Monte Carlo treatment planning for electron beams

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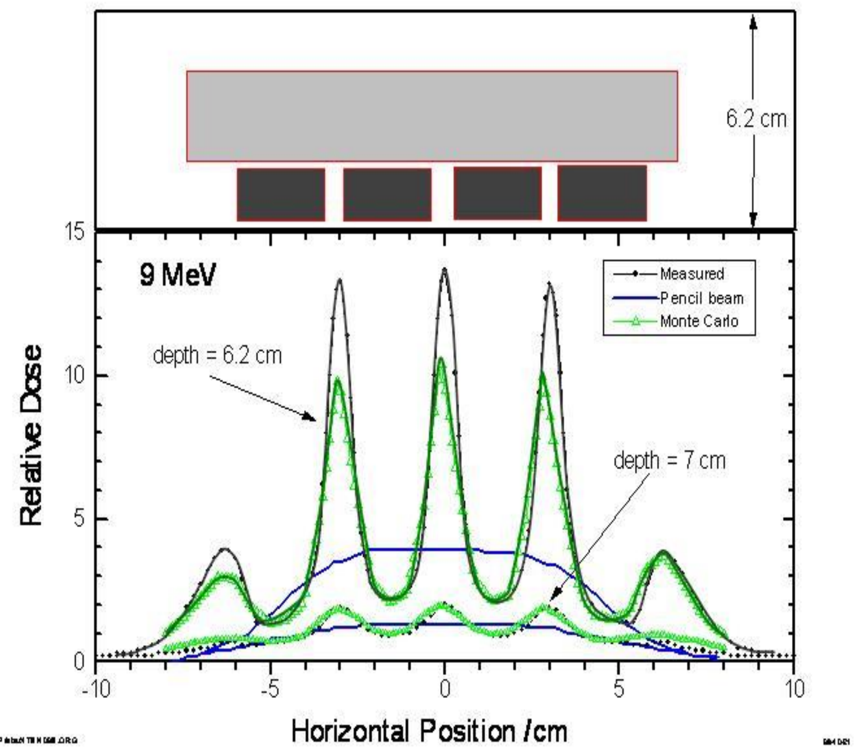
Objectives

- To discuss currently available commercial MC-based treatment planning systems for electron beams.
- To describe commissioning of such systems in terms of beam models and dose calculation modules.
- To discuss the factors associated with MC dose calculation within the patient-specific geometry, such as statistical uncertainties, CT-number to material density assignments, and reporting of dose-to-medium versus dose-to-water.
- To discuss possible clinical impact of MC-based electron beam dose calculations

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 distributions in heterogeneous media have large errors for complex geometries



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

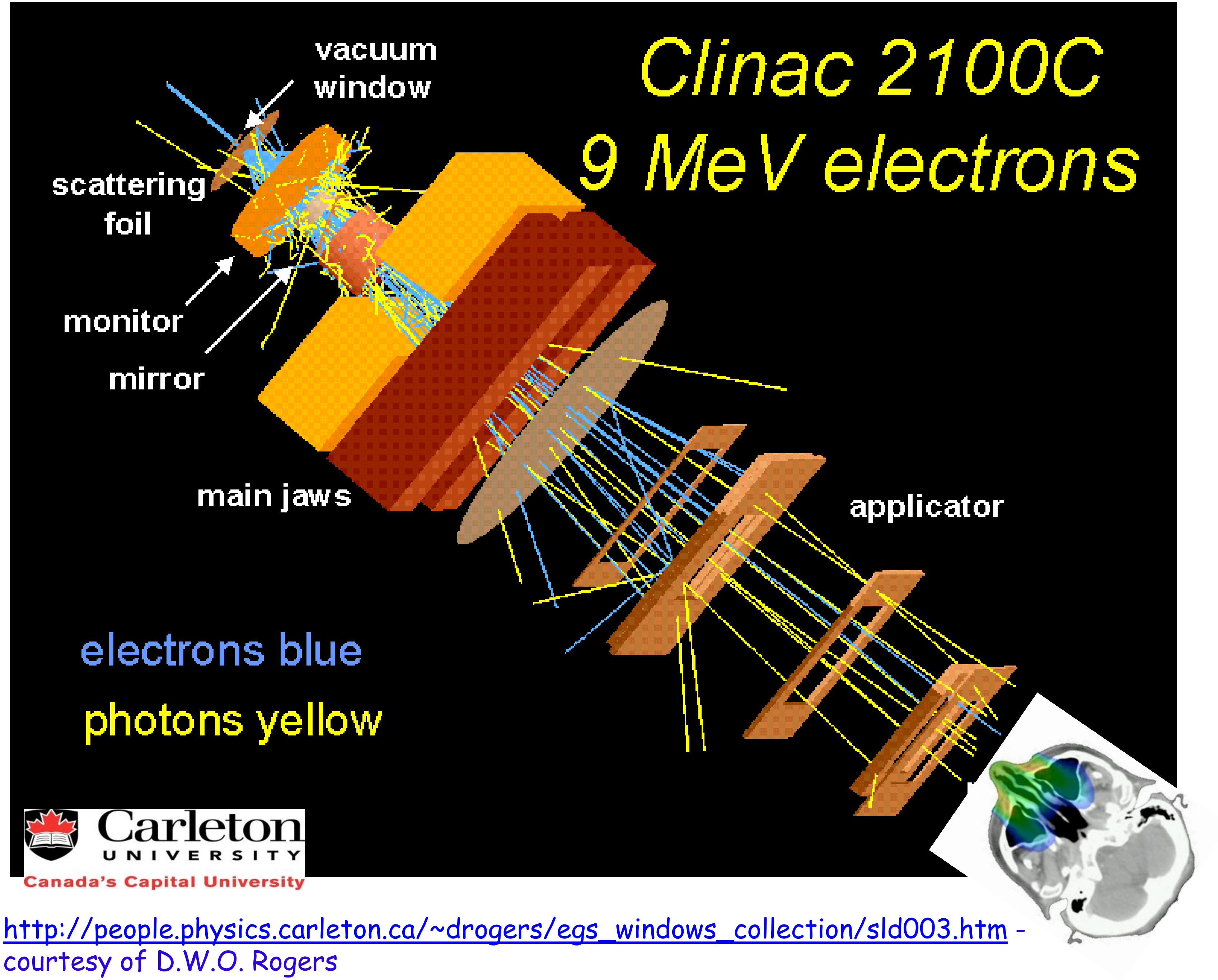
Ding, G. X., et al, Int. J. Rad. Onc. Biol. Phys. (2005) 63:622-633

Components of Monte Carlo based dose calculation system

There are two basic components of MC dose calculation, see the next slide:

1. Particle transport through the accelerator head
   - explicit transport (e.g. BEAM code)
   - accelerator head model (parameterization of primary and scattered beam components)

2. Dose calculation in the patient



http://people.physics.carleton.ca/~drogers/egs_windows_collection/sld003.htm - courtesy of D.W.O. Rogers

Example of a beam model

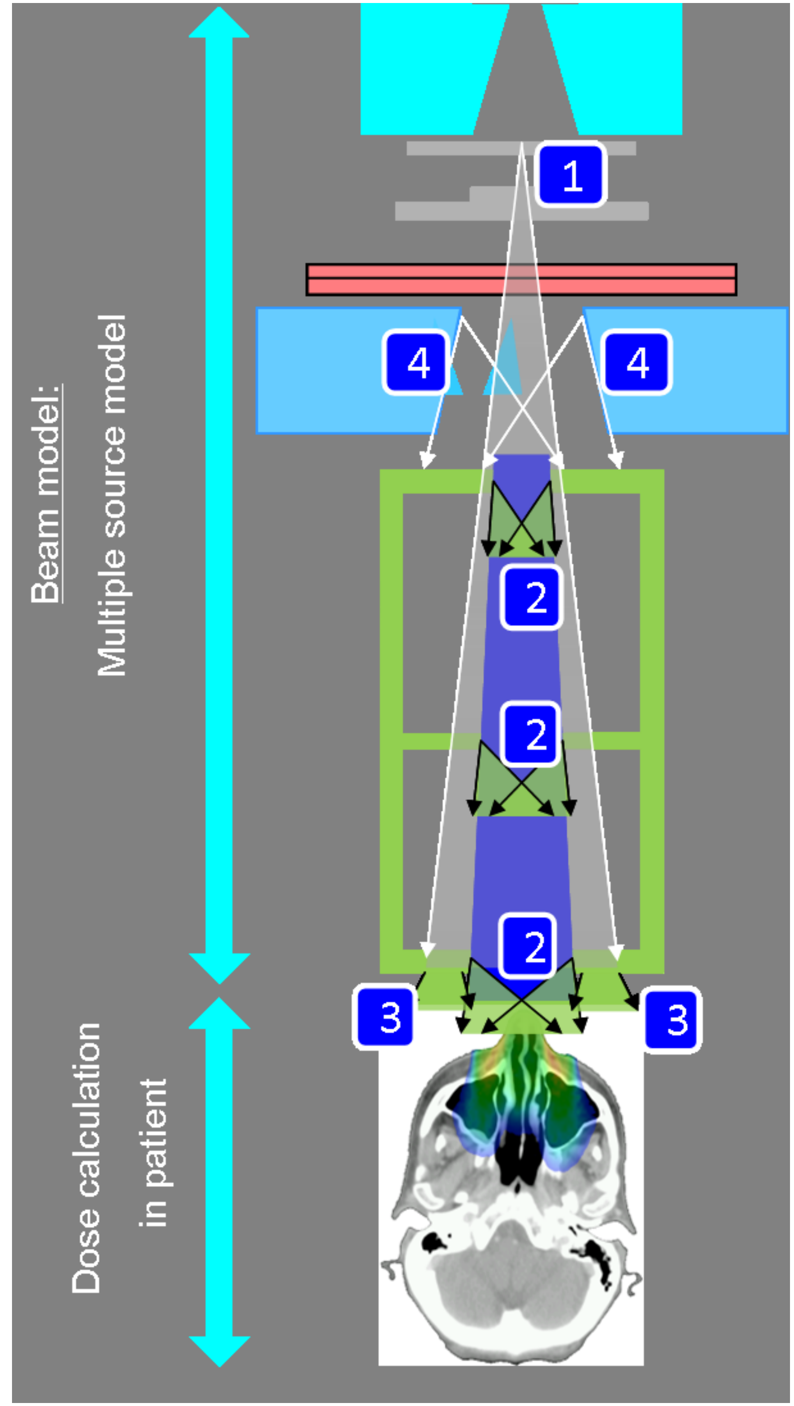
Sub-sources

1 - the main diverging source of electrons and photons;

2 - edge source of electrons;

3 - transmission source of photons;

4 - line source of electrons and photons.

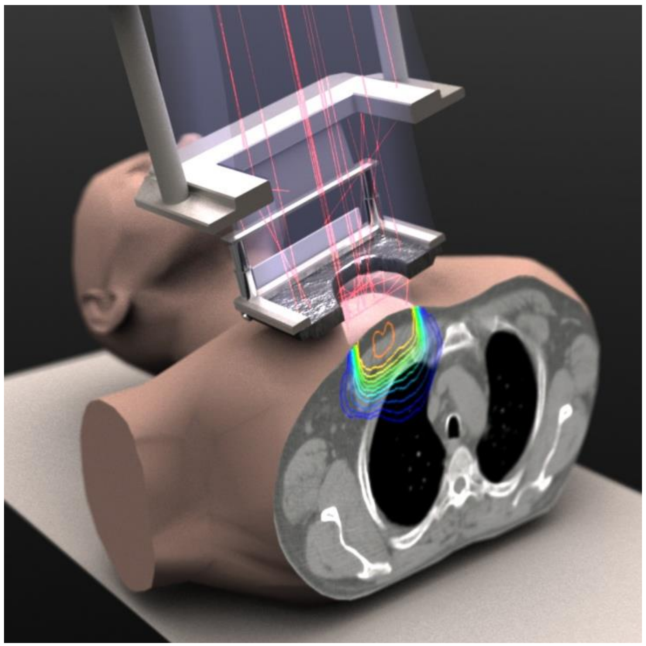


M.K. Fix et al, Phys. Med. Biol. 58 (2013) 2841–2859

Commercial implementations

- MDS Nordion (Nucletron→Elekta) 2001
  - First commercial Monte Carlo treatment planning for electron beams
  - Kawrakow's VMC++ Monte Carlo dose calculation algorithm (2000)
  - Handles electron beams from all clinical linacs
- Varian Eclipse eMC 2004
  - Neuenschwander's MMC dose calculation algorithm (1992)
  - Handles electron beams from Varian linacs only (23EX)
  - work in progress to include beam models for linacs from other vendors (*M.K. Fix et al, Phys. Med. Biol. 58 (2013) 2841–2859)*
- Elekta-CMS XiO eMC for electron beams 2010
  - Based on VMC (Kawrakow, Fippel, Friedrich, 1996)
  - Handles electron beams from all clinical linacs

Nucletron Electron Monte Carlo Dose Calculation Module

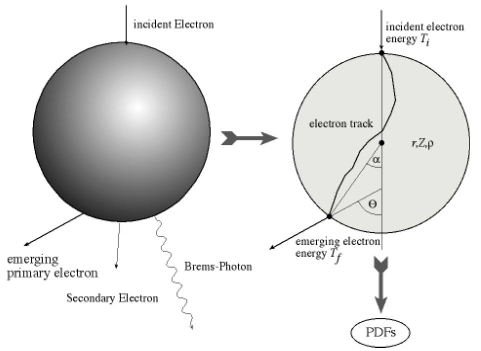


510(k) clearance (June 2002)

- Originally released as part of Theraplan Plus
- Currently sold as part of Oncentra Master Plan
- Fixed applicators with optional, arbitrary inserts, or variable size fields defined by the applicator like DEVA
- Calculates absolute dose per monitor unit (Gy/MU)
- User can change the number of particle histories used in calculation (in terms of particle #/cm^2)
- Data base of 22 materials
- Dose-to-water is calculated in Oncentra
- Dose-to-water or dose-to-medium can be calculated in Theraplan Plus MC DCM
- Nucletron performs beam modeling

Varian Macro Monte Carlo transport model in Eclipse

- An implementation of Local-to-Global (LTG) Monte Carlo:
  - Local: Conventional MC simulations of electron transport performed in well defined local geometries (“kugels” or spheres).
    - Monte Carlo with EGSnrc Code System - PDF for “kugels”
    - 5 sphere sizes (0.5-3.0 mm)
    - 5 materials (air, lung, water, Lucite and solid bone)
    - 30 incident energy values (0.2-25 MeV)
    - PDF table look-up for “kugels”

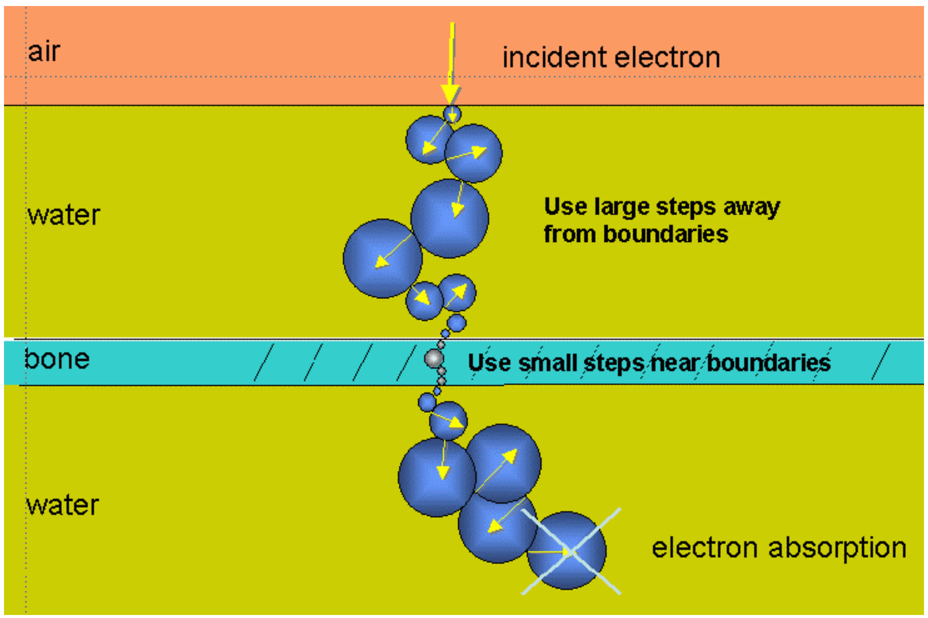


This step is performed off-line.

  - Global: Particle transport through patient modeled as a series of macroscopic steps, each consisting of one local geometry (“kugel”)

from C. Zankowski et al “Fast Electron Monte Carlo for Eclipse”

Varian Macro Monte Carlo transport model in Eclipse



- Global geometry calculations
  - CT images are pre-processed to user defined calculation grid
  - HU in CT image are converted to mass density
  - The maximum sphere radius and material at the center of each voxel is determined
    - Homogenous areas → large spheres
    - In/near heterogeneous areas → small spheres

from C. Zankowski et al "Fast Electron Monte Carlo for Eclipse"

Varian Eclipse Monte Carlo

- User can control
  - Total number of particles per simulation
  - Required statistical uncertainty
  - Random number generator seed
  - Calculation voxel size (several sizes available)
  - Isodose smoothing on / off
    - Methods: 2-D Median, 3-D Gaussian
    - Levels: Low, Medium, Strong
- Dose-to-medium is calculated

Elekta - CMS XiO Monte Carlo system

- XiO eMC module is based on the early VMC* code
  - simulates electron (or photon) transport through voxelized media
- The beam model and electron air scatter functions were developed by CMS
- The user can specify
  - voxel size
  - dose-to-medium or dose-to-water
  - random seed
  - total number of particle histories per simulation
  - or the goal Mean Relative Statistical Uncertainty (MRSU)
  - minimum value of dose voxel for MRSU specification
- CMS performs the beam modeling

**Kawrakow, Fippel, Friedrich, Med. Phys. 23 (1996) 445-457;*
**Fippel, Med. Phys. 26 (1999) 1466–1475*

Clinical implementation of MC treatment planning software

- Beam data acquisition and fitting
- Software commissioning tests*
  - Beam model verification
  - Dose profiles and MU calculations in a homogeneous water tank
  - In-patient dose calculations
- Clinical implementation
  - procedures for clinical use
  - possible restrictions
  - staff training

**should include tests specific to Monte Carlo*

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

User input data for MC based 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

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

User input data for MC TPS *cont.*

Dosimetric data for beam characterization (beam model), as specified in User Manual, for example:

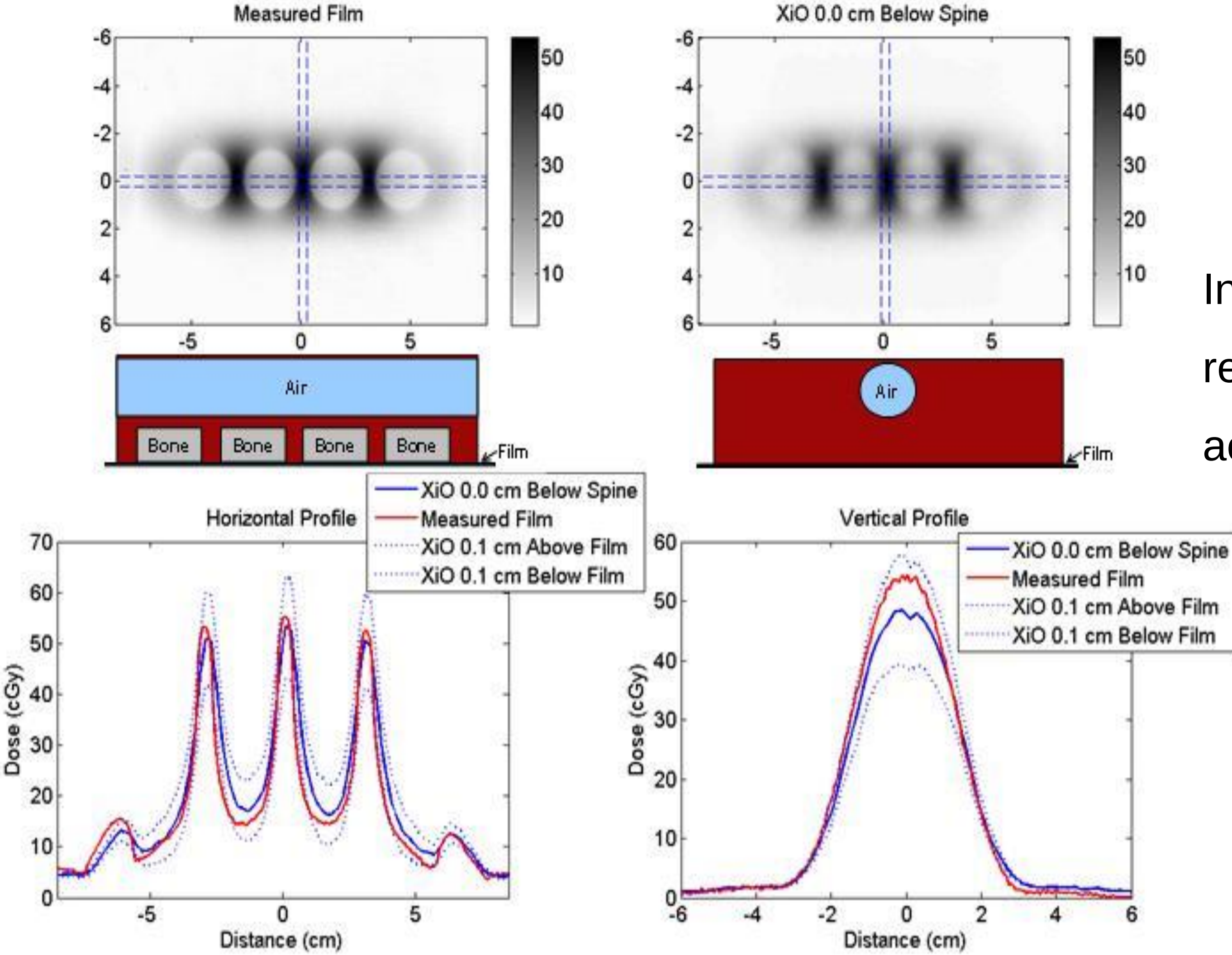
- Beam profiles without applicators:
  - in-air profiles for various field sizes
  - in-water profiles
    - central axis depth dose for various field sizes
    - some lateral profiles
- Beam profiles with applicators:
  - Central axis depth dose and profiles in water
  - Absolute dose at the calibration point
- Dosimetric data for verification
  - Central axis depth doses and profiles for various field sizes

Software commissioning tests: goals

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

XiO: 9 MeV - Trachea and spine

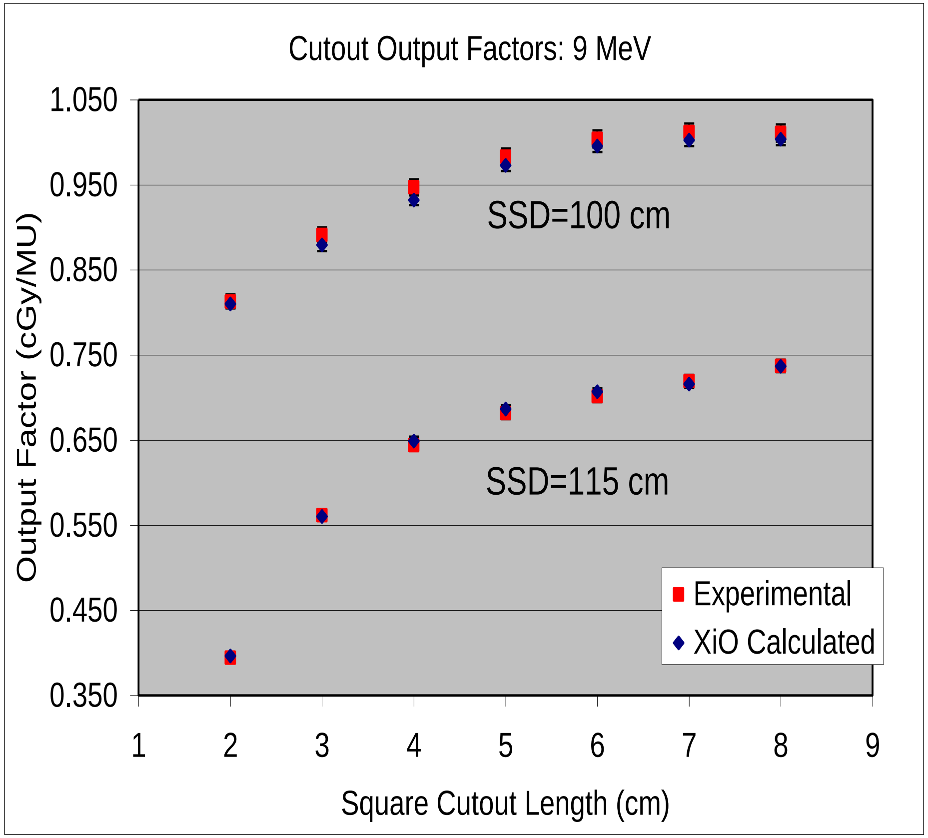
importance of high quality data

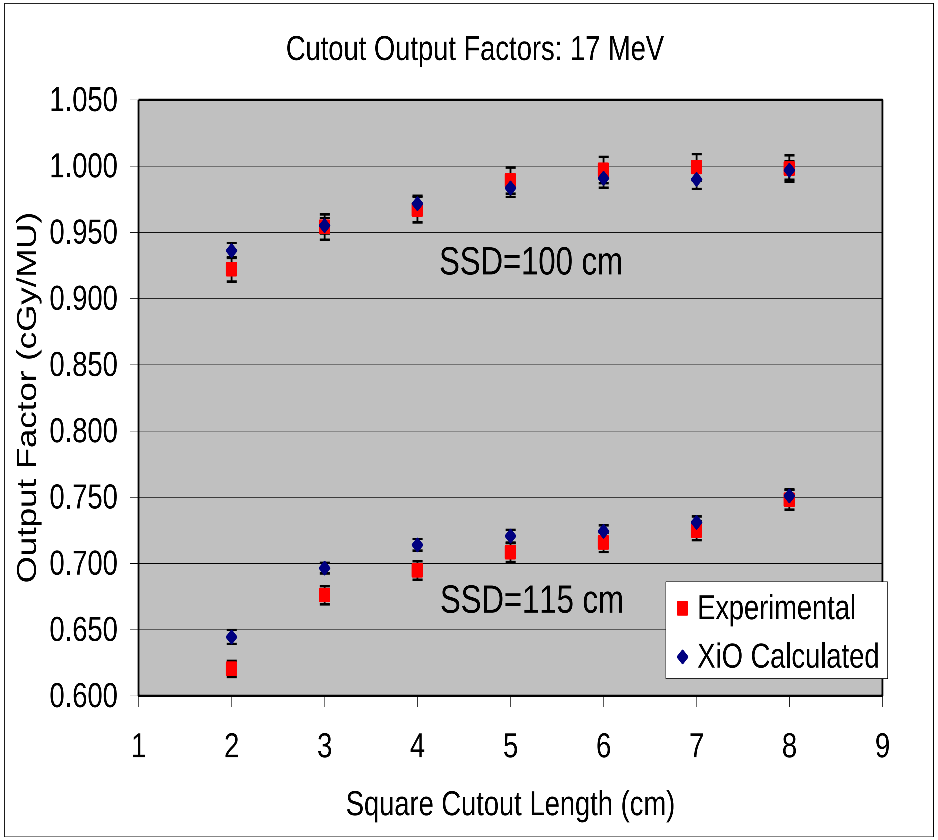


In high-dose-gradient region sub-millimetre accuracy is required

Vandervoort and Cygler, COMP 56th Annual Scientific Meeting, Ottawa, June 2010

Example of beam model verification CMS eMC: cutout factors



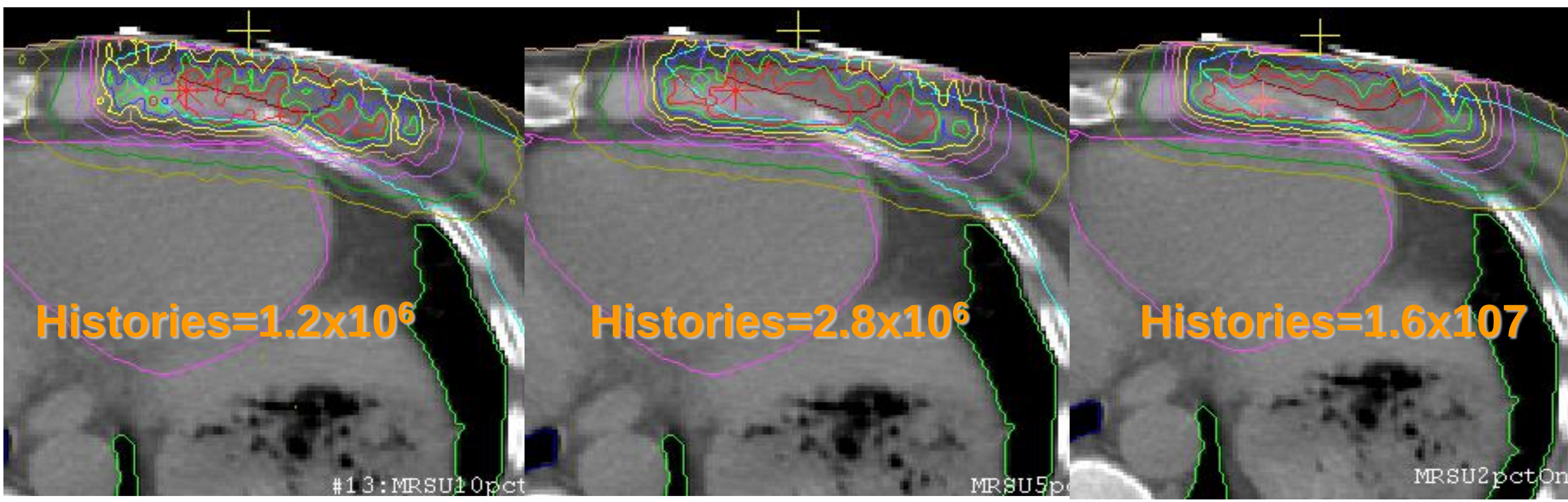


Vandervoort and Cygler, COMP 56th Annual Scientific Meeting, Ottawa, June 2010

Monte Carlo settings: noise in the dose distributions

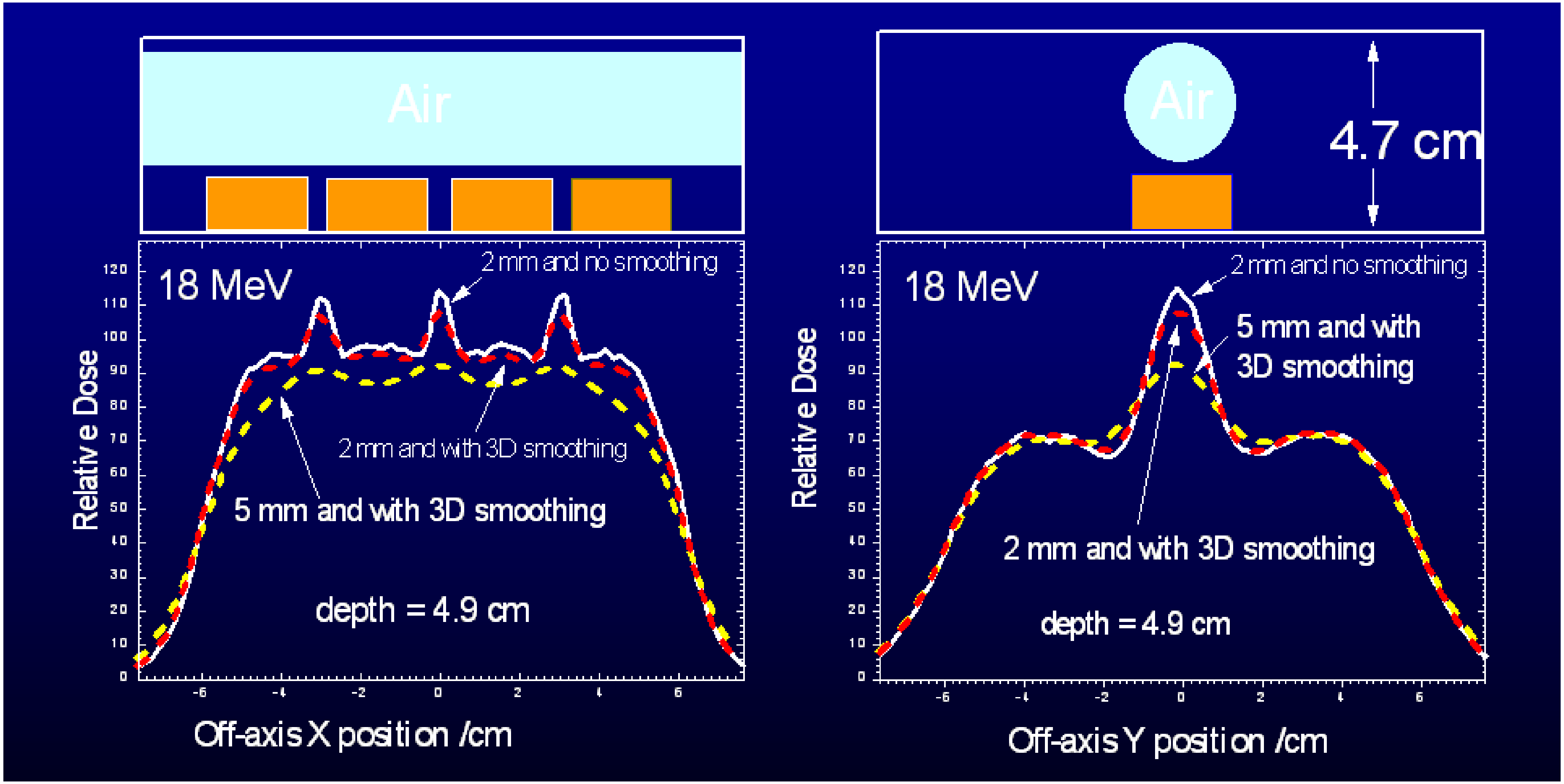
Effect of Mean Relative Statistical Uncertainty (MRSU):

6 MeV beam, 10x10 cm2 applicator, voxel size=$2.5 \times 2.5 \times 2.5$ mm^3, dose-to-medium



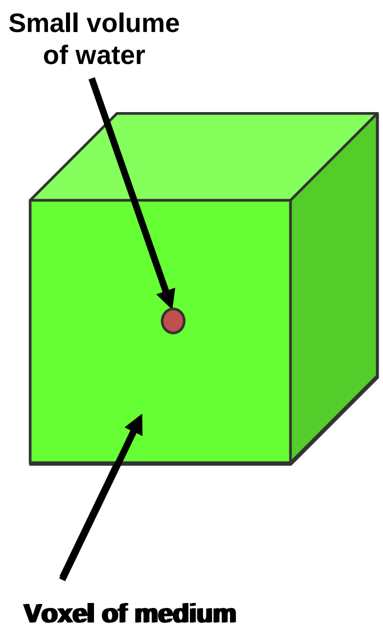
MRSU=10% MRSU=5% MRSU=2%

Eclipse eMC
Effect of voxel size and smoothing



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

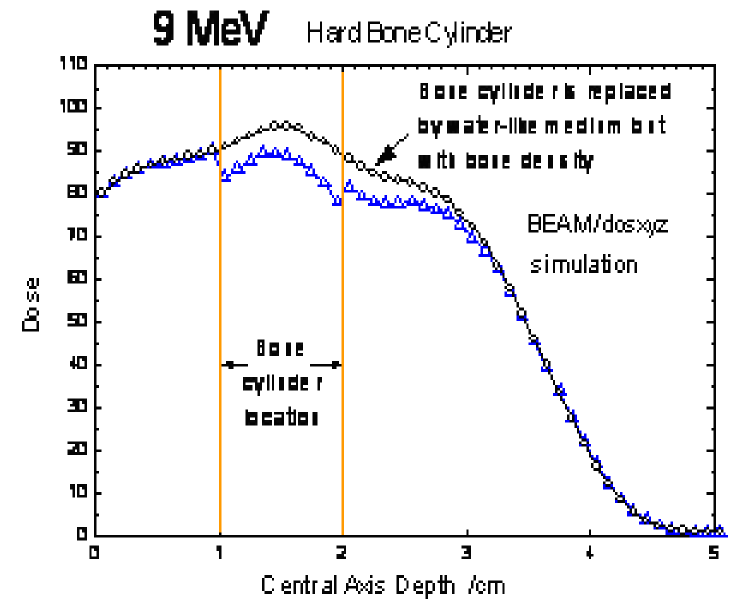
Dose-to-water vs. dose-to-medium

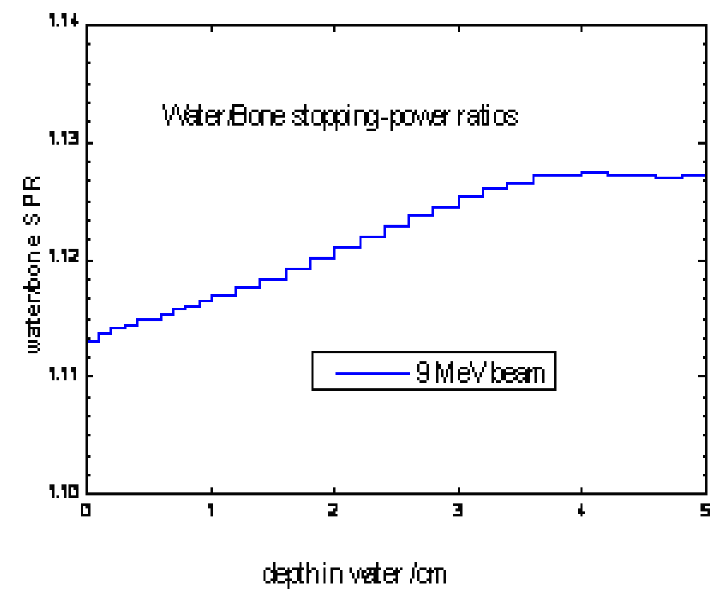


D_m - energy absorbed in a medium voxel divided by the mass of the medium element.

D_w - energy absorbed in a small cavity of water divided by the mass of that cavity.

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



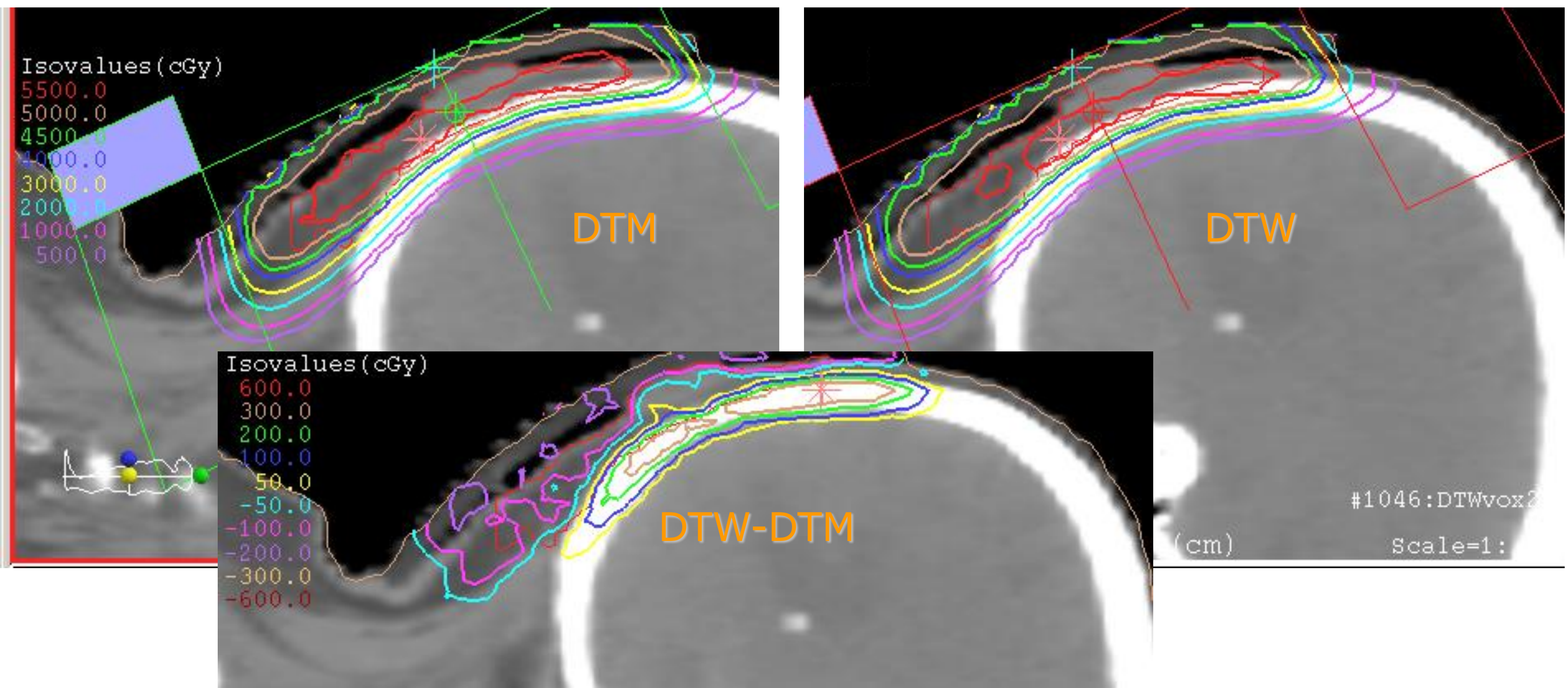


Ding, G X., et al Phys. Med. Biol. 51 (2006), 2781-2799

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

6 MeV beam, 15x15 cm^2 applicator, both 602 MU

MRSU=2%, voxel size=$4 \times 4 \times 4$ mm^3

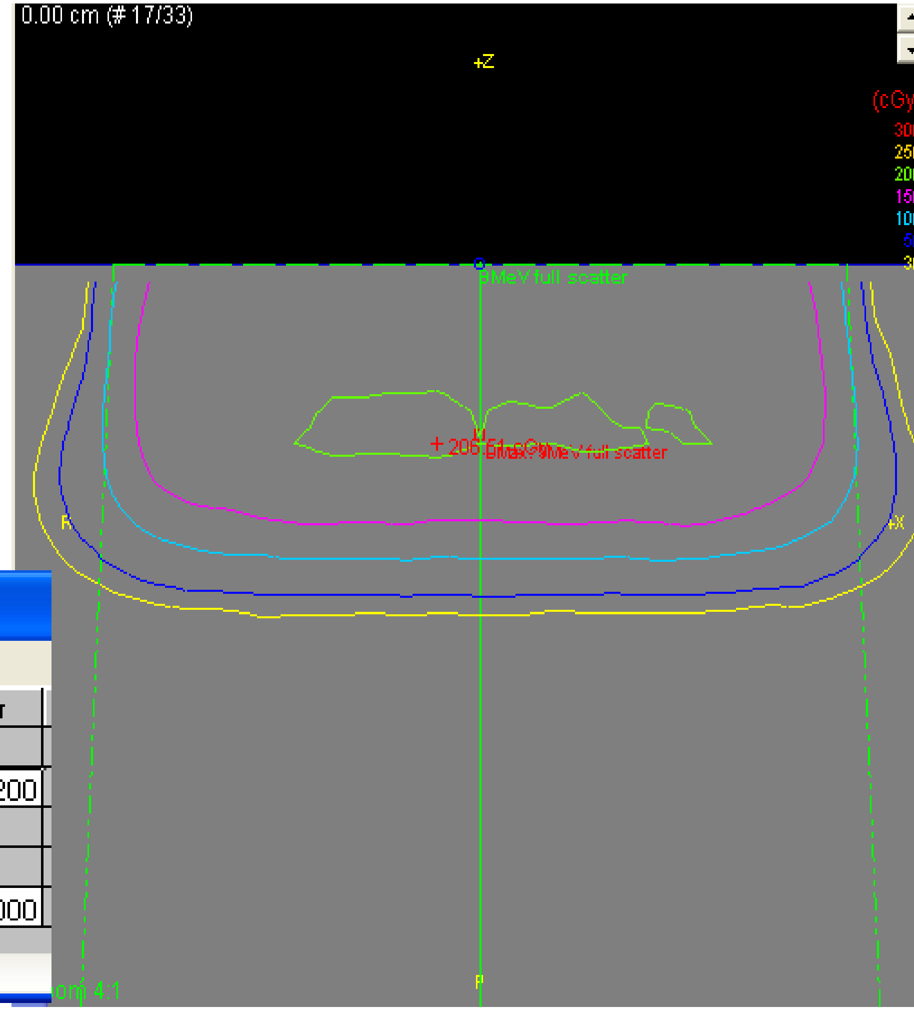


MU - MC vs. hand calculations

Monte Carlo	Hand calculations
Real physical dose calculated on a patient anatomy	Rectangular water tank
Heterogeneity 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

100% isodose at the <u>nominal (reference)</u> dmax depth

Lateral scatter missing

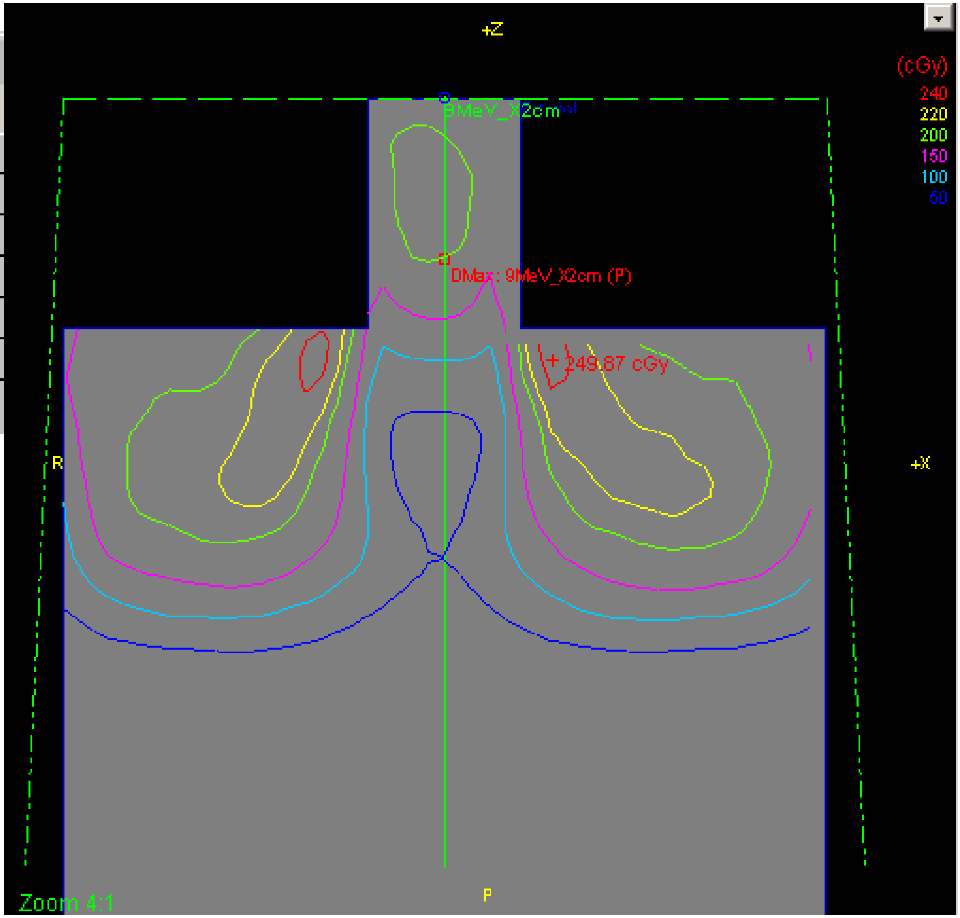
Point Dose Data

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

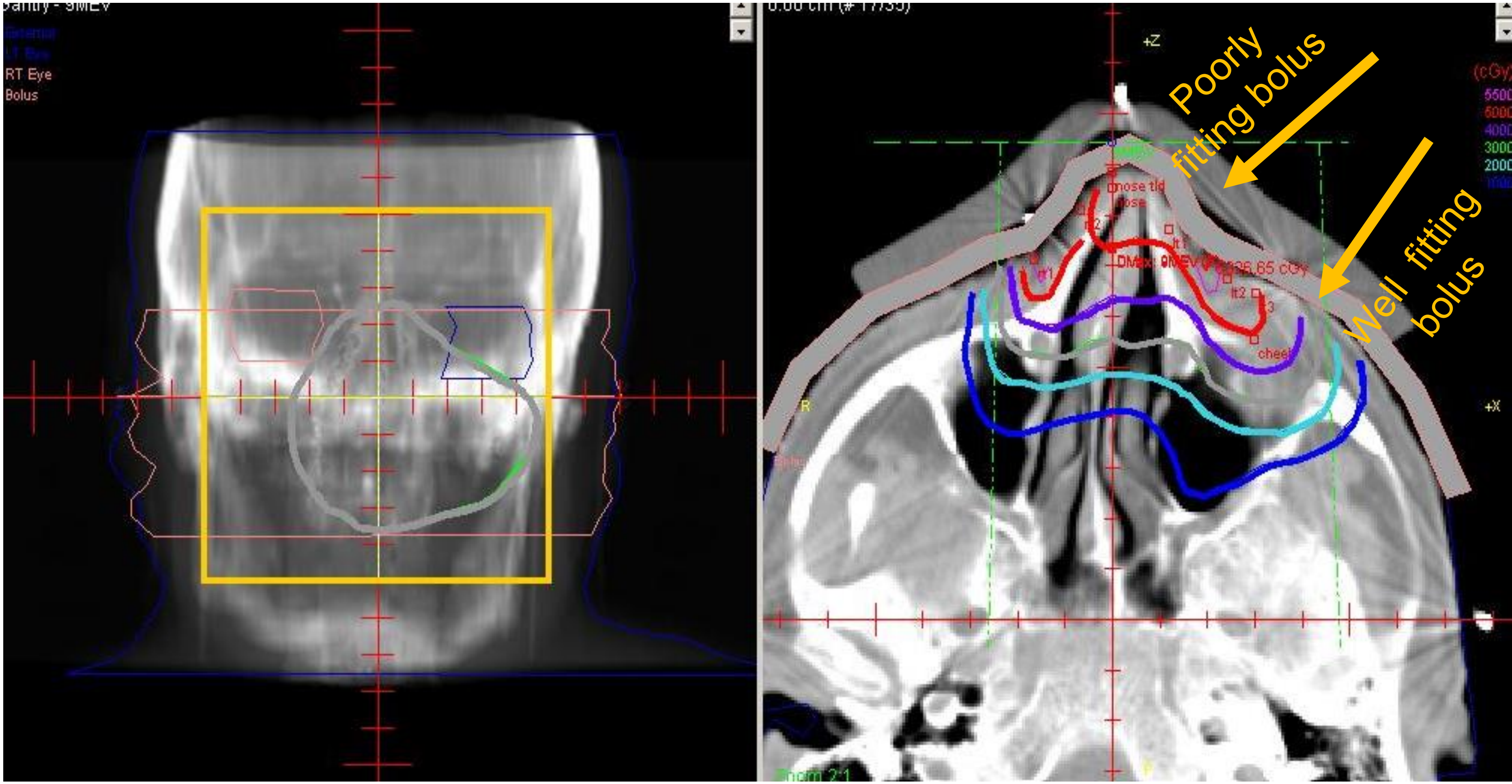


Real contour / Water tank =

=234MU / 200MU=1.17

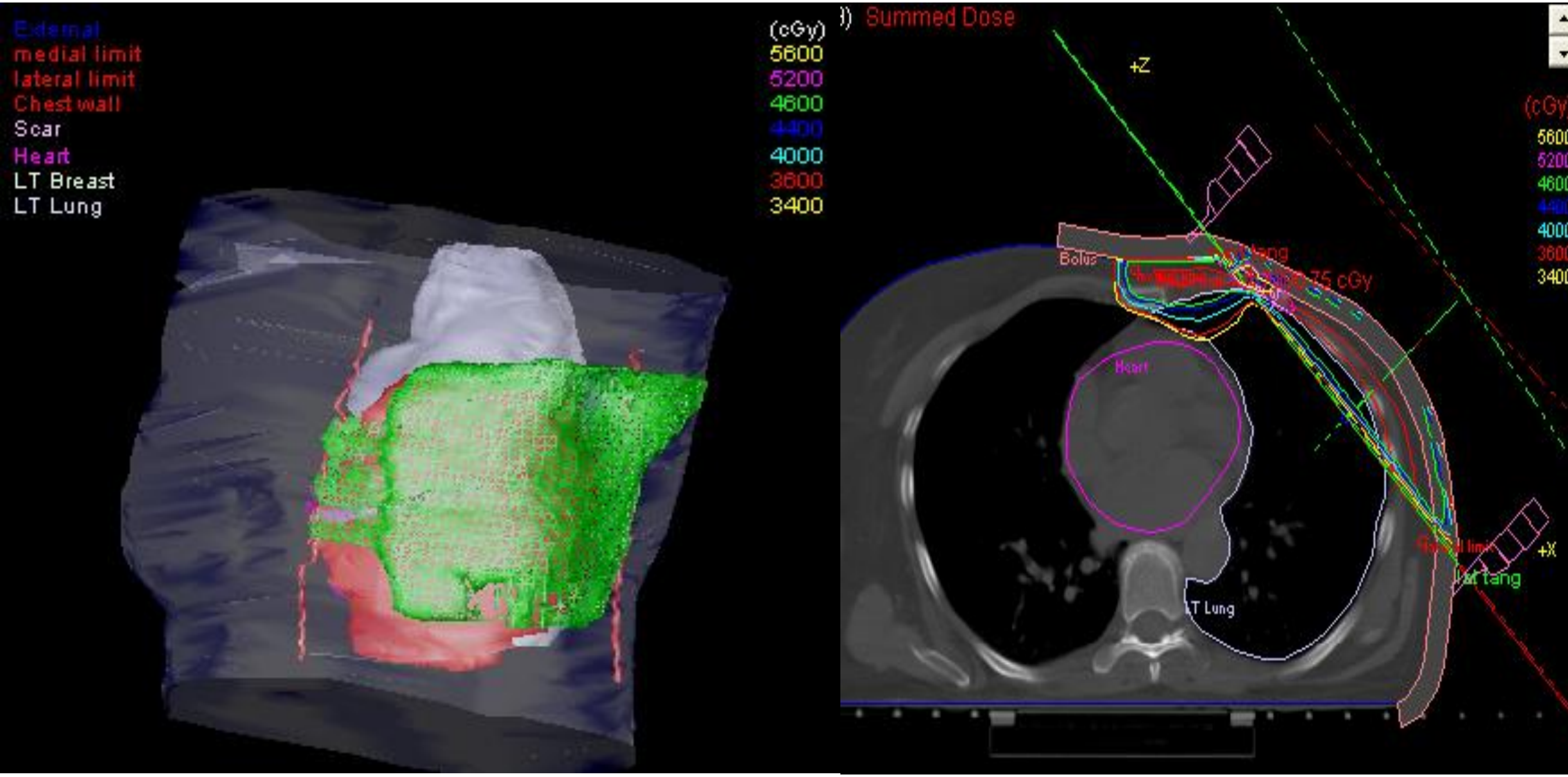
Reason for more MU: % isodose at the <u>nominal (reference)</u> d_{max} depth is less than 100%

MU real patient vs.water tank



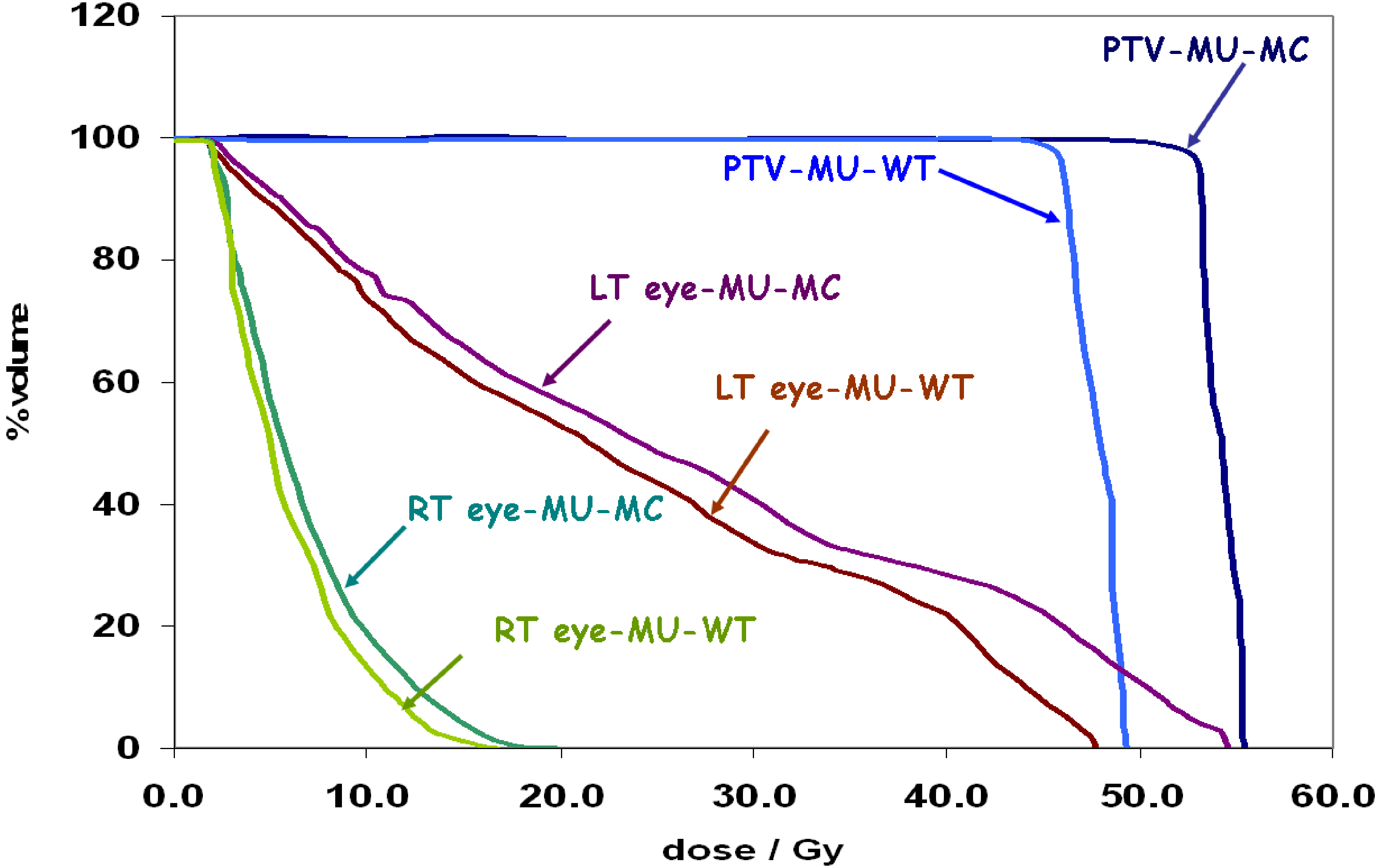
MC / Water tank= 292 / 256=1.14

Internal mammary nodes

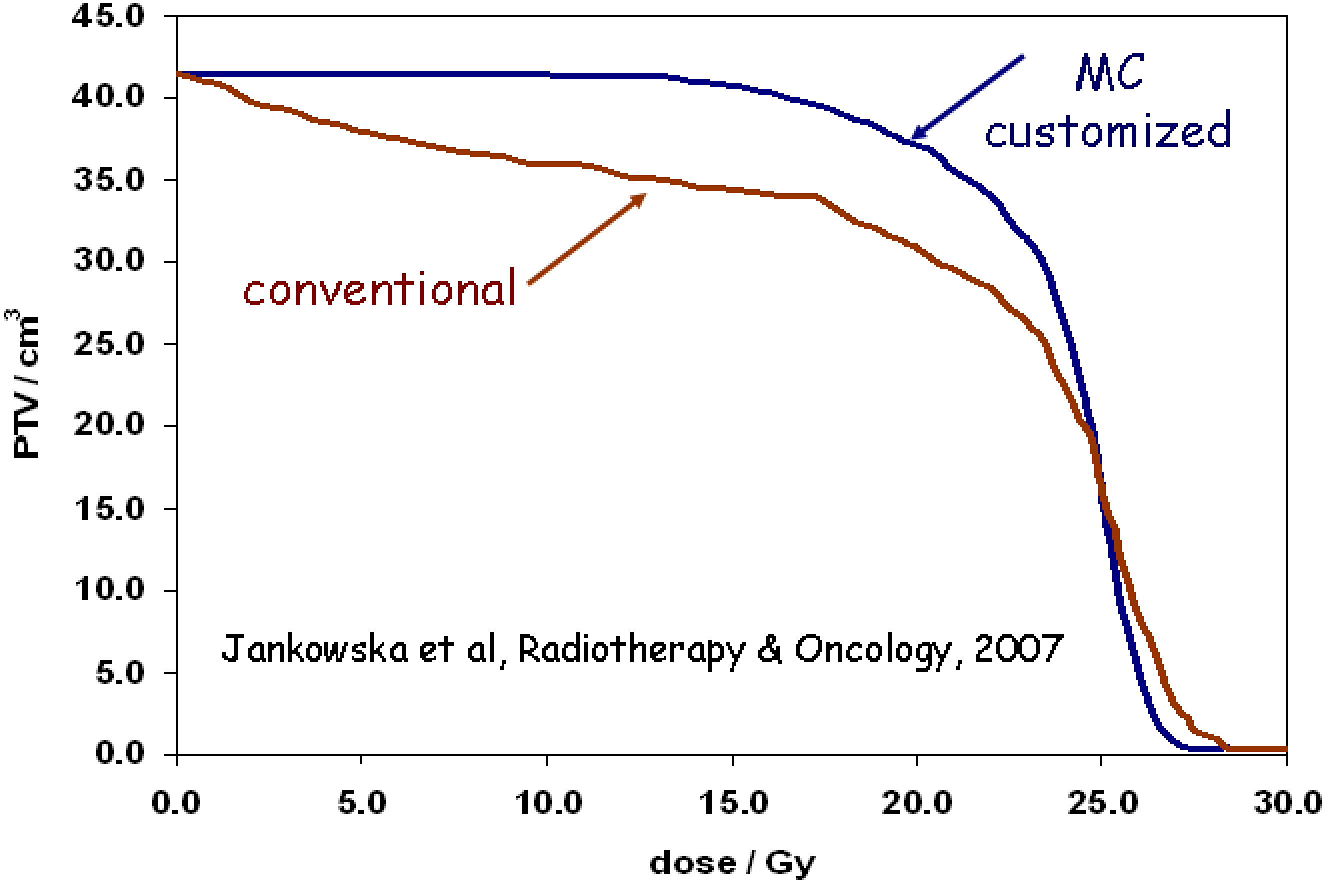


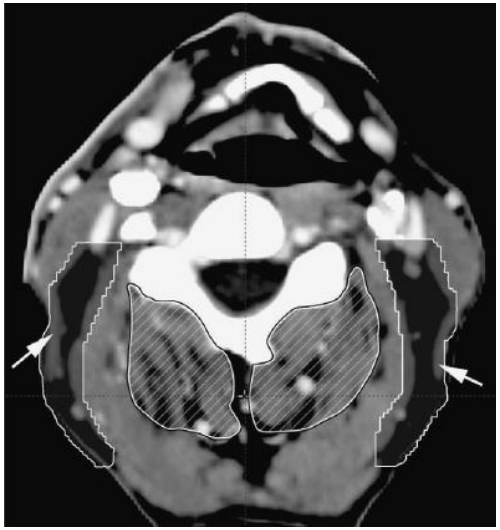
MC / Water tank= 210 / 206=1.019

MU-real patient vs. water tank: Impact on DVH



Posterior cervical lymph node irradiation - impact on DVH





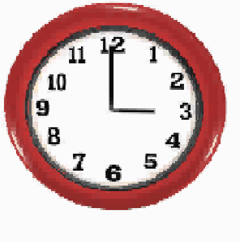
MU eMC vs. pencil beam

	Smoothing				
	None	*Low*	*Medium*	*Strong*	
Patient	*eMC*				*PB*
1 (neck)	120	128	134	138	147
2 (head)	192	198	204	210	224
3 (breast boost)	204	208	215	221	224
4 (breast boost)	192	199	200	202	201
5 (breast boost)	189	192	195	198	199
6 (breast boost)	187	192	196	199	200
7 (breast boost)	176	179	183	188	201
8 (breast boost)	212	219	225	229	222
9 (chest wall)	195	203	204	213	220
10 (melanoma in sternum)	421	429	436	440	448
11 (breast boost)	193	199	205	208	212
12 (internal mammary node)	56	57	59	59	61
13 (breast boost)	186	189	192	194	199
14 (breast boost)	204	206	214	216	224
15 (breast boost)	192	200	207	214	222

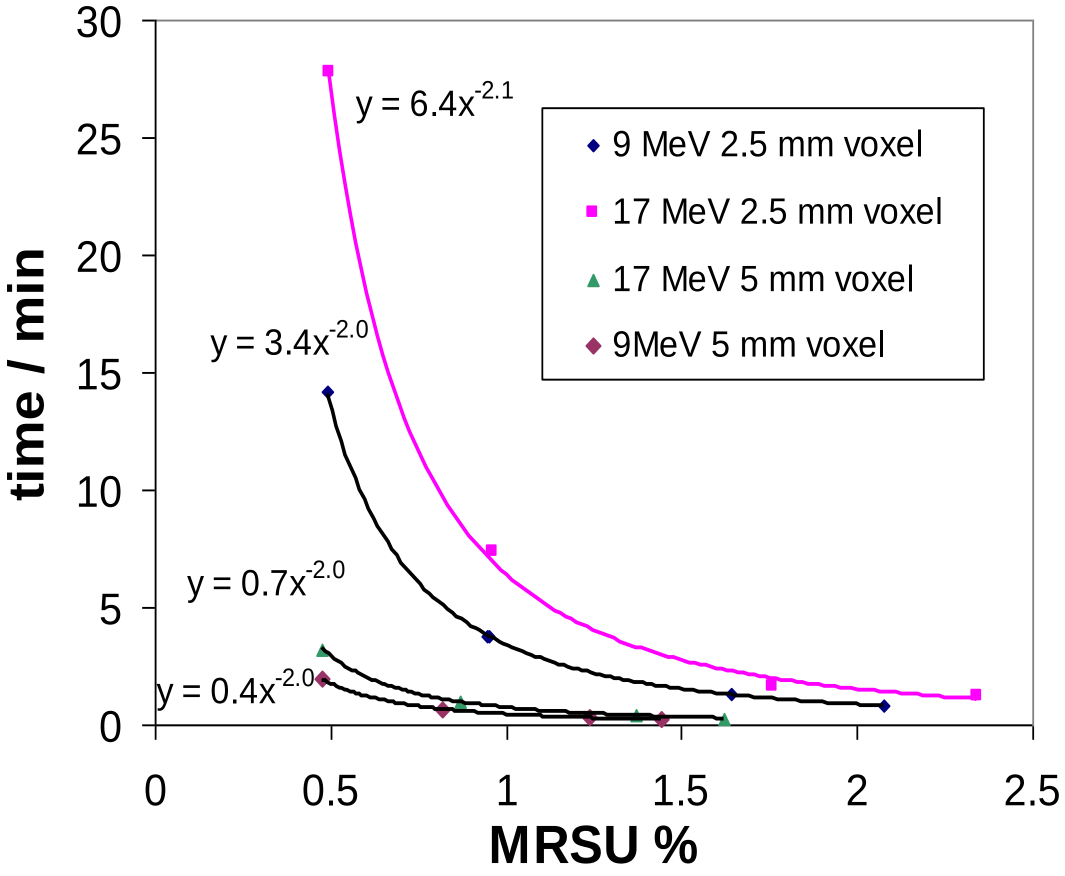
Zhang, A., (2013), J. .Appl. Clin. Med. Phys., 14, (2), 127-145

How long does it take?

- MC gives entire dose distribution in the irradiated volume, not just a few points
- time for N beams is the same as for 1 beam
- timing is a complex question since it depends on
  – statistical uncertainty and how it is defined
  – voxel size
  – field size
  – beam energy and whether photons or electron
  – speed of CPU and optimization of compiler
  - complexity of patient specific beam modifiers



Monte-Carlo Settings: Effect on computation time



Timing Results XiO TPS:

For 9 and 17 MeV beams, 10x10 cm^2 applicator and the trachea and spine phantom, timing tests were performed for a clinical XiO Linux workstation, which employs 8 processors, 3 GHz each, with 8.29 GB of RAM.

Cygler, J.E., and Ding, G.X., in Monte Carlo Techniques in Radiation Therapy, ISBN-10: 1466507926, Taylor & Francis (CRC Press INC) Boca Raton 2013, p 155-166

Timing – Nucletron TPS Oncentra 4.0

Anatomy - 201 CT slices
Voxels 3 mm^3
10x10 cm^2 applicator
50k histories/cm^2

System

Manufacturer:	Hewlett-Packard Company
Model:	HP Z800 Workstation
Rating:	6.1 Windows Experience Index
Processor:	Intel(R) Xeon(R) CPU E5520 @ 2.27GHz 2.26 GHz
Installed memory (RAM):	12.0 GB
System type:	64-bit Operating System

4 MeV Timer Results:
Init = 0.321443 seconds
Calc = 42.188 seconds
Fini = 0.00158201 seconds
Sum = 42.5111 seconds

20 MeV Timer Results:
Init = 0.311014 seconds
Calc = 110.492 seconds
Fini = 0.00122603 seconds
Sum = 110.805 seconds

Faster than pencil beam!

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

Summary

- Commercial MC based TP systems are available
  - fairly easy to implement and use
  - MC specific testing required
- Fast (minutes) and accurate 3-D dose calculations
- Single virtual machine for all SSDs
- Large impact on clinical practice
  - Accuracy of dose calculation improved
  - More attention to technical issues needed
  - Dose-to-medium is calculated, although some systems calculate dose-to-water as well
  - MU based on real patient anatomy (including contour irregularities and tissue heterogeneities)
- Requirement for well educated physics staff

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    J. .Appl. Clin. Med. Phys., 14, (2), 127-145

Thank you