Monte Carlo treatment planning in the clinic - successes and challenges

Part II-electron beams

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Objectives – electron beams

- Currently available commercial MC-based treatment planning systems for electron beams.
- Commissioning of such systems in terms of beam models and dose calculation modules.
- 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.
- 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 distribution in inhomogeneous media has large errors for complex geometries

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

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

Monte Carlo based Treatment Planning Systems

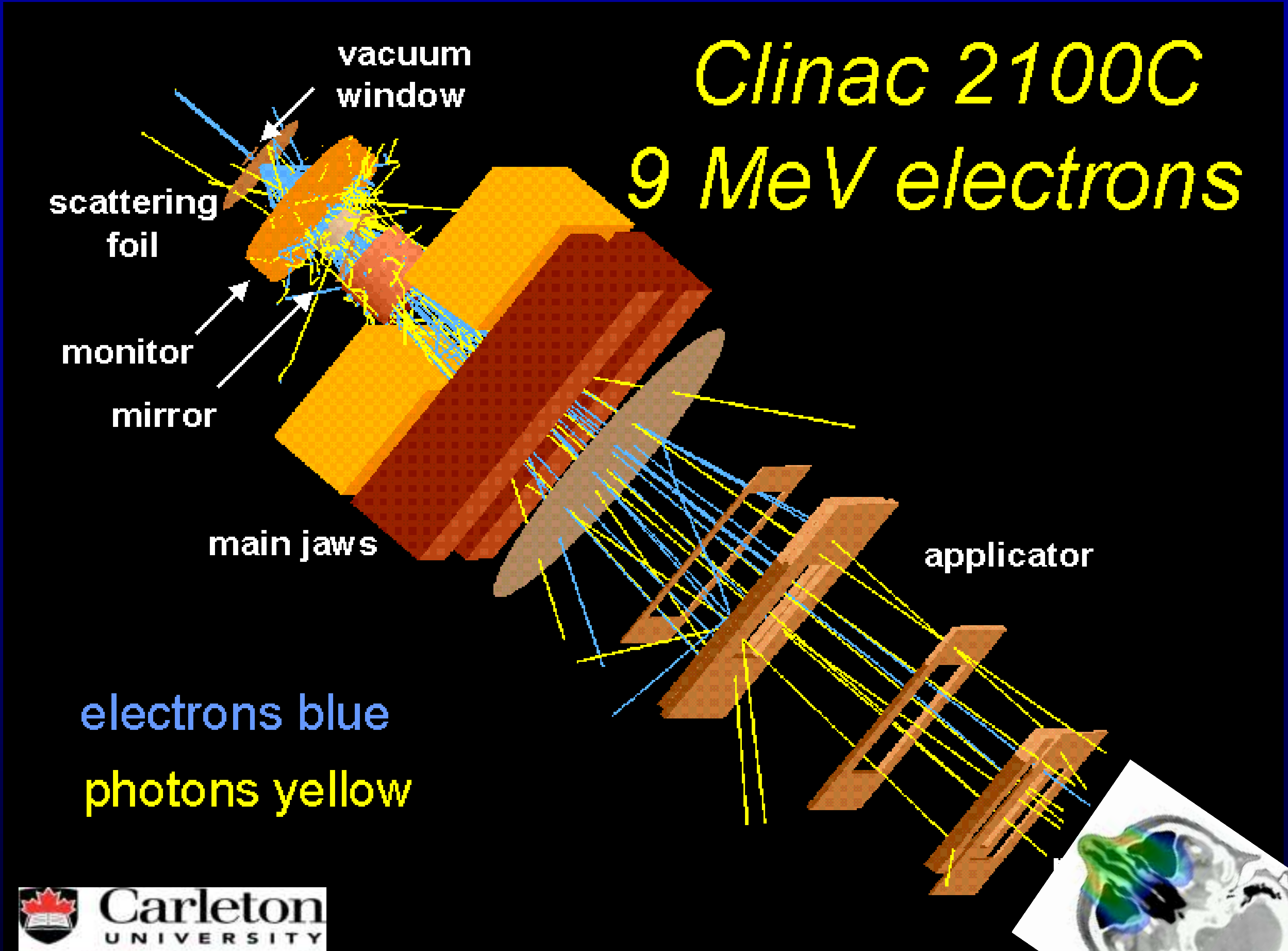
M C dose calculations give in general the right answer

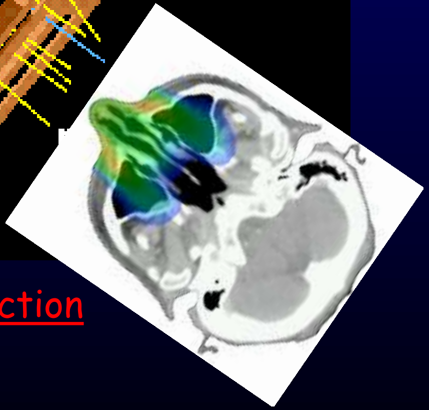
- There are no significant approximations
  - no approximate scaling of kernels is needed
  - electron transport is fully modelled
  - geometry can be modelled as exactly as we know it
  - all types of heterogeneities can be properly handled
- There are many experimental benchmarks showing M C calculations can be very accurate (see the references)

Components of Monte Carlo based dose calculation system

There are two basic components of MC dose calculations, 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

Particle transport through the machine head - beam models

- Direct MC simulation of the accelerator head
  - beam simulations can be done accurately if all the parameters are known - but they often are not

- Beam models provide a solution to the above problem
  - is any algorithm that delivers the location, direction and energy of particles to the patient dose-calculating algorithm.

Example of a beam model

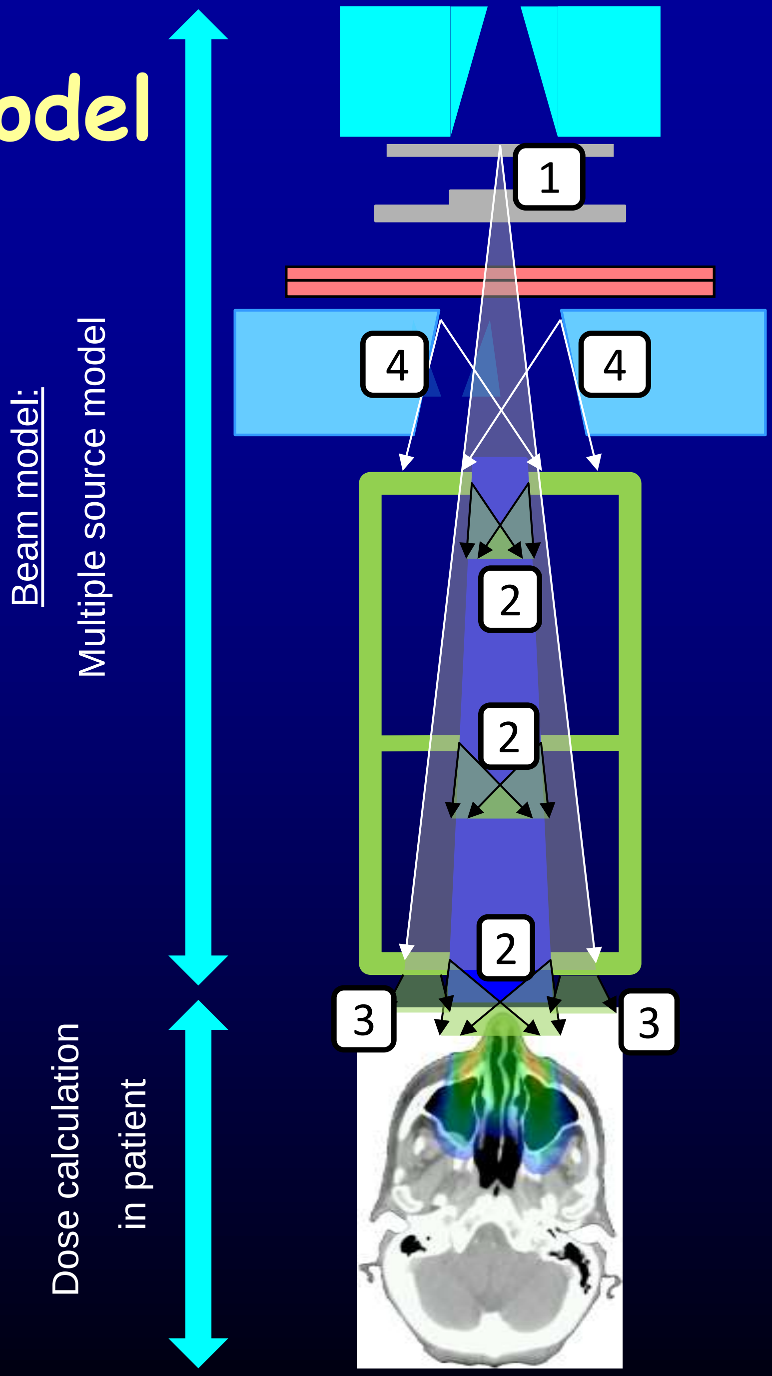
Sub-sources

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.



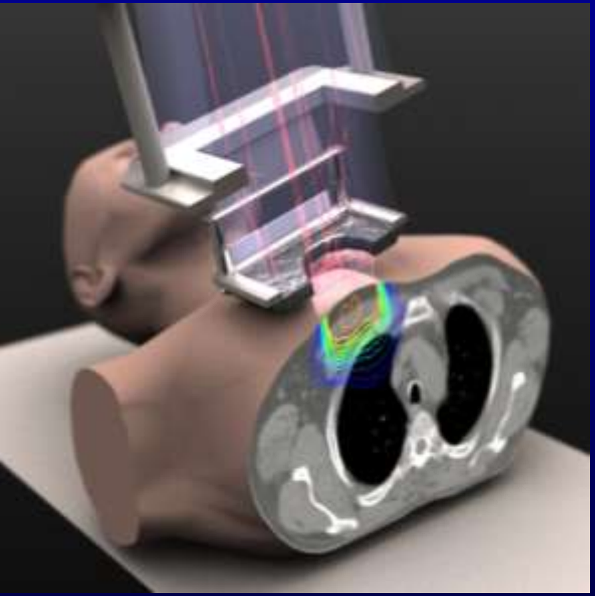
M.K. Fix et al,

Phys. Med. Biol. 58 (2013) 2841-2859

Commercial implementations

- MDS Nordion (Nucletron – now 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)*
- CMS (now Elekta) 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



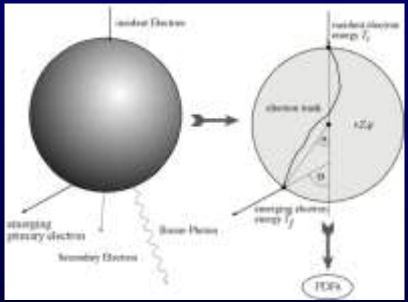
510(k) clearance (June 2002)

- 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"

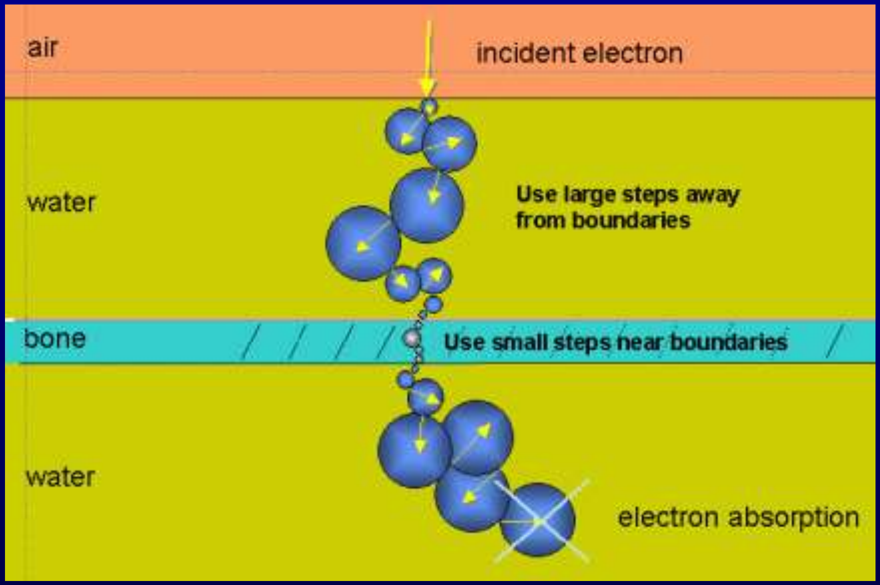
    The above step is performed off-line.



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

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

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

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
- CMS performs the beam modeling
- 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

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

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

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

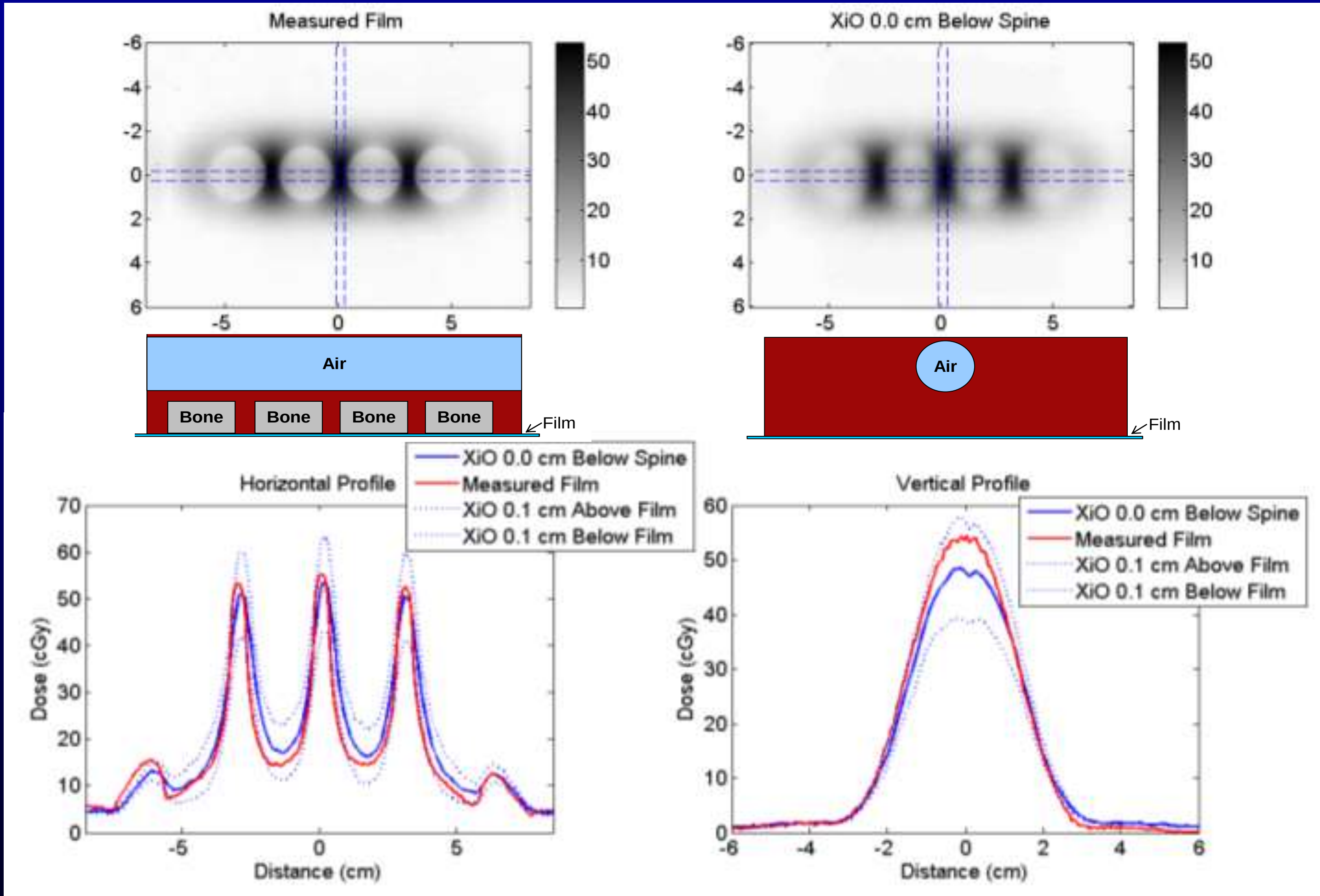
**should include tests specific to Monte Carlo*

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

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

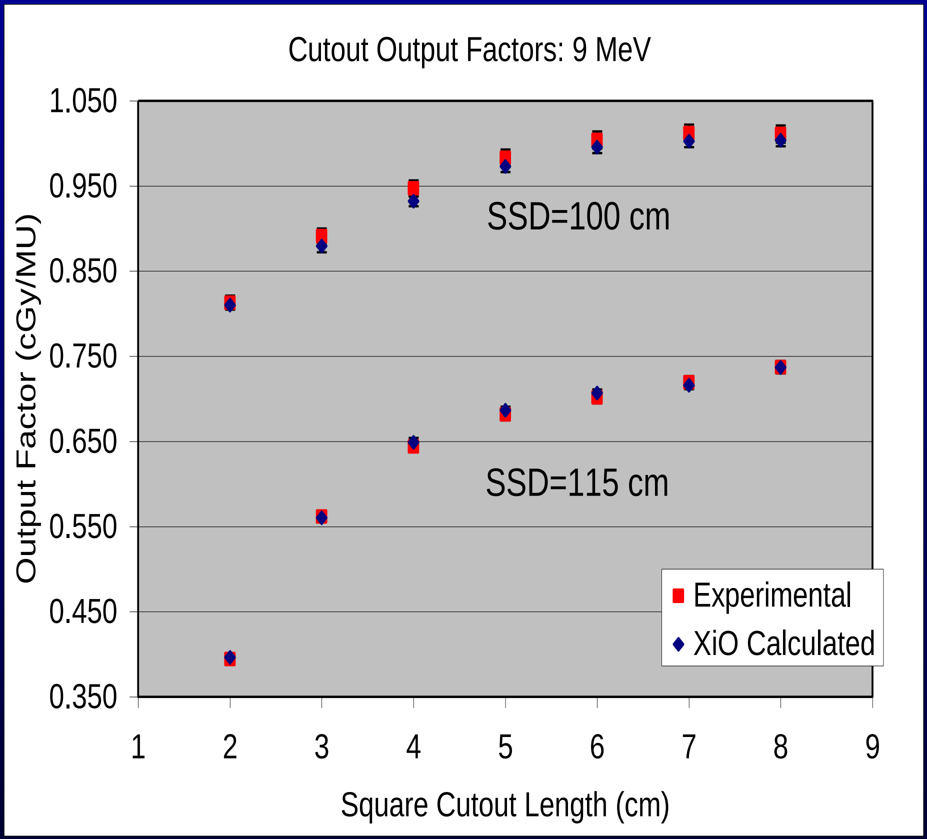
XiO: 9 MeV - Trachea and spine importance of high quality data

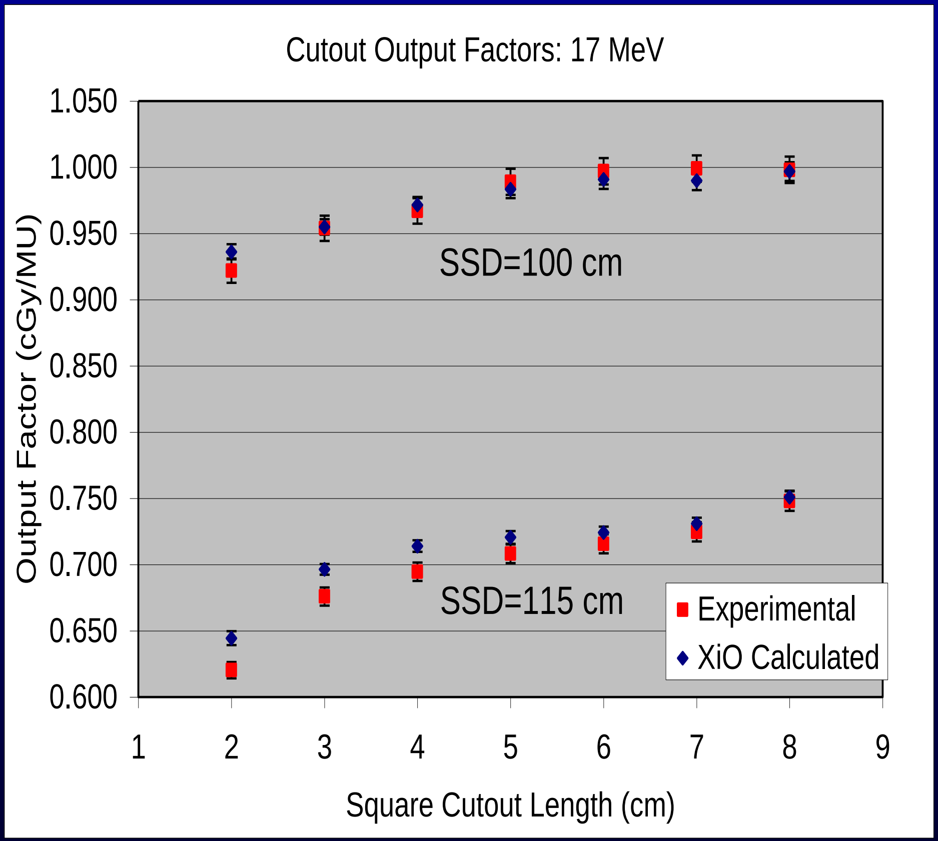


SU-E-T-669

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

Example of beam model verification CMS eMC: cutout factors

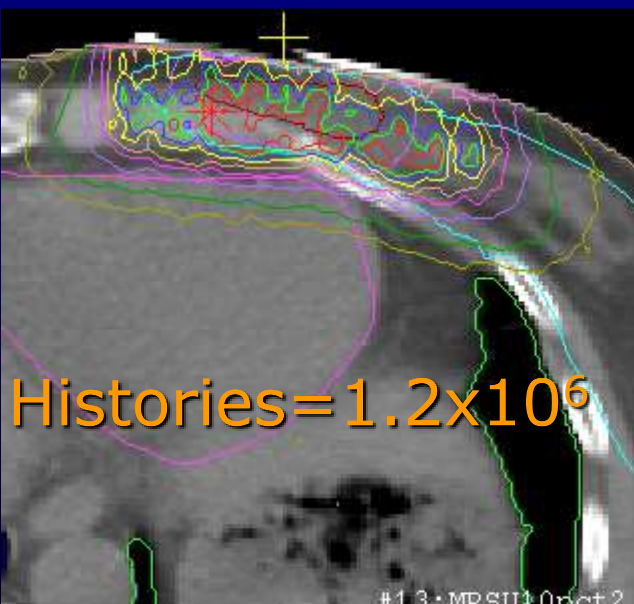




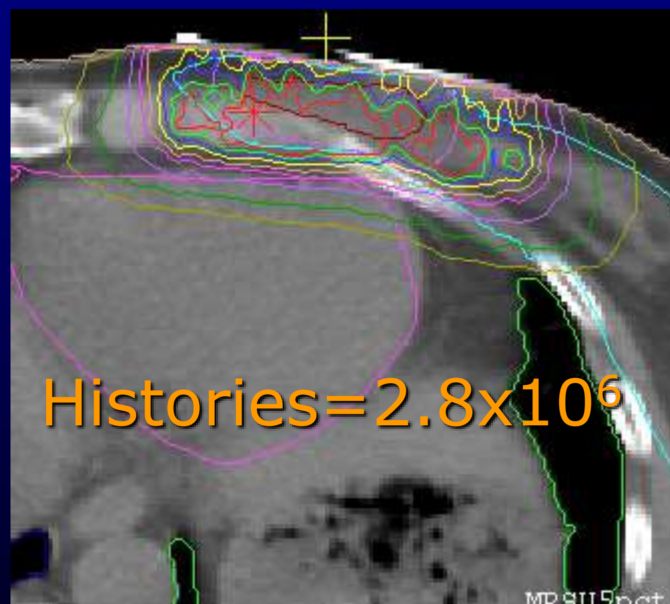
Vandervoort and Cygler, COMP 56th Annual Scientific Meeting, Ottawa ,June 2010

Monte Carlo Settings: Noise in the dose distributions

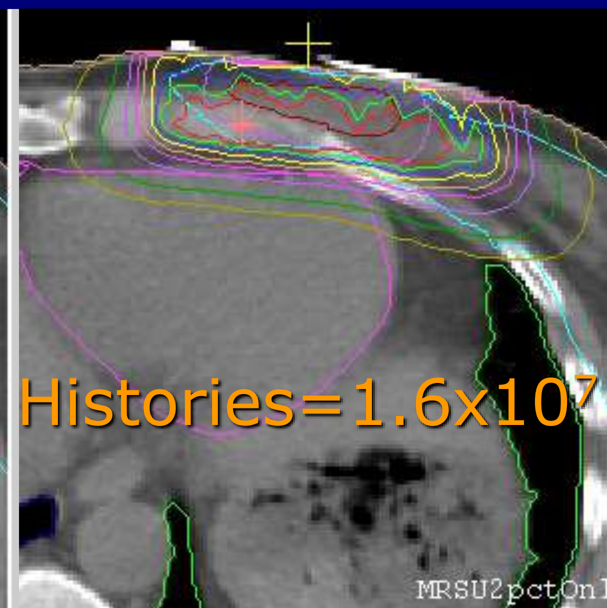
Varying MRSU, voxel size=2.5×2.5×2.5 mm^3, dose-to-medium, 6 MeV beam, 10x10 cm^2 applicator



MRSU=10%

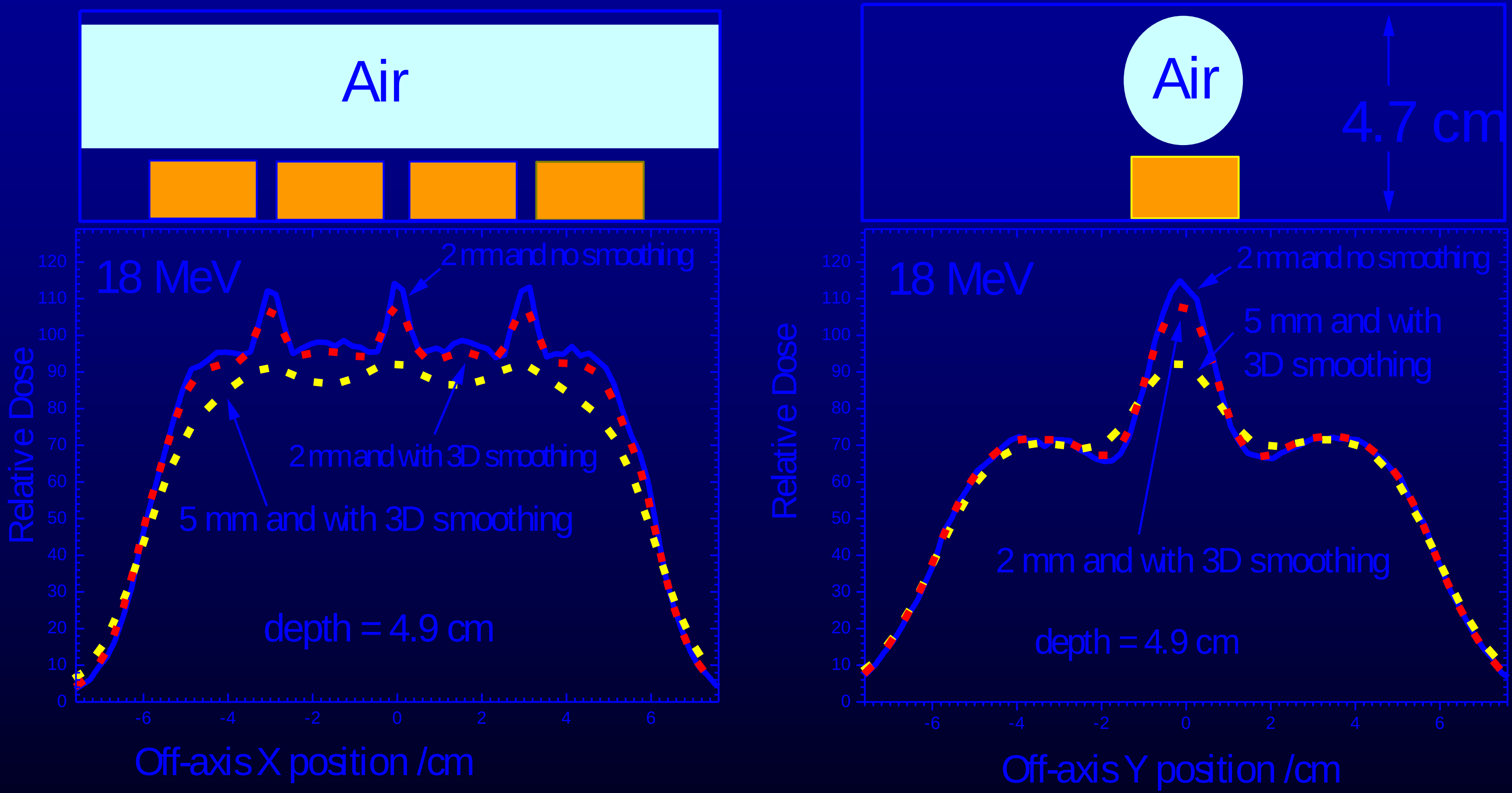


MRSU=5%



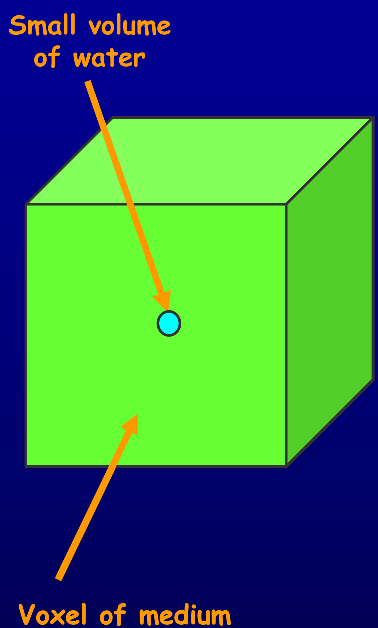
MRSU=2%

Eclipse eMC
Effect of voxel size and smoothing



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

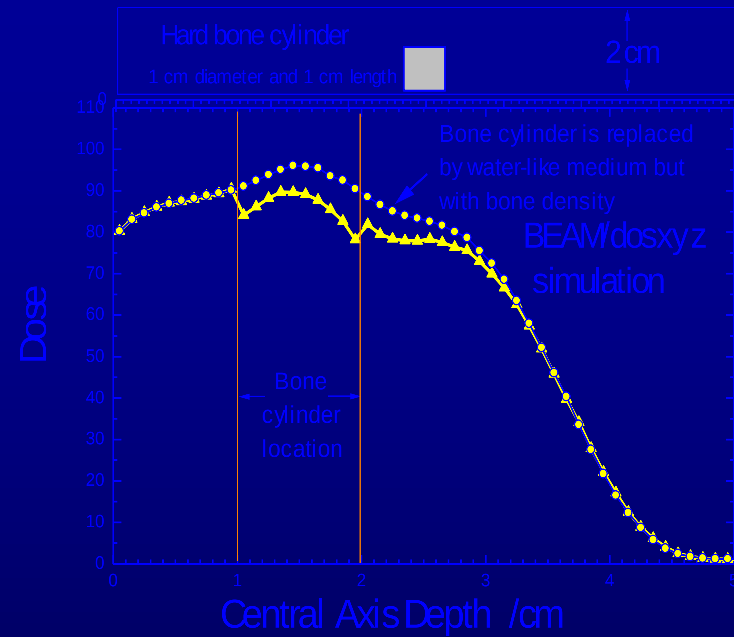
Dose-to-water vs. dose-to-medium

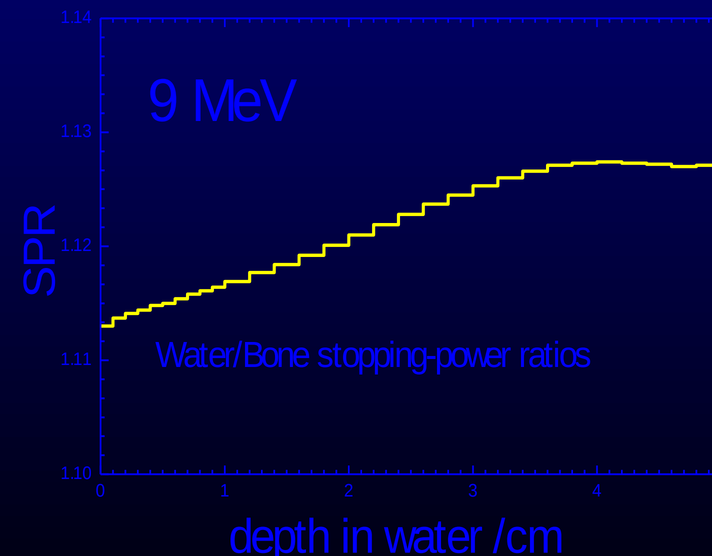


D_m - energy absorbed in a medium voxel divided by the mass of the medium element.

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

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

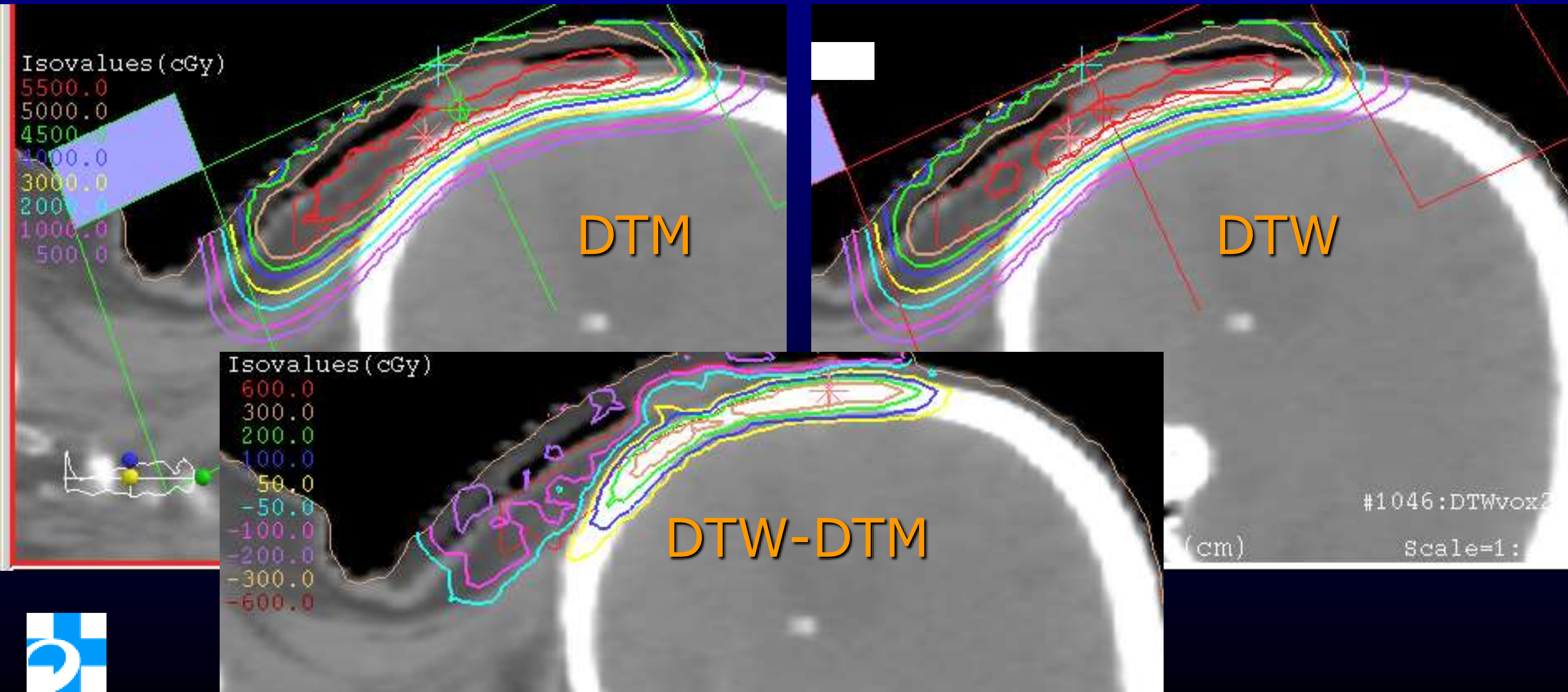




Ding, G X., et al Phys. Med. Biol. 51 (2006) 2781-2799.

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

Dose-to-water vs. dose-to-medium, MRSU=2%, voxel size=4×4×4 mm^3, 6 MeV beam, 15x15 cm^2 applicator, both 602 MU



MU MC vs. hand calculations

Monte Carlo

Real physical dose calculated on a patient anatomy

Inhomogeneity correction included

Arbitrary beam angle

Hand Calculations

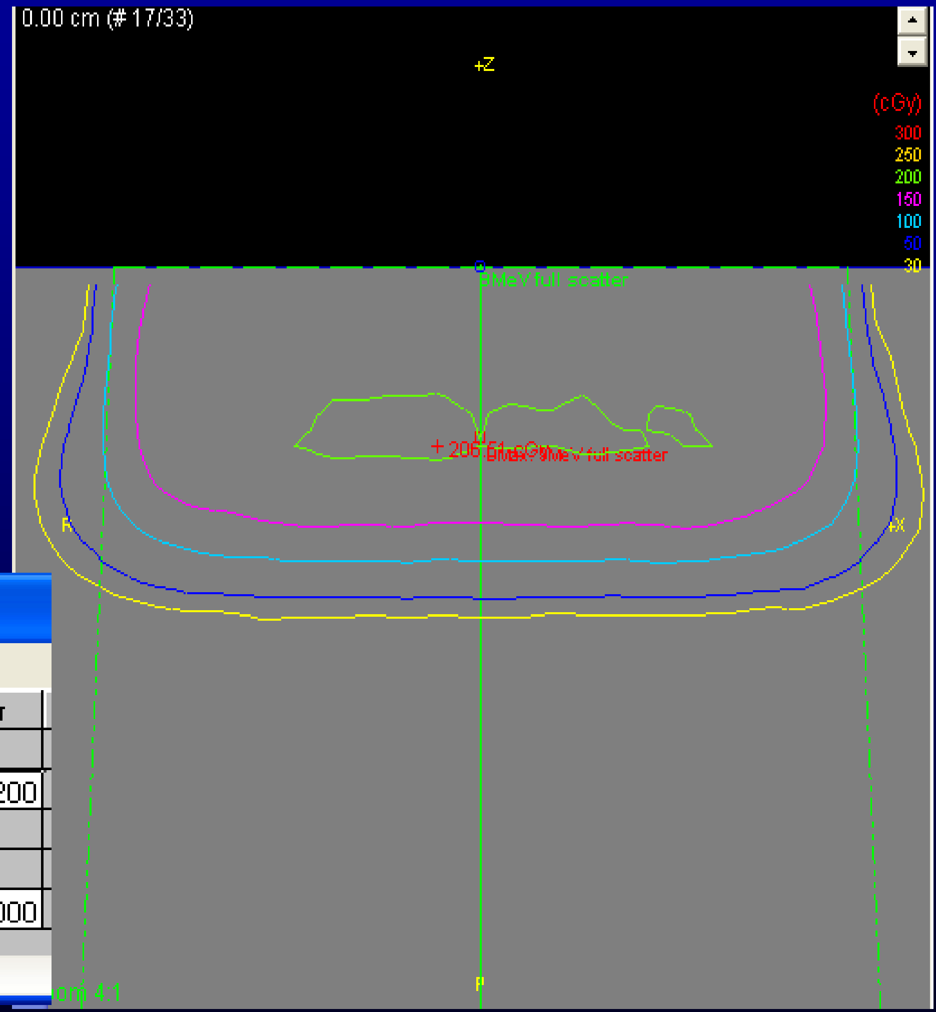
Rectangular water tank

No inhomogeneity correction

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

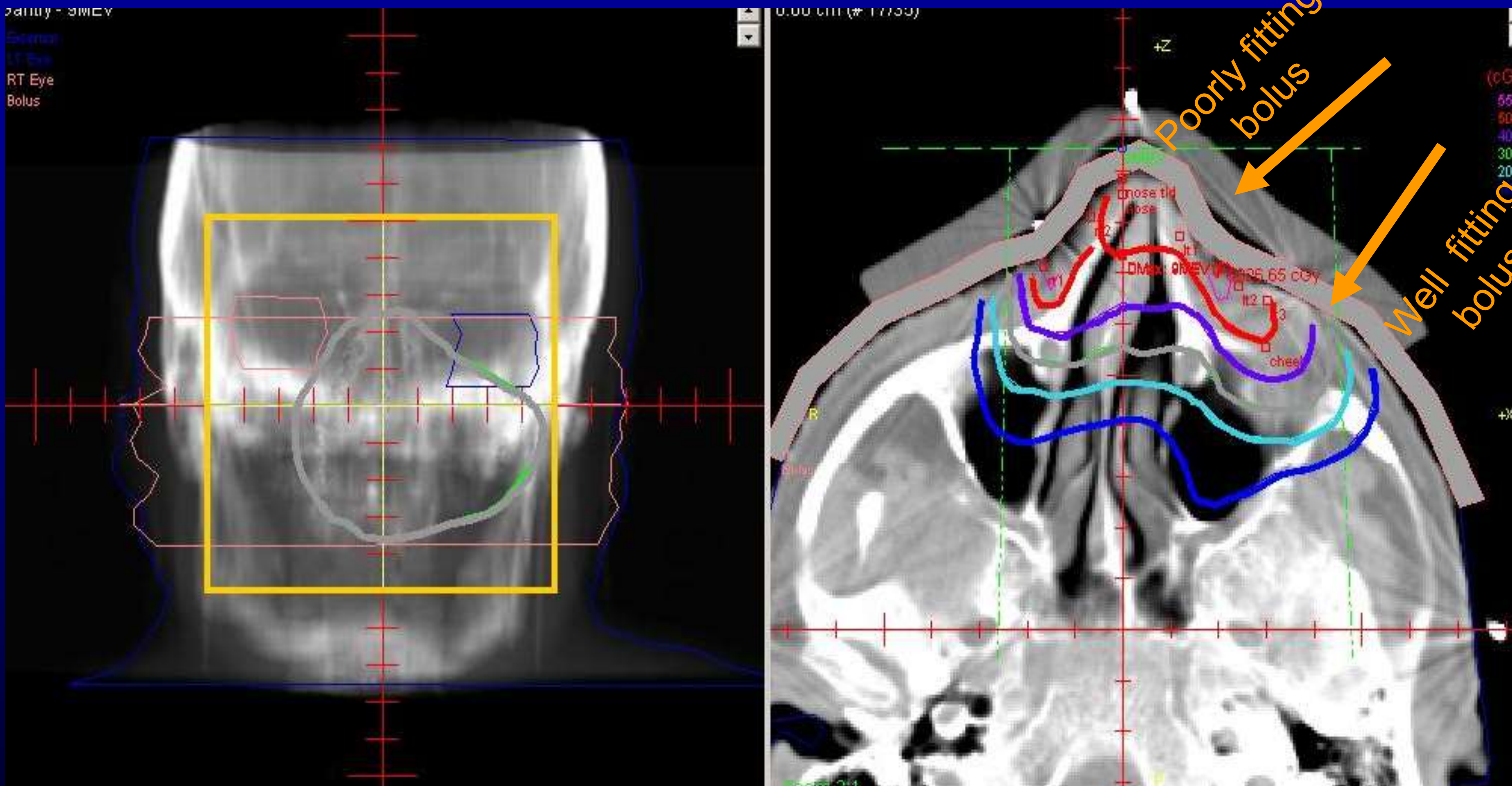
Number of Fractions	1
MU or min / Fraction	234

Real contour / Water tank =

=234MU / 200MU=1.17

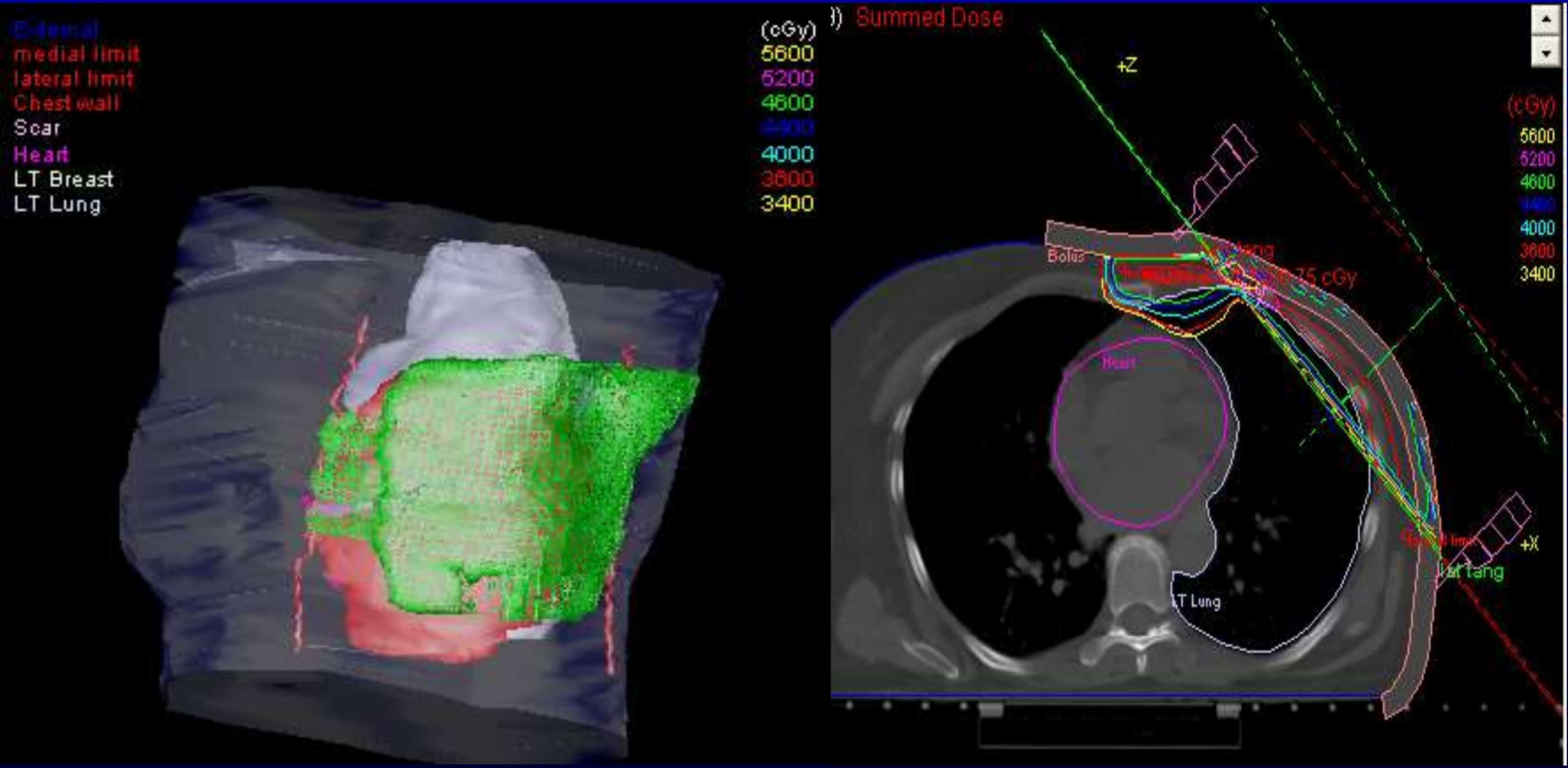
Reason for more MU: % isodose at the nominal (reference) d_{max} depth < 100%

MU real patient vs.water tank



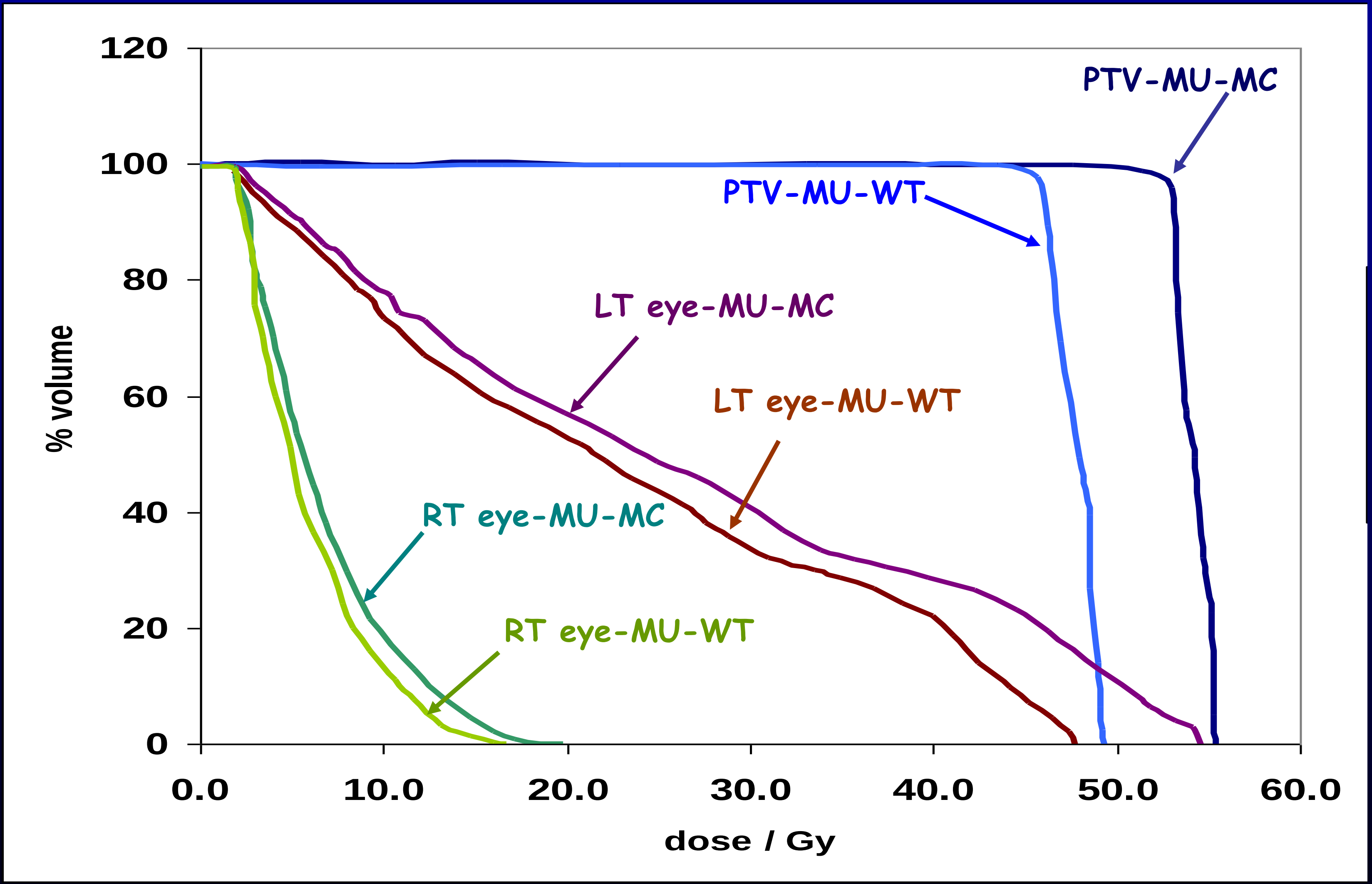
MC / Water tank= 292 / 256=1.14

Internal mammary nodes

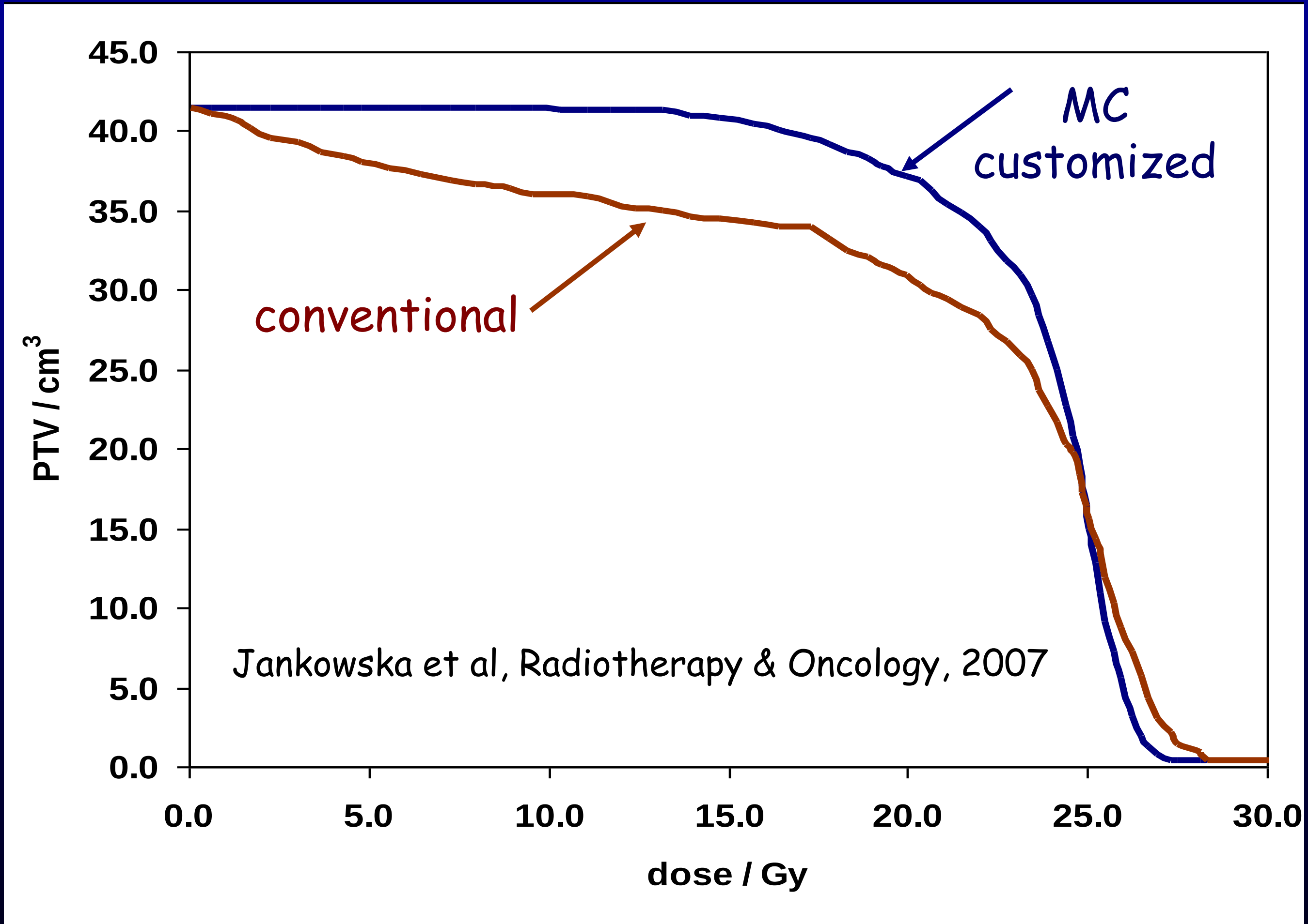


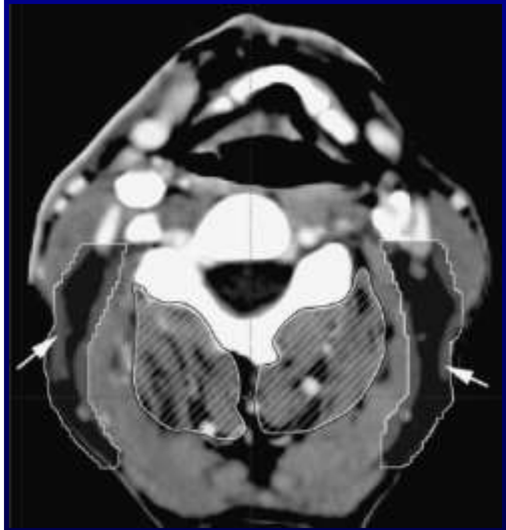
MC / Water tank= 210 / 206=1.019

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



Posterior cervical lymph node irradiation - impact on DVH

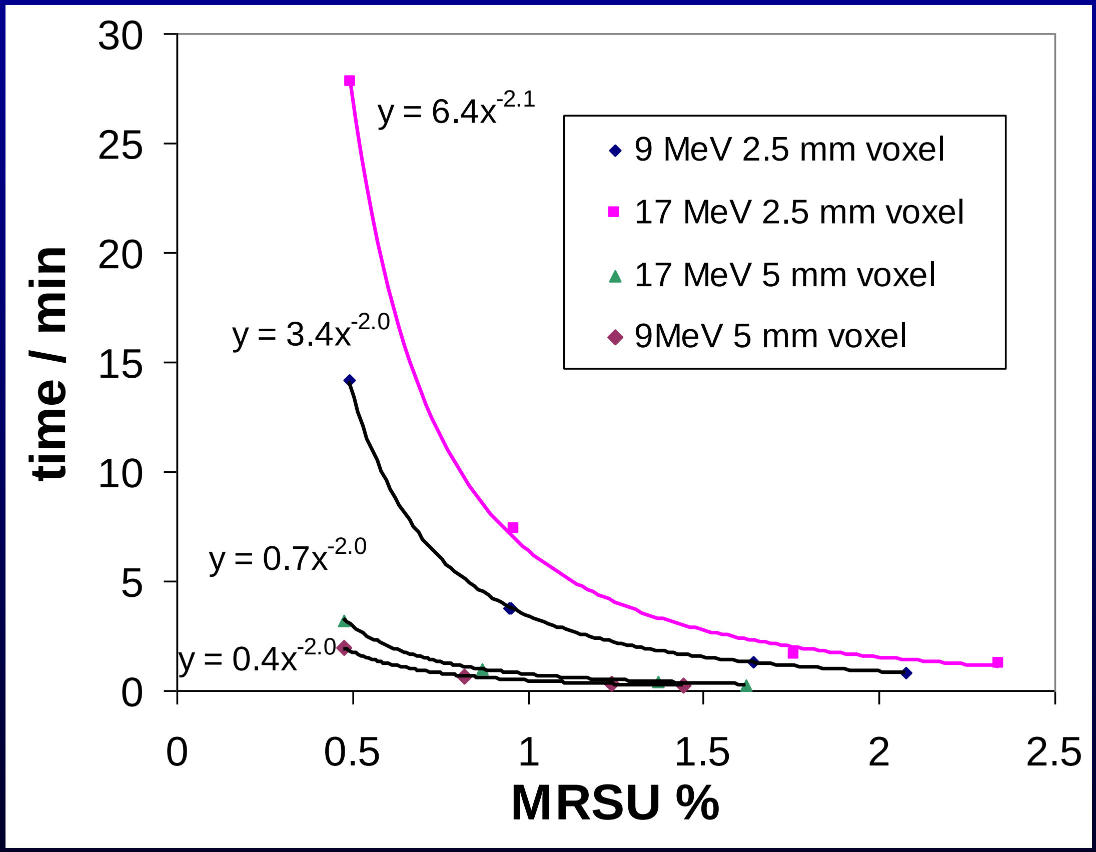




How long does it take?

- 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 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.

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

Summary - electron beams

- 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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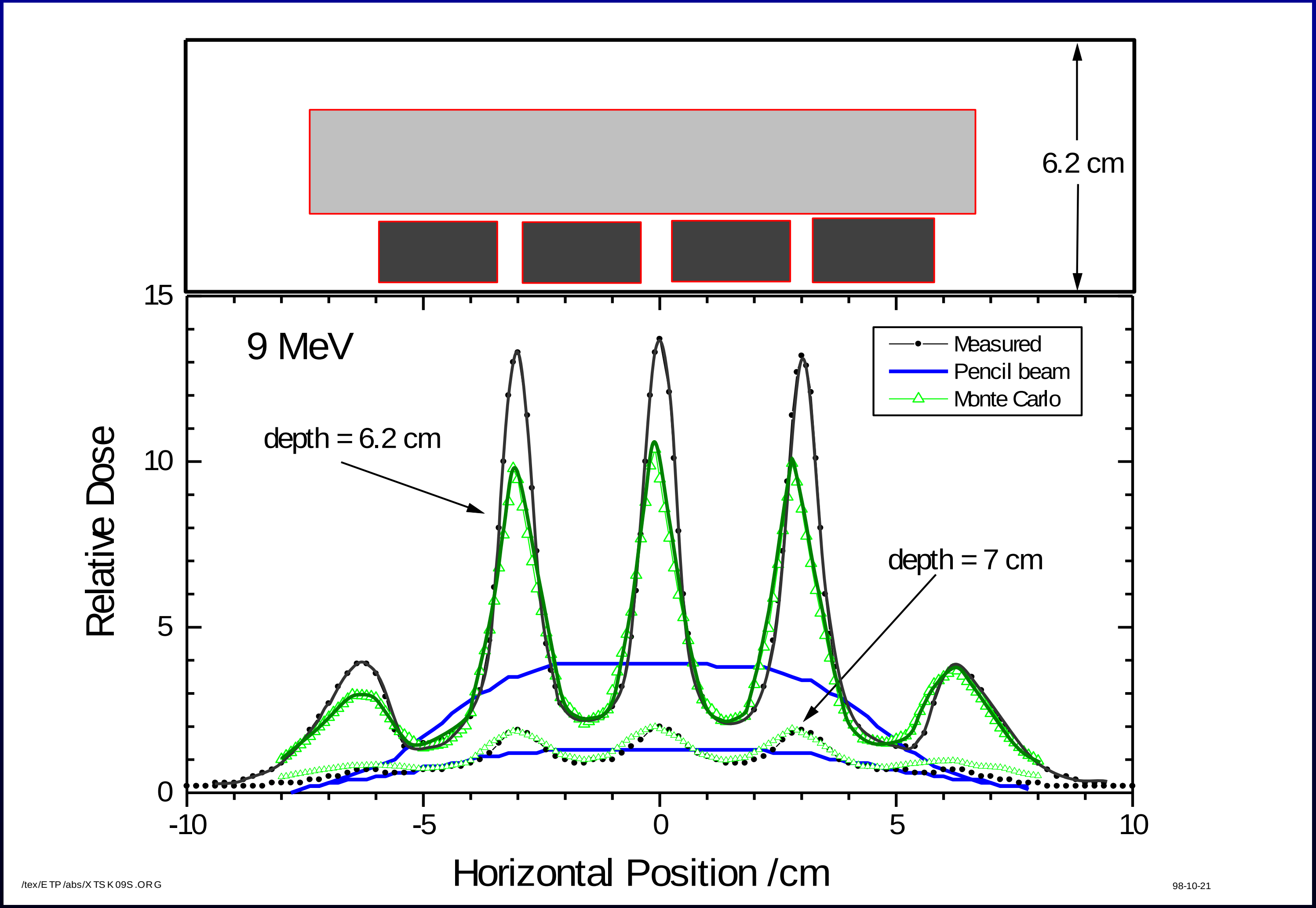
Thank You

Rationale for Monte Carlo dose calculation for electron beams



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

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