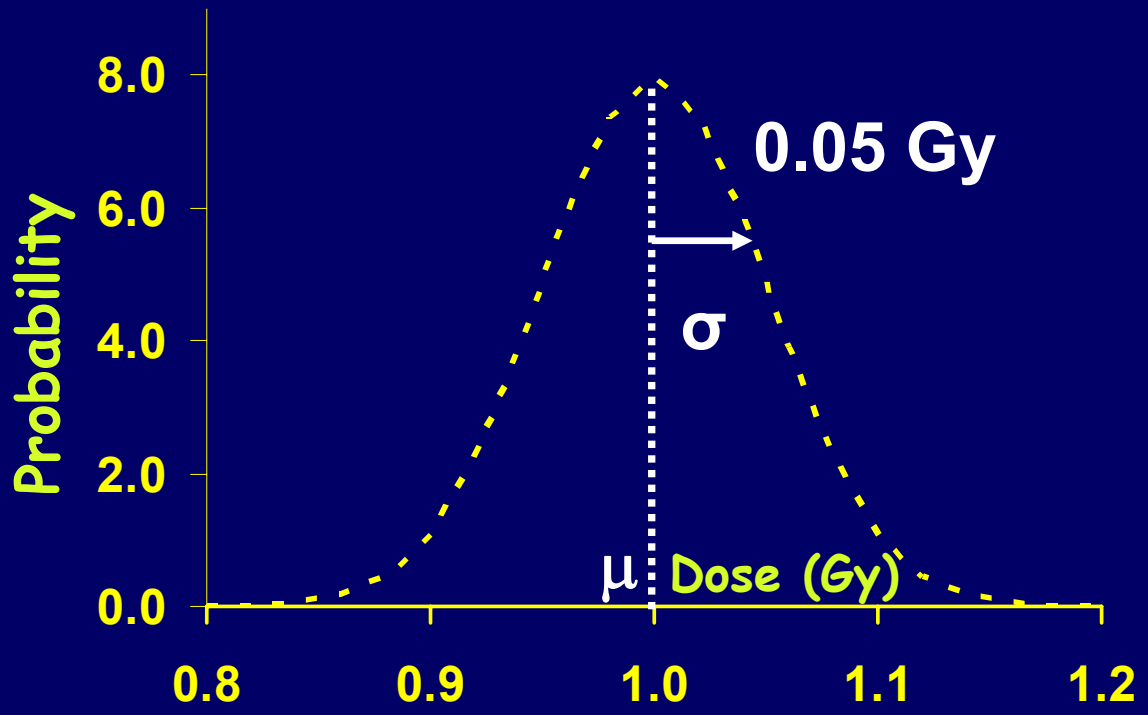
Question: Are statisticians normal?

Answer: Probably

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

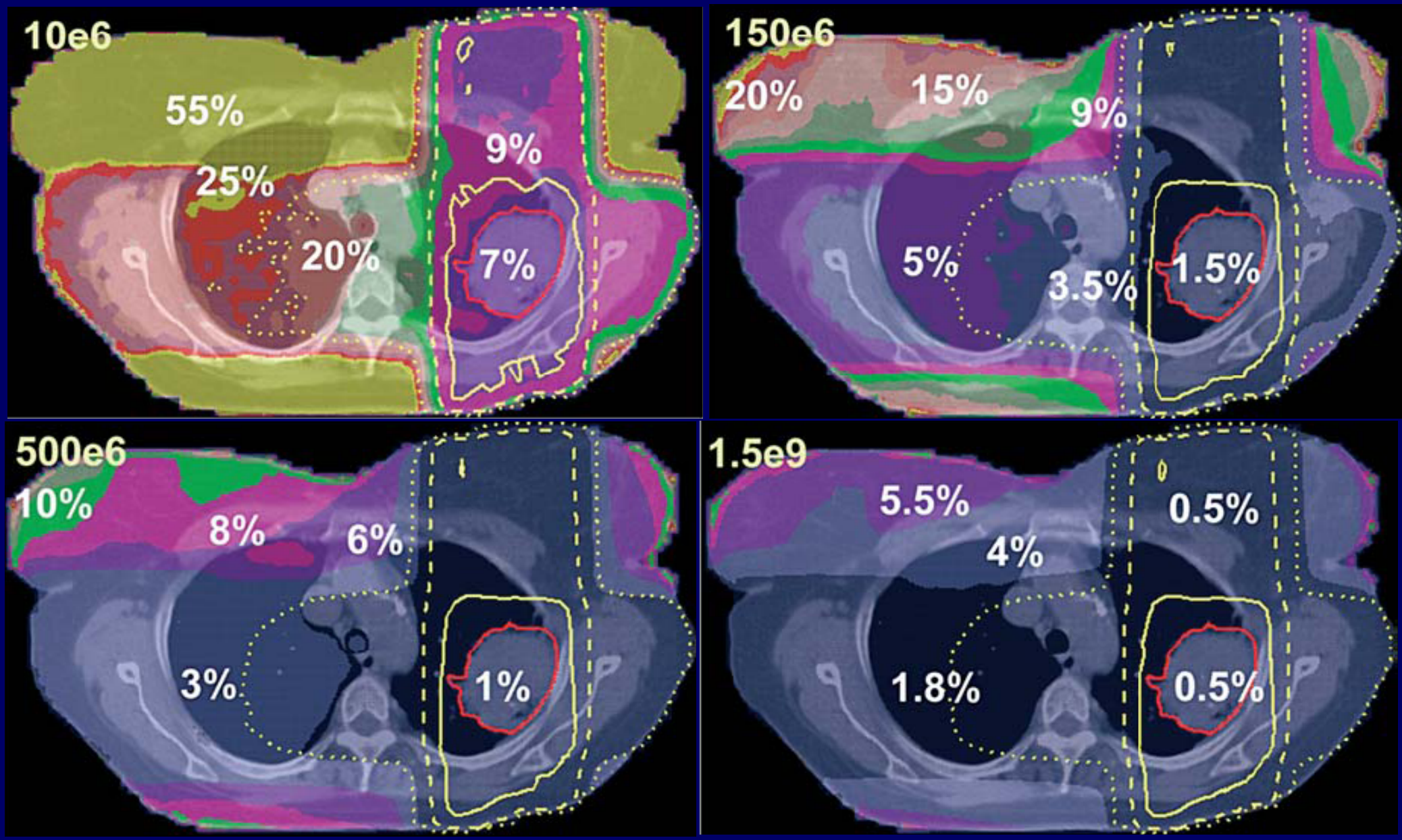
$\sigma \sim 1/\sqrt{N}$ N= total no. of particles simulated



In Tx planning,
Relative uncertainty
$= \sigma / \mu$

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

3F lung plan (RT_DPM): (1σ/μ)x100 %



Sources of uncertainty

Two sources of uncertainty: treatment head simulation (latent uncertainty – term coined by Sempau) and the patient simulation

The statistical uncertainty in calculated dose will approach (as a function of $1/\sqrt{N}$, where N is the number of simulated particles), the finite, latent uncertainty associated with the phase space, regardless of the number of times the phase space is sampled

Latent variance and beam models

Beam models consisting of full PS simulation of the treatment are subject to latent variance

Virtual source models reconstructed from the PS will also be subject to latent variance; fluctuations may be somewhat smoothed out

Measurement-driven models will not be subject to latent variance although other, systematic uncertainties may exist in the generation of these models

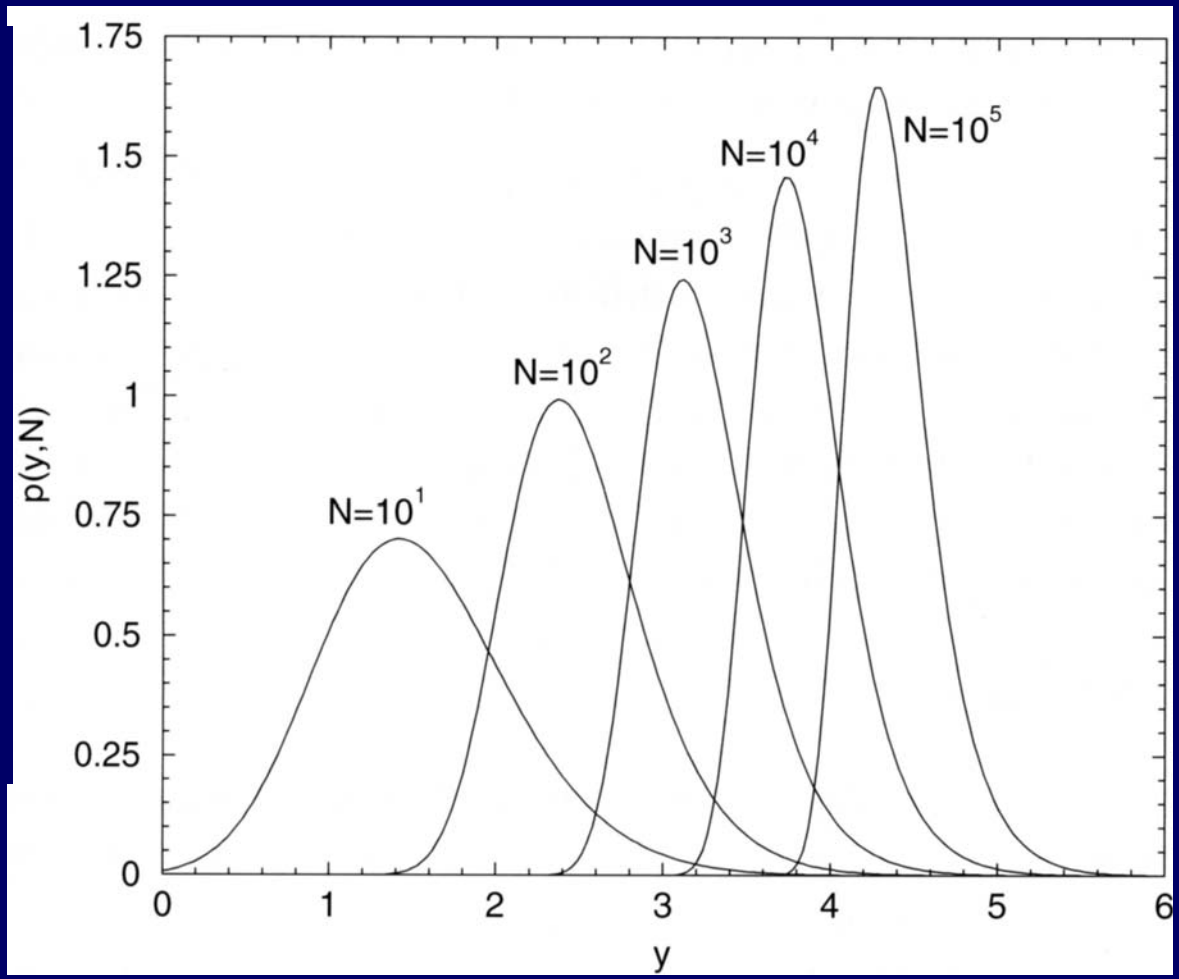
Statistical uncertainties: Recommendations

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

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

Statistical uncertainties: Recommendations

Probability that the max. dose differs from the uniform dose by *y* std. devs. in a region with *N* voxels



From Kawrakow, PMB: 47: 3087 (2002)

Prescribing doses to the max. pt. will underdose the target and vice versa for the min. pt.

Statistical uncertainties: Recommendations

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

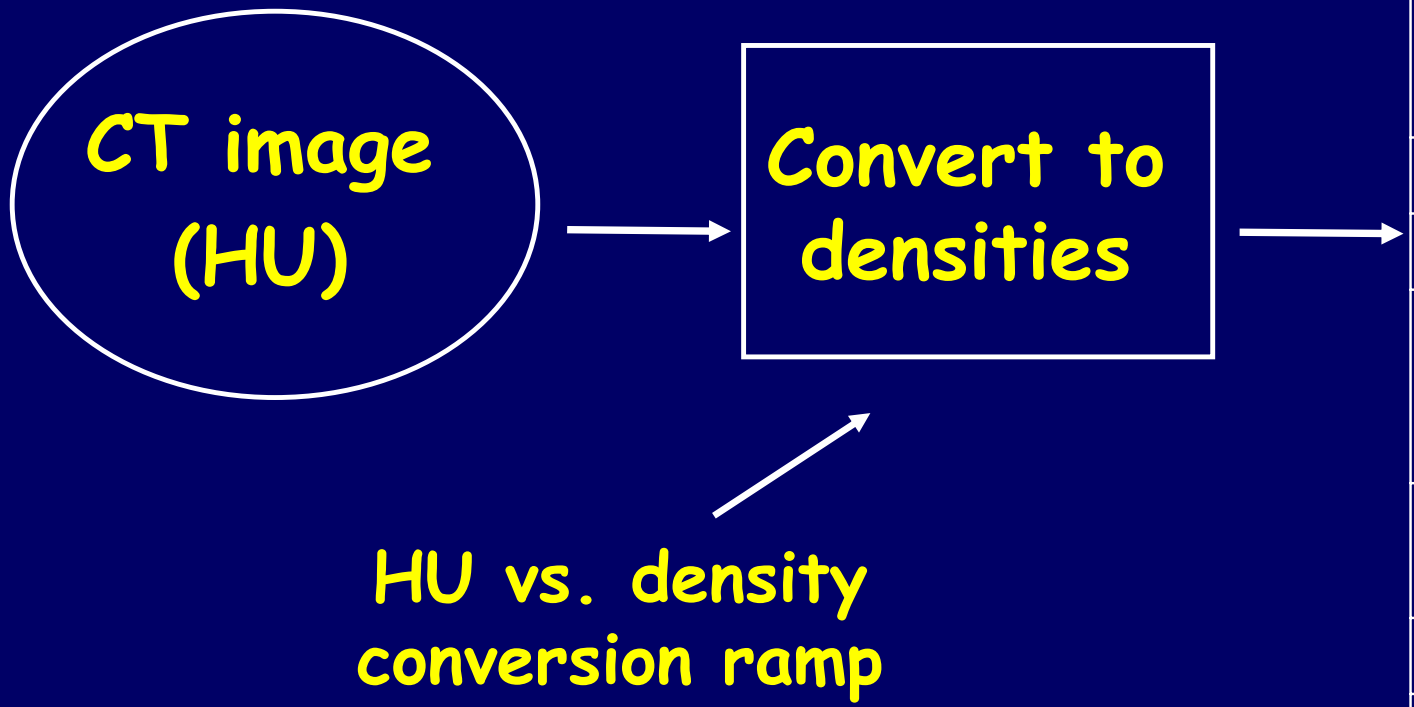
Dose volume indices for parallel organs like the lung (e.g. the mean lung dose) are minimally impacted by statistical noise

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

D.1. CT number to material conversions

Methods for CT-to-material conversions

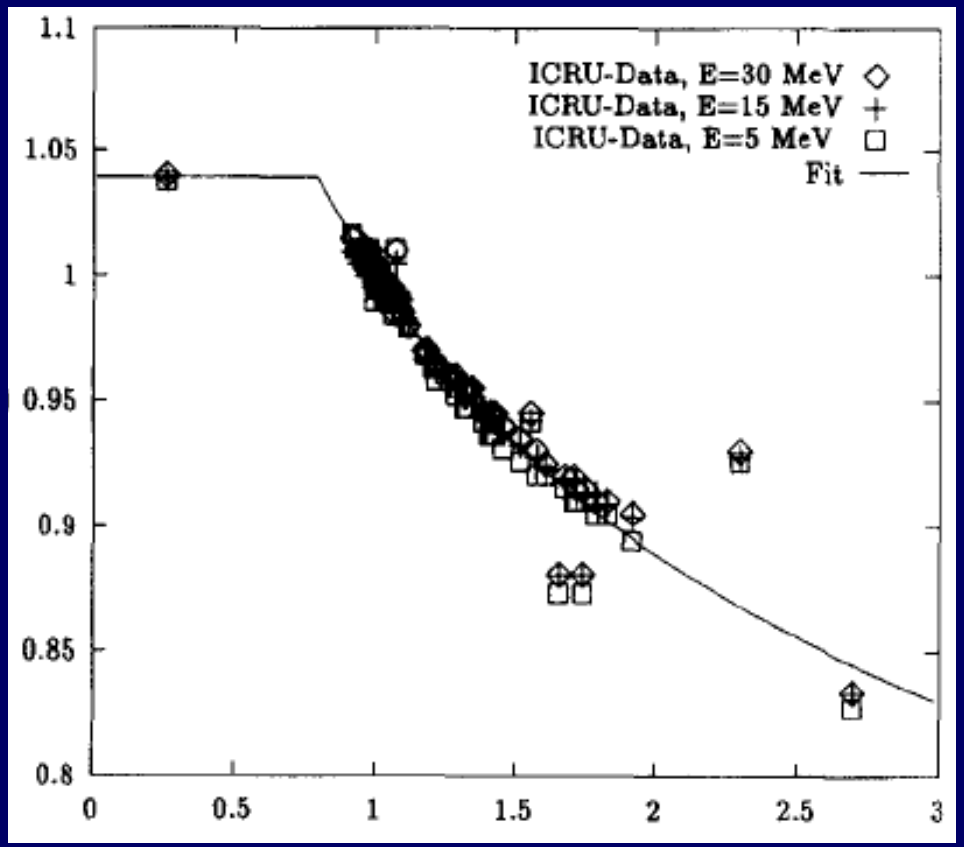
Patient tissues (via imaging data) need to be converted into cross sections required for MC simulation



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

Methods for CT-to-material conversions

Directly convert CT HU to material cross sections; simple relationships between mass density and mass scattering and stopping powers have been derived by Kawrakow et al. (Med Phys, 23: 445 (96')

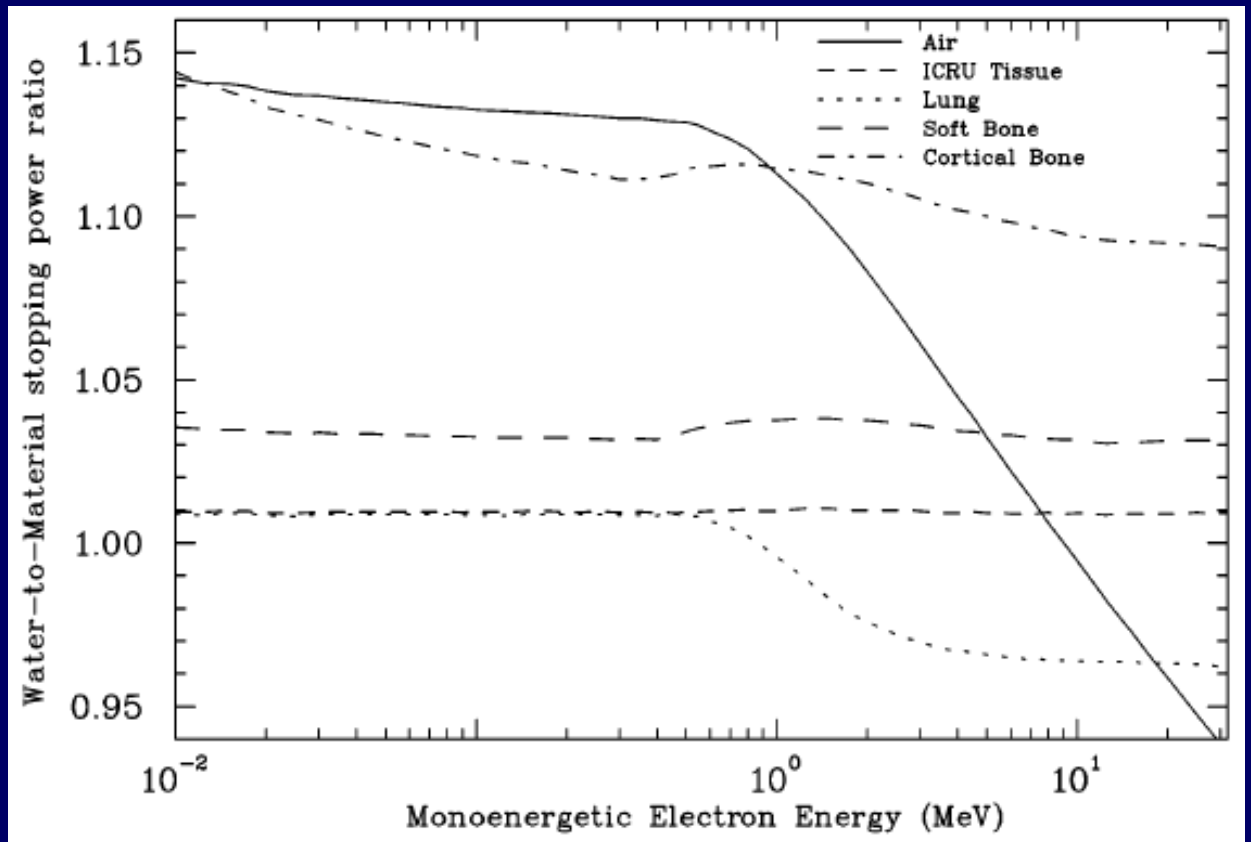


From Kawrakow, Fippel, Friedrich Med Phys: 23: 445 (1996)

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)

D.2. Dose to water and dose to medium

The Great Debate!

In favor of D_w: Historical clinical experience is based on D_w; therapeutic doses and normal tissue tolerance doses are therefore based on D_w

In favor of D_m: D_m (or dose to the tissue of interest) is inherently computed by MC dose algorithms. This may be of more clinical relevance than the doses on which historical clinical experience is based, which are approximate estimates of the true dose in the first place

Converting D_m to D_w

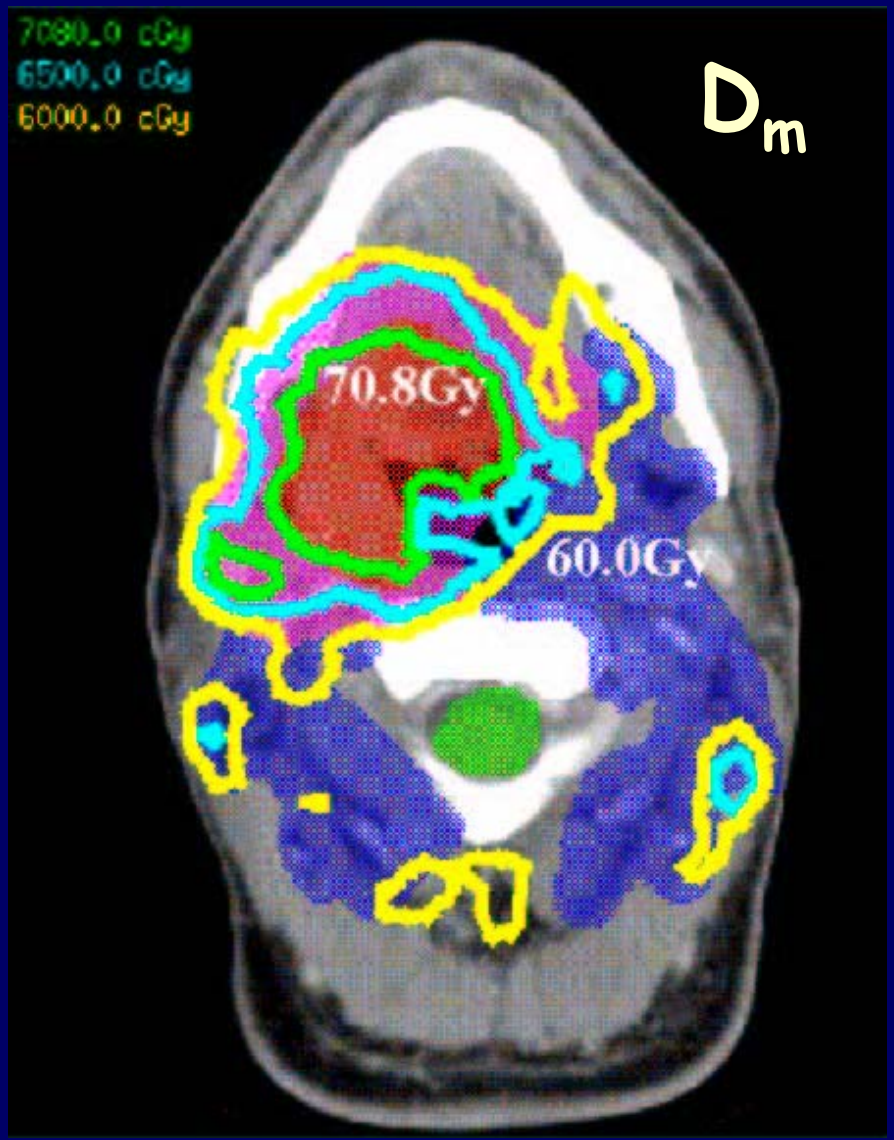
The conversion can be accomplished using the Bragg-Gray formalism:

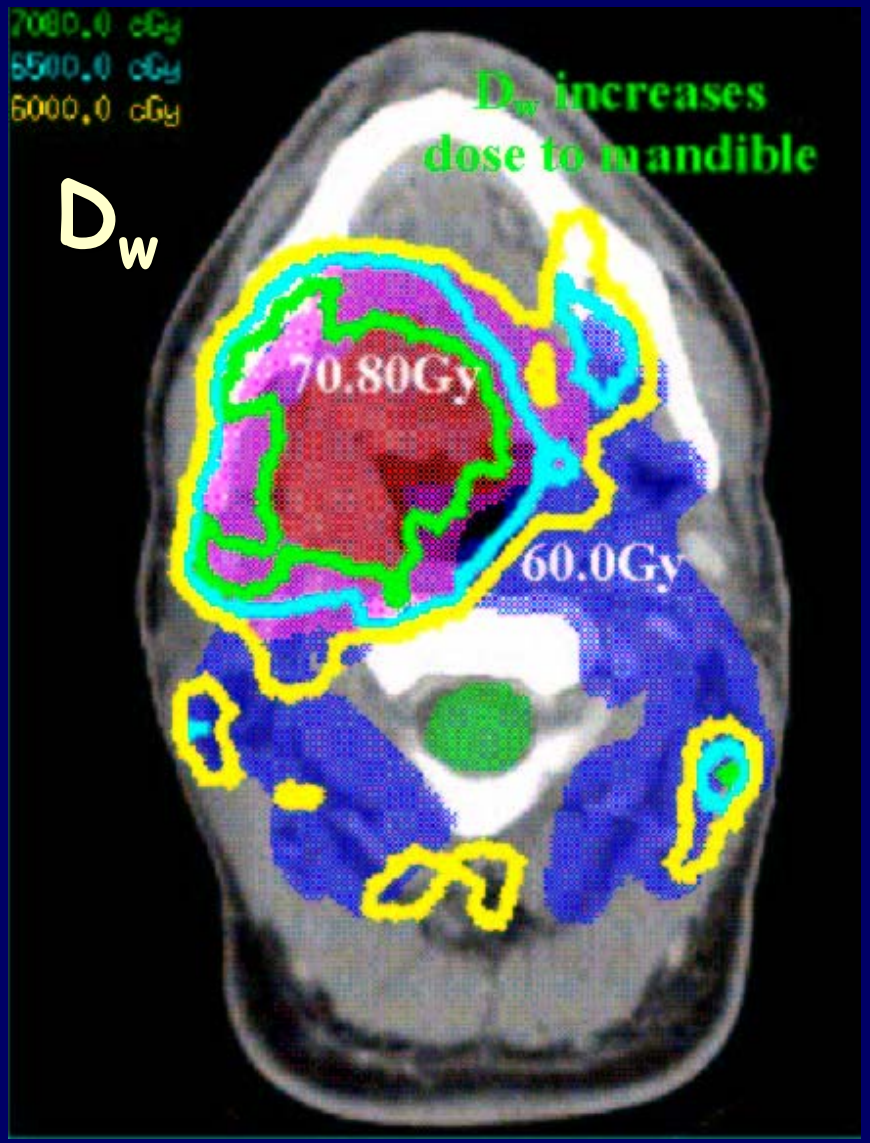
$$D_w = D_m \left(\frac{S}{\rho} \right)_m^w$$

$\left(\frac{S}{\rho} \right)_m^w$ Unrestricted wat-to-med mass collision stopping 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

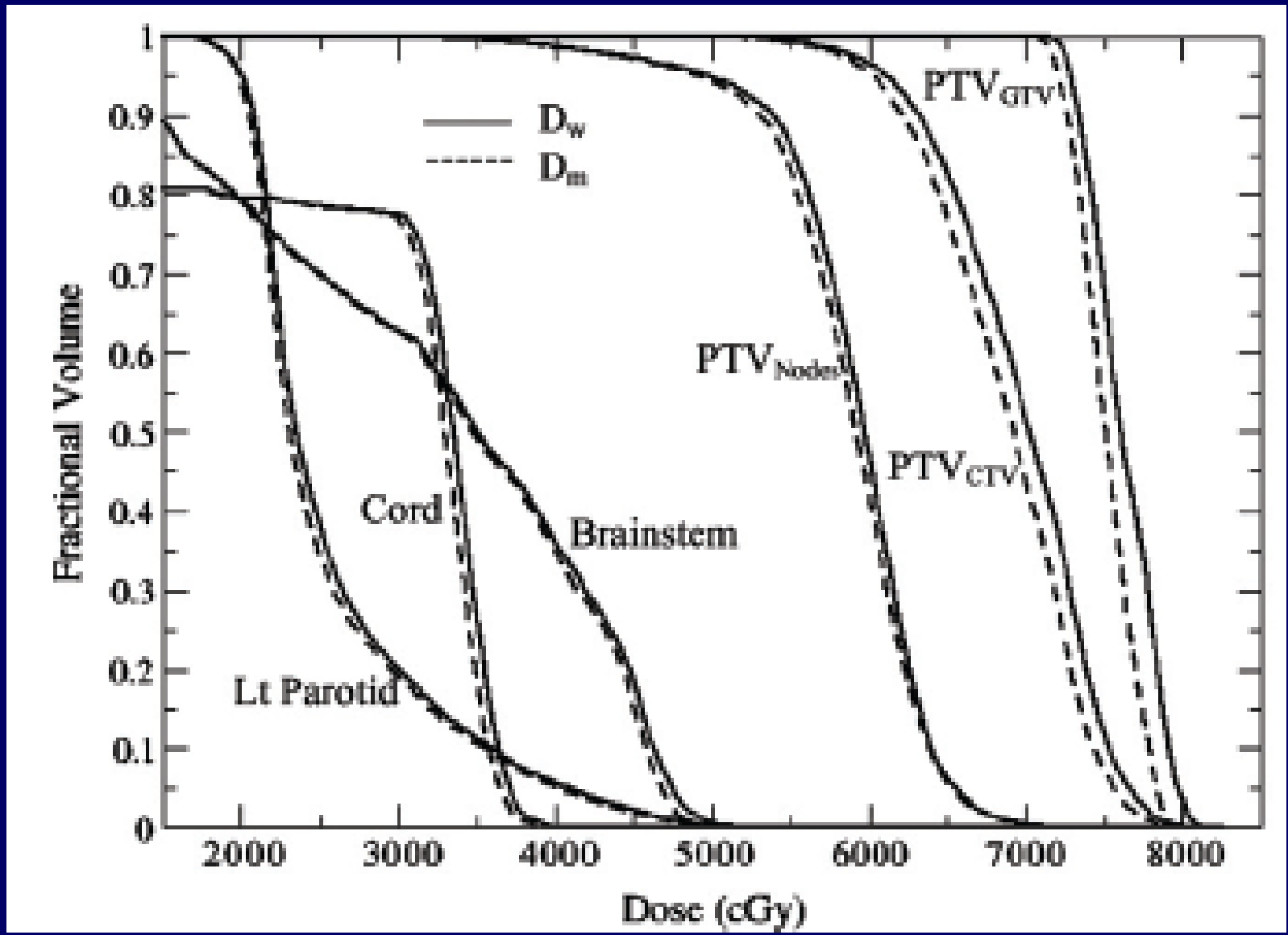
Clinical Examples: D_w and D_m





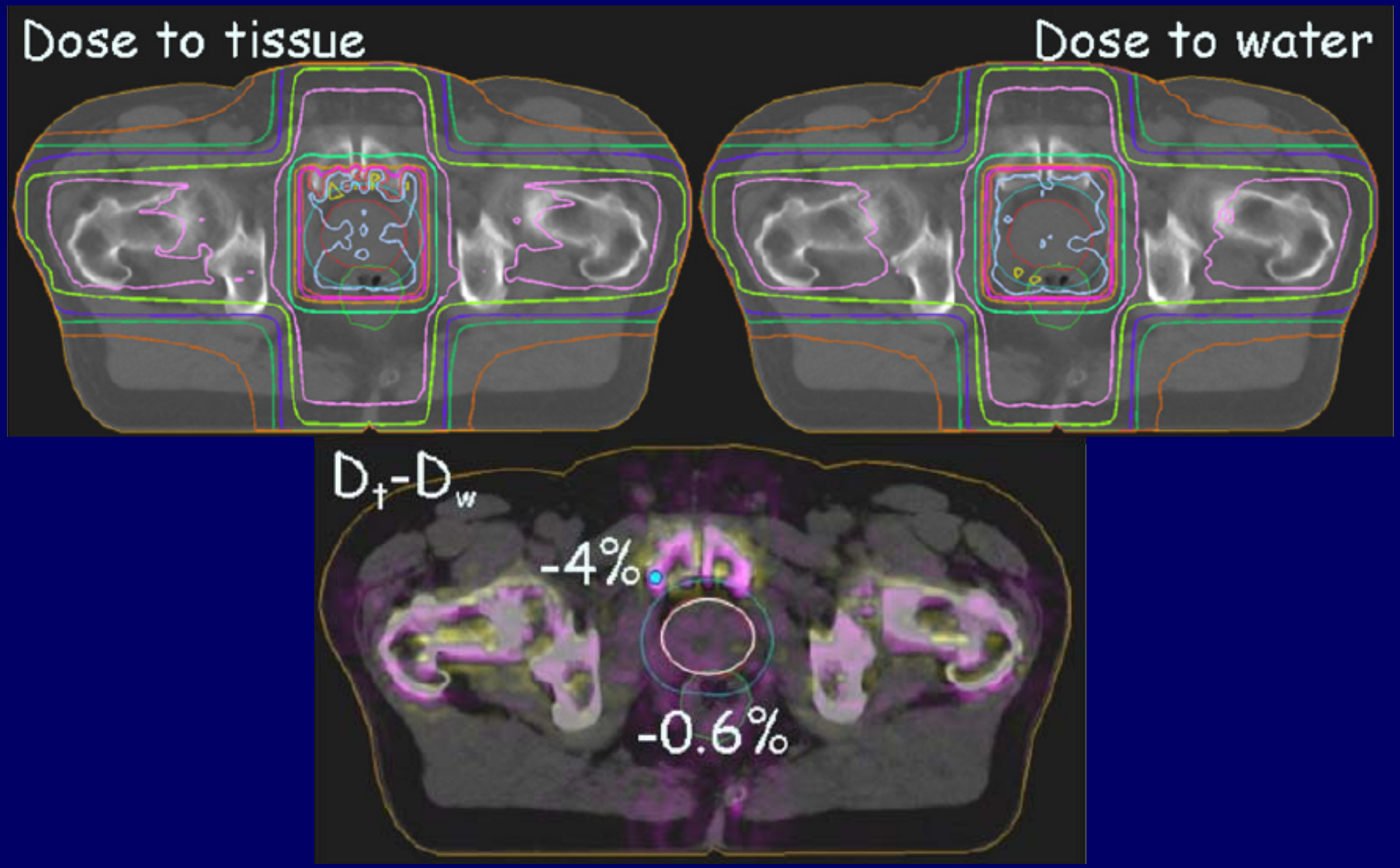
Dogan, Siebers, Keall: Phys Med Biol 51: 4967-4980 (2006)

Clinical Examples: D_w and D_m



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

Clinical Examples: D_w and D_m



Knoos *et al*: Phys Med Biol 51: 5785-5807 (2006)

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

The AAPM TG report 105 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

E. Clinical treatment planning: dose prescriptions and clinical outcomes

Dose prescriptions

MC-calculated doses in lung cancer planning can in some instances be significantly different (10-20%) than conventional algorithms, such as radiological path length, and convolution-based methods

In light of these differences: How should dose prescriptions change with MC-based calculations ?

AAPM TG 105 perspective:

Dose prescription issues are not specific to MC-based dose calculation; the MC method is just a more accurate dose algorithm

As with other changes to the therapy treatment process users should correlate doses and prescriptions with respect to previous clinical experience

Retrospective dose-effect studies in lung ca planning

How do the more accurate MC-based dose distributions impact clinical outcome in terms of tumor response (control) and normal tissue effects ?

- De Jaeger *et al.* Radioth. Oncol. 69, 1-10 (2003), in comparing outcomes for 68 lung ca patients showed that parameterizing the Lyman (NTCP) model using CS (vs. EPL) dose distributions, resulted in observed incidence of radiation pneumonitis occurring at a 12-14% lower dose

- It is likely that the use of MC-based dose calculation will add a higher degree of accuracy to the dose effect relationships

Retrospective dose-effect studies in lung ca planning

Ongoing outcome studies involving retrospective MC-based dose calculation:

J Seuntjens *et al.*; Lindsay and Deasy *et al.*; IJ Chetty *et al.*; and others

Initial results from these studies (though anecdotal at this early stage) are suggestive that MC-based dose calculations are likely to impact clinical outcome with respect to both tumors and normal tissues

Current commercial system MC implementations

Vendor	Code	Options
Nomos	Peregrine	Photon beam 3D-CRT
Konrad	MMC	Photon/electron 3D-CRT/IMRT
Varian (Eclipse)	MMC/ VMC++	Photon/electron 3D-CRT
BrainLab (iPlan)	XVMC	Photon beam 3D-CRT
Elekta (PrecisePlan)	XVMC	Photon beam 3D-CRT/IMRT
CMS (Monaco)	XVMC	Photon beam 3D-CRT/IMRT
Nucletron	VMC++	Electron beam
Philips (Pinnacle)	DPM	Electron beam

Recent timing results

Presented at ESTRO 2006

TPS	Description of test	Time (min.)
Nomos (Peregrine)	6 MV, 10x10 AP, 2 mm voxels, 16 CPUs, 800 MHz, P III	48, σ_{Dmax}=2%)
BrainLab (XVMC)	6 MV, 5F CRT lung, 3.5x3.5, 3 mm voxels, 4 CPUs, 2.61 GHz, Opt.	1.8, (σ_{Dmax}=1%)
CMS (XVMC)	6 MV, 7F CRT prostate, 8x8, 2 and 3 mm voxels, 4 CPUs, 3.4 GHz, Xeon	24.5, 5.5 σ_{Diso} = 1%, 2%
Elekta (XVMC)	6 MV, 7F (23 segs), IMRT lung 7.5x7.5, 4 mm voxels, 2x2 CPUs, P4 Xeon, 3.2 G	24, 11.4 σ_{Diso} = 2%, 3%
Nucletron	17 MeV e', 10x10 AP, 4.9 mm voxels, 1 CPU, 2.2 GHz, P4, Xeon	8.2, $\sigma_{D_{cax}}$ = 1.5%
Varian (VMC++)	6 MV, 10x10 AP, 5 mm voxels, wat/lung/wat, 1 CPU, 2.1 GHz, M	19.3, σ_{Dmax}=0.9%

Conclusion

- Clinical implementation of MC-based systems must be performed thoughtfully and physicists must understand the differences between MC-based and conventional dose algorithms

- Successful implementation of clinical MC algorithms will require strong clinician support and an understanding of the paradigm shift with MC algorithms

- A properly commissioned MC-based dose algorithm will improve dose calculation accuracy in 3D-CRT and IMRT treatment planning and is likely to improve dose-effect correlations

Acknowledgements

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