Clinical Implementation and Application of Monte Carlo Methods in Photon & Electron Dose Calculation – New Issues to Consider in Clinical Practice

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Outline

- Introduction to Monte Carlo methods
- Commissioning and clinical implementation of Monte Carlo based system
- Implementation, Operational and Physics related issues
- Clinical significance of Monte Carlo based system

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Photon Monte Carlo

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What are Monte Carlo methods?

- Use probability distributions governing the individual interactions of electrons and photons to simulate the random trajectories of individual particles (Rogers and Bielajew)
- The process is simulated a number of times to obtain the average quantity

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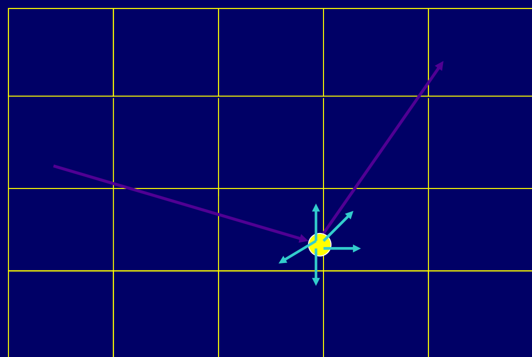
Monte Carlo transport of radiation
photon transport



Analog Transport

At each interaction Point:
- Compton
- photo-electric
- pair production

Interaction probabilities depend on energy, atomic no., density

Courtesy I.J. Chetty

Photon transport schemes

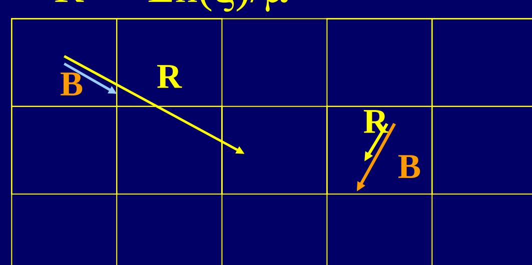
Conventional Photon Tracking

- The probability distribution function for photons interacting in a homogeneous medium is given by : $P(R) = \mu e^{-\mu R}$

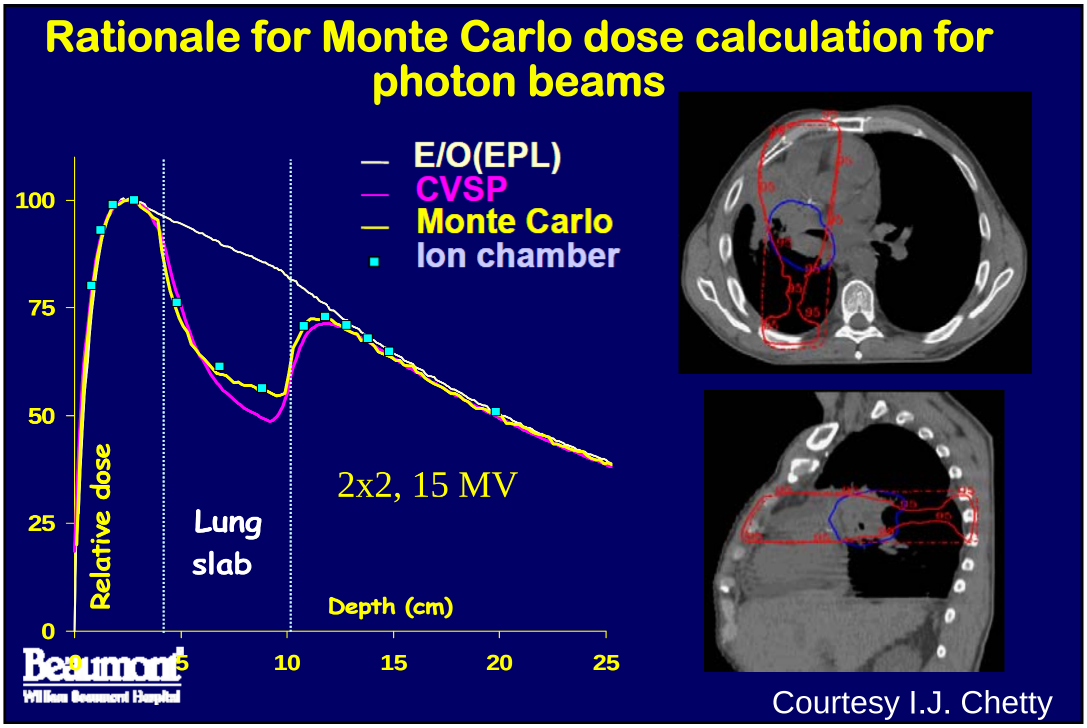
where μ is the mass attenuation coefficient, and R the distance to next collision

$$P'(R) = \int_0^R \mu e^{-\mu R} \Rightarrow R = -Ln(\xi)/\mu$$

The mean collision distance for a 2 MeV photon in water is ~ 20 cm



Courtesy I.J. Chetty



Rationale for Monte Carlo dose calculation for photon beams
E/O(EPL)
CVSP
Monte Carlo
Ion chamber
100
75
50
25
0
Relative dose
Lung slab
2x2, 15 MV
Depth (cm)
5
10
15
20
25
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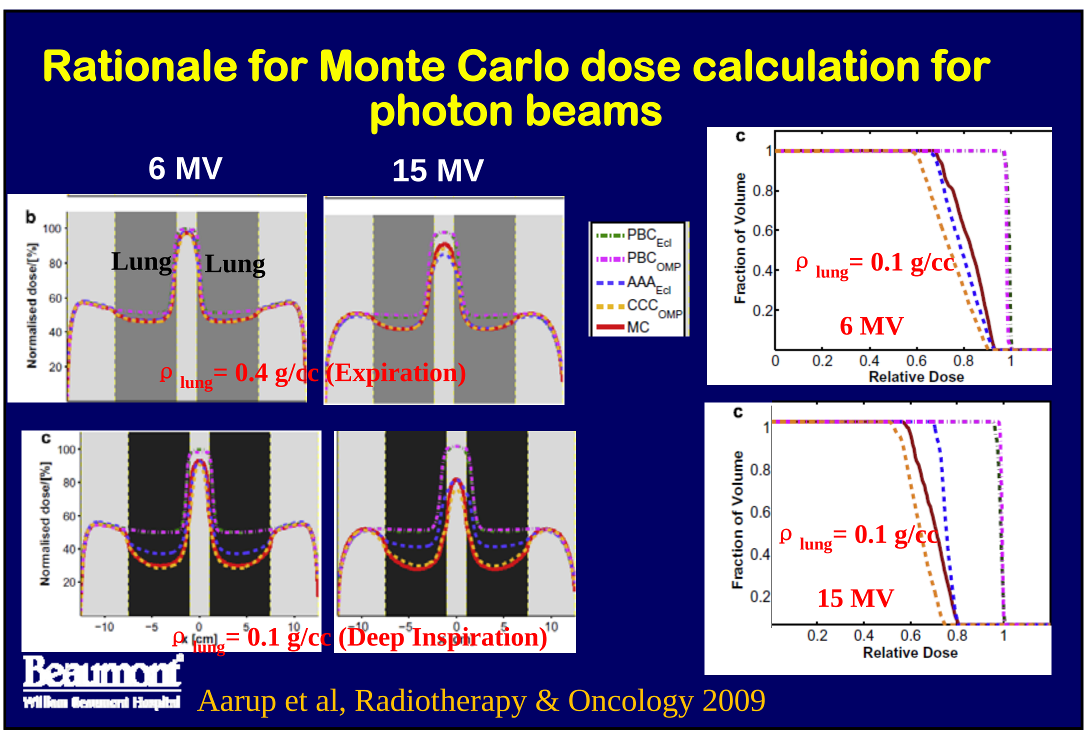
Courtesy I.J. Chetty



Rationale for Monte Carlo dose calculation for photon beams
6 MV
15 MV
Lung
Lung
Normalised dose [%]
ρ lung = 0.4 g/cc (Expiration)
ρ lung = 0.1 g/cc (Deep Inspiration)
PBC Ecl
PBC OMP
AAA Ecl
CCC OMP
MC
Fraction of Volume
Relative Dose
ρ lung = 0.1 g/cc
6 MV
ρ lung = 0.1 g/cc
15 MV
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Aarup et al, Radiotherapy & Oncology 2009

Radiotherapy specific general purpose codes

Modeling Radiotherapy beams

- BEAMnrc
- MCNP
- GEANT
- Penelope

Optimized for Patient dose calculation only

- Peregrine
- VMC/XVMC
- DPM
- MCDose

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Commercially available Monte Carlo systems

- **CMS Monaco**
  Algorithm: source model
  3D conformal, IMRT (SMLC & DMLC) and VMAT capability No wedges

- **Brainlab iPlan**
  Algorithm: source model
  3D conformal, IMRT (SMLC & DMLC) and VMAT capability No wedges

- **Accuray Multiplan**
  - Algorithm, source model
  - Radiosurgery specific

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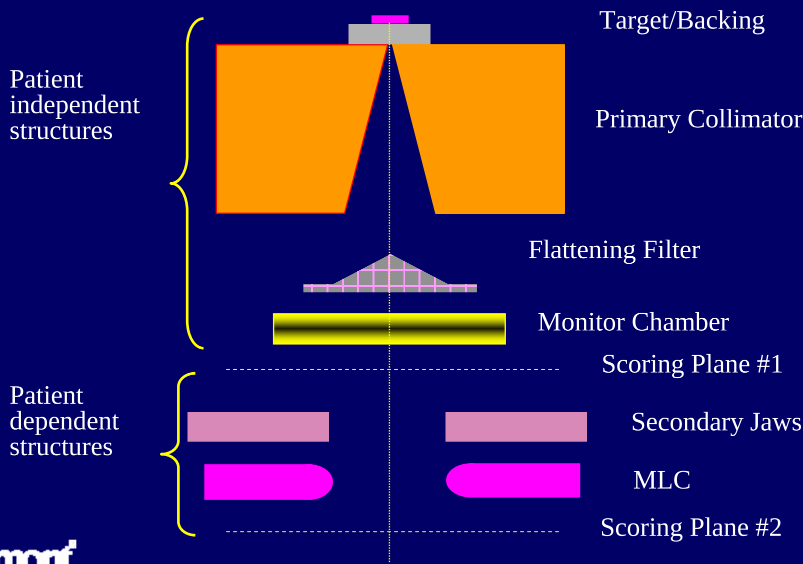
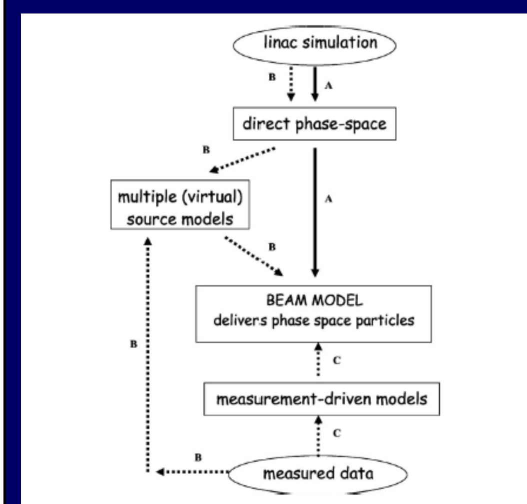
Linear accelerator beam modeling



Phase space - *x, y, z (position), u,v,w (direction),energy*

Linear Accelerator Beam Modeling: Three different approaches



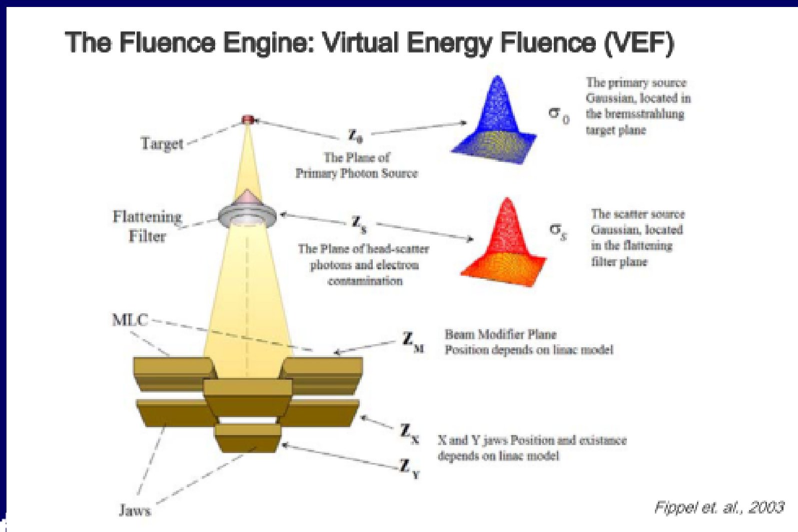
-Direct phase space simulation

-Virtual source model derived from phase space simulation

-Virtual source model derived from measurements

Chetty *et al* AAPM TG-105

Virtual Source model in Commercial TPS



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Commissioning of Monte Carlo based System

Data for beam Characterization specified by the vendor (Fraass et al, AAPM TG-53, Das et al, AAPM TG 106)

- CAX pdd & profile scans in water: square fields (1x1 to 40x40 cm^2), rectangular fields, Diagonal profile scans in water
- Output factors in water
- Absolute dose in water (linac calibration geometry)

Requires two levels of testing:

1. **Radiation output from the linear accelerator**
   - Beam model (square fields, output factors, electron contamination)
   - Beam modifying devices
2. **Dose calculation in homogeneous and heterogeneous geometries**

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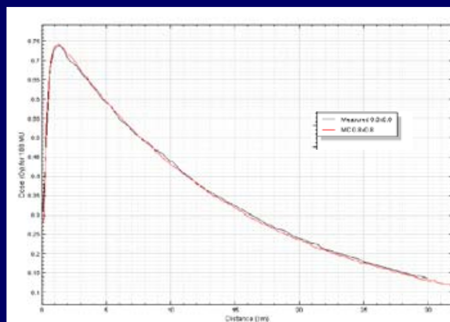
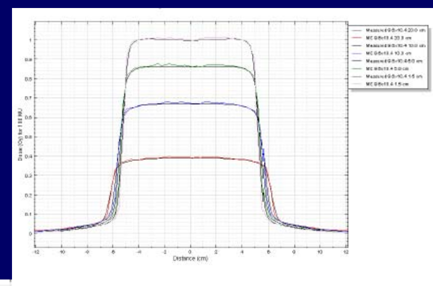
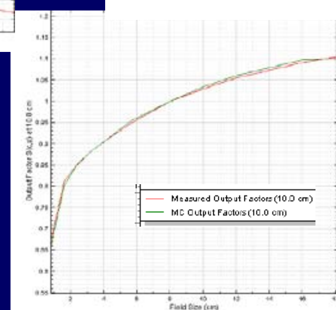
MC validation report: pdds , profiles & output factors







PDDs, and Profiles for various field sizes & depths

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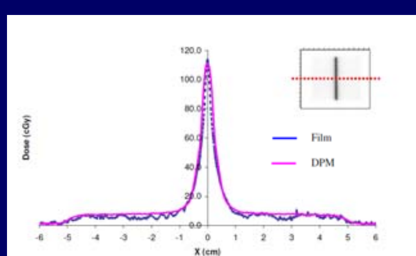
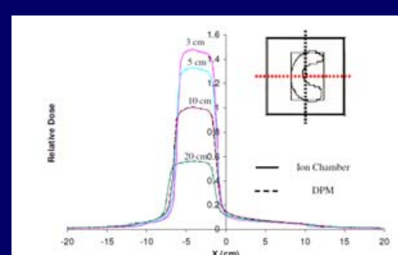
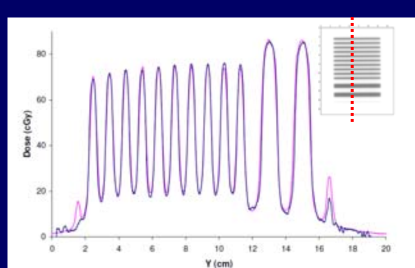
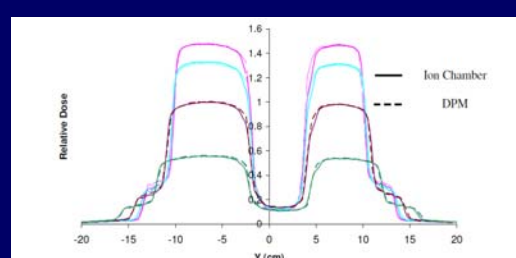
Beam model verification: beam modifiers









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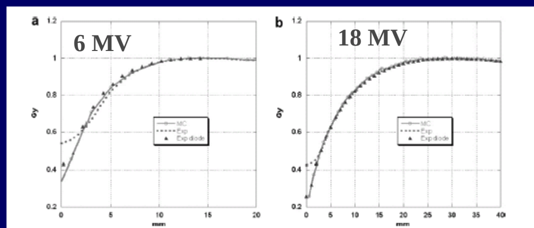
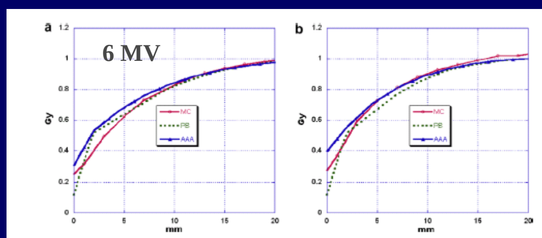
Beam model verification: build-up dose region, oblique incidence



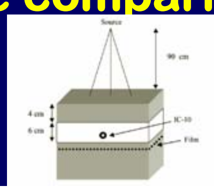


- Choice of measurement detector
- Electron contamination model

Important for breast & Head and Neck plans

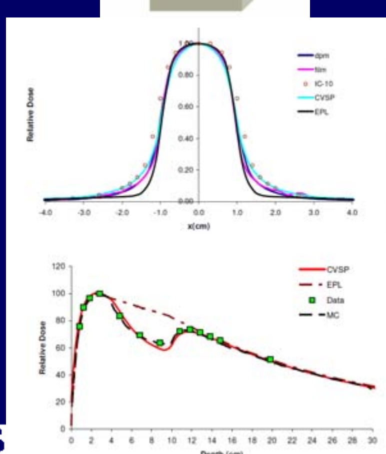
Panettieri et al, Radiotherapy Oncology, 2009

Dose comparisons in heterogeneous medium



Slab inhomogeneity phantom

Head & Neck phantom



Case #	IC placement	Measured Data (cGy)	Monte Carlo (cGy)	% difference $(\frac{IC-MC}{IC})x100$
SMLC	Inside Tissue	179.43	176.75	1.5
DMLC	Inside Tissue	181.59	183.75	-1.2
SMLC	Inside Bone	176.22	176.45	-0.2
DMLC	Inside Bone	177.4	180.55	-2.0
1	Inside Tissue	72.33	72.43	-0.1
2	Inside Tissue	73.04	72.40	0.9
3	Inside Tissue	83.09	82.19	1.1
4	Inside Tissue	57.47	58.02	-1.0
5	Inside Bone	72.22	73.68	-2.0
6	Inside Bone	82.51	83.68	-1.4
7	Inside Bone	57.64	56.50	2.0
8	Inside Tissue (bone to the left)	68.76	68.52	0.4
9	Inside Tissue (air to the left)	80.4	80.3	0.1
10	Inside Tissue (bone to the left and air at the center)	57.74	57.89	-0.3

Chetty et al, PMB, 2003
Tyagi et al, PMB, 2006

Implementation and operational issues

Issues addressed in

- **NCI report**

  Fraass *et al*, "Summary and recommendations of a National Cancer Institute workshop on issues limiting the clinical use of Monte Carlo dose calculation algorithms for megavoltage external beam radiation therapy", Med Phys 30 (12), 3206-16 (2003)

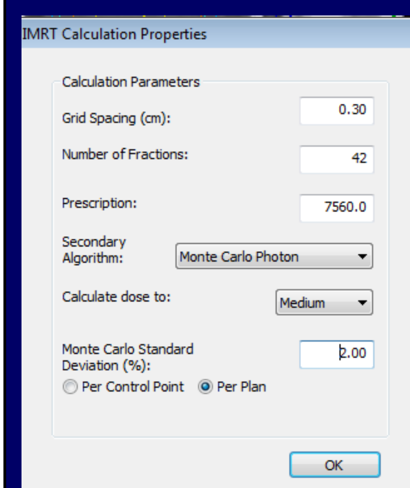
- **AAPM Task group 105**

  Chetty *et al*, "Issues associated with clinical implementation of Monte Carlo-based treatment planning: Report of the AAPM Task group No 105", Med Phys (Med. Phys. 34, 2007)

- **AAPM Summer School**

  "Integrating new technologies into the clinic: Monte Carlo and Image-Guided Radiation Therapy", AAPM Summer school 2006

Commercial Treatment Planning System



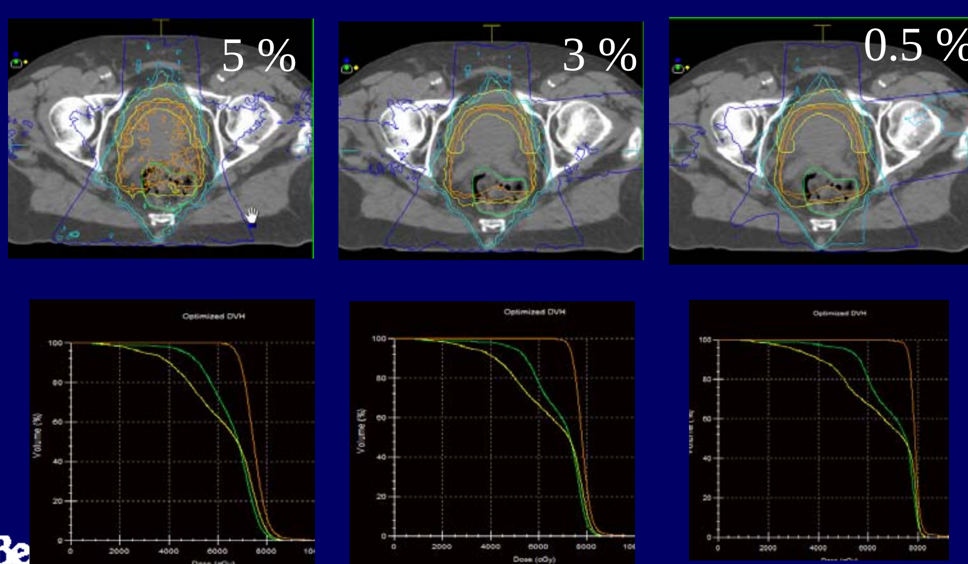
User Input
- Grid/Voxel spacing
- Uncertainty based # of Histories
- Dose reporting (Dose-to-medium vs. Dose-to-water)

Effect of statistical uncertainty

- Sources of statistical uncertainty –
  - treatment head uncertainty (concern for PS based models, not a concern for measurement based source models)
  - patient simulation uncertainty

- Commercial MC systems based on uncertainty based # of histories
  (specify % uncertainty per control point or per plan)

Effect of statistical uncertainty : IDLs & DVHs



CT-number to material conversion

- Conventional TPS algorithm are based on HU-to-material density conversion
- Particle interactions in MC simulations require knowledge of both material density and material composition for appropriate cross-section
- Medium and/or mass density mis-assignment could result in dose errors of up to 10% for 6MV and 30% for 18 MeV (Verhaegen and Devic, PMB, 2005)

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CT- number to material conversion

- Relating CT # to interaction probabilities
  (Kawrakov et al, Med Phys, 1996)
- Stoichiometric CT calibration method
  (Vanderstraeten et al, PMB 2007)
- Dual energy CT based material extraction
  (Bazalova et al, PMB 2008)

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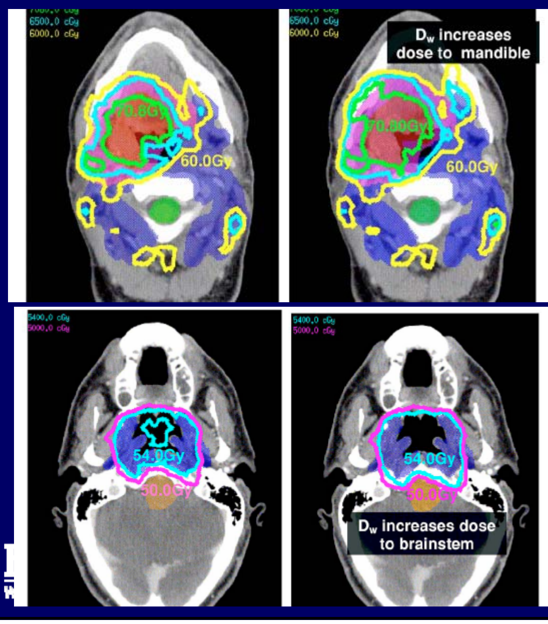
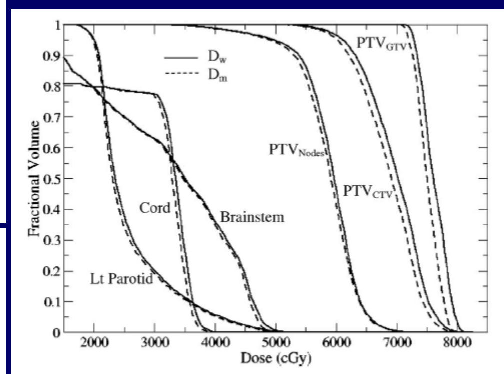
Dose-to-medium vs. Dose-to-water



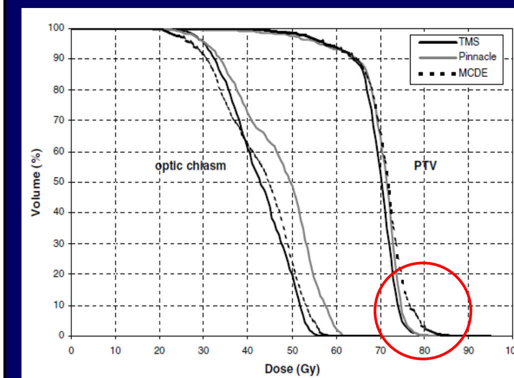


Dogan et al, PMB 2006

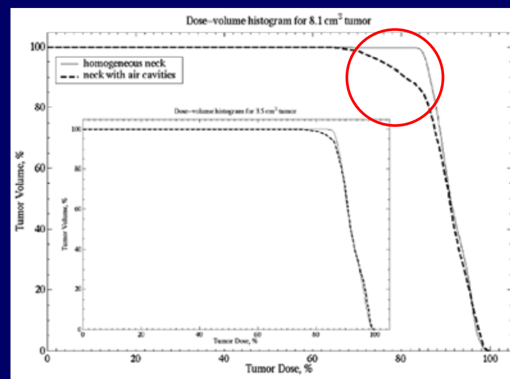
Clinical significance of a Monte Carlo based TPS

- VMAT planning for kernel based method vs. Monte Carlo in terms of planning QA and planning time
- Comparison of Kernel based methods vs. Monte Carlo for clinical sites such as breast, head and neck and lung
- Optimizing prescription based on Monte Carlo dose calculation
- TCP and NTCP or outcome modeling based on MC dose calculation engine

Head and Neck

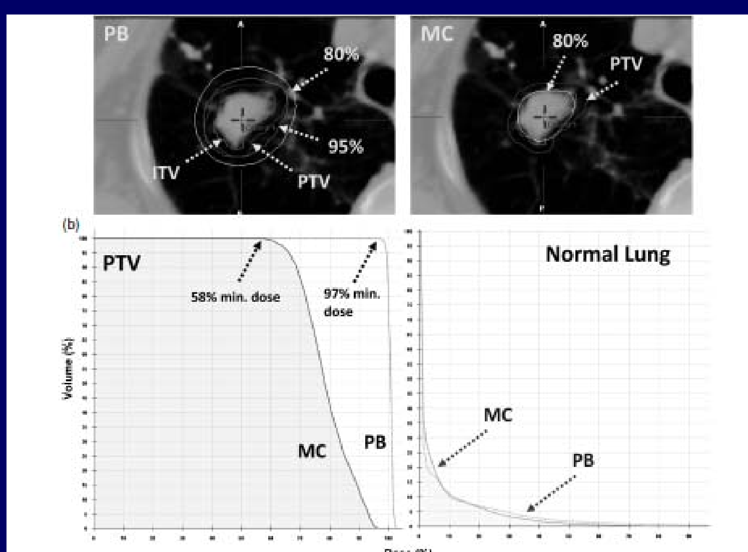


Paelinck et al, Radiotherapy & Oncology 2006



Spirodovich et al, Radiotherapy & Oncology 2006

Lung SBRT (Pencil Beam vs. Monte Carlo)



Fragoso et al PMB 2010

Lung SBRT: Effect of Tumor size & location

		Peripheral Tumors	Central Tumors	
PTV				D95
	<3 cm	21 ± 8 (6–33)	–	
	3–5 cm	17 ± 6 (6–30)	12 ± 5 (7–22)	
	>5 cm	10 ± 4 (7–18)	8 ± 4 (3–18)	
GTV				
	<3 cm	14 ± 6 (2–25)	–	
	3–5 cm	12 ± 6 (4–25)	8 ± 3 (6–16)	
	>5 cm	8 ± 2 (4–10)	7 ± 3 (3–14)	
PTV				D99
	<3 cm	21 ± 8 (7–35)	–	
	3–5 cm	18 ± 7 (5–33)	10 ± 7 (3–25)	
	>5 cm	11 ± 4 (6–18)	8 ± 5 (1–19)	
GTV				
	<3 cm	15 ± 7 (1–27)	-	
	3–5 cm	13 ± 7 (4–25)	9 ± 3 (6–15)	
	>5 cm	8 ± 2 (6–10)	6 ± 4 (0–13)	
PTV				Dmean
	<3 cm	17 ± 7 (3–28)	–	
	3–5 cm	13 ± 5 (6–23)	12 ± 3 (7–16)	
	>5 cm	8 ± 3 (5–13)	8 ± 4 (3–15)	
GTV				
	<3 cm	14 ± 5 (2–22)	–	
	3–5 cm	11 ± 4 (5–19)	10 ± 3 (6–14)	
	>5 cm	7 ± 2 (4–11)	7 ± 3 (3–14)	

Van der Voort van Zyp et al
Radiotherapy & Oncology
2010

Optimizing prescription for lung SBRT

Peripheral Tumors	**EPL dose = 3x20 Gy**
< 3 cm	3x16 Gy
3-5 cm	3x17 Gy
> 5 cm	3x18 Gy
Central Tumors (close to esophegus)	**EPL dose = 6x8 Gy**
3-5 cm	6x7 Gy
> 5 cm	6x7.3 Gy
Central Tumors	**EPL dose =5x12 Gy**
3-5 cm	5x10.4 Gy
> 5 cm	5x11 Gy

Van der Voort van Zyp et al, Radiotherapy & Oncology 2010