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

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Outline

A. Experimental verification of MC-based algorithms

B. Factors associated with MC dose calculation in the patient geometry:
   - statistical uncertainties,
   - CT-to-material conversions,
   - dose-to-water and dose-to-medium

C. MC-based dose prescription issues

D. Summary of the findings of the TG-105 report

A. Experimental Verification

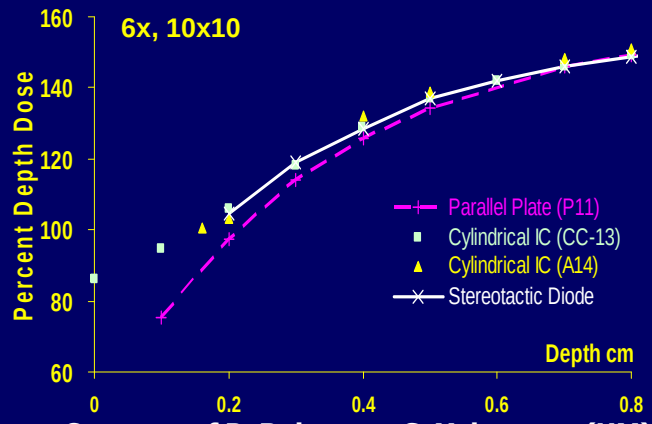
How should one commission and verify a MC-based dose algorithm?

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

(a) the beam model: to verify characterization of e' parameters (e.g. energy), Tx head components (e.g. FF), and beam-modifiers (e.g. MLC) – this is done against depth dose and profile measurements in water phantoms for square and shaped fields

(b) radiation transport accuracy in the patient: done with measurements in heterogeneous phantoms: small field sizes, low-density media, high beam energies, non-equilibrium conditions are useful

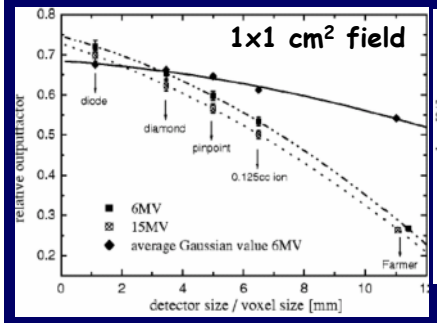
Issues with measurements – buildup region

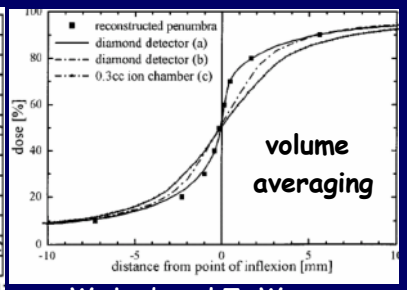


Courtesy of P. Roberson, S. Yokoyama (UM)

Issues with measurements – small field sizes

Measurements with small field sizes are complicated





W. Laub and T. Wong, Med. Phys. 30:341-347 (2003)

Measurements with small field sizes in inhomogeneous media are even more complicated!

Experimental Verification

The MC method is just another dose calculation technique and as such should be subjected to the same level of testing as reported in articles on commissioning of dose algorithms, such as AAPM TG-53 and IAEA TRS-430

In addition, inclusion of experimental testing in complex configurations designed to verify the improved accuracy expected with the use of the MC method, will be helpful

Accurate measurements are a requirement for accurate simulations!

B. Statistical Uncertainties in MC-computed dose

Interesting Fact:

A Norwegian statistics professor has the name Just Gjessing

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

Calculating uncertainties: Batch method

The estimate of the uncertainty (S_x) of a scored quantity X (e.g. dose) is given by:

$$s_{\bar{x}} = \sqrt{\frac{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2}{n(n-1)}}$$

In the batch method, n is the number of independent batches and X is the mean value of X over all batches

Calculating uncertainties: History-by-history method

In the history-by-history method, N is the number of independent histories and X_i is the scored quantity in history i rather than batch i:

$$s_{\bar{x}} = \sqrt{\frac{1}{N-1}\left(\frac{\sum_{i=1}^{N} X_i^2}{N} - \left(\frac{\sum_{i=1}^{N} X_i}{N}\right)^2\right)}$$

Since with the batch method the number of batches, n, is typically small, there is statistical fluctuation in the uncertainty itself (Walters *et al* Med Phys '02)

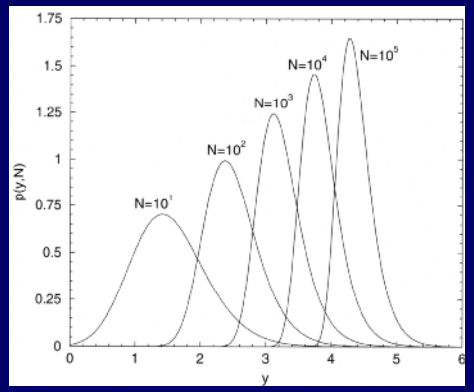
Statistical uncertainties: Dose prescriptions

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

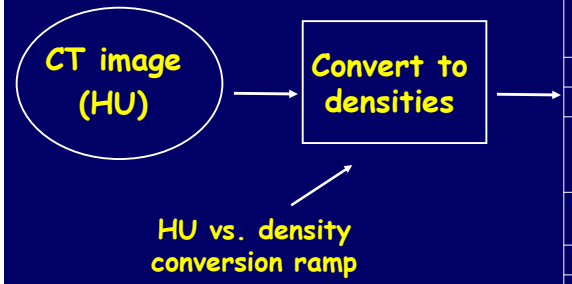
Dose volume indices for parallel organs like the lung (e.g. the mean lung dose) are minimally impacted by statistical noise

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

C. CT number to material conversions

Methods for CT-to-material conversions

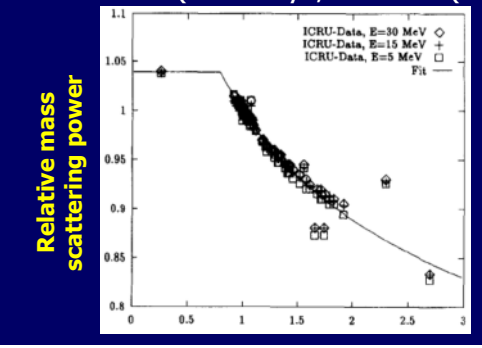
Patient tissues (via imaging data) need to be converted into cross sections required for MC simulation



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)

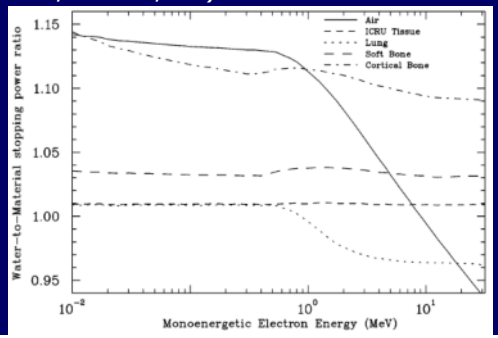


From Kawrakow, Fippel, Friedrich Med Phys: 23: 445 (1996)

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)

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

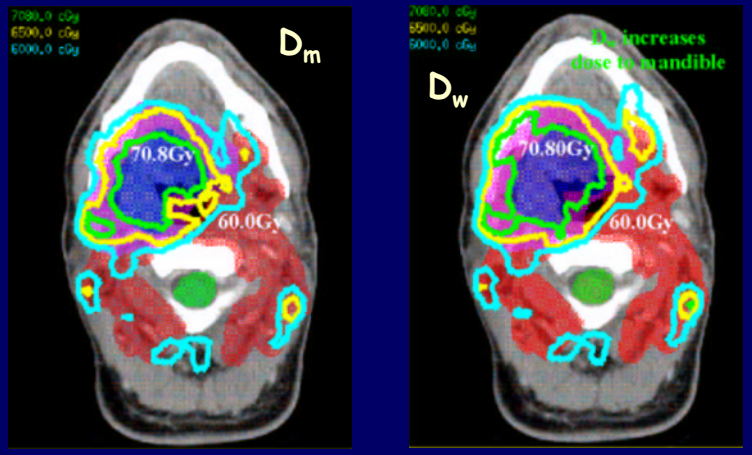
The conversion can be accomplished using the Bragg-Gray formalism:

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

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

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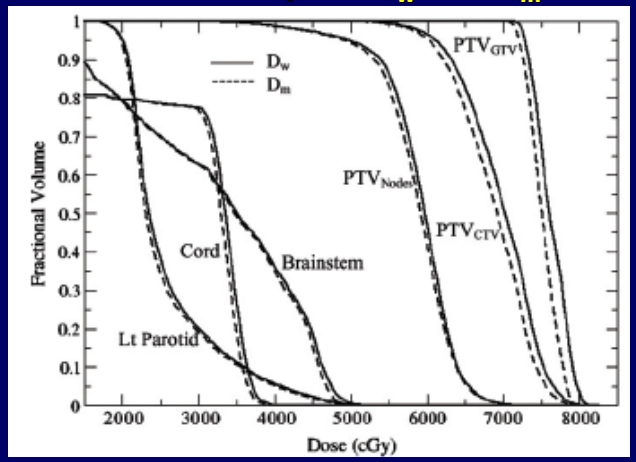

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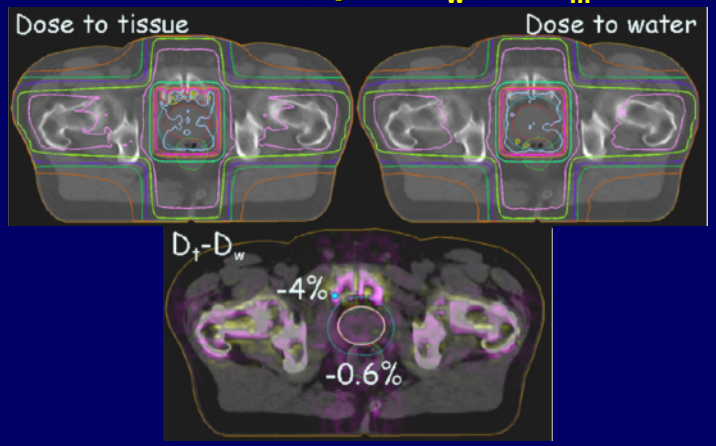
Clinical Examples: D_w and D_m



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

D. MC-based dose prescriptions

MC-calculated doses can in some instances be significantly different (5-20%) 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

Summary of Recommendations

Treatment Head Simulation:

(a) Vendors should provide the necessary support and assistance with the beam modeling and benchmarking process, e.g. fine-tuning of the models

(b) If the model is based on direct PS simulation, the latent variance in the model should be estimated by the vendor and be made available to users

Patient Simulation:

Statistical Uncertainties: Should be specified to doses within volumes consisting of many voxels; single-voxel dose uncertainty estimates should be avoided as should be specification to the maximum or minimum dose voxels

Summary of Recommendations

Patient Simulation: **VRTs and EETs:** Users should understand the influence on the dose accuracy of VRTs and EETs. Vendors should provide documentation on these methods and on their influence, as well as flexibility to adjust these parameters where possible

Dose Prescriptions: Vendors are strongly discouraged from prescribing doses to single voxels (point doses). Doses should be prescribed to volumes consisting of more than a single voxel; e.g. an isodose volume

CT to material conversions: Should be based on both mass density and atomic no. compositions of materials

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 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 in 3D-CRT and IMRT treatment planning and may improve dose-effect correlations

Acknowledgements

Colleagues at University of Michigan

Grant Support: NIH P01-CA-59827 (UM) and R01 CA106770 (HFHS)

AAPM-TG 105 committee co-authors