Commissioning and clinical implementation of Monte Carlo treatment planning system for electron beams

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Educational Objectives

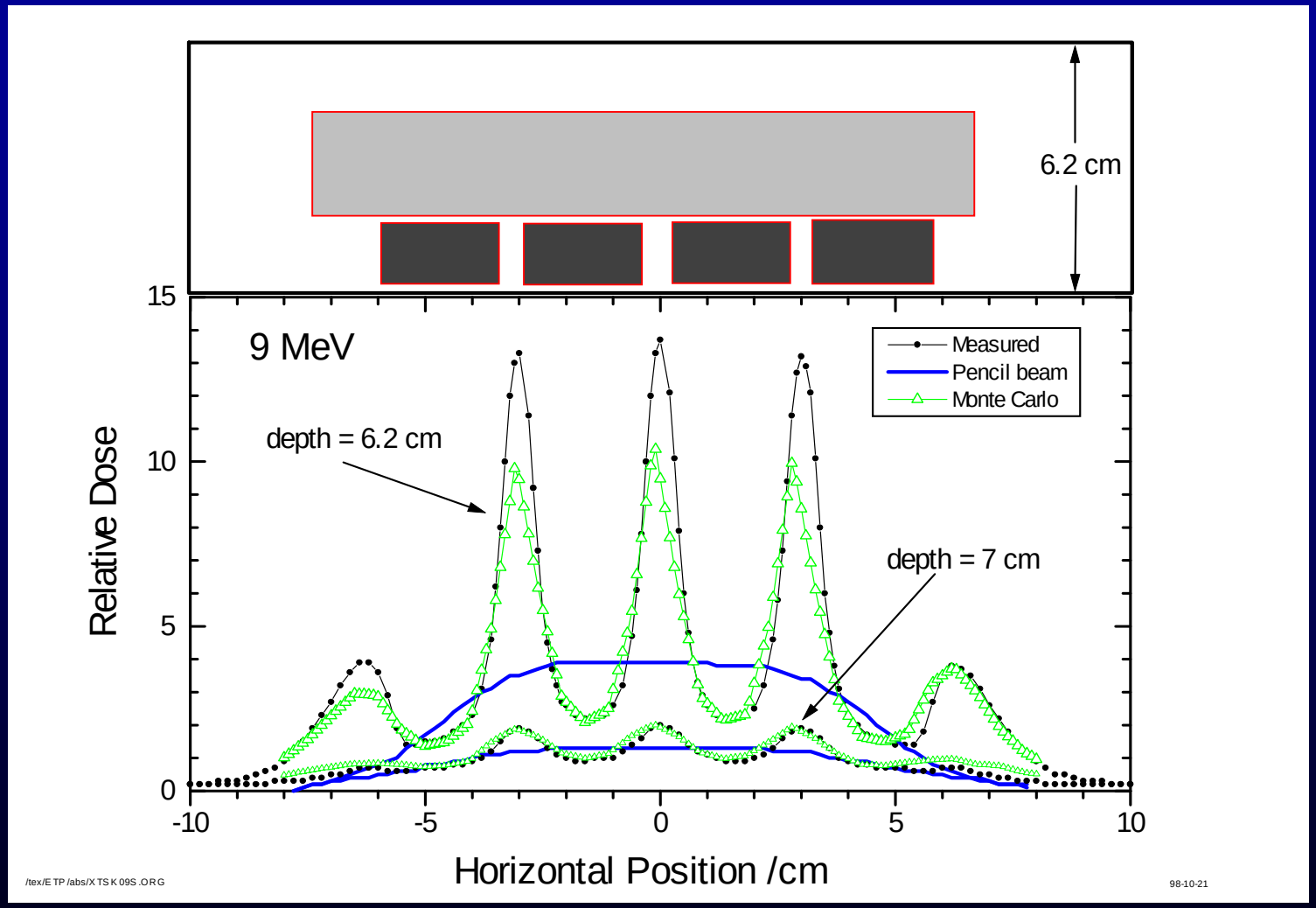
- Appreciate the need for MC based treatment planning systems
- Understand the effect of different types of heterogeneities (geometry and density) on dose distribution
- Understand how to set user control parameters in the TPS to achieve optimum results (minimum statistical noise, minimum distortion of real dose distribution)
- Learn and understand differences between water tank and real patient anatomy based monitor unit values

Rationale for Monte Carlo dose calculation for electron beams

- Difficulties of commercial pencil beam based algorithms
  - Monitor unit calculations for arbitrary SSD values – large errors*
  - Dose distribution in inhomogeneous media has large errors for complex geometries

** can be circumvented by entering separate virtual machines for each SSD – labour consuming*

Rationale for Monte Carlo dose calculation for electron beams



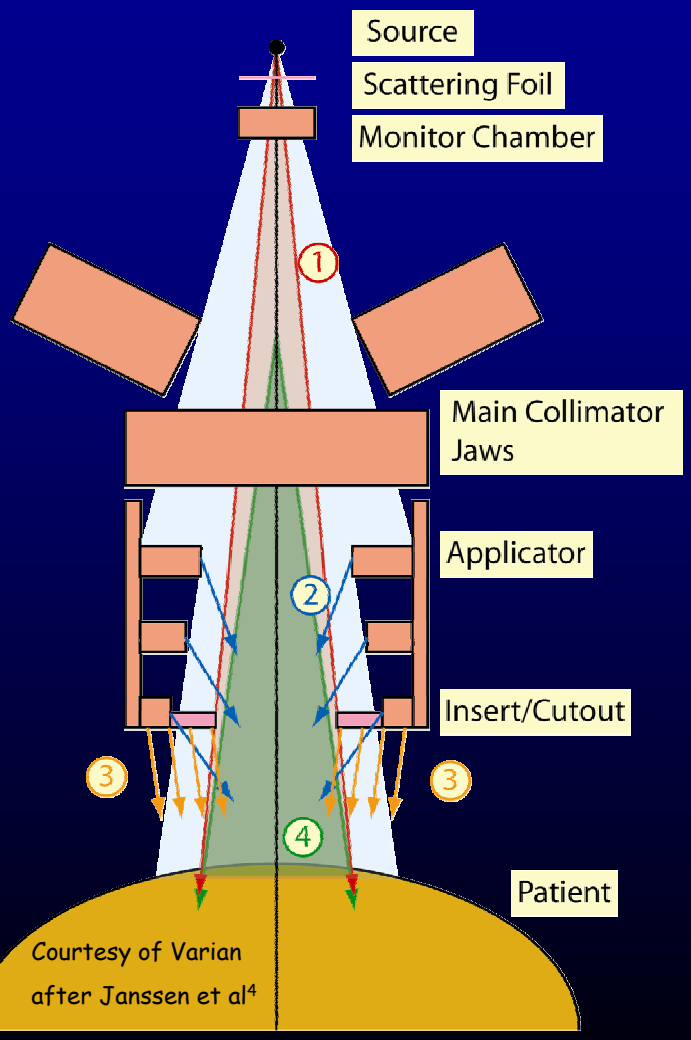
Ding, G. X., et al, Int. J. Rad. Onc. Biol Phys. (2005) 63:622-633

Commercial implementations

- MDS Nordion 2001*
  - First commercial Monte Carlo treatment planning for electron beams
  - Implementation of Kawrakow's VMC++ Monte Carlo dose calculation algorithm (2000)
  - Handles electron beams from all clinical linacs
- Varian Eclipse eMC 2004
  - Based on Neuenschwander's MMC dose calculation algorithm (1992)
  - Handles electron beams from Varian linacs only

**presently Nucletron*

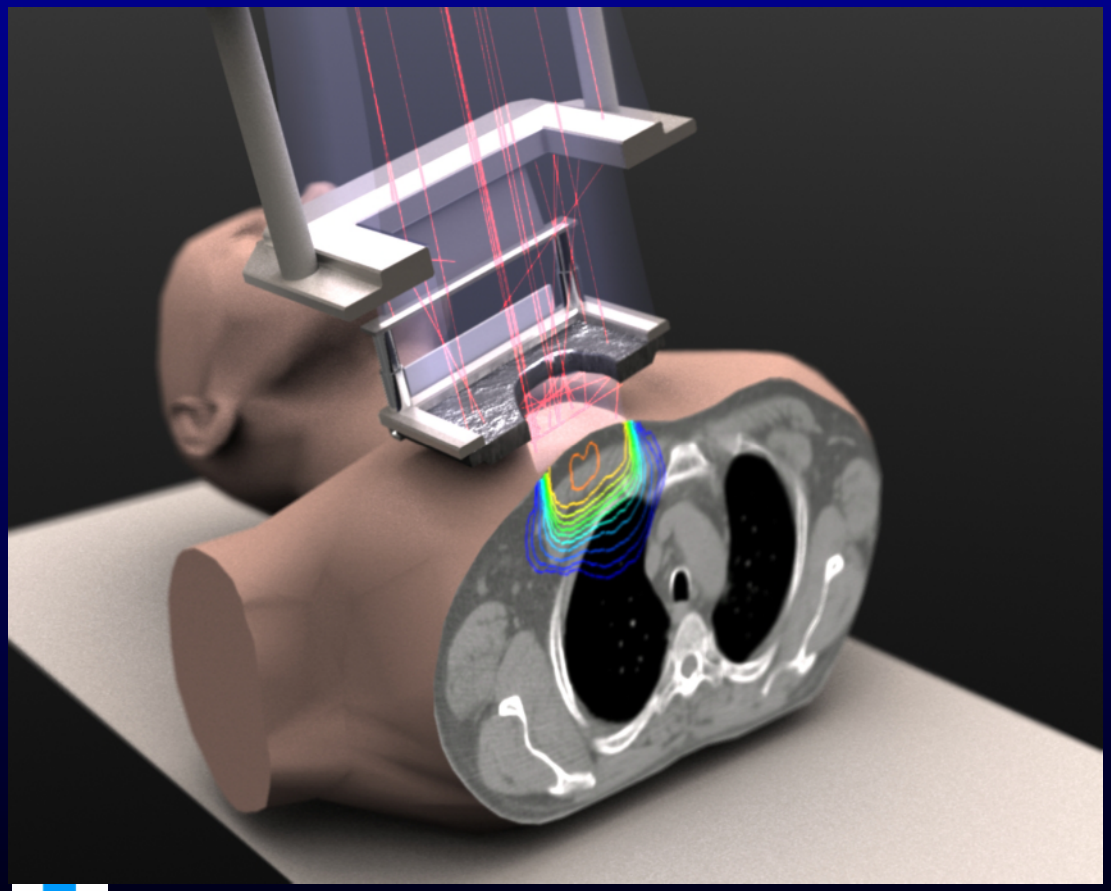
Monte Carlo calculations in commercial TPS



Courtesy of Varian after Janssen et al[4]

- Divide the beam into treatment-independent and treatment-dependent components
- Simulate treatment-independent components
  - characterize phase space distribution with a beam model
- Simulate transport through the patient anatomy – dose distribution

Description of Nucletron Electron Monte Carlo DCM



Fixed applicator with optional, arbitrary inserts

Calculates absolute dose per monitor unit (Gy/MU)

510(k) clearance (June 2002)

User input data Nucletron TPS

Treatment unit specifications:

- Position and thickness of jaw collimators and MLC

- For each applicator scraper layer:
  - Thickness
  - Position
  - Shape (perimeter *and edge*)
  - Composition

- For inserts:
  - Thickness
  - Shape
  - Composition

User input data Nucletron TPS *cont*

Dosimetric data for beam characterization

- Without applicators:
  - X and Y in-air profiles (8x8, 8x20, 8x35, 35x35, SDD = 70 & 90 cm)
  - Central axis Depth Dose in water for various field sizes
- With applicators:
  - Central axis depth dose and profiles in water
  - Absolute dose at the calibration point

Dosimetric data for verification

- Central axis depth doses and profiles for various field sizes

Varian Macro Monte Carlo

- PDF table look-up for "kugels" or spheres instead of analytical and numerical calculation
- CT images pre-processes
  - Homogenous areas → large spheres
  - In/near heterogeneous areas → small spheres
- Database with probable outcome for every combination of:
  - 30 incident energy values (0.2-25 MeV)
  - 5 materials (air, lung, water, Lucite and solid bone)
  - 5 sphere sizes (0.5-3.0 mm)

EGSnrc used to create beam data

User input data - Varian eMC

Open field measurements (no applicator)

- Depth-dose curves in water at the source-to-phantom distance (SPD) = 100 cm
- Absolute dose, expressed in [cGy/MU], at a specified point on the depth dose curve
- Profile in air at source-detector distance,

SDD = 95 cm for the wide open field without an applicator, e.g. 40x40 cm^2.

User input Varian eMC *cont.*

For each energy/applicator combination:

- PDD in water at SSD = 100 cm
- Absolute dose, expressed in [cGy/MU], at a specified point on the depth dose curve

No head geometry details required, since at this time Eclipse works only for Varian linac configuration

Clinical implementation of treatment planning software

- Beam data acquisition and fitting
- Software commissioning tests
- Clinical implementation
  - procedures for clinical use
  - possible restrictions
  - staff training

A physicist responsible for TPS implementation should have a thorough understanding of how the system works.

User controlled calculation parameters

- Nucletron
  - User can define number of histories used in calculation (in terms of particle #/cm^2)
- Varian
  - User can define:
    - Maximum number of histories used in calculation >/=0
    - statistical uncertainty (within the high dose volume)
    - Calculation grid size (voxel size)
    - Smoothing method and level
    - Random number generator seed

Software commissioning tests: goals

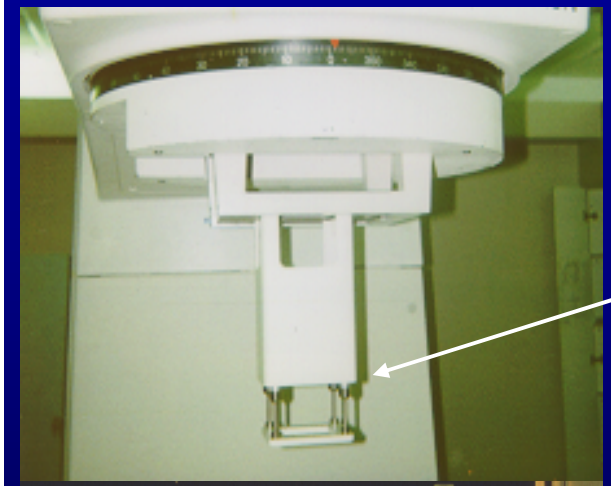
- Setting user control parameters in the TPS to achieve optimum results (minimum statistical noise, accuracy vs. speed of calculations)
  - Number of histories
  - Voxel size
  - Smoothing
- Understand differences between water tank and real patient anatomy based monitor unit values

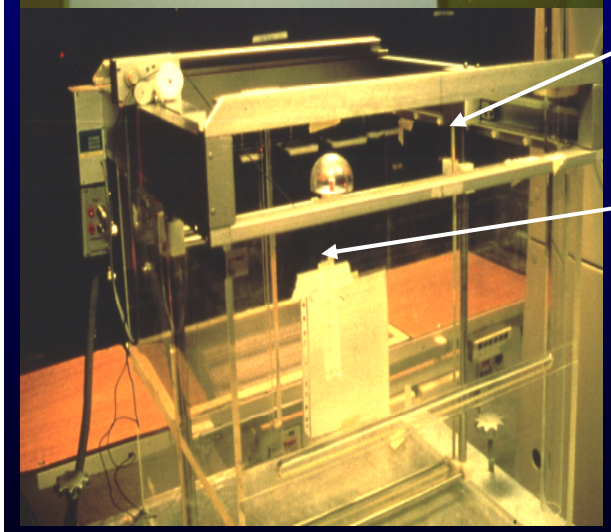
Software commissioning tests

- Homogeneous water phantom
- Inhomogeneous phantoms (Cygler et al, Phys. Med. Biol., ***32***, 1073 (1987) and *Ding G.X.et al, Med. Phys.,* ***26,*** *2571-2580, 1999)*
  - Shiu *et al*, Med.Phys. **19**, 623—36, 1992;
  - Boyd *et al, Med. Phys.,* ***28, 950-8, 2001***
- All scans done with a high (1 mm) resolution
- Criteria for acceptability (Van Dyk et al, *Int. J. Rad. Oncol. Biol. Phys.,* ***26****, 261-273,1993;*

  Fraass, et al, AAPM TG 53: Quality assurance for clinical radiotherapy treatment planning," Med. Phys. 25, 1773–1829 1998)

Typical Experimental setup





Electron applicator

Water tank

Diode detector

- RFA300 (Scanditronix) dosimetry system
- p-type electron diode
- Scan resolution = 1mm

In-air or in water beam profiles

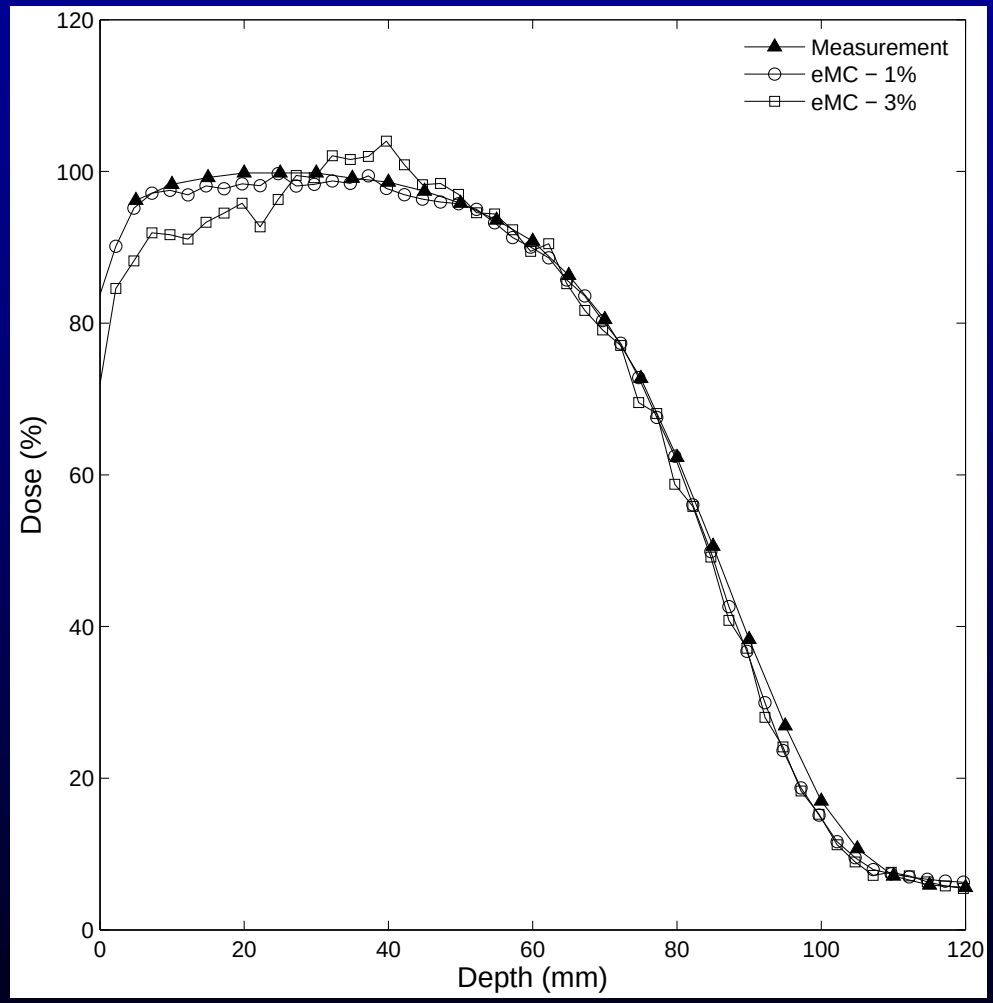
Homogeneous water phantom tests

- Standard SSD 100 cm and extended SSD
  - Open applicators – PDD and profiles
  - Square and circular cut-outs
- Oblique incidence
  - GA = 15^0 and 30^0
- MU tests – SSD 100 and extended SSD
  - All open applicators
  - Square, rectangular, circular, some irregular cutouts

Inhomogeneous phantoms

- Low and high density inhomogeneities
  - 1 D (slab) geometry
  - 2 D (ribs) geometry
  - 3 D (small cylindrical) geometry
- Complex (trachea and spine) geometry

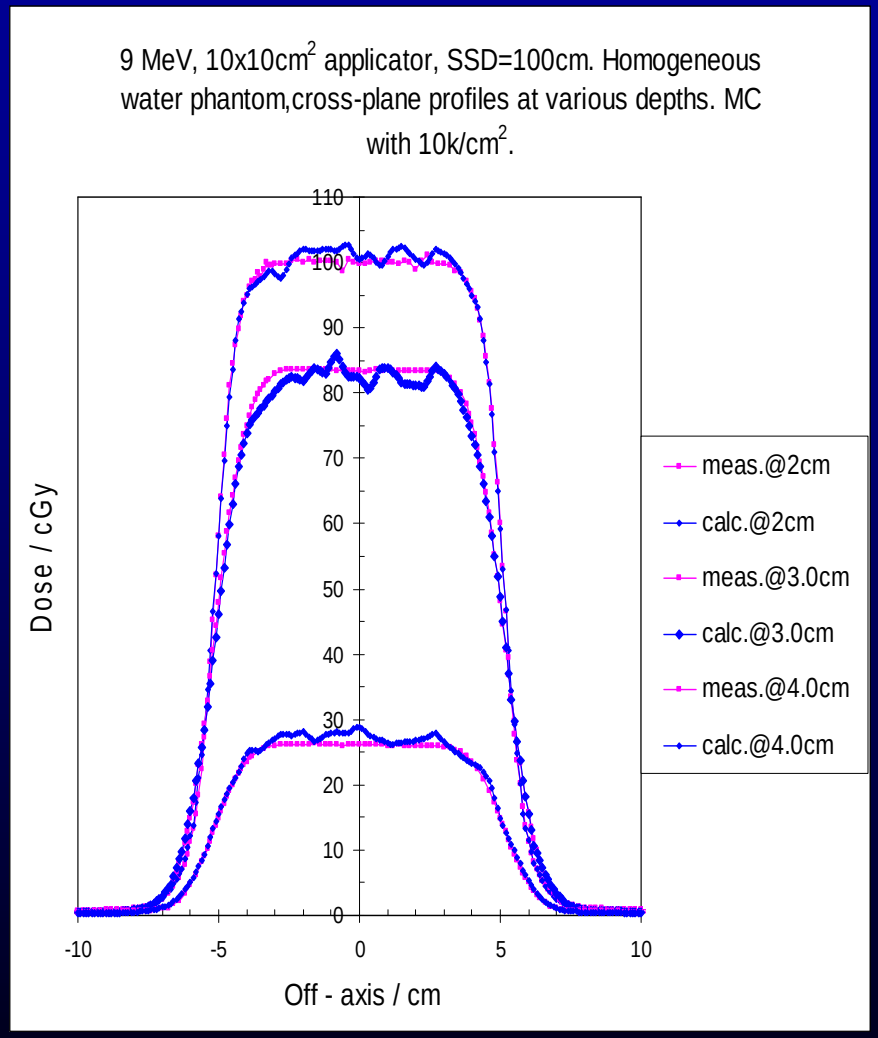
Effect of statistical uncertainty on MC calculations

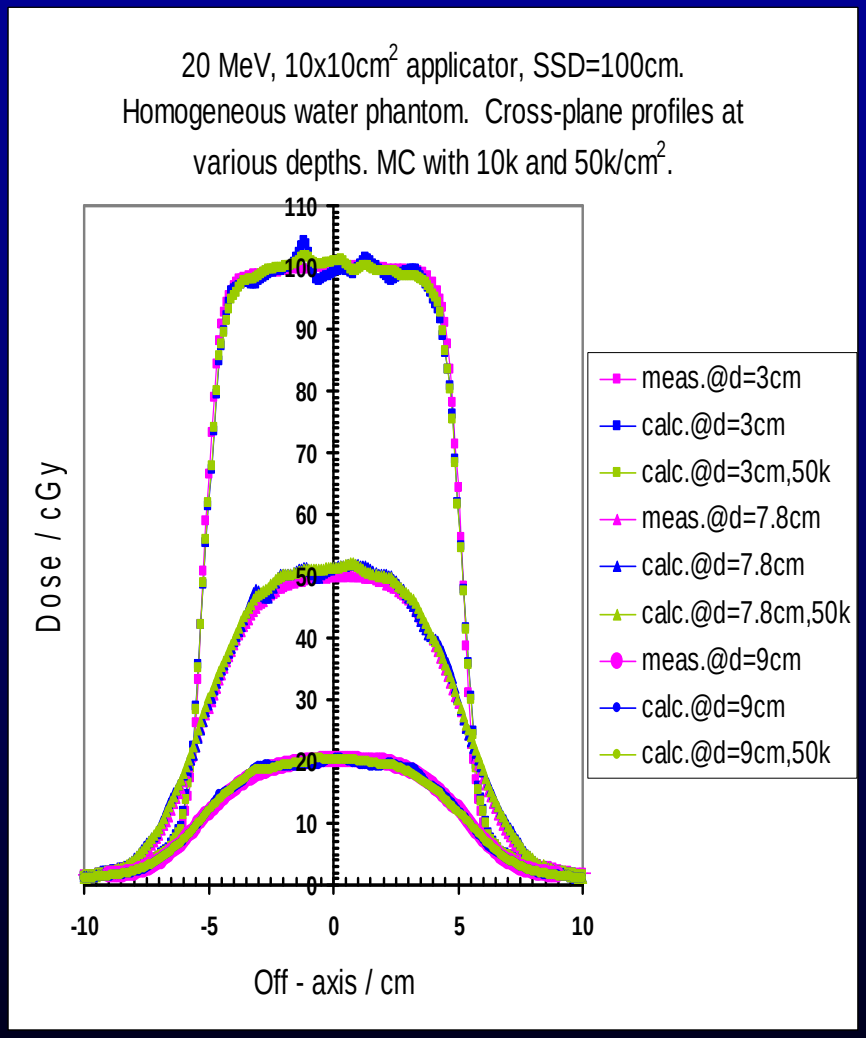


20 MeV, SSD=100 cm, homogeneous water phantom. Central axis PDD measured and eMC (Eclipse) calculated for 1% and 3% statistical precision, 2.5 mm voxel size, no smoothing.

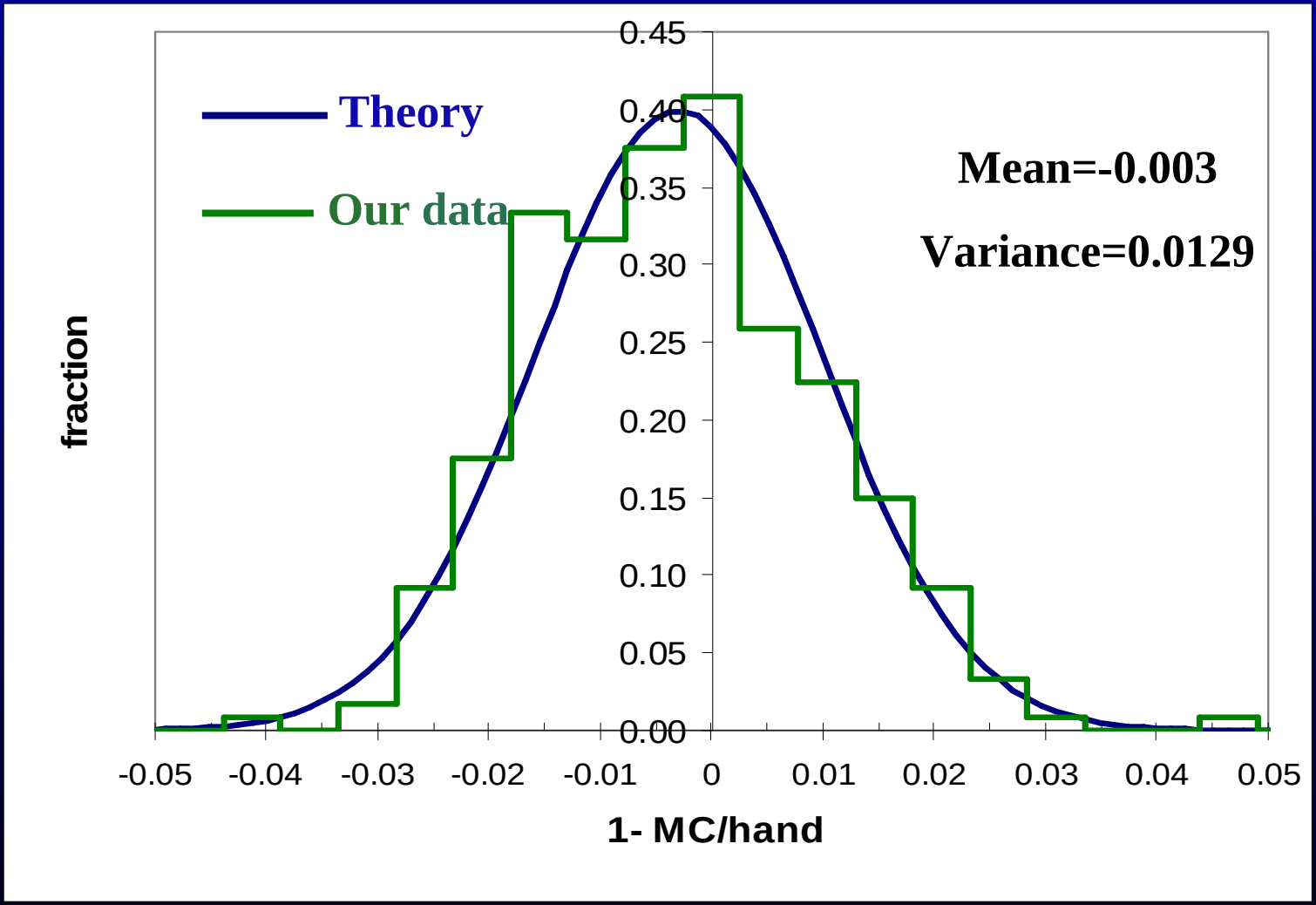
Courtesy of R. Popple, Med Phys. 33, 1540- 51, 2006

Lateral profiles at various depths, SSD=100 cm, Nucletron TPS





Overall mean and variance of MC/hand monitor unit deviation, Nucletron TPS

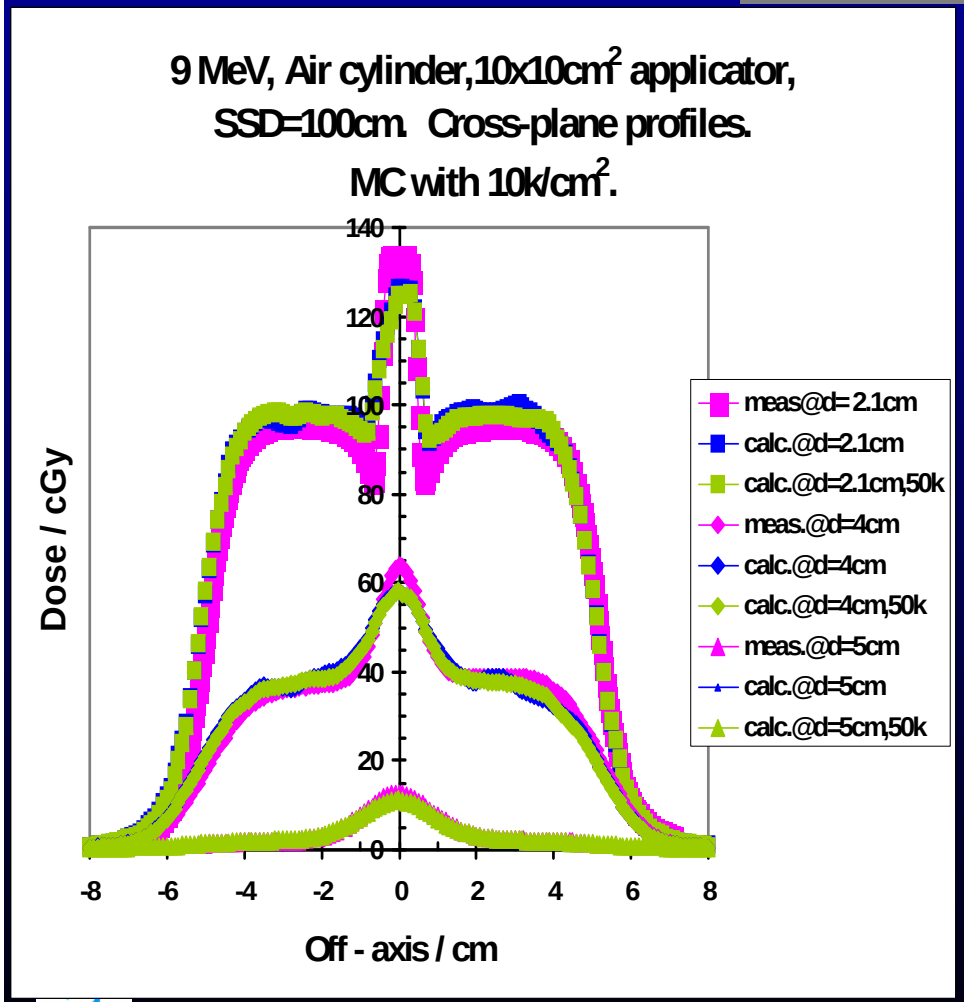


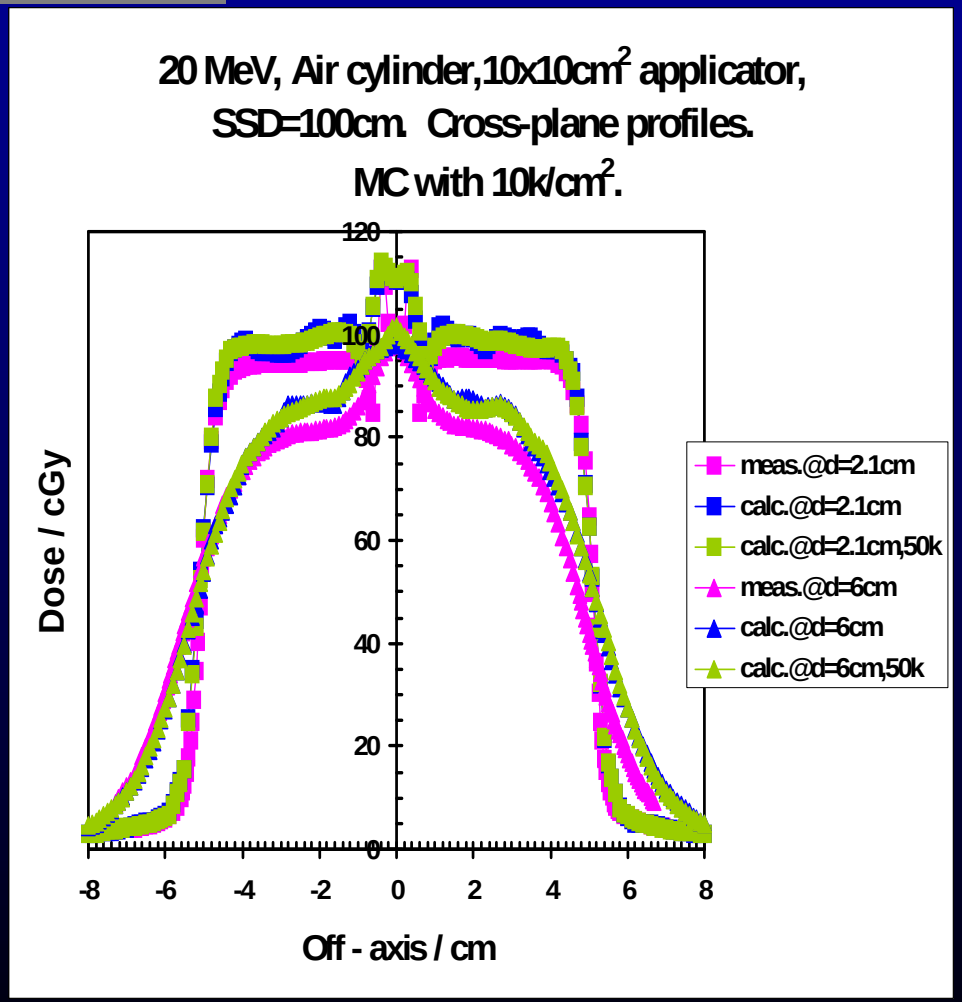
Cygler et al. Med. Phys. ***31*** *(2004) 142-153*

Air cylinder

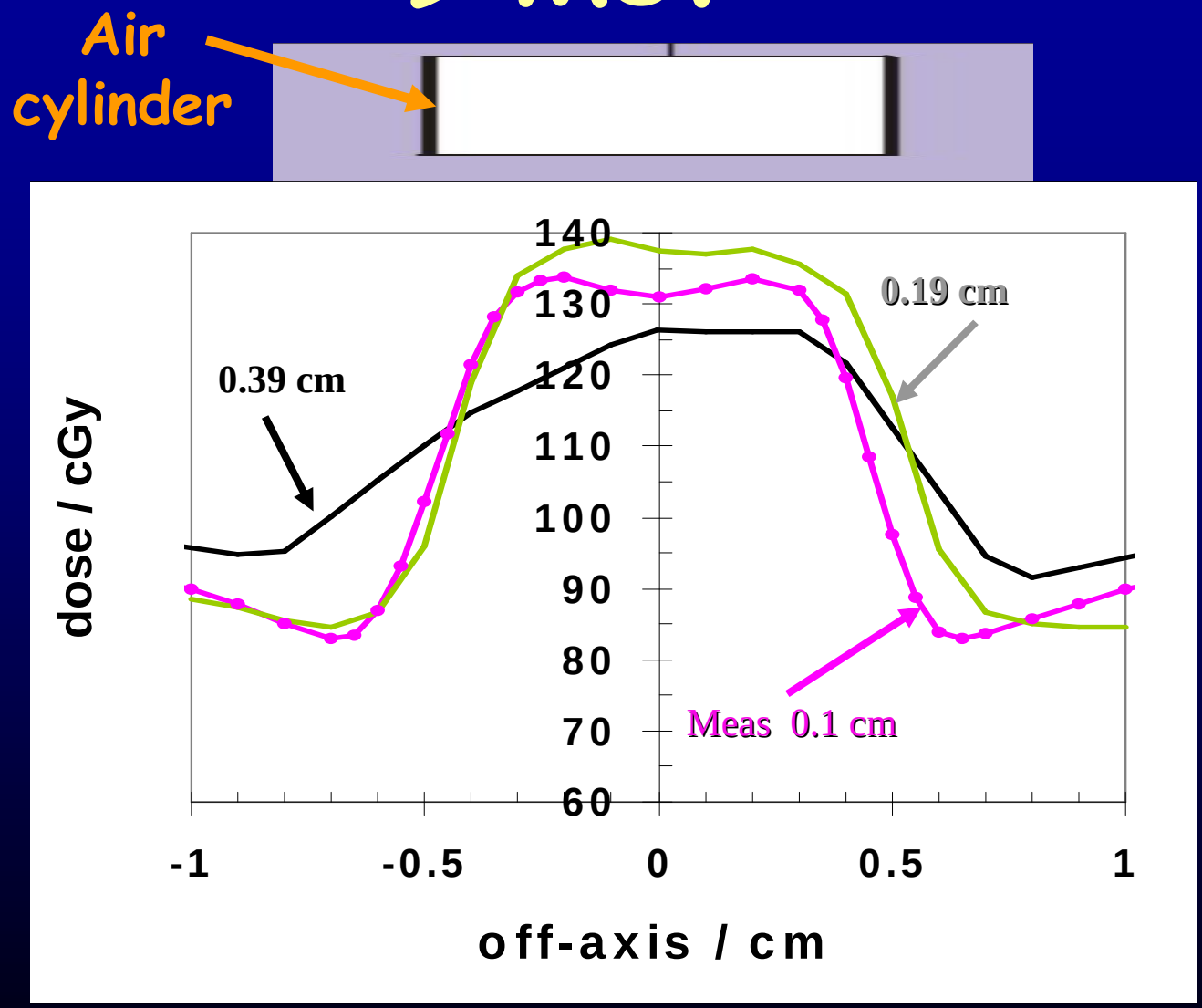
Voxel size 0.39 cm, 47 slices

900 MHz, CPU time for 50k/cm^2
14:01-20 MeV , 9:31 – 9MeV





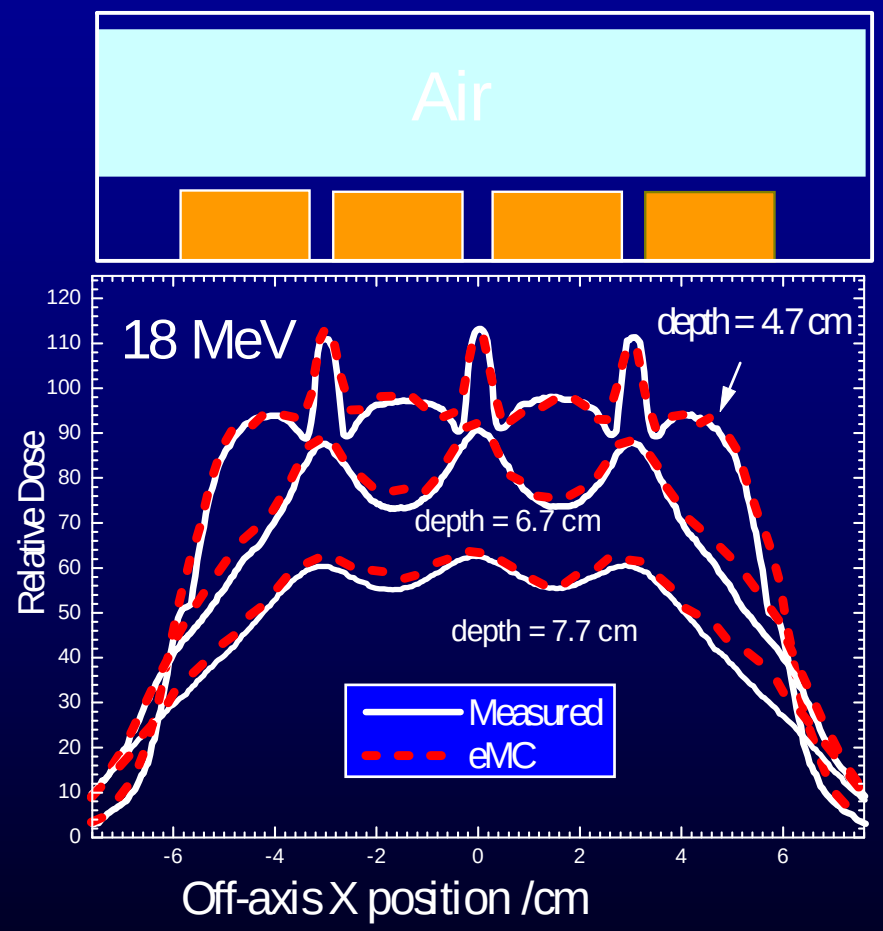
Results MC tests:voxel size 9 MeV

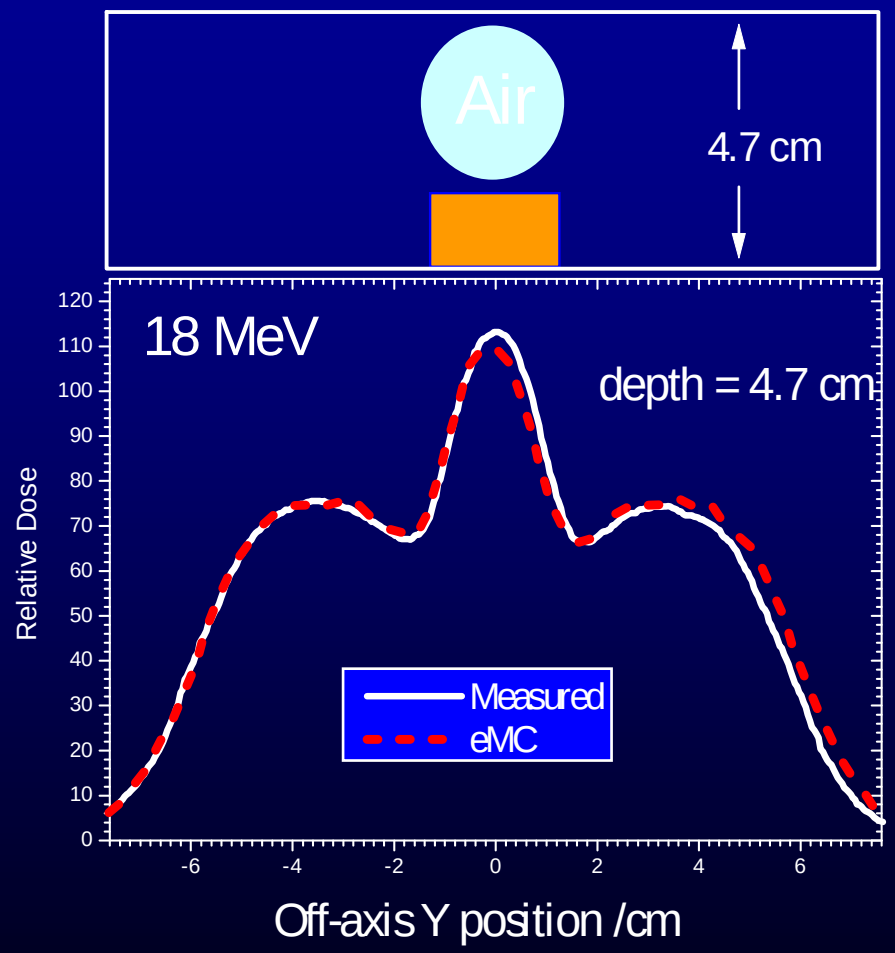


Cygler et al. Med. Phys. ***31*** *(2004) 142-153*

Eclipse eMC no smoothing

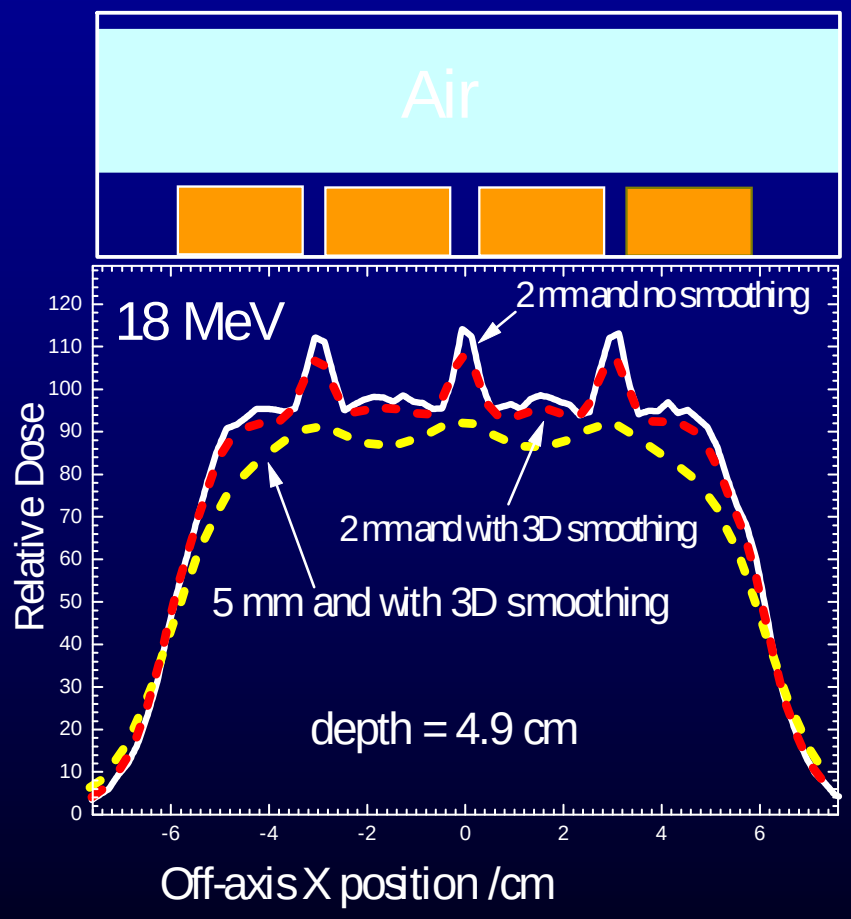
Voxel size = 2 mm

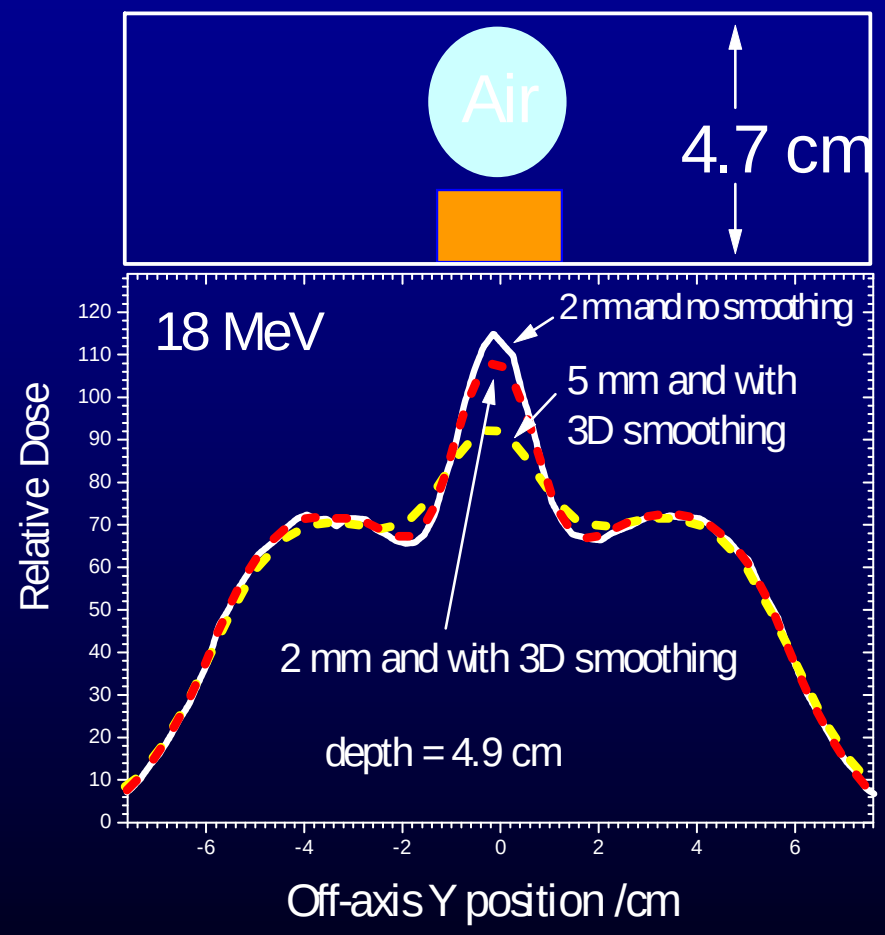




Ding, G X., et al (2006). Phys. Med. Biol. 51 (2006) 2781-2799.

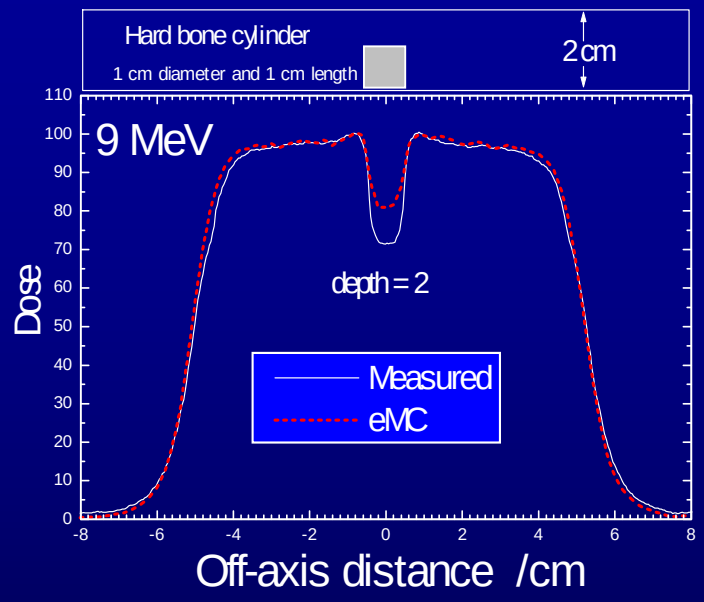
Eclipse eMC
Effect of voxel size and smoothing

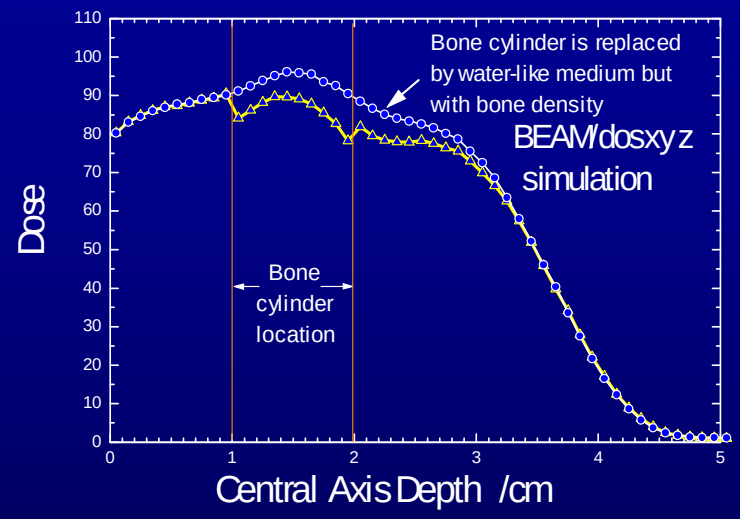


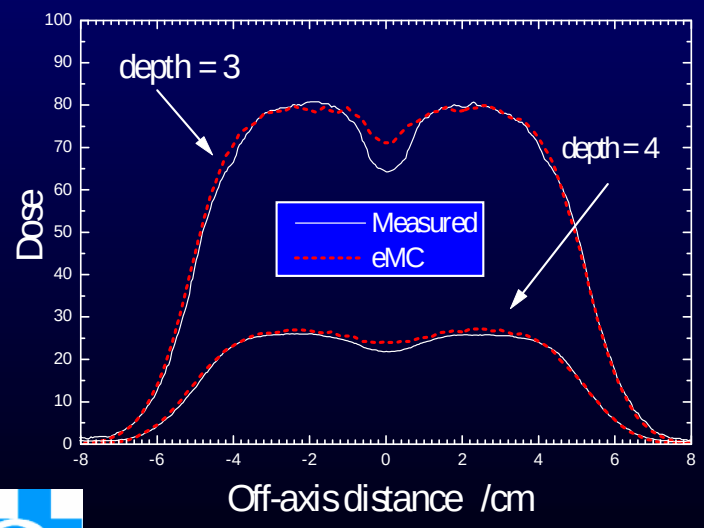


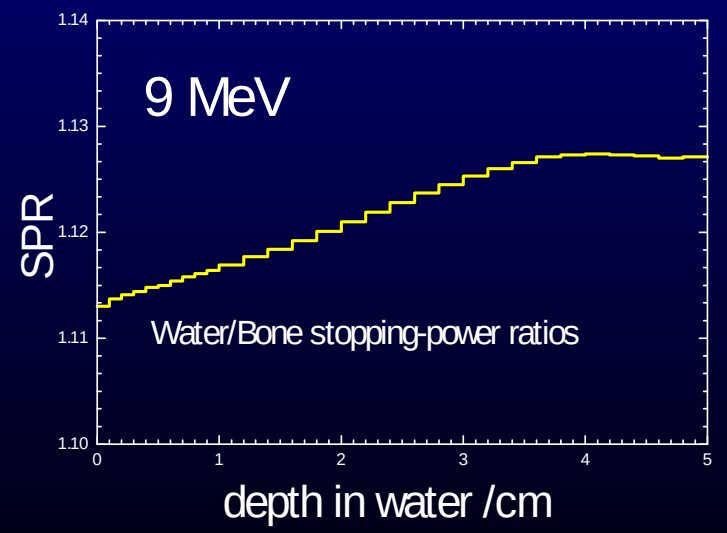
Ding, G X., et al (2006). Phys. Med. Biol. 51 (2006) 2781-2799.

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









Ding, G X., et al Phys. Med. Biol. 51 (2006) 2781-2799

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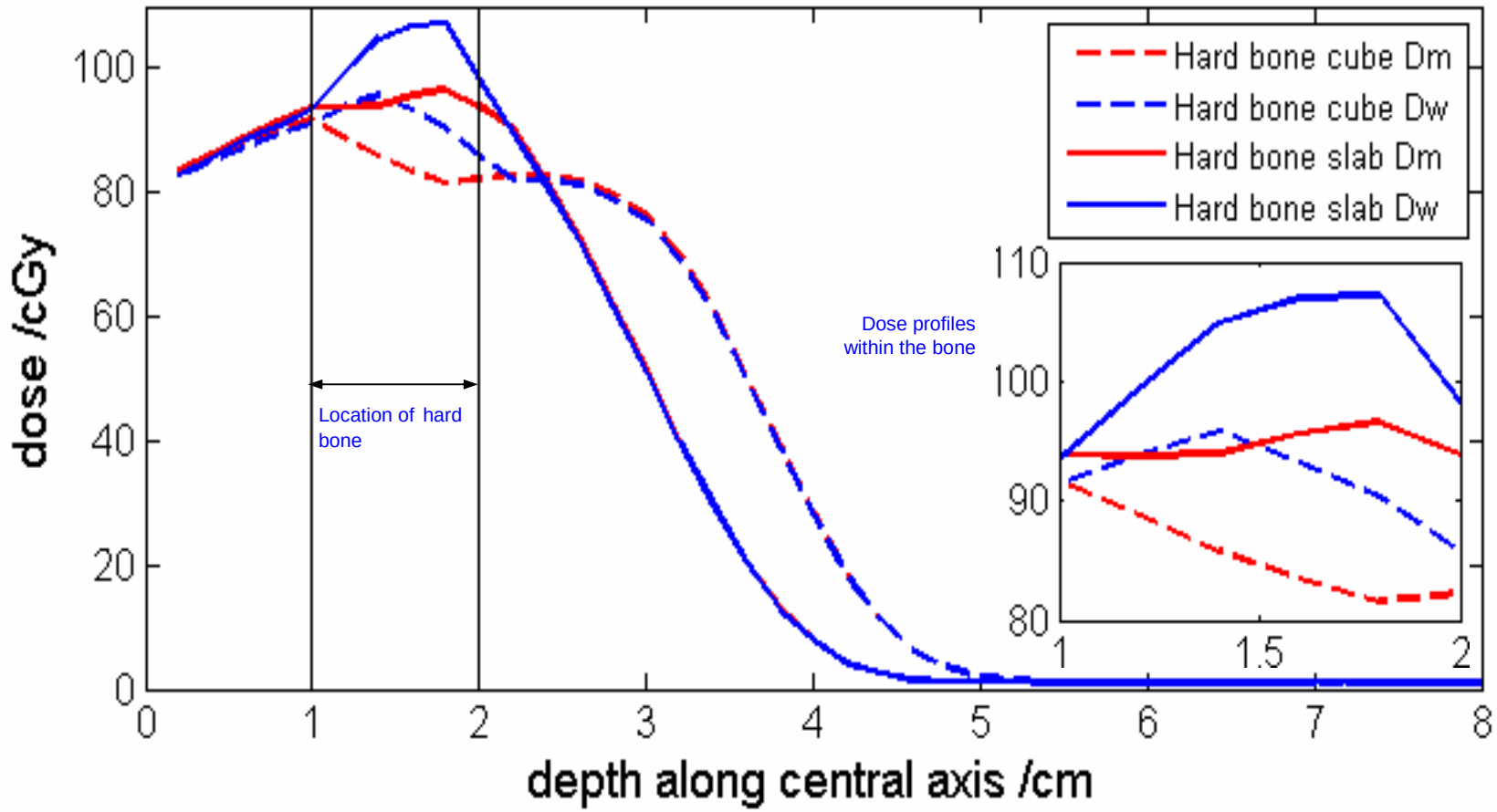
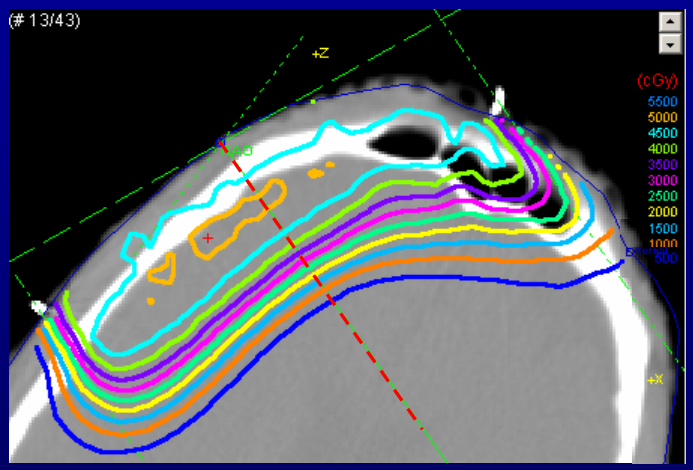
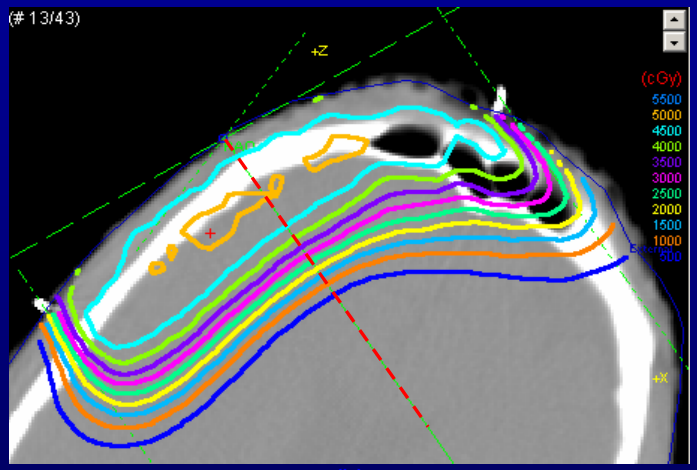
9 MeV – hard bone D_m vs. D_w



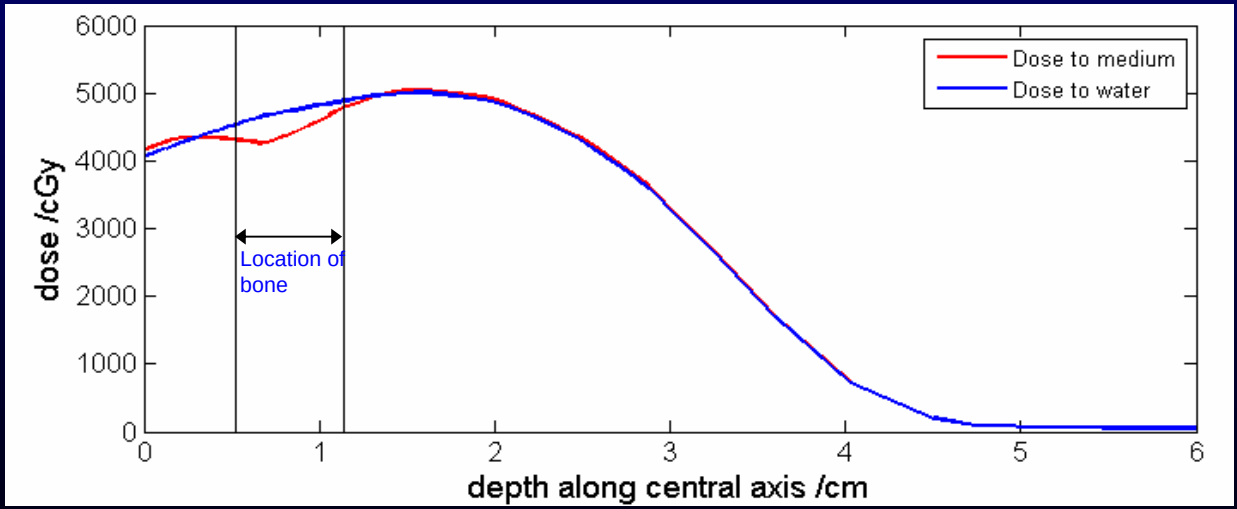
9 MeV – clinical hard bone D_m vs. D_w



(a)



(b)



(c)

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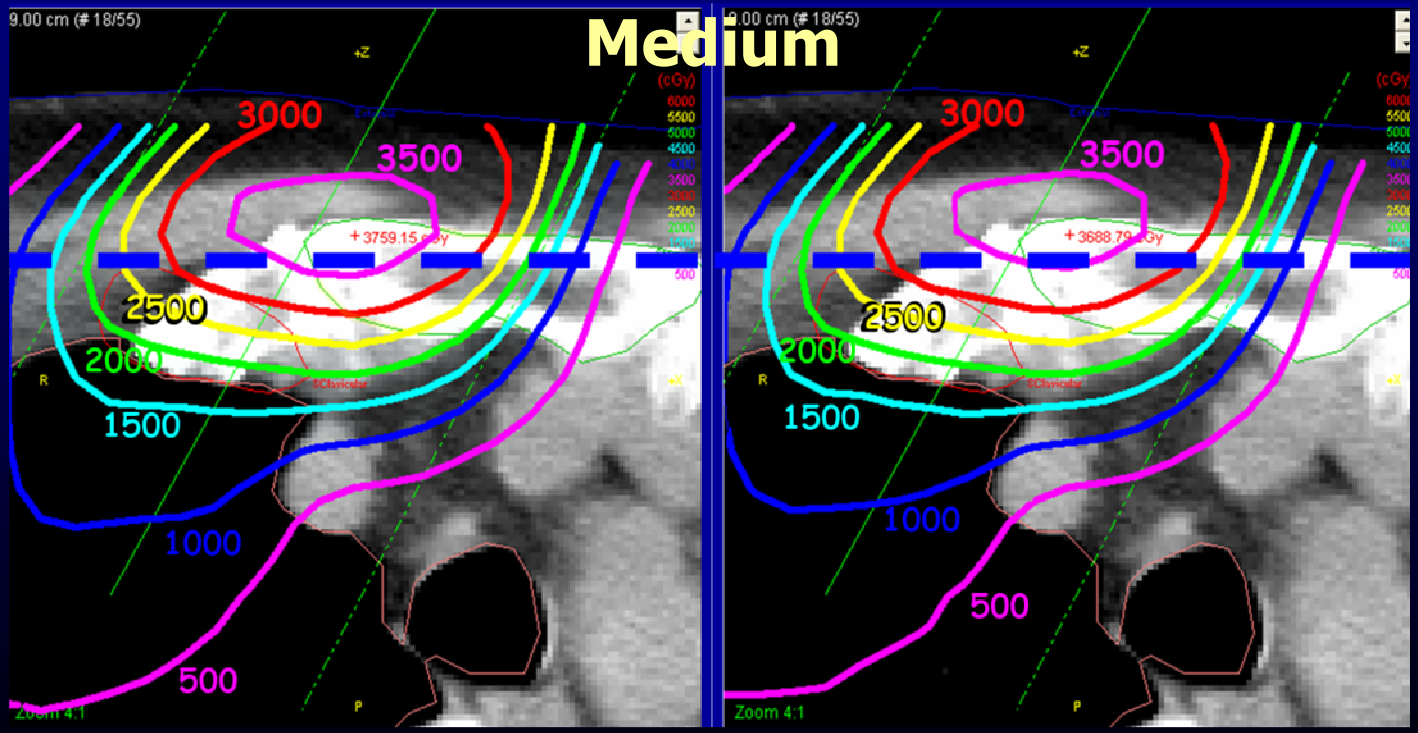
Results: Clinical – soft bone

- The maximum difference in dose is 1.8%, in agreement with soft bone phantom study and consistent with stopping power ratio

Dose-to-Water **Dose-to-Medium**



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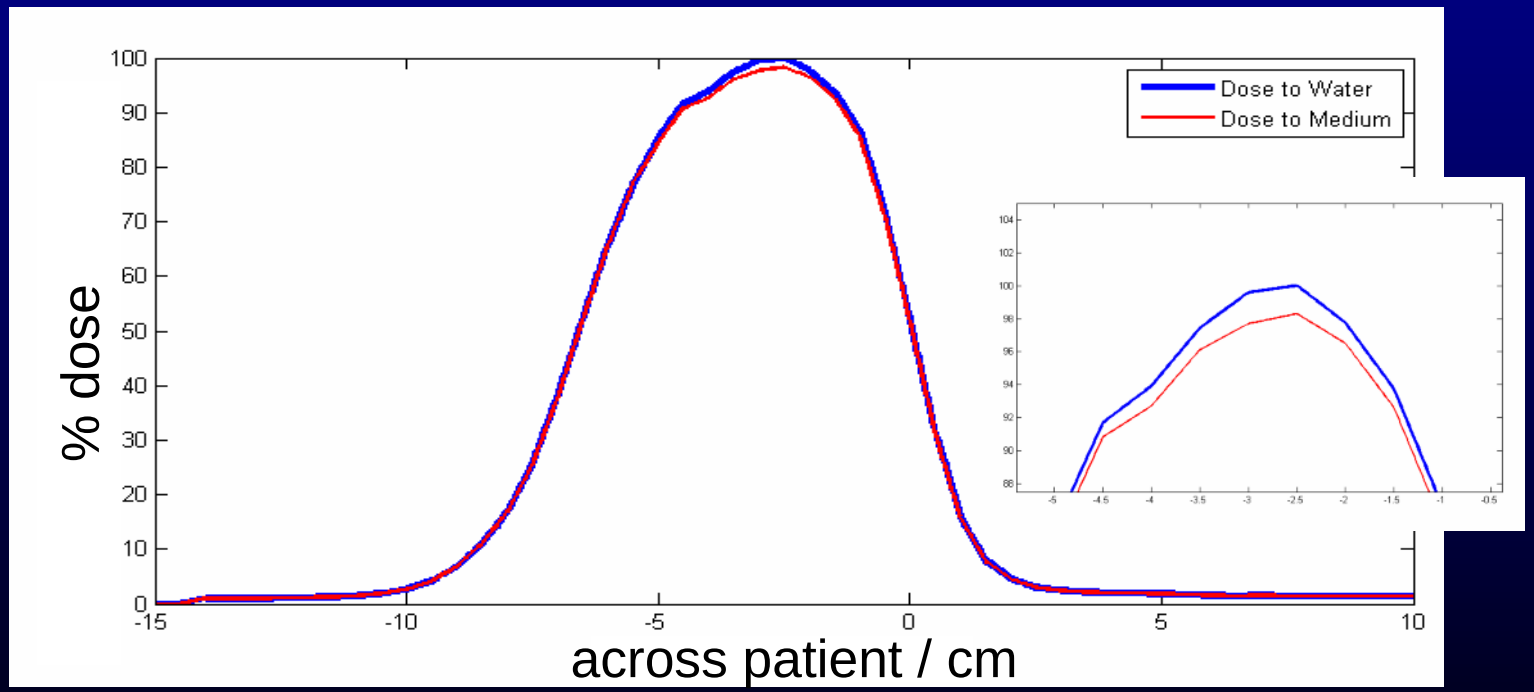
Results: Clinical – soft bone

- The maximum difference in dose is 1.8%, which is in agreement with the phantom studies



Treatment Planning Procedure

The physician:

- outlines CTV and/or GTV

The dosimetrist / physicist:

- models the beam (energy, custom cutout)
  - CTV covered by 90% isodose line

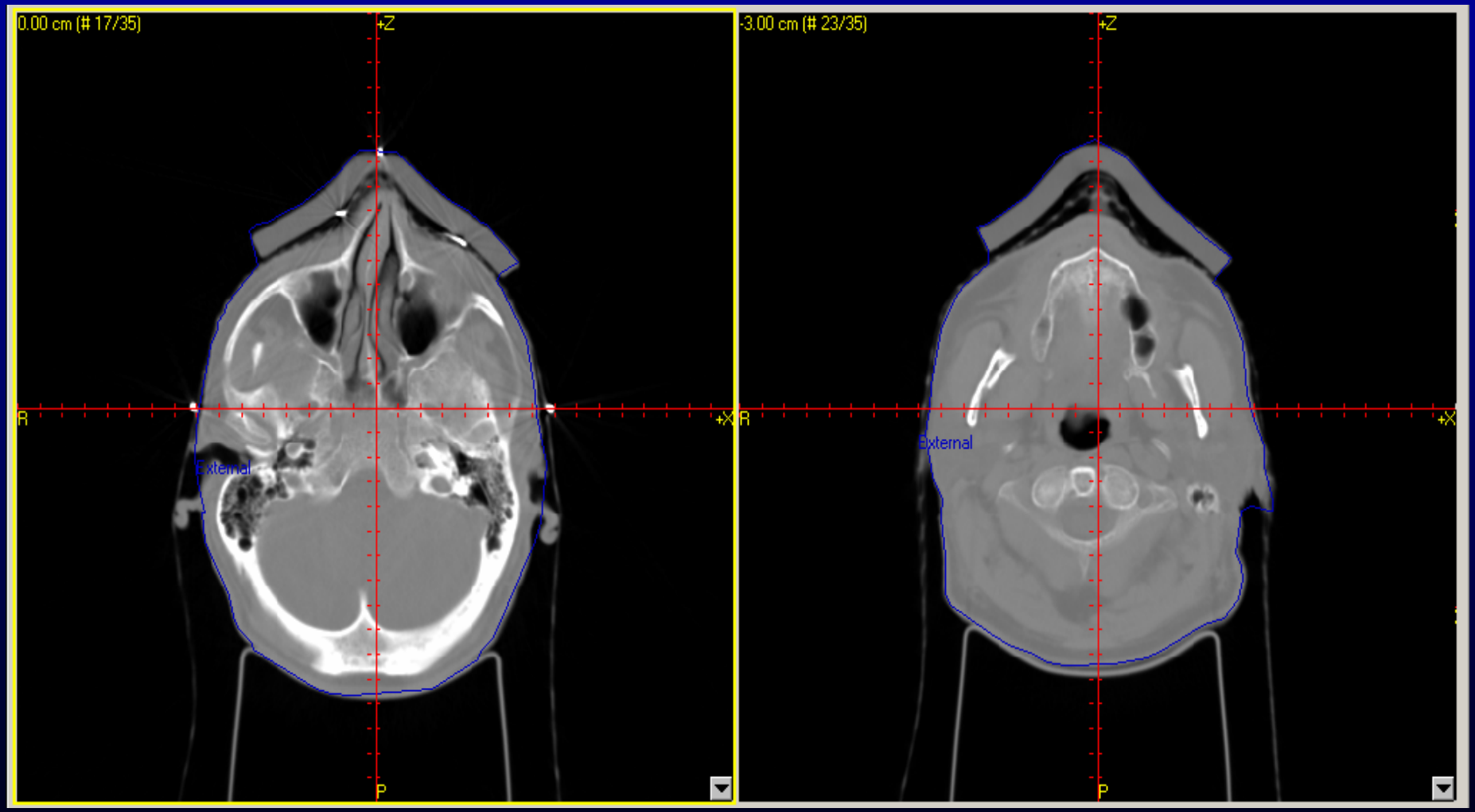
The software calculates :

- absolute dose distribution in cGy
- number of monitor units, MU

Clinical implementation issues

- Bolus fitting (no air gaps)
- Lead markers (wires, lead shots) used in simulation
- Monitor unit calculations
  - Water tank or real patient anatomy
  - Dose to water or dose to medium
- Workload

Example of poorly fitting bolus



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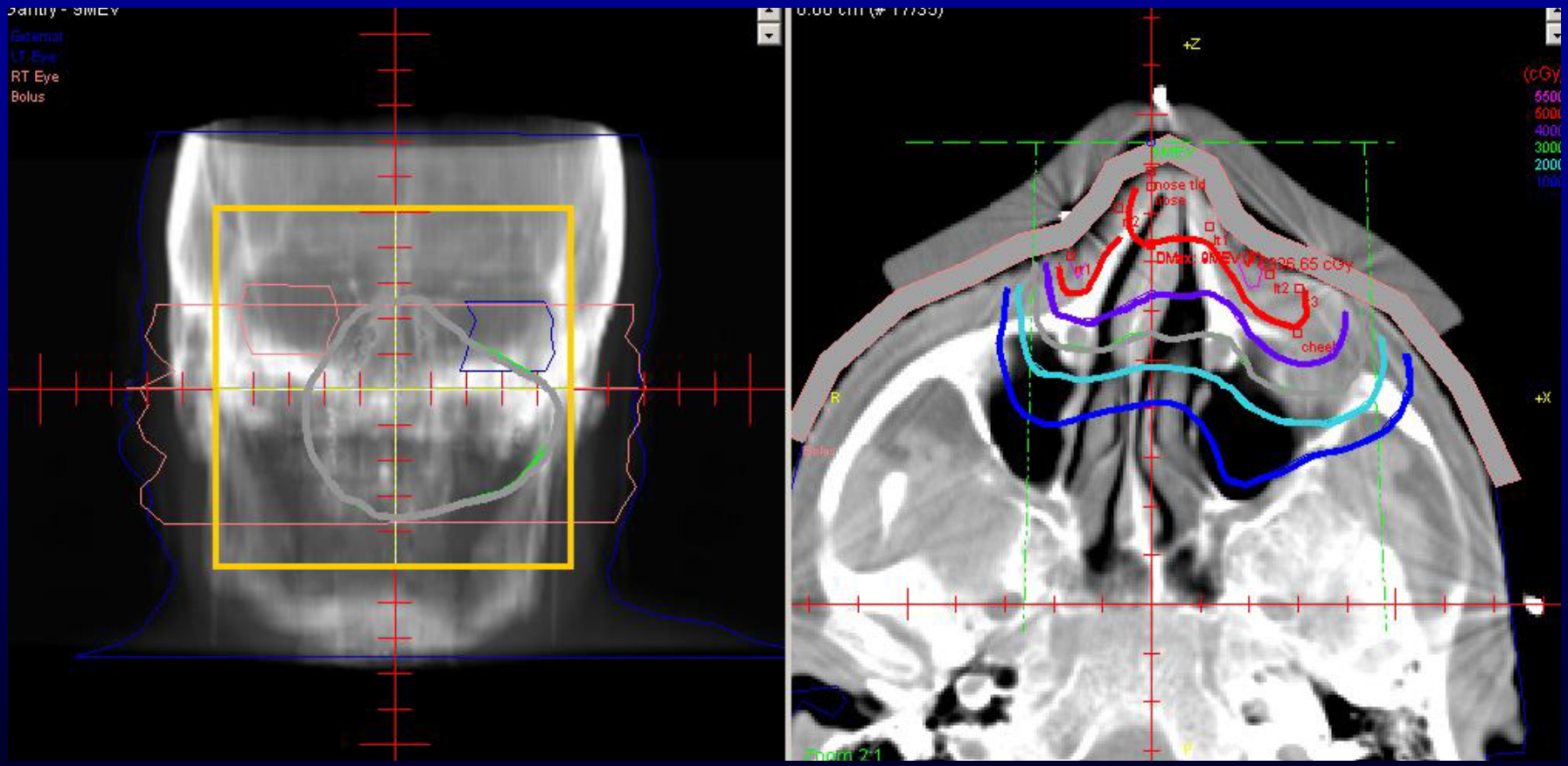
How to correct poorly fitting bolus



Good clinical practice

- Murphy's Law of computer software

"All software contains at least one bug"

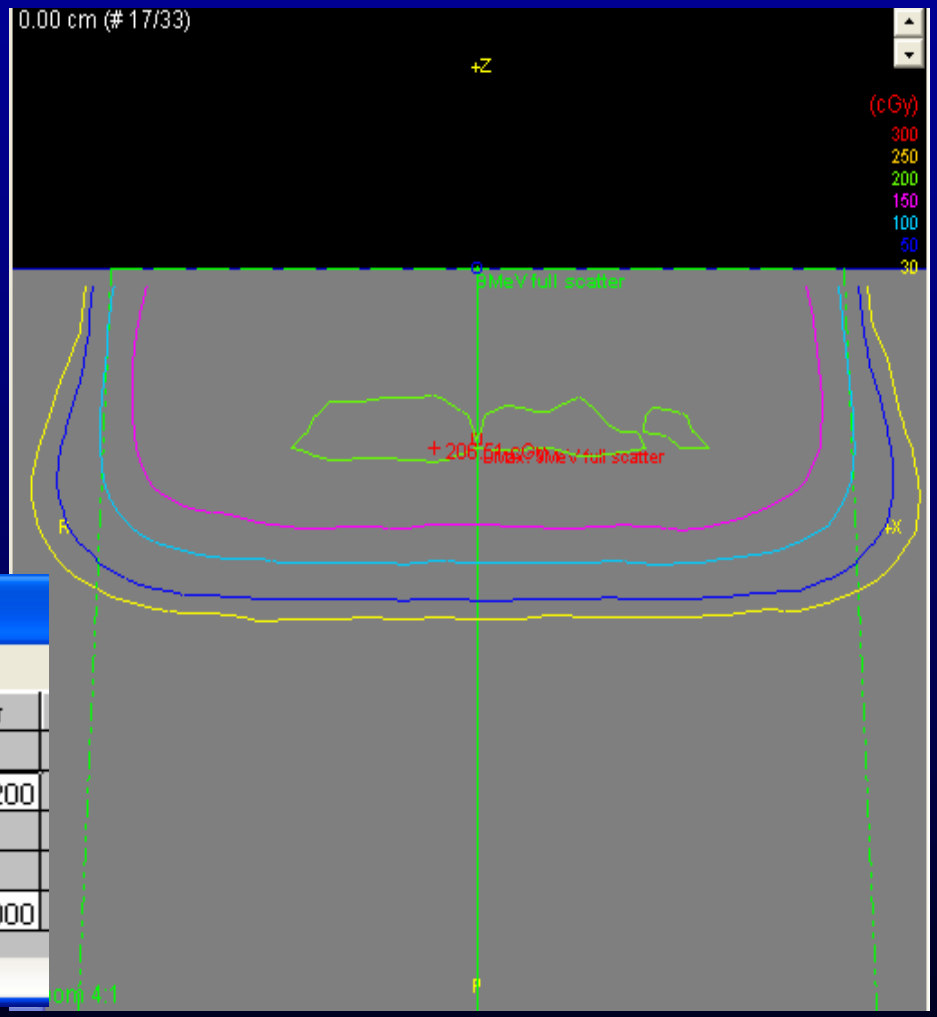
- Independent checks

MU MC vs. hand calculations

Monte Carlo	Hand Calculations
Real physical dose calculated on a patient anatomy	Rectangular water tank
Inhomogeneity correction included	No inhomogeneity correction
Arbitrary beam angle	Perpendicular beam incidence only

9 MeV, full scatter phantom (water tank)

RDR=1 cGy/MU



Point Dose Data

File Edit

	9MeV full scatter
Weight	N/A
MU or min	200
Iso: 9MeV full scatter	N/A
dMax: 9MeV full scatter	N/A
DMax: 9MeV full scatter (0.00,0.00,-2.10)	200.000

Lateral scatter missing

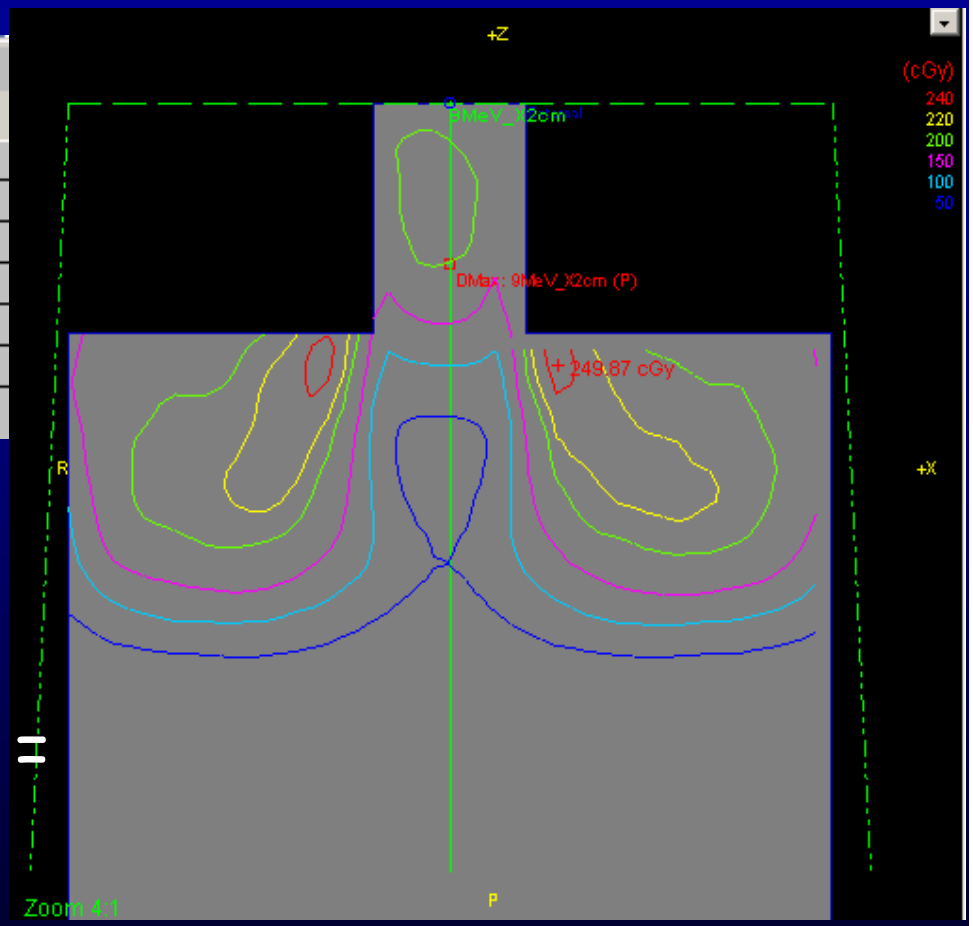
Point Dose Data

File Edit

	9MeV_X2cm	Total Rel. Dose
Weight	N/A	N/A
MU or min	234	N/A
Iso: 9MeV_X2cm	N/A	N/A
dMax: 9MeV_X2cm	N/A	N/A
DMax: 9MeV_X2cm (P) (0.00,0.00,-2.10)	200.000	N/A

Plan Data - Norm: 100.00

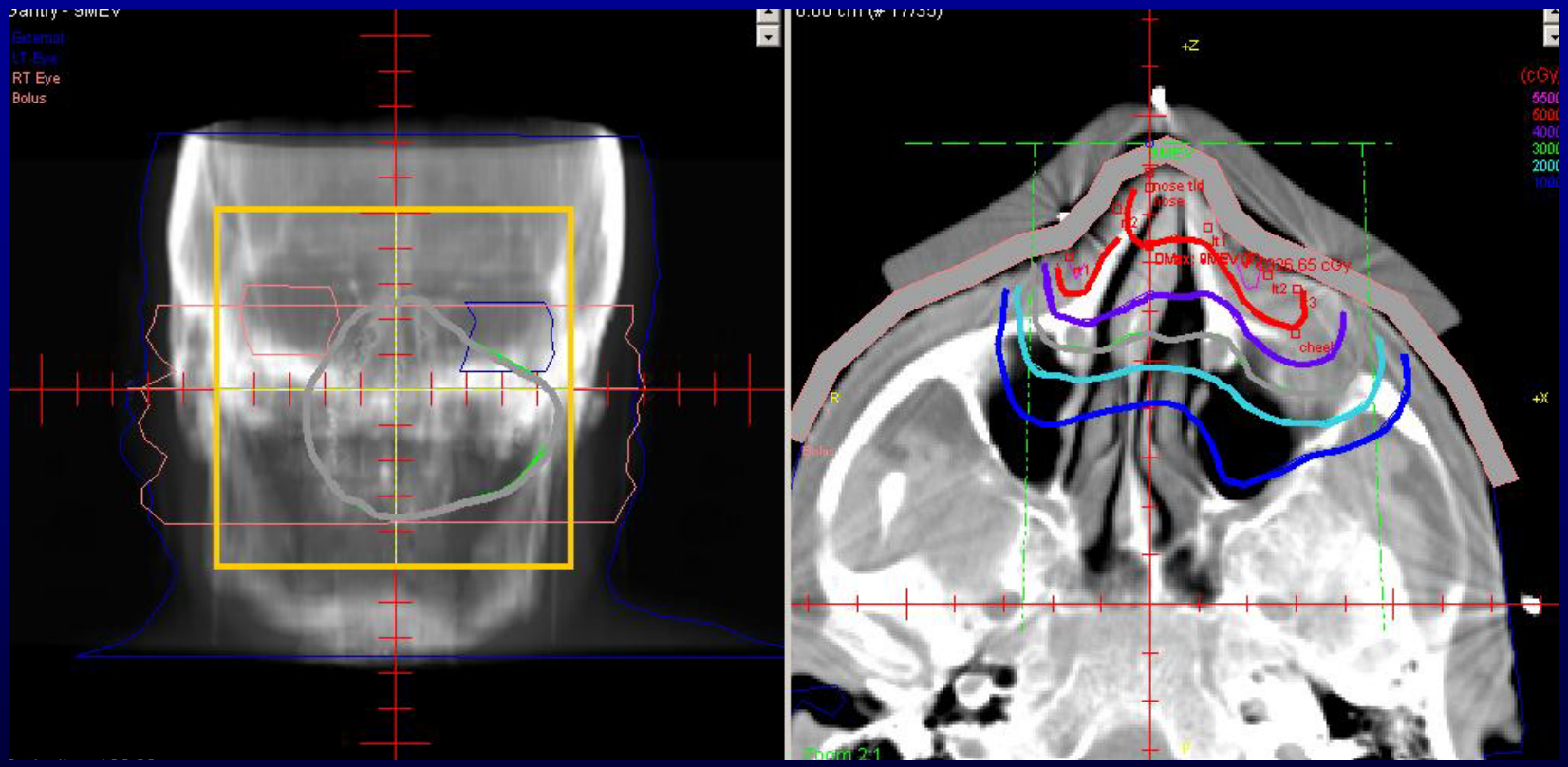
Number of Fractions	1
MU or min / Fraction	234



Real contour / Water tank =

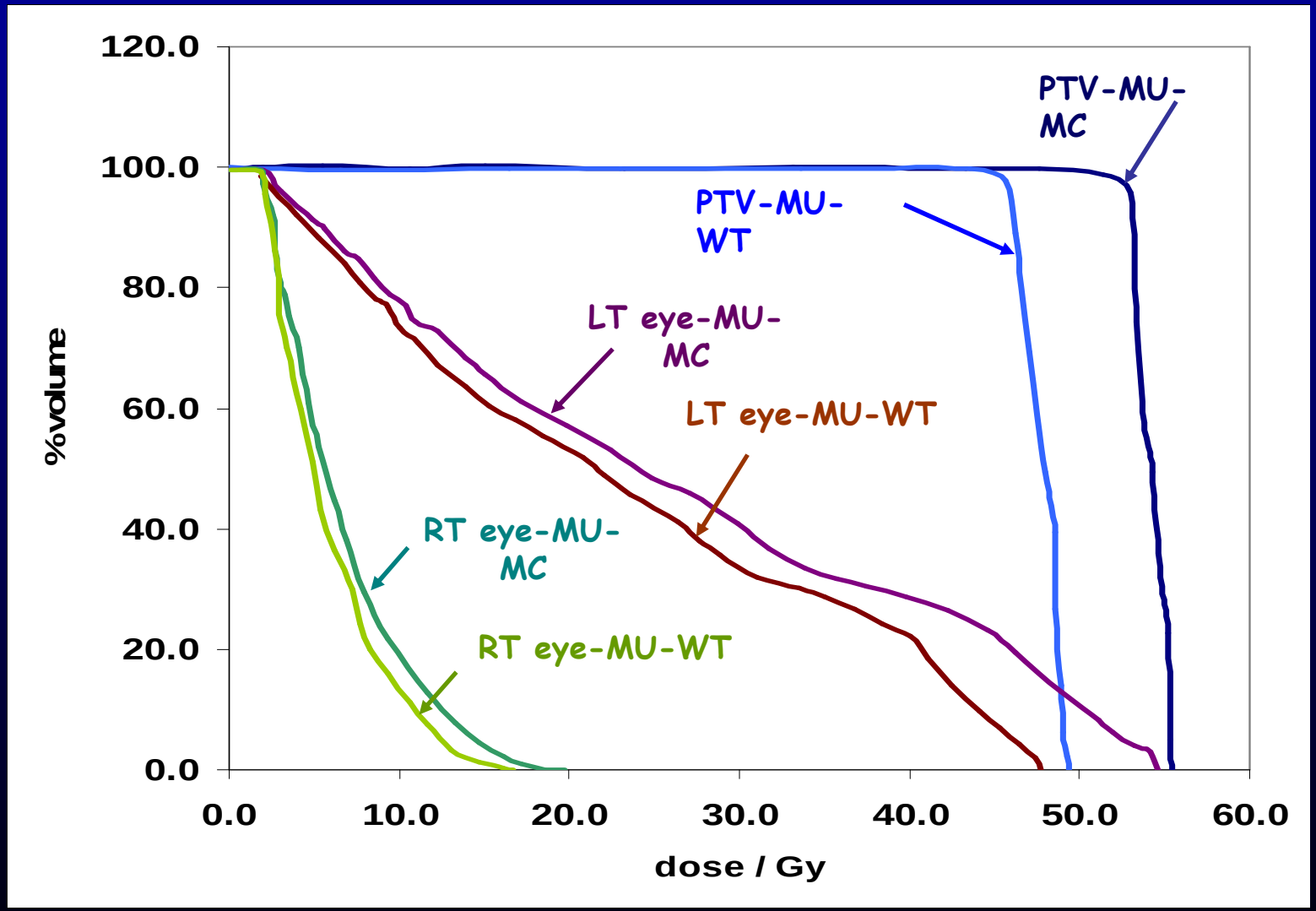
=234MU / 200MU=1.17

MU real patient vs.water tank



MC / Water tank= 292 / 256=1.14

MU-real patient vs. water tank Impact on DVH



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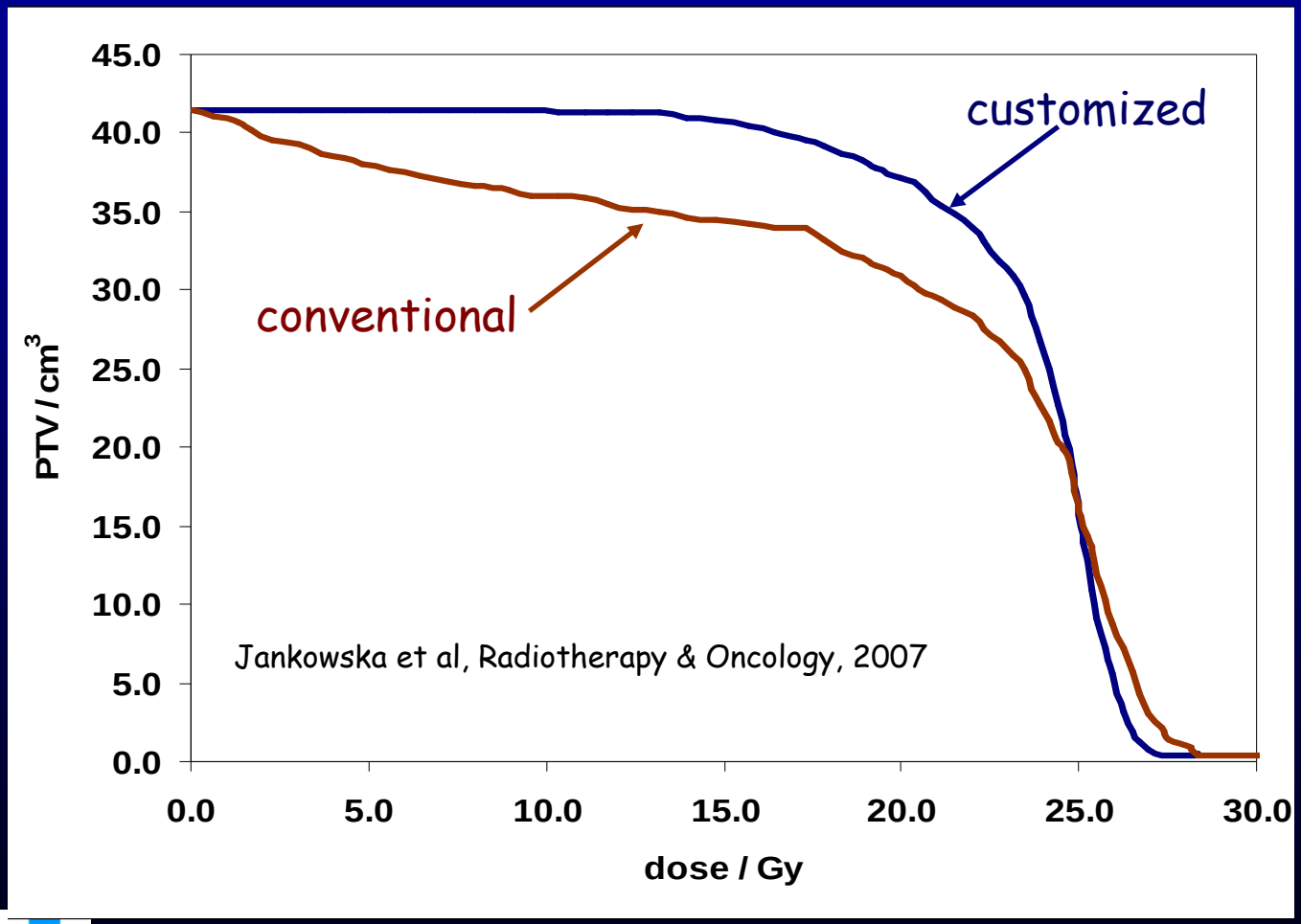
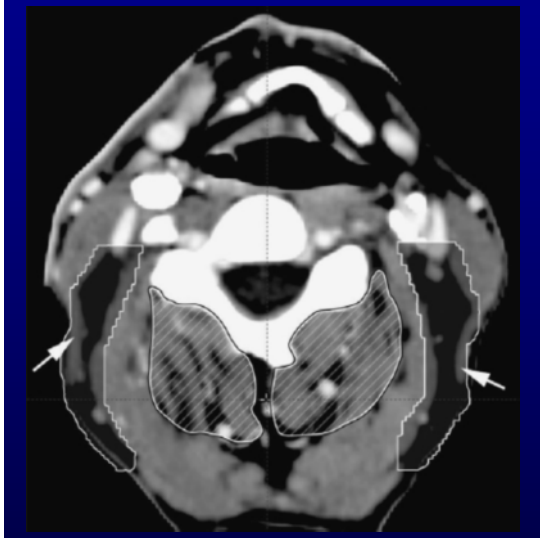
Posterior cervical lymph node irradiation - impact on DVH





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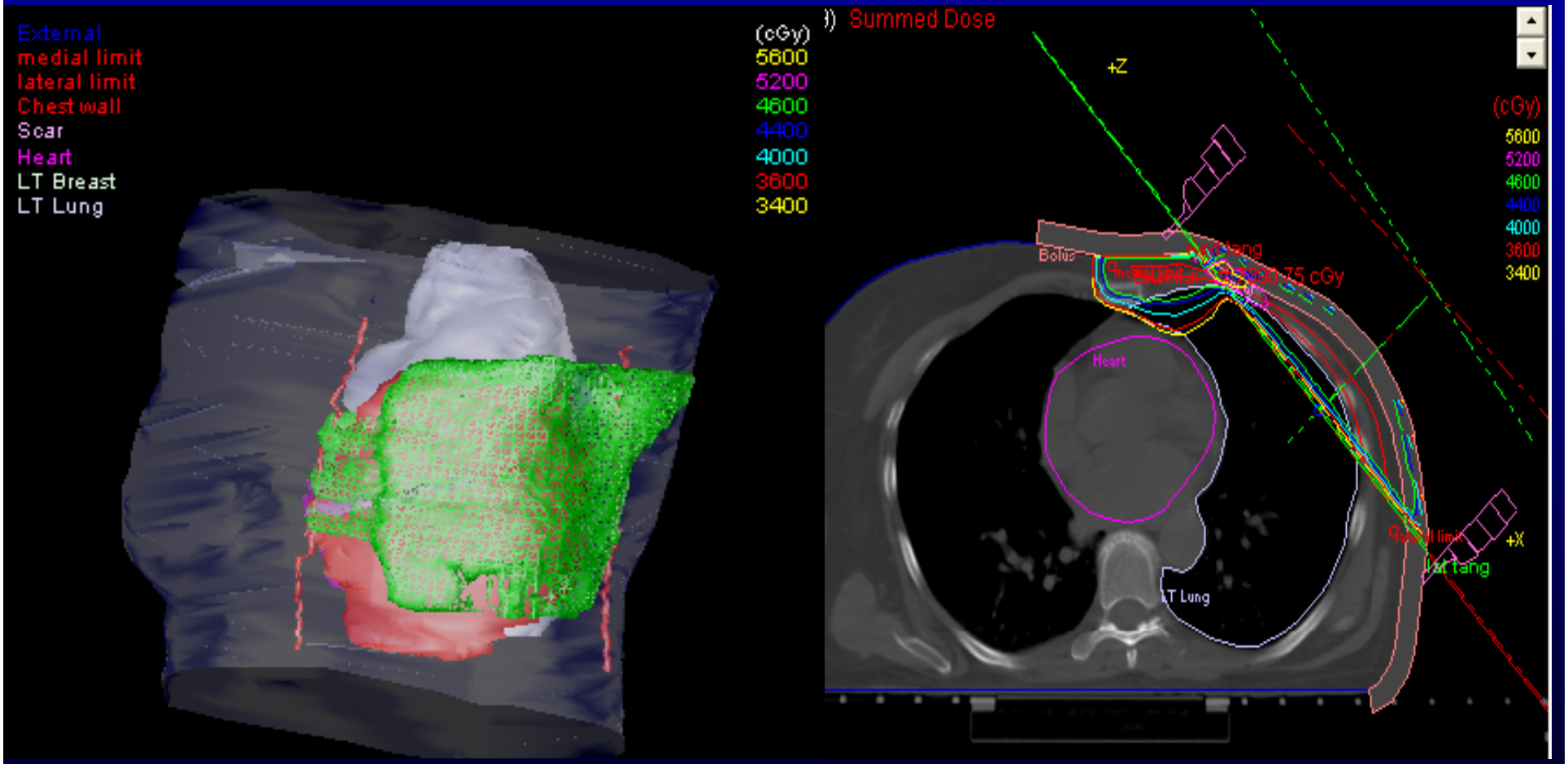
Internal mammary nodes



MC / Water tank= 210 / 206=1.019

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Timing – Nucletron TPS Theraplan Plus

- 10x10 cm^2 applicator
- 50k histories/cm^2
- Anatomy - 41 CT slices
- Voxels 3 mm^3
- Pentium 4 Xenon 2.2 GHz
- Calculation time
  - 1.5 min. for 6 MeV beam
  - 8.5 minutes for 20 MeV beam

Faster than pencil beam!

Timing – Nucletron TPS Oncentra MasterPlan

Anatomy - 41 CT slices
Voxels 3 mm^3
10x10 cm^2 applicator
50k histories/cm^2

Dell Inspiron 16000
Intel(R) Pentium(R) M processor 1.60GHz
1.60 GHz, 2.00 GB of RAM

9 MeV Timer Results:
Init = 0.586793 seconds
Calc = 204.069 seconds
Fini = 0.262845 seconds
Sum = 204.919 seconds

20 MeV Timer Results:
Init = 0.628385 seconds
Calc = 331.551 seconds
Fini = 0.232272 seconds
Sum = 332.412 seconds

Timing – Varian Eclipse

Eclipse MMC, Varian single CPU Pentium IV

XEON, 2.4 GHz

10x10 cm^2, applicator, water phantom,

cubic voxels of 5.0 mm sides

6, 12, 18 MeV electrons,

3, 4, 4 minutes, respectively

Chetty et al.: AAPM Task Group Report No. 105: Monte Carlo-based treatment planning, Med. Phys. 34, 4818-4853, 2007

Timing – Pinnacle^3

dual processor 1.6 GHz Sun workstation, 16 GB RAM.

Overall uncertainty						
2%			1%		0.5%	
Patient	# histories	CPU time (min)	# histories	CPU time (min)	# histories	CPU time (h)
1(cheek)	3.4×10^6	4.8	1.4×10^7	20	1.6×10^8	3.9
2 (ear)	1.7×10^6	2.1	6.5×10^6	8.1	7.1×10^7	1.5
3 (breast)	3.3×10^6	7.1	1.4×10^7	29.9	1.5×10^8	5.4
4 (face)	1.1×10^7	32.1	4.7×10^8	134.5	5.2×10^8	24.5

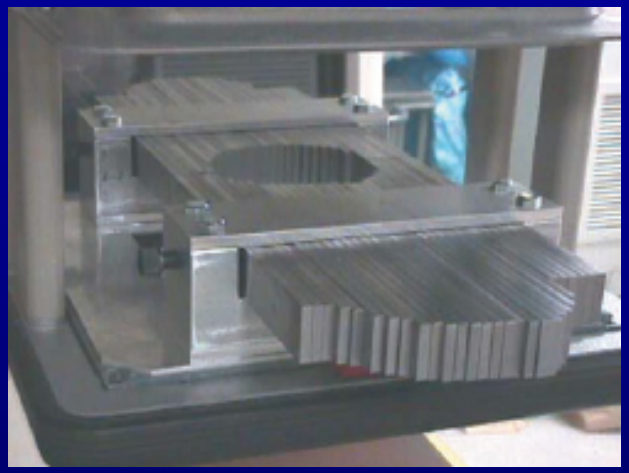
Fragoso et al.: Med. Phys. 35, 1028-1038, 2008

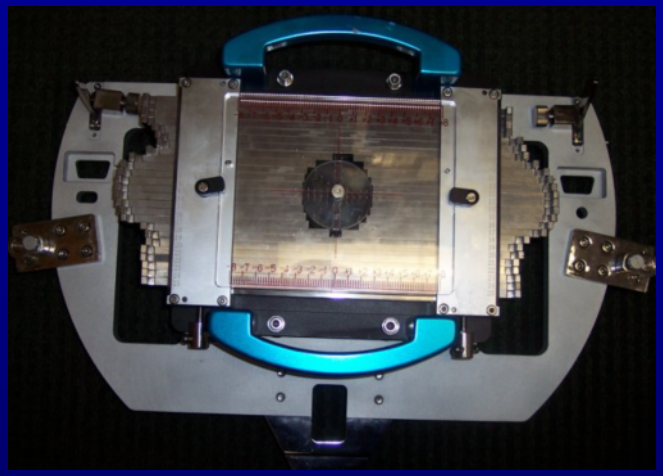
New developments

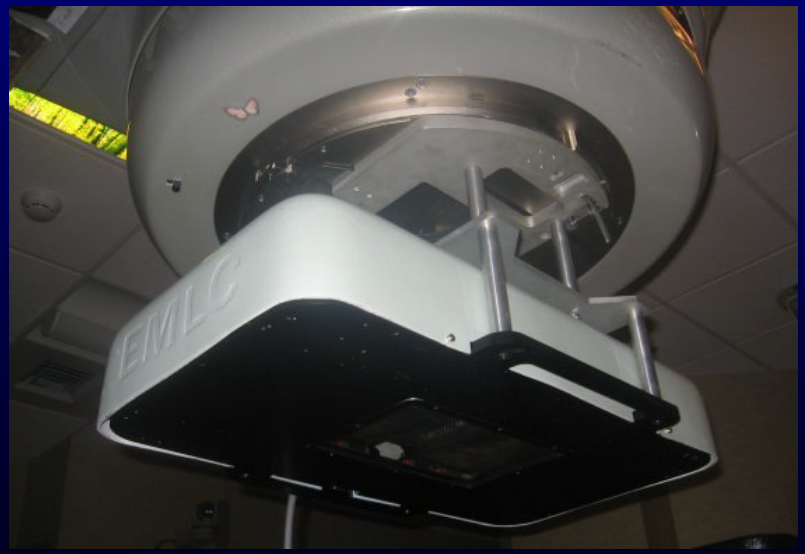
Energy modulated electron radiation therapy

- IMRT using photon beams is a widely used treatment modality and has become feasible with the introduction of the MLC.
- Energy modulated electron therapy (EMET) using Monte Carlo dose calculations is a promising new technique that enhances the treatment planning and delivery of dose to superficially located tumors.

MLC for electron beams







Pictures courtesy of C. Ma

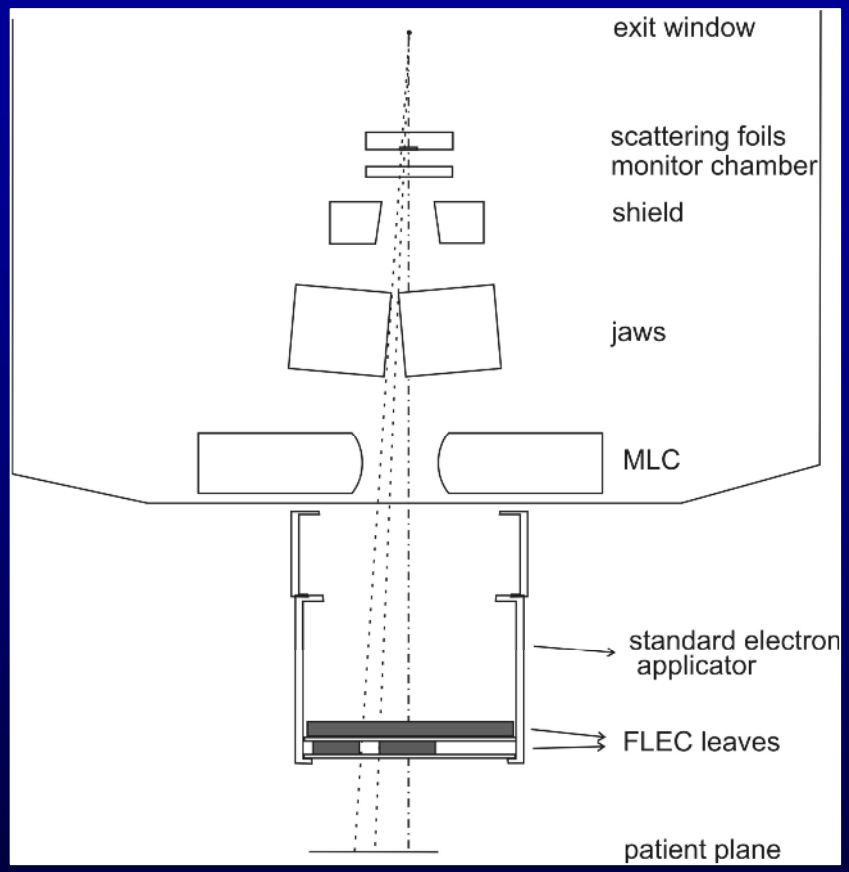
C-M Ma, et al ,Phys. Med. Biol. **45** (2000) 2293–2311

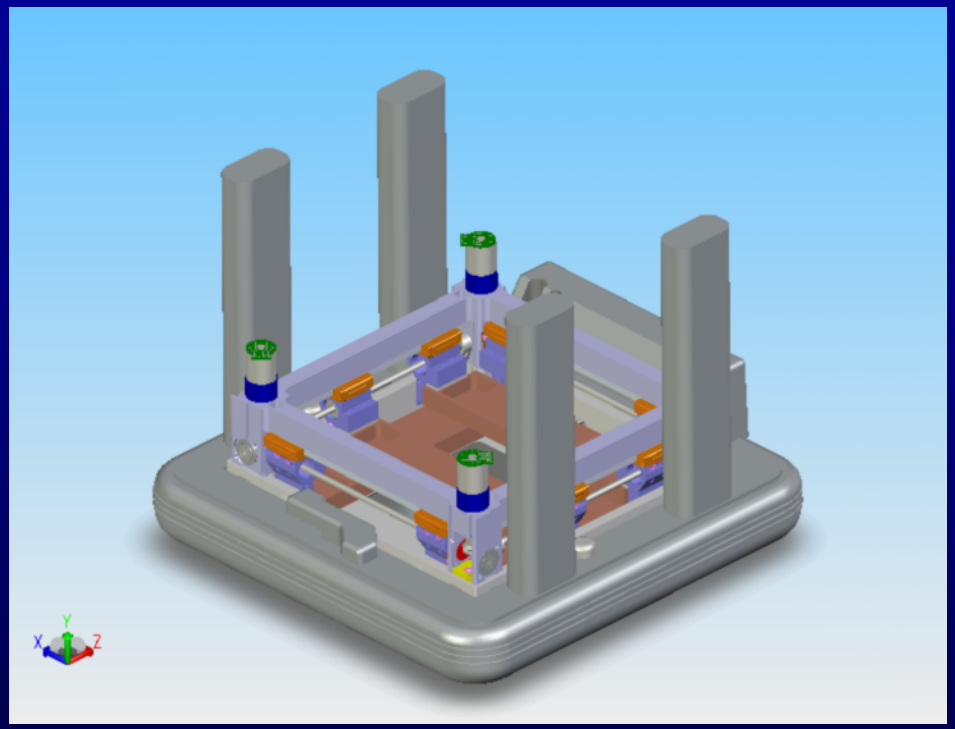
MLC for electron beams EMET with FLEC

- Medical Physics Group at McGill University (Al-Yahiya, Verhaegen and Seuntjens) recently proposed and studied the feasibility of a practical "few-leaf electron collimator" (FLEC) for delivering energy modulated electron therapy (EMET).

K. Al-Yahiya et al, Phys. Med. Biol. ***50****, (2005), 847-857*

The Few Leaf Electron Collimator



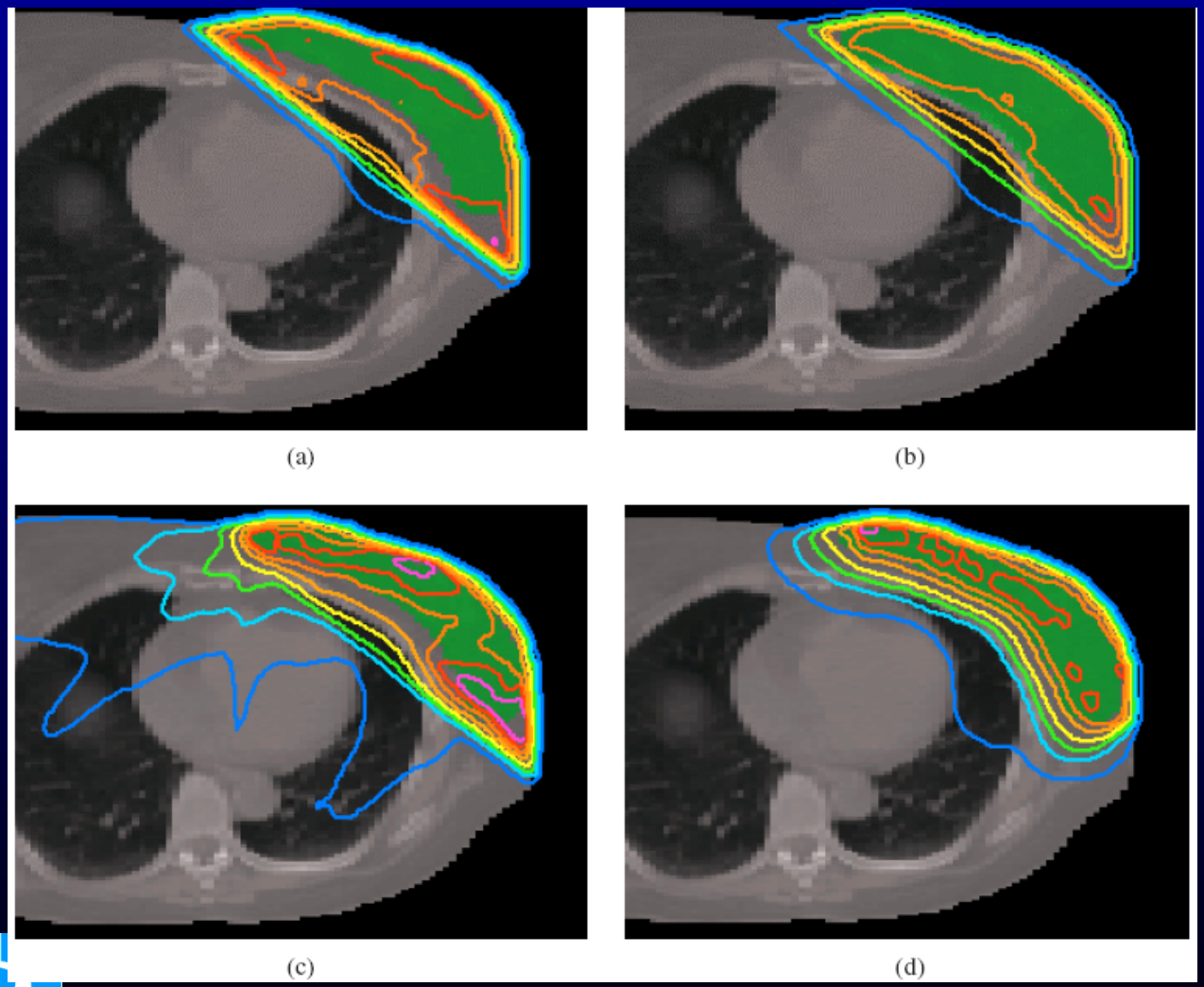


The compact design of the FLEC makes it suitable to be attached to a clinical electron applicator. FLEC can be automated and remotely controlled.

K. Al-Yahiya et al, Phys. Med. Biol. ***50****, (2005), 847-857*

MERT –dose distributions

Ma et al.PMB 48 (2003) 909-924



patient planned using

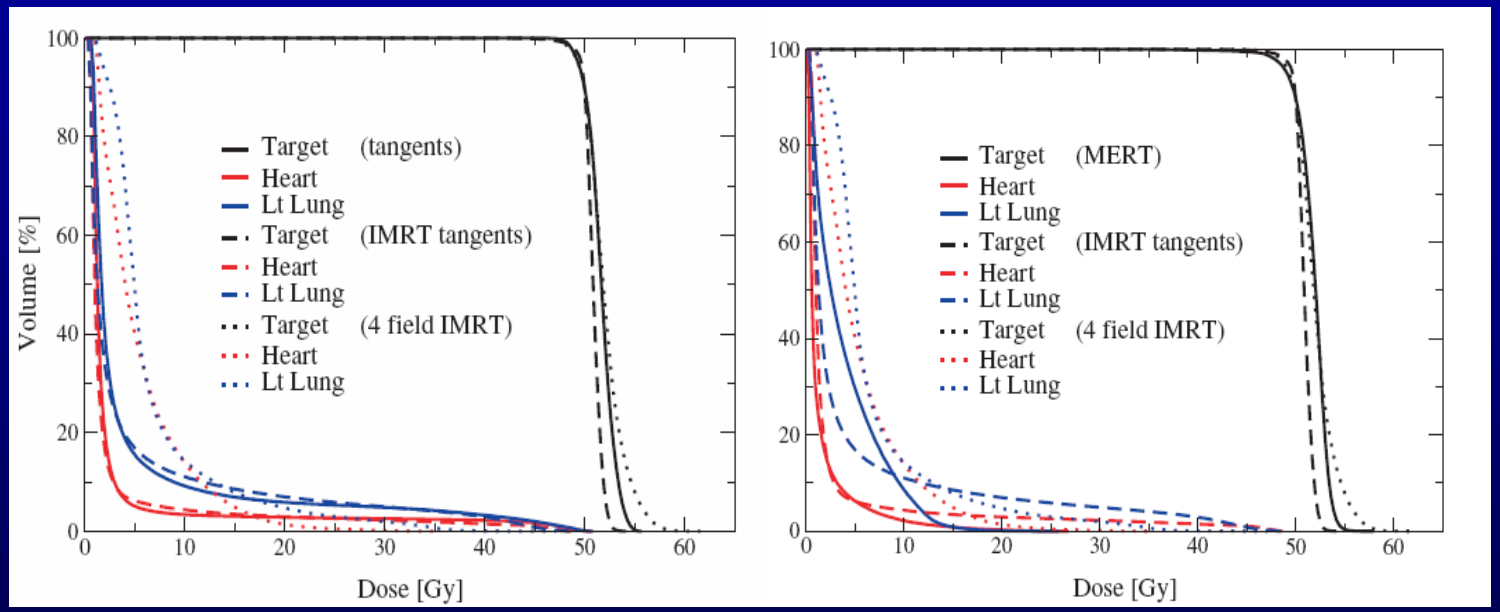
a) wedged tangential photon beams
b) IMRTtangential beams
c) four field IMRT
d) eight field MERT

Isodose lines shown:

55, 52.5, 50, 45, 40, 25, 15 and 5 Gy.

Dose Volume Histograms

Ma et al. PMB 48 (2003) 909-924



DVH for the target, lung and heart for:

a) the three photon beam plans

b) the three IMRTplans for the chest wall patient

- Healthy tissues (non-target volumes) receive the least dose with MERT high dose regions are significantly reduced in normal tissues
- MERT reduces both max cardiac and lung doses by >20 Gy relative to tangents
- Almost no volume receives dose greater than 20 Gy in MERT.
- Electron range increases low lung dose

J.E. Cygler, ACMP 2009

Conclusions

- Commercial MC based TP system are available
  - easy to implement and use
  - MC specific testing required
- Fast and accurate 3-D dose calculations
- Single virtual machine for all SSDs
- Large impact on clinical practice
  - CT based planning for most sites – workload increase; accuracy improved
  - More attention to technical issues needed
  - Dose-to-medium calculated
  - MU based on real patient anatomy (including contour irregularities and tissue heterogeneities)
- Requirement for well educated physics staff

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