Review of AAPM's TG105: Issues associated with clinical implementation of Monte Carlo-based photon and electron external beam treatment planning

D. W. O. Rogers,
Carleton Laboratory for Radiotherapy Physics,
Physics Dept,
Carleton University,
Ottawa

Indrin Chetty
Henry Ford Hospital
Detroit , MI

http://www.physics.carleton.ca/~drogers

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Disclosure

I used to work for, and still receive some royalty income from the National Research Council of Canada which has licensing agreements re Monte Carlo software with:

Elekta Philips/ADAC NAS/NOMOS
Nucletron Varian

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MDS Nordion Varian

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

Indrin J. Chetty[a)]
University of Michigan, Ann Arbor, Michigan 48109
and University of Nebraska Medical Center, Omaha, Nebraska 68198-7521

Bruce Curran
University of Michigan, Ann Arbor, Michigan 48109

Joanna E. Cygler
Ottawa Hospital Regional Cancer Center, Ottawa, Ontario K1H 1C4, Canada

John J. DeMarco
University of California, Los Angeles, California 90095

Gary Ezzell
Mayo Clinic Scottsdale, Scottsdale, Arizona 85259

Bruce A. Faddegon
University of California, San Francisco, California 94143

Iwan Kawrakow
National Research Council of Canada, Ottawa, Ontario K1A 0R6, Canada

Paul J. Keall
Stanford University Cancer Center, Stanford, California 94305-5847

Helen Liu
University of Texas MD Anderson Cancer Center, Houston, Texas 7703(

C.-M. Charlie Ma
Fox Chase Cancer Center, Philadelphia, Pennsylvania 19111

D. W. O. Rogers
Carleton University, Ottawa, Ontario K1S 5B6, Canada

Jan Seuntjens
McGill University, Montreal, Quebec H3G 1A4, Canada

Daryoush Sheikh-Bagheri
The Regional Cancer Center, Erie, Pennsylvania 16505

Jeffrey V. Siebers
Virginia Commonwealth University, Richmond, Virginia 23298

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Charge of TG-105

Develop an overview report on the Monte Carlo method and its application to radiotherapy treatment planning.
Aims are:

- educational: provide an understanding of the MC method and how it is used in radiotherapy
- discuss issues associated with clinical implementation and experimental verification
- provide perspectives and possible methods on how to deal with the issues

Not meant to be prescriptive or to provide specific guidance on clinical commissioning.

What is the Monte Carlo method?

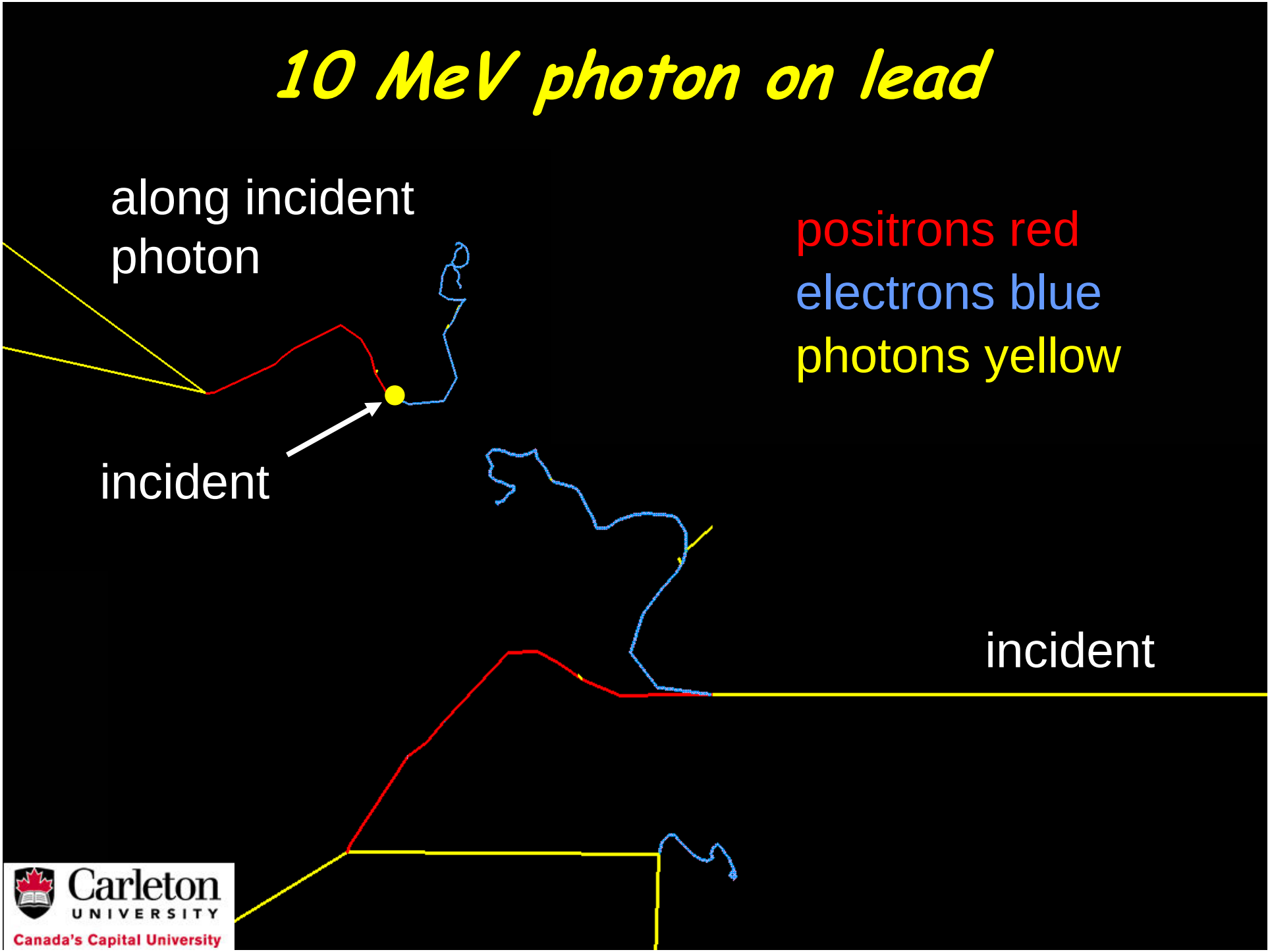
"The Monte Carlo technique for the simulation of the transport of electrons and photons through bulk media consists of using knowledge of the probability distributions governing the individual interactions of electrons and photons in materials to simulate the random trajectories of individual particles. One keeps track of physical quantities of interest for a large number of histories to provide the required information about the average quantities" *

In principle, very straightforward application of radiation physics. Much easier to understand than convolution / superposition or EQTAR.

Virtually no approximations of consequence.

*TG105 quotes Rogers&Bielajew, 1990, in Dosimetry of Ionizing Radiation V3 http://www.physics.carleton.ca/~drogers/pubs/papers/RB90.pdf

10 MeV photon on lead



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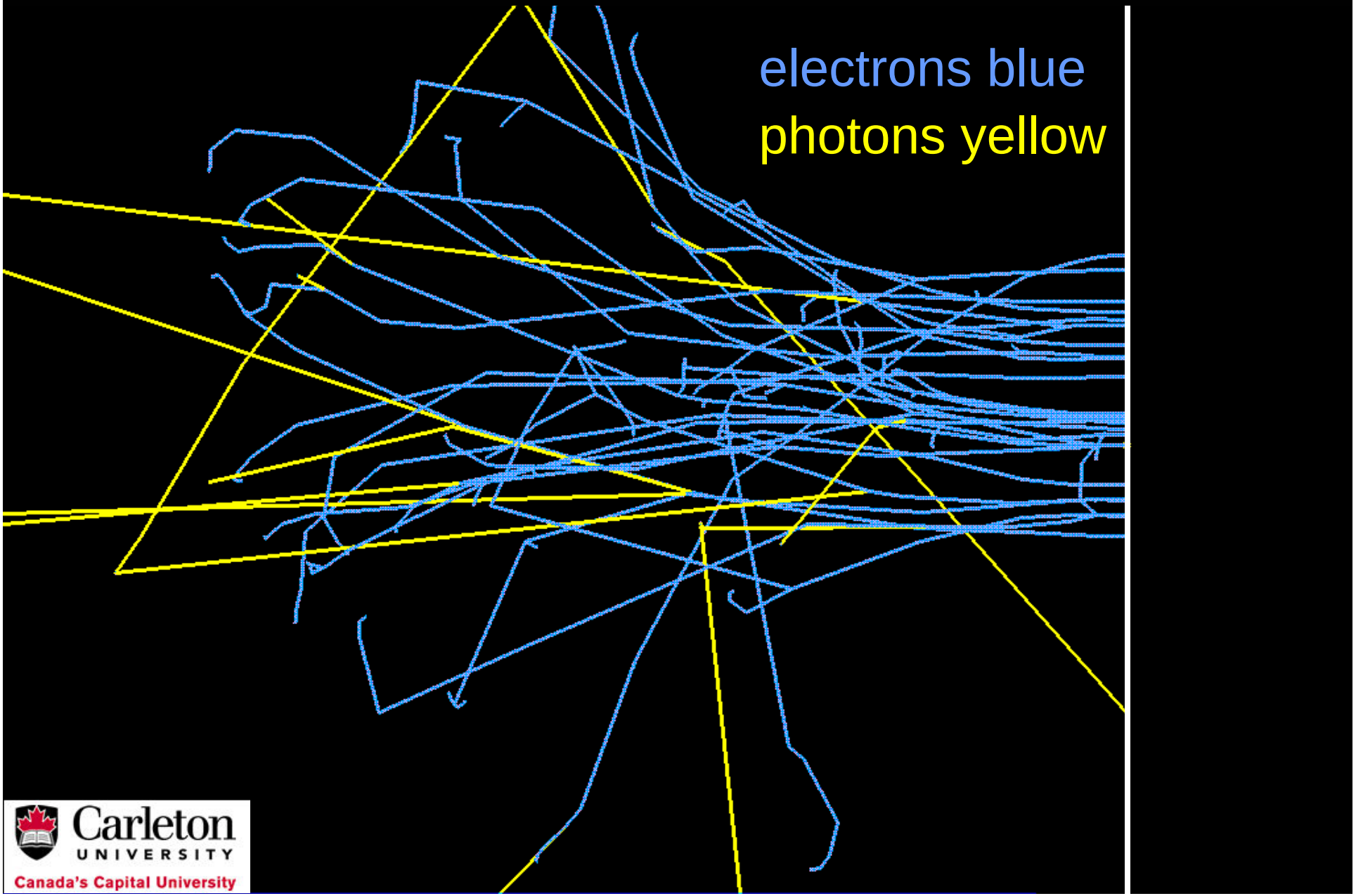
10 MeV electrons on water from right



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Simple photon simulation

- say: $\Sigma_{total} = \Sigma_{compton} + \Sigma_{pair}$ cm^{-1}

- select 2 random numbers R1, R2
  - uniform between 0 and 1
  - whole careers devoted to doing this
  - cycle length now $10^{>40}$

Photon transport (cont)

How far does photon go before interacting?

$$X = -\ln(R1) \; / \; \Sigma_{total} \quad cm$$

is exponentially distributed $[0,\infty)$

with a mean of $1/\Sigma_{total}$

Photon transport (cont)

After going x, what interaction occurs?

$$\text{if } R2 < \frac{\Sigma_{compton}}{\Sigma_{total}}$$

then a compton scatter occurs

otherwise
a pair production event occurs

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How is simulation used?

- score whatever data wanted
  - average distance to interaction
  - how many of each type
  - energy deposited by each type
  - etc
- more useful in complex cases

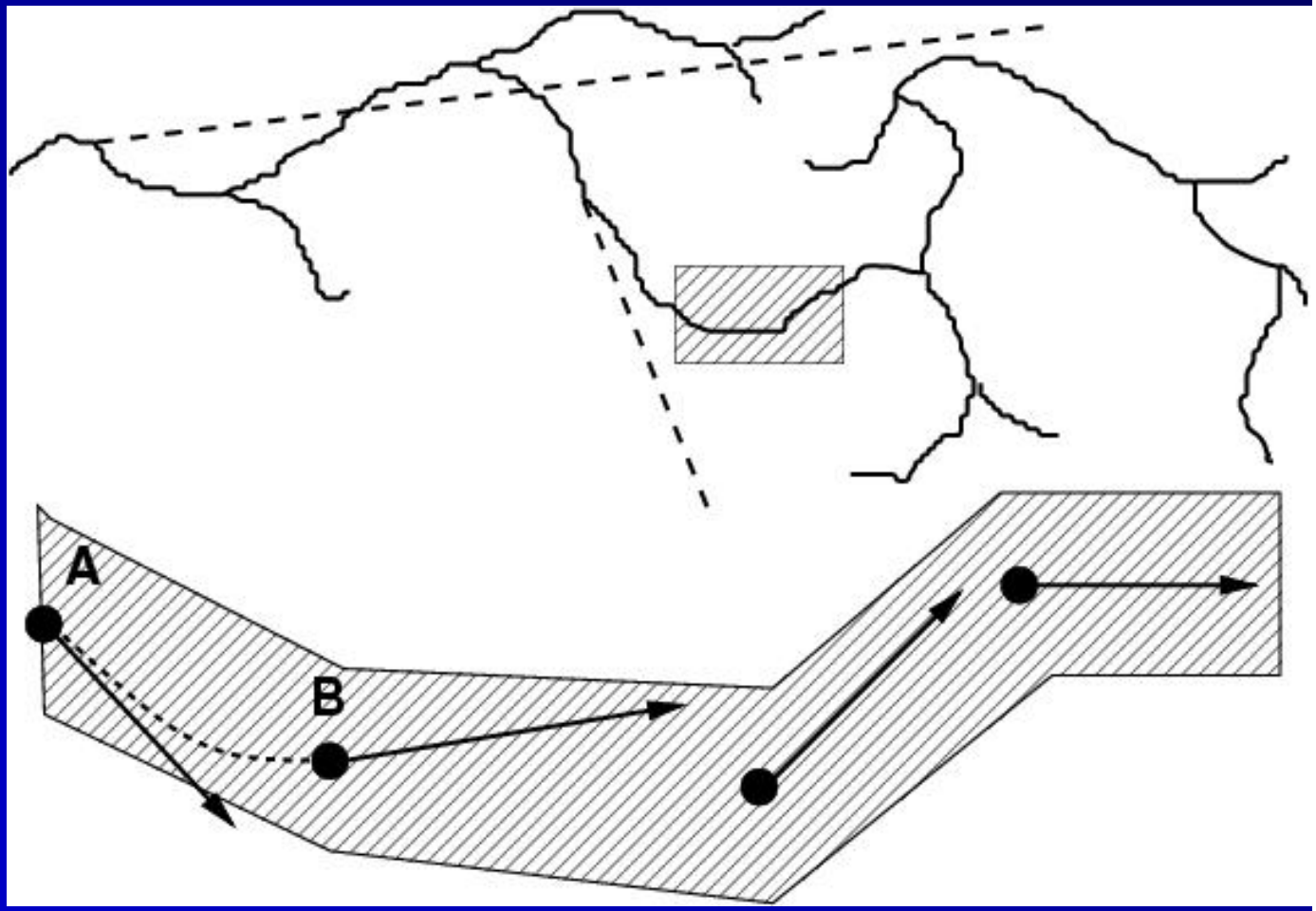
Condensed history technique for e- transport

- as electrons slow, they have many interactions
- Berger's grouping into condensed history steps made Monte Carlo transport of electrons feasible.
  - individual scattering events grouped via multiple-scattering theories
  - low-energy-loss events grouped into restricted stopping powers
- increases efficiency by decreasing time,T, (a lot)
- modern transport mechanics algorithms are very sophisticated in order to maximize step size while maintaining accuracy (to gain speed).

e- transport is much more complex

hard collisions
create
secondaries
eg δ-rays / brem

soft collisions
-grouped
-multiple scatter
-restricted
energy loss



condensed history technique: group many individual interactions into steps

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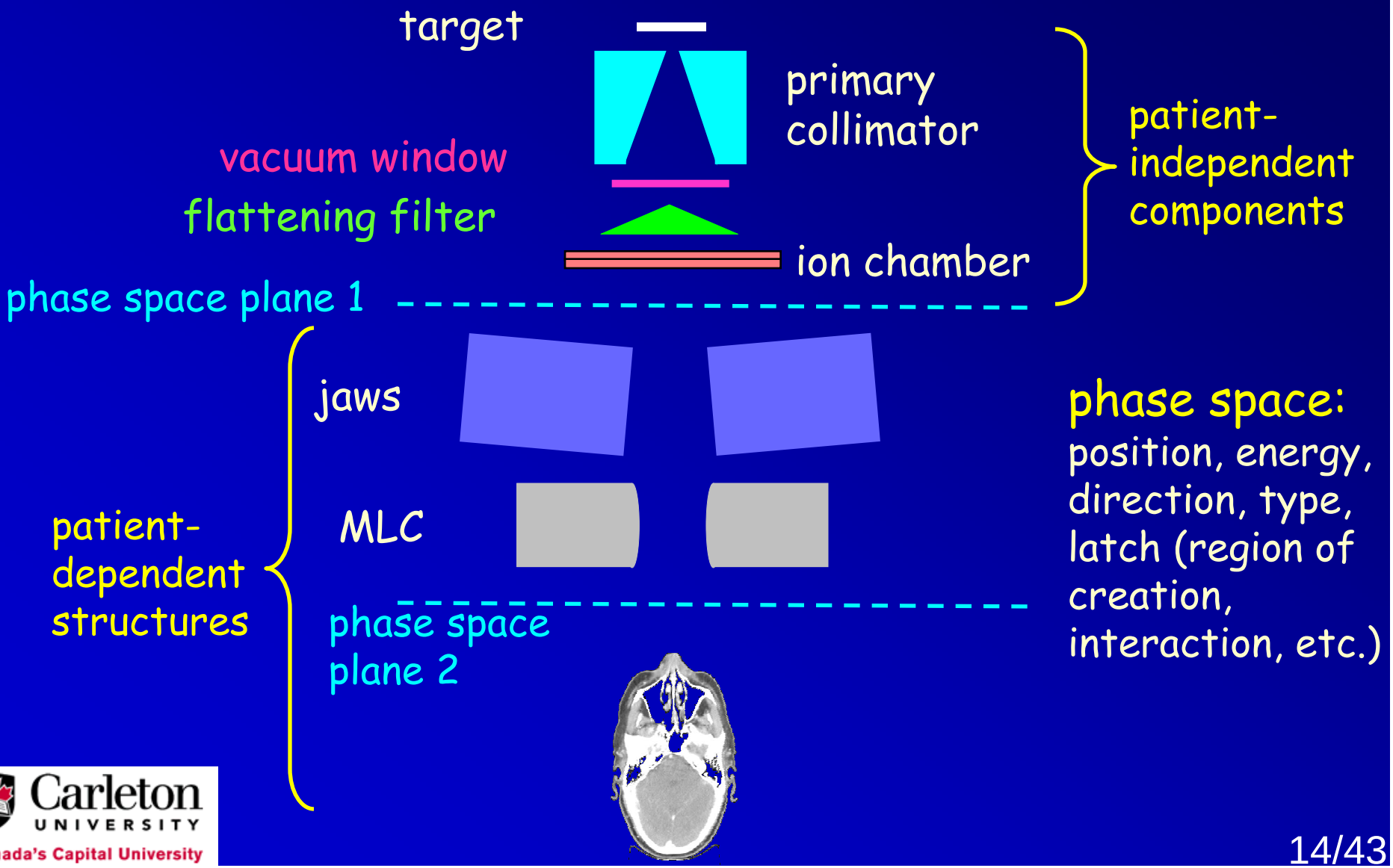
Overview of the entire process



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How do we get calculational efficiency?

- the efficiency of a calculation is given by $\epsilon = \frac{1}{s^2 T}$
  - s^2 is an estimate of the variance (σ^2) on a quantity of interest (discussed later)
  - T is the CPU time for the calculation

$$s^2 \propto \frac{1}{N} \quad T \propto N \Rightarrow \epsilon \text{ is independent of } N$$

- improve the efficiency by decreasing s^2 or T

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Variance reduction techniques (VRTs)

- A VRT is a method which increases the efficiency for some quantity of interest by decreasing s^2 for a given N while not biasing the result.
  - they often increase time per history
  - VRTs may simultaneously make s^2 for some other quantity increase
    - eg pathlength shrinking will improve the efficiency for dose near the surface but decrease the efficiency for dose at depth

Variance reduction techniques

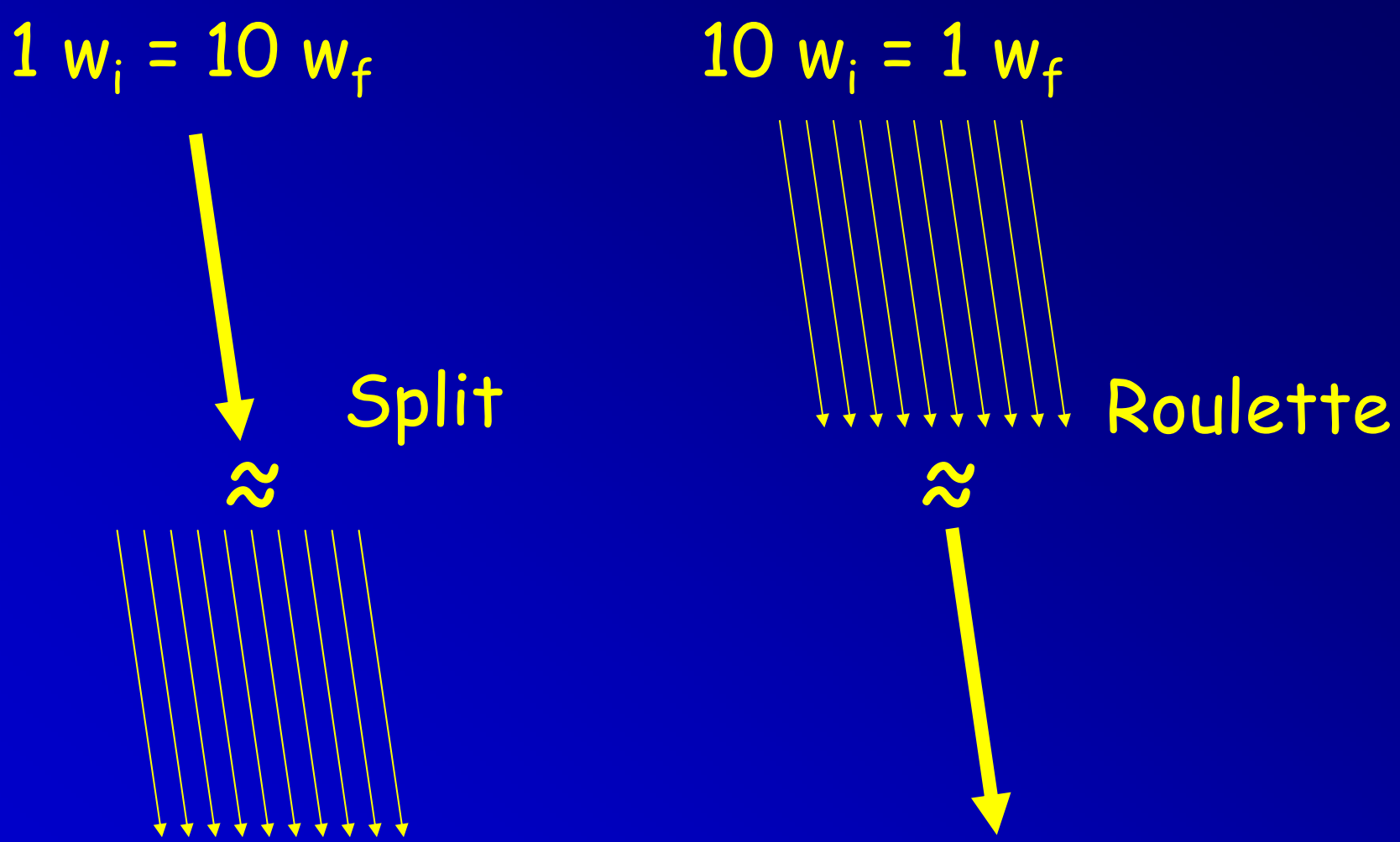
- for a review, see Sheikh-Bagheri et al's 2006 AAPM summer school chapter

  http://www.physics.carleton.ca/~drogers/pubs/papers/SB06.pdf

- examples
  - splitting (brem splitting: UBS, DBS; in-phantom)
  - Russian roulette
  - interaction forcing
  - track repetition
  - STOPS (simultaneous transport of particle sets)

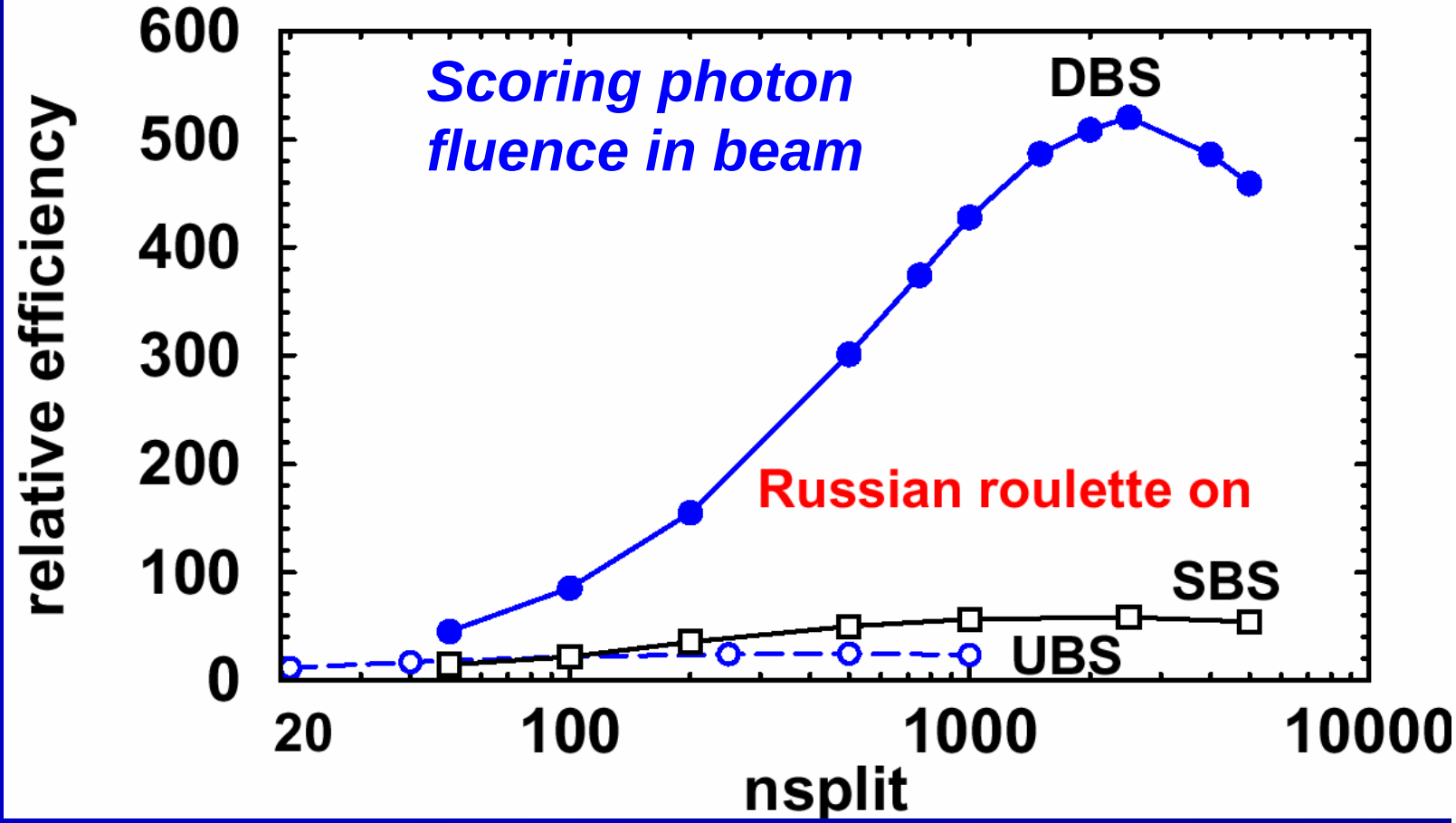
  enhanced cross sections (brem: BCSE)

Splitting, Roulette & particle weight



Directional Brem Splitting

trick is to only split when it pays off



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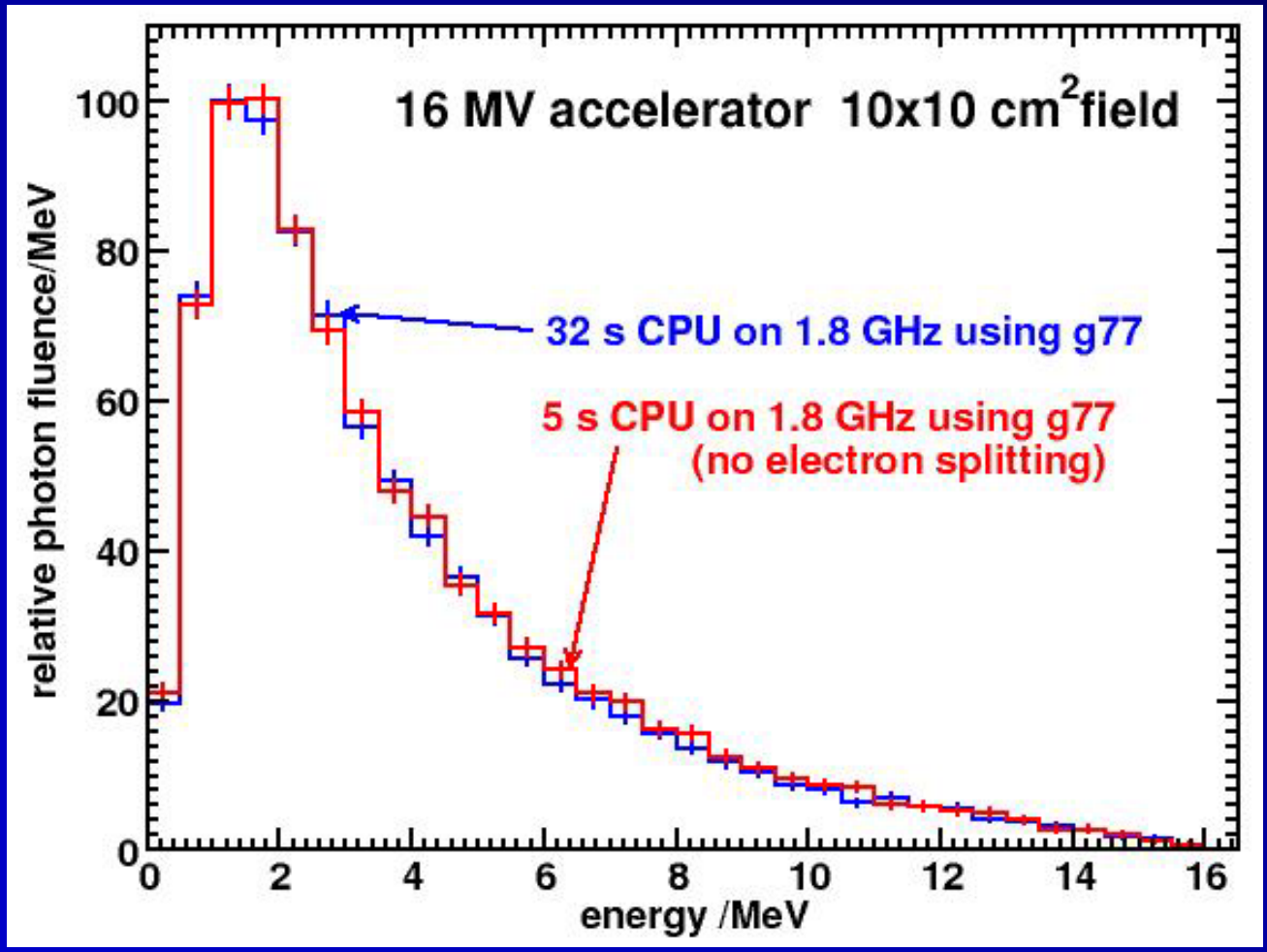
Kawrakow et al Med Phys 31 (2004) 2883

Tx head simulation using BEAMnrc with Directional Bremsstrahlung Splitting

Todays commodity PCs are 5 times faster

& BCSE => 2.6 times faster

Ali Med Phys 34(2007)2143



from Sheikh-Bagheri et al. Efficiency Improvement Techniques and Statistical Considerations AAPM Summer School 2006

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Other efficiency-improving techniques

- one can improve the efficiency by decreasing T
  - usually implies an approximation being made
    - must demonstrate the approximation does not lead to significant errors
- Examples
  - range rejection: terminate an e- history if it cannot reach any boundary
    - an approximation since no brem possible
  - higher cutoff energies: terminate tracks sooner
    - an approximation since energy deposited locally
  - both are usually OK (within reason)

Monte Carlo in radiotherapy

- Monte Carlo calculations are the basis of much of clinical dosimetry for years.
  - AAPM's dosimetry protocols
  - TG-51 (and earlier TG-21) external beam dosimetry
  - TG-43 brachytherapy dosimetry
  - TG-61 x-ray dosimetry

Monte Carlo transport: major general purpose codes

- Berger 1963/ ETRAN/ CYLTRAN/ ITS/ MCNP
- EGS3 1978/ EGS4/ PRESTA/ EGSnrc
- MCPT (photon only – brachytherapy)
- PENELOPE 1995
- GEANT3/GEANT4

- BEAMnrc for modelling accelerators

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Commercial codes available/under development

- PEREGRINE (North American Scientific/NOMOS)
  - developed by Livermore National Lab
  - photon beams only
  - modified EGS4 electron transport
  - beam modelling based on source models and BEAM code simulations of accelerators
  - multiple processors for speed

Commercial codes available/under development (cont)

- VMC/XVMC/VMC++
  - developed by Kawrakow and Fippel
  - new code, multiple variance reduction techniques
  - various approaches to accelerator beam models
  - VMC++ commercially available for electrons (Nucletron)
    - VMC++ or XVMC for photon beams is in pipeline with
      - Varian
      - BrainLab
      - CMS
      - Elekta
      - Nucletron

Commercial codes available/under development (cont)

- MMC - Macro Monte Carlo
  - developed by Neuenswander et al
  - uses pre-calculated distributions and runs a MC simulation based on the "kugels".
  - commercialized by Varian

Summary of ICCR timing/accuracy benchmarks

Timing: 6 MV 10x10 cm^2, 5 mm^3 voxels, 2% uncertainty > $D_{max}/2$

Accuracy: 18 MV, 1.5x1.5 cm^2, 5x5x2 mm^3 voxels(H_2O,Al,lung slabs)

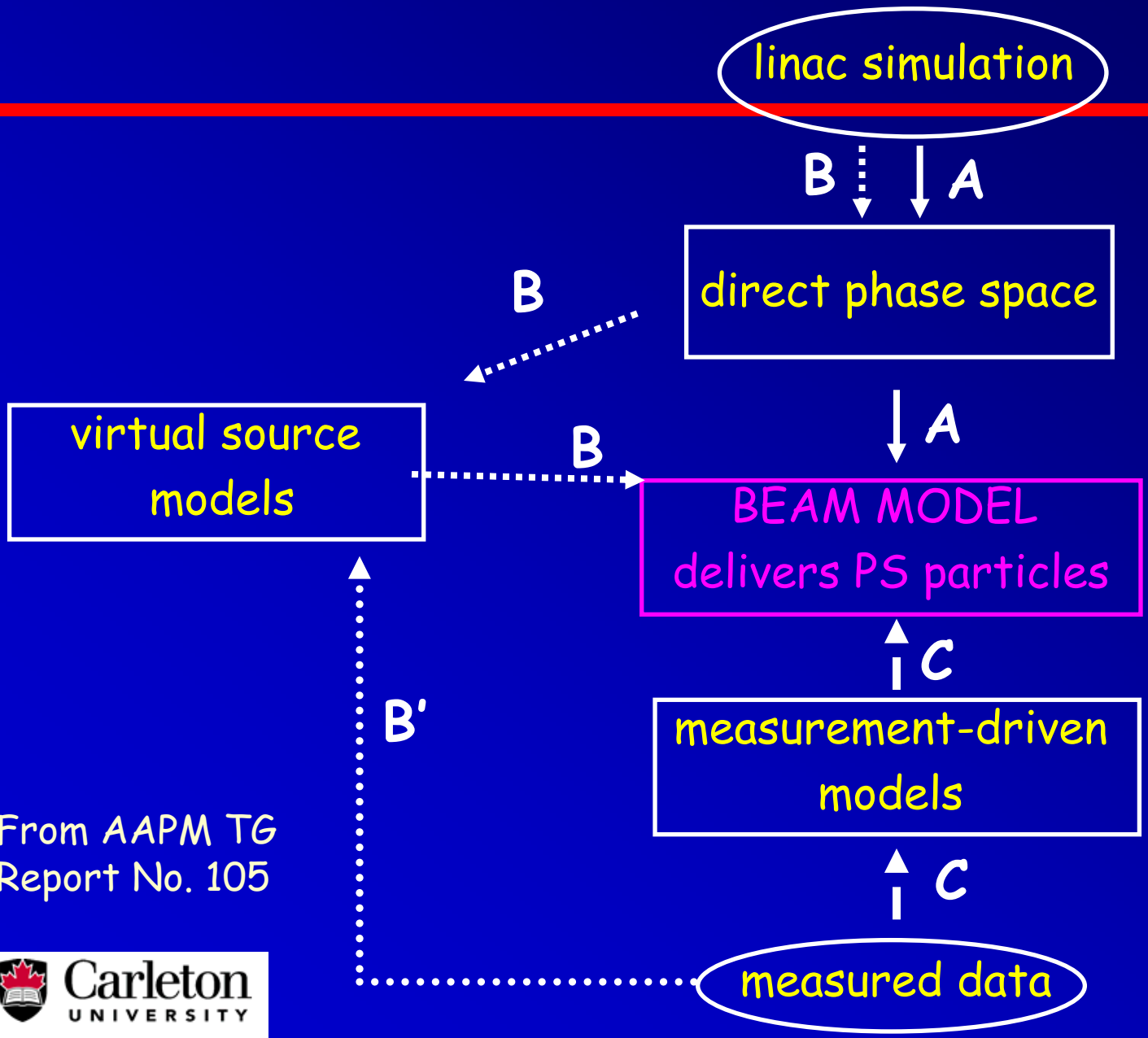
Monte Carlo code	Time estimate (min) P IV 3GHz	% mean difference relative to ESG4/PRESTA/DOSXYZ
ESG4/PRESTA/DOSXYZ	43	0, benchmark calculation
VMC++	0.9	±1
XVMC	1.1[a]	±1
MCDOSE (modified ESG4/PRESTA)	1.6	±1
MCV (modified ESG4/PRESTA)	22	±1
DPM (modified DPM)	7.3[b]	±1
MCNPX	60[c]	Maximum difference of 8% at Al/lung interface (on average ±1% agreement)
PEREGRINE	43[d]	±1
GEANT4 (4.6.1)	193[e]	±1 for homogeneous water and water/air interfaces

[abcde]footnotes are longer than table in TG105!

Beam models

- a beam model, in this context, is any algorithm that delivers the location, direction and energy of particles to the patient dose-calculating algorithm.
- one type of beam model is a direct MC simulation of the accelerator head, but we refer to it as a beam simulation for clarity
- beam simulations can be done accurately if all the parameters are known - but they often are not

possible ways to specify a beam model



From AAPM TG Report No. 105

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Sources of statistical uncertainty

Two sources of uncertainty:

-treatment head simulation (latent uncertainty – term coined by Sempau) and

-patient simulation

One cannot improve the dose uncertainty in phantom past the finite, latent uncertainty associated with the phase space.

Latent variance and beam models

-phase space always has a latent variance

-virtual source models will also be subject to this latent variance, but if properly constructed the variance will be much reduced

-measurement driven beam models will not be subject to this latent variance but may suffer from other systematic uncertainties

Dose prescriptions & statistics

-MC-based dose prescriptions should be volume-based (e.g. to the PTV)

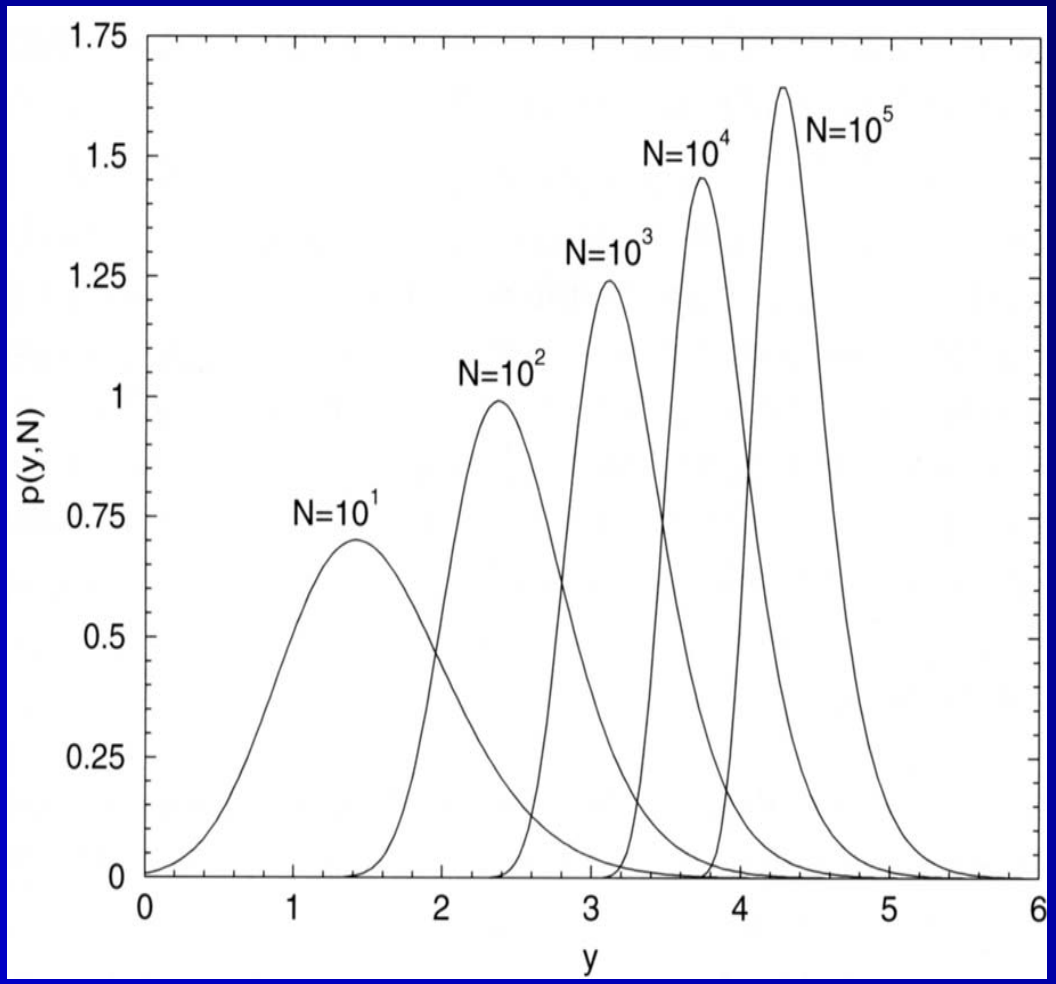
- doses should not be prescribed to the max. or min. dose points

In a region of uniform dose (e.g. the PTV), MC-calculated doses fluctuate about the mean dose

- the statistical outliers (max. or min. dose points) can deviate from mean dose by many standard deviations

Statistical uncertainties: outliers

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



Kawrakow, PMB: 47, 3087 (2002)

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

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Statistical uncertainties: implications

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 are more reliable

How do we calculate statistical uncertainties?

Batch Method: To estimate the uncertainty of a scored quantity x (eg dose), do the calculation in n batches

$$s_{\overline{x}} = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \overline{x})^2}{n(n-1)}}$$

Problem: uncertainty is uncertain

n is number of batches, x_i is estimate for i-th batch.

History by history method: N is number of independent histories and x_i is estimate for i-th history, not batch.

$$s_{\overline{x}} = \sqrt{\frac{1}{N-1}\left[\frac{\sum_{i=1}^{N} x_i^2}{N} - \left(\frac{\sum_{i=1}^{N} x_i}{N}\right)^2\right]}$$

Much smaller uncertainty on the uncertainty.

see Walters et al Med Phys 29 (2002) 2745

Dose to water vs dose to medium

Pro D_w

- historical experience is D_w
- dosimetry protocols are based on D_w
- tumour cells in a medium are more water-like than medium-like (eg in bone)

Pro D_m

- D_m is the natural quantity scored and in many cases is expected to be clinically more relevant
- D_m to D_w conversion may introduce uncertainty
- differences are small for tissue like materials
- complex when organ motion included

TG105 recommends a TPS be able to deliver both

Converting D_m to D_w

Conversion can be accomplished using Bragg-Gray formalism

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

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

Unrestricted water-to-medium mass collision stopping power averaged over the energy spectrum of electrons at the pt. of interest

Can be applied either as post-processing step or as multiplicative factor to the energy loss on each step (restricted st. power)

TG105 recommends TPS clearly state how done

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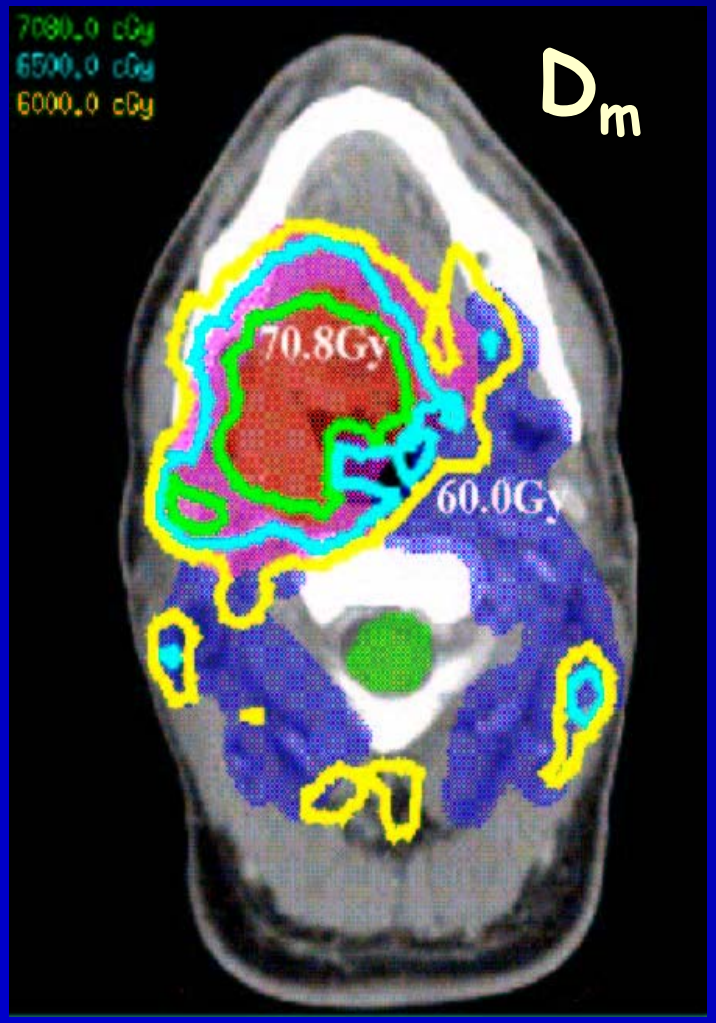
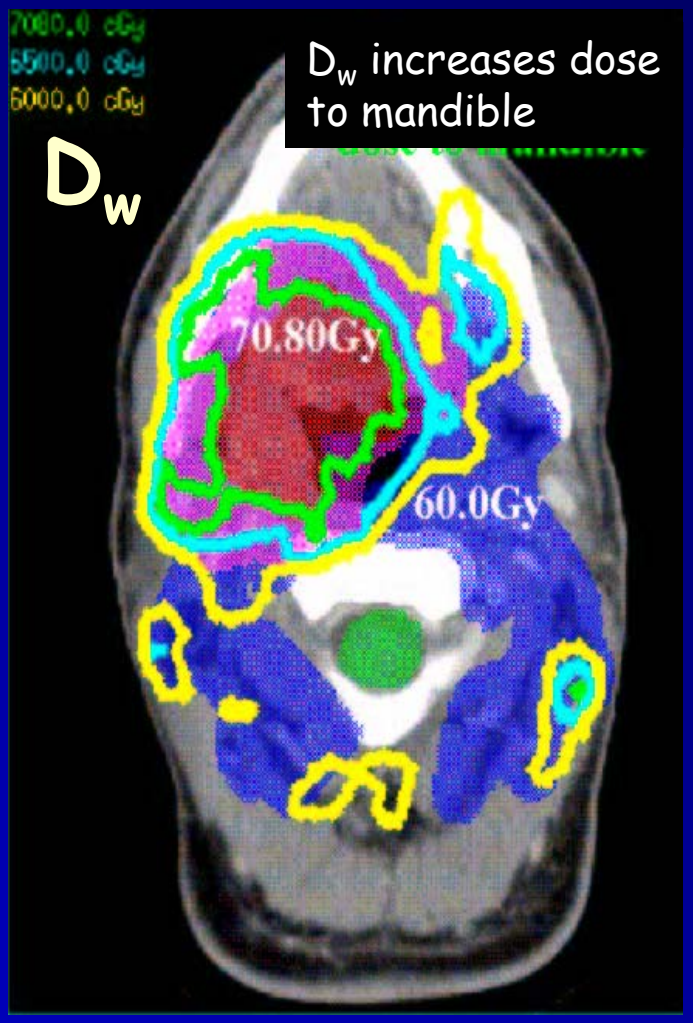
Clinical Examples: D_w and D_m





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

TG105: summary of recommendations

Treatment Head Simulation:

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

(b) If beam model is based on direct PS simulation, latent variance in the model should be estimated by vendor and 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 specification to maximum or minimum dose voxels

TG105: summary of recommendations

Patient Simulation:
VRTs and EETs: Users should understand influence on dose accuracy of VRTs and EETs (effic. enhanc. tech.).
Vendors should provide
- documentation on these methods & on their influence,
- 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

TG105: summary of recommendations

Patient Simulation:

Dose to water and dose to medium: Vendors should:

(a) state explicitly to which material dose is reported;

(b) allow for conversion between D_w and D_m

Experimental Verification:

(a)in addition to standard dose algorithm commissioning tests, verification should include testing in complex situations to verify the expected improved accuracy with the MC method;

(b) detector perturbations need to be carefully assessed particularly under conditions of electronic disequilibrium

(c) measurement uncertainties should be understood and estimated in the verification process

Conclusions

- 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

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