Algorithmes : comment calculer et rapporter la dose

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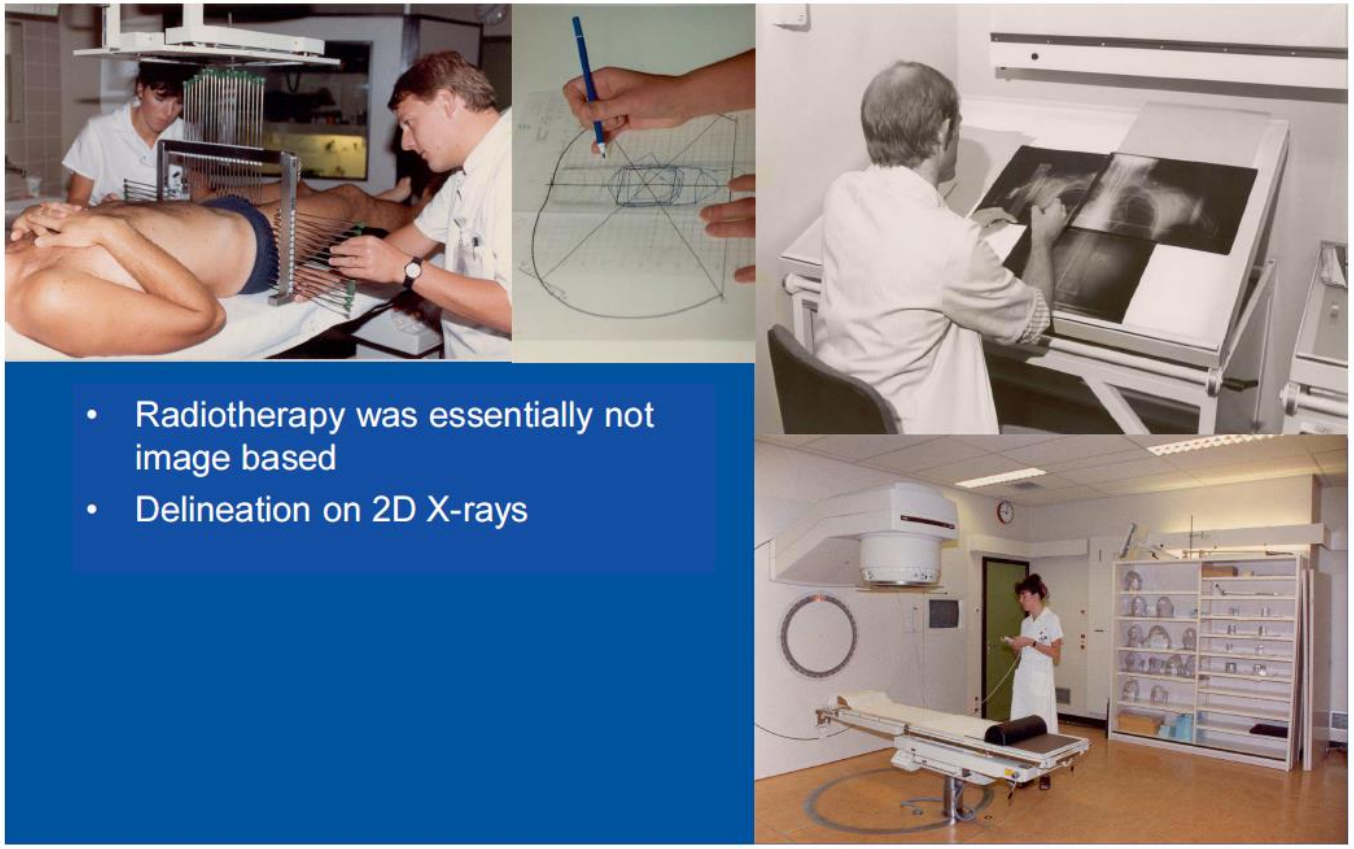
Introduction

- Until 1970: No CT data available: Patient consists of water → 2D planning → approximate dose calculation



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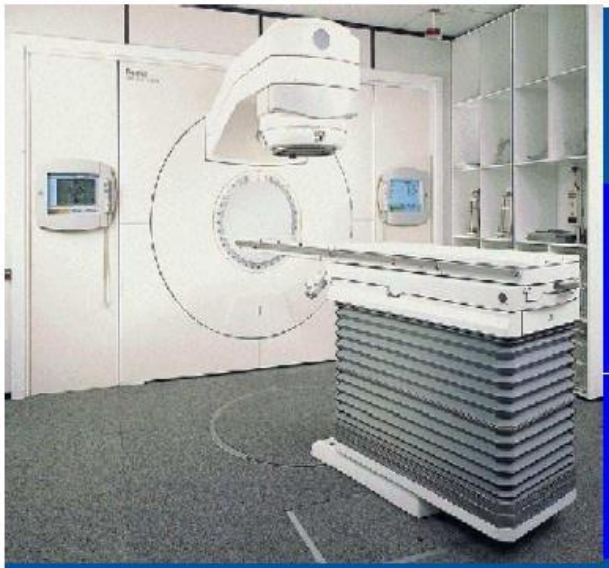
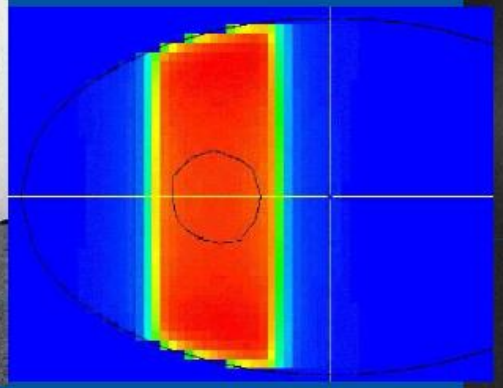
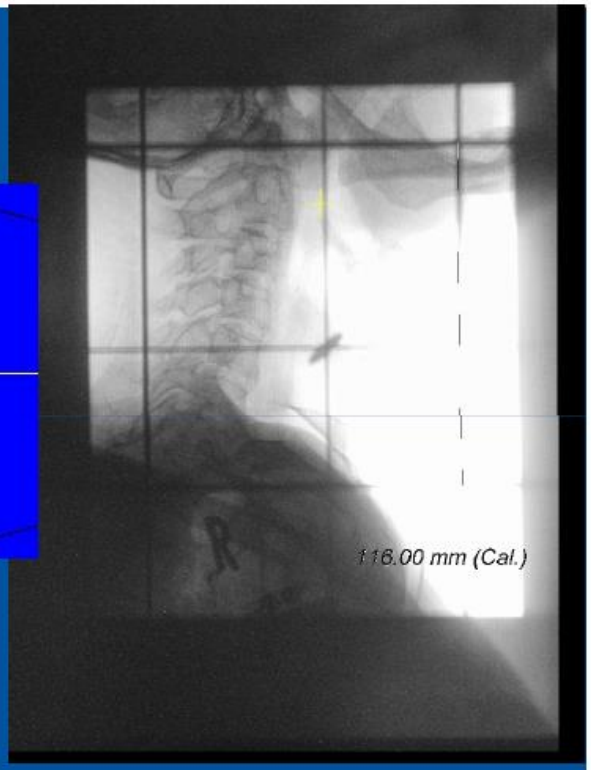
Radiotherapy before image guidance







Classical paradigm in radiotherapy

- Treat a large volume of normal tissue with a tumour somewhere inside
- Dose is limited by normal tissue tolerance

Introduction

- Now: Very precise 4D CT information, MR, PET → 3D dose calculation
- Dose escalation
- IMRT: Large dose gradients
- Extra cranial SBRT: hypofractionation
- Small irradiation fields → lack of lateral CPE

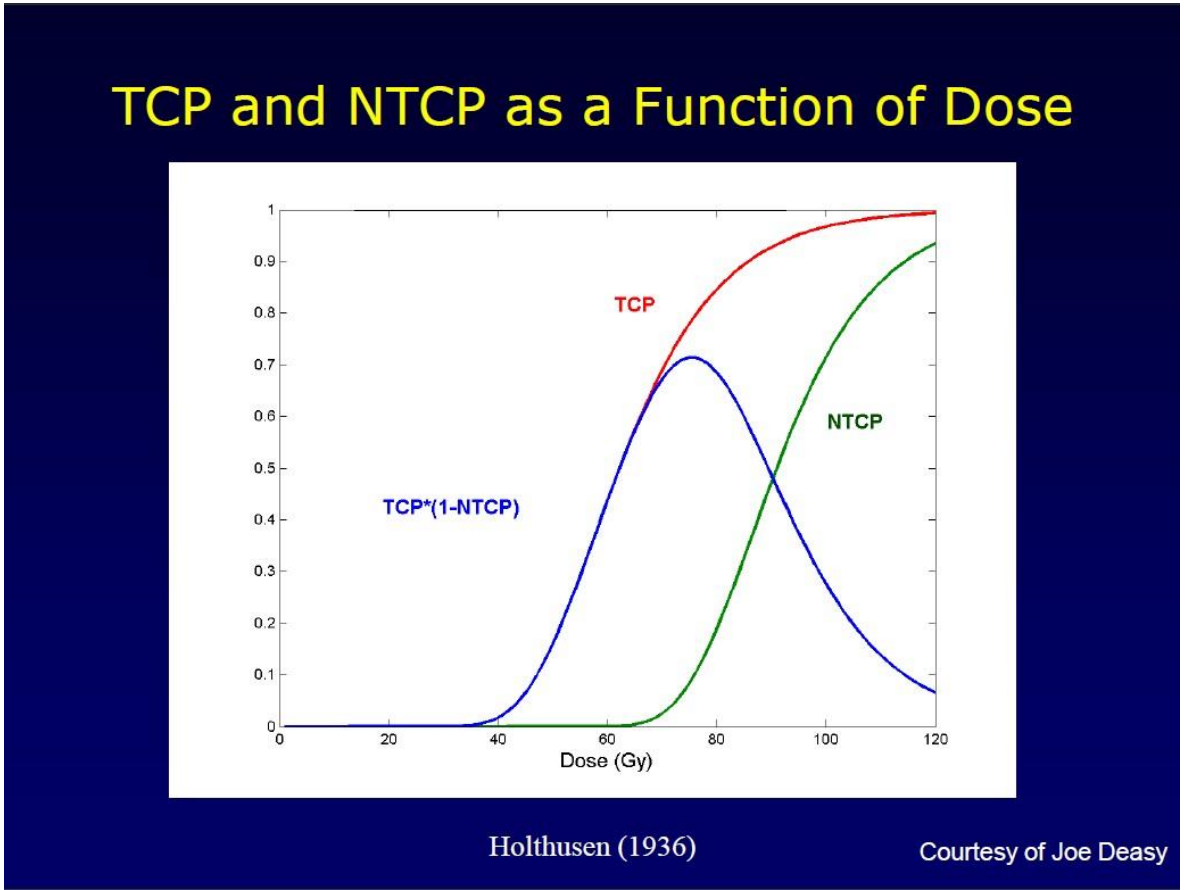
- AAPM Report No. 85 (Papanikolaou et al, 2004), Ahnesjö and Aspradakis (1999), AAPM TG101 (2010).

Required Dose accuracy

- ✓ Different factors:
- The slope of dose-effect curves
- The level of dose differences that can be detected clinically
- Clinical studies
- What is practically achievable (evolving …)

The slope of dose effect curves (TCP, NTCP)

- Early stage tumours: 1 % increase accuracy → 2 % increase in cure rate (Boyer and Schultheiss, 1988)
- Mid range dose effect curve: 5 % change in dose → 10-20 % change in TCP, 20-30 % change in NTCP



Clinically detectable effects

- Clinical observation: tumor regression (Dutreix, 1984): Study the difference between electron and photon treatment (squamous cell carcinoma tonsil (amigdale)) → smaller efficiency electrons: but 7 % dose error in electron dose calculation
- Gynecological patients: 25 MV: radiotherapist reported skin reactions and diarrhea → Dosimetric study: calibration problem linac: 7 %

(B)

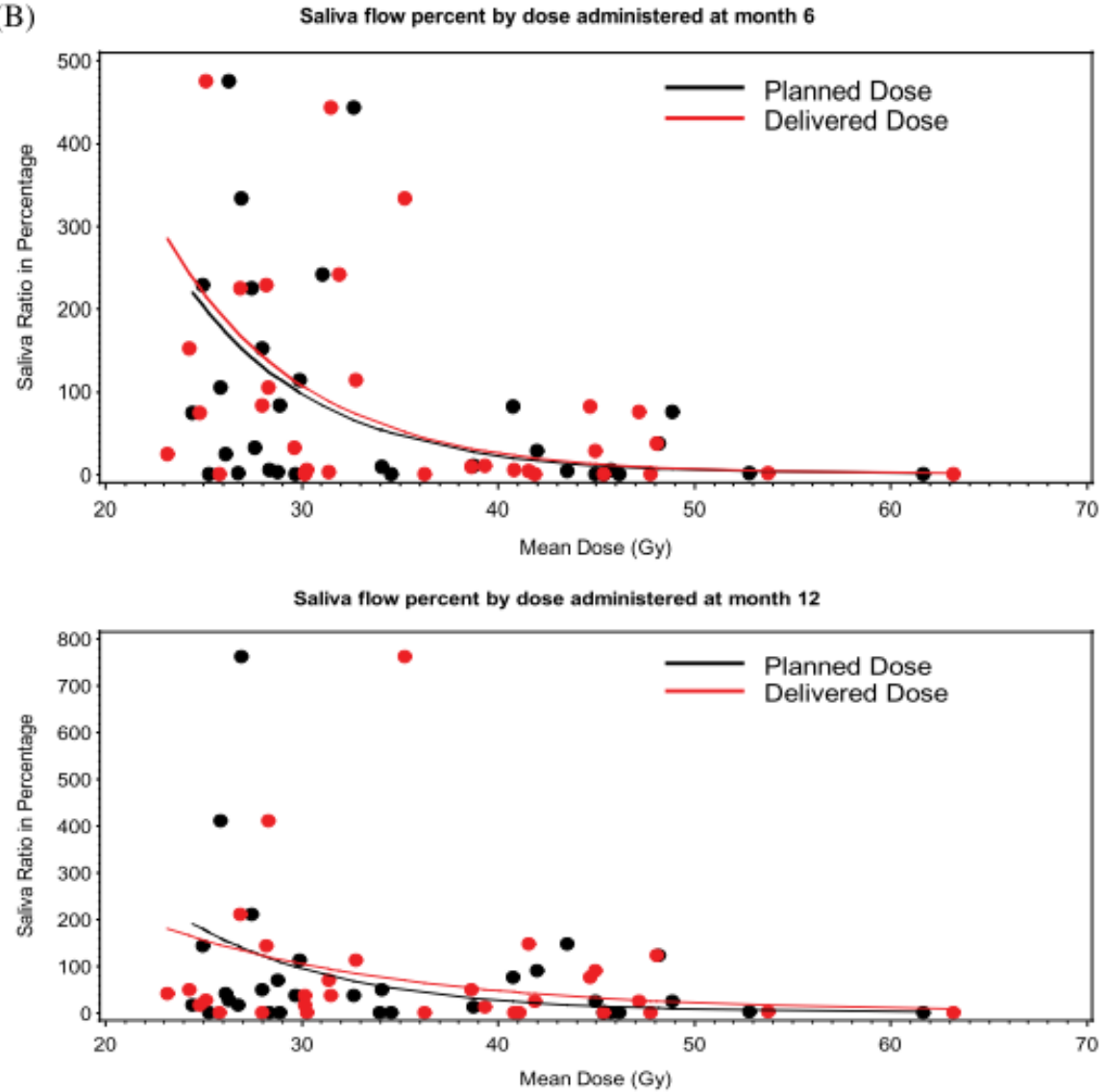


Fig. 2. *(Continued)*

Clinical trials

- Dose escalation studies: e.g. lung: impact of accurate dose calculations > 20 % (what if 3x20 Gy is actually 3x20 for some patients, but only 3x15 for other patients ?)

Achievable accuracy

- AAPM Report 85, Mijnheer *et al.* 1987, ICRU 1976, Brahme 1988: 5 % global uncertainty (1 stdev)

- ✓ → TPS: 3 % accuracy → decreasing in the future → 2 % providing an overall uncertainty of 3 to 4 %

- Dose calibration: Now 2.5 % → going to 1 %
- Positioning: Now: 2.5 % → going to 2 %
- Patient Data: 1.5 % → going to 1 %
- ….

- → Accurate algorithms needed, especially in lung !

Overview Dose calculation algorithms

- 2 main categories:
- Correction based algorithms: Based on measured data (PDD, TMR, OAR, OFs, …)
- Model-based algorithms: Modeling dose distribution based on first principles: source model, patient information

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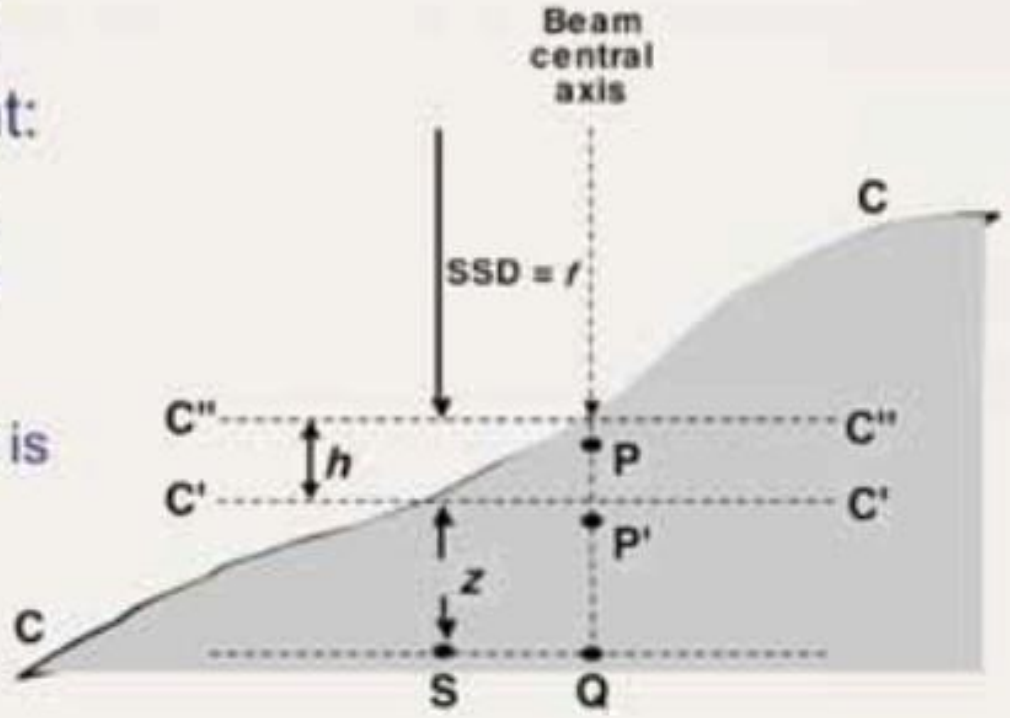
Correction based algorithms

- Start from phantom measurements: PDD, TAR, TPR, OAR, OFs
- Contour correction/ beam obliquity: Effective SSD, Isodose shift, TAR/TMR method
- Heterogeneity corrections: Multiple solutions ranging from 1D density corrections to 3D correction methods

Effective SSD method for determination of dose at arbitrary point S in patient:

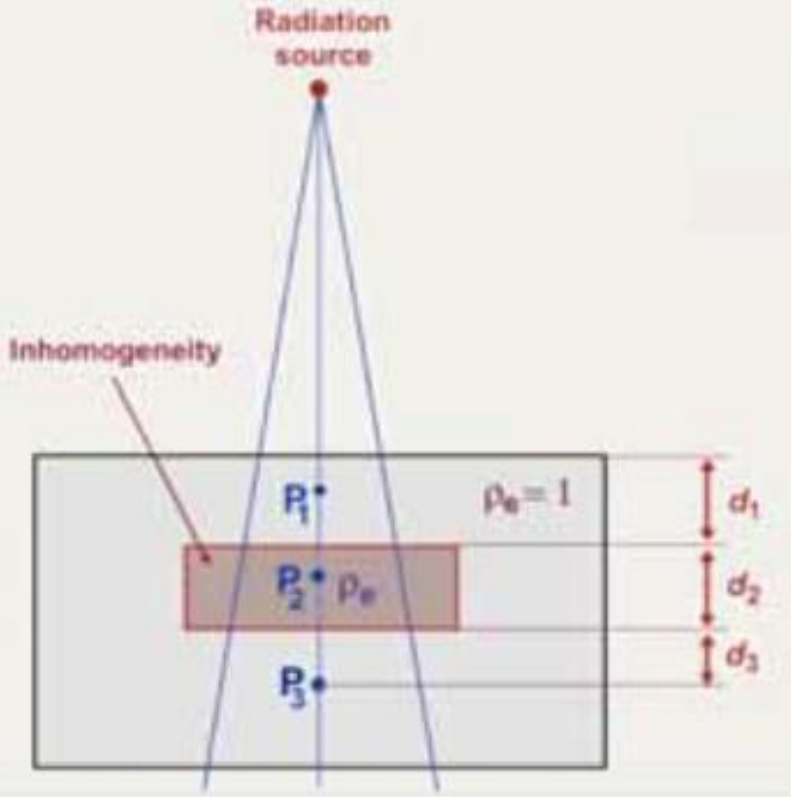
- Isodose chart is shifted to the flat surface level at the CC' contour.
- The PDD value for point S is read to get PDD'.
- The reading is corrected by an inverse square factor.



$$PDD_{corr} = PDD'(z, A, f, h\nu)\left(\frac{f + z_{max}}{f + h + z_{max}}\right)^2$$

6.11.3 Corrections for tissue inhomogeneities

- Four empirical methods have been developed for correcting the water phantom dose to obtain the dose at points P_3 in region (3) beyond the inhomogeneity:
  - TAR method
  - Power law TAR method
  - Equivalent TAR method
  - Isodose shift method



1D/3D corrections for heterogeneities: Density scaling

- Radiological pathlength: ρ.t (g/cm^2): Compton → electron density
- Dose = Dose_primary + Dose_scatter
- If beam traverses layer density < 1.0

→ Attenuation ↓ → Dose_primary ↑

→ Scatter ↓ → Dose_scatter ↓

→ 1D correction ignores reduction of scatter contribution → overestimates effect heterogeneity

→ Also field size has to be scaled: D(t,r) = D(ρt,ρr)

Heterogeneity corrections: Categories

- According to AAPM Report No. 85
- Electron transport: using kernels
- 1D, 3D correction: scaling of primary dose, scatter dose, sampling anatomy along one dimensional rays, or the full three dimensions

- Category 1: 1D correction, no electron transport (local energy deposition)
- Category 2: 3D correction, no electron transport
- Category 3: 1D correction, electron transport
- Category 4: 3D correction, electron transport

Model-based algorithms

- Primary dose plus first order Compton scatter: monoenergetic parallel beam ignoring heterogeneities
- Convolution-superposition
- Monte Carlo

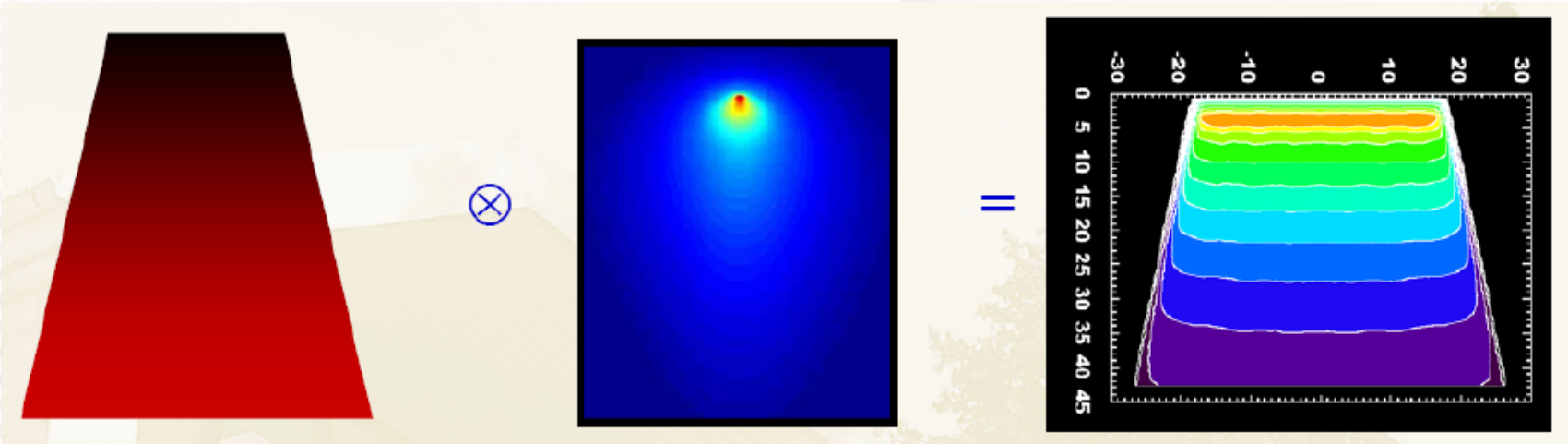
Categories

- Category 1: Linear attenuation, RTAR (effective SSD, isodose shift), Power law (Batho)
- Category 2: ETAR, DSAR, DVOL, dTAR, 3D beam subtraction
- Category 3: PB convolution, FFT techniques
- Category 4: Superposition/convolution, Monte Carlo, Acuros XB (grid-based Boltzmann equation solver*)

✓ * Vassiliev et al, 2010; Fogliata, 2011

Convolution/Superposition Overview

1) Calculate TERMA: Total Energy Released per unit Mass
2) Account for scatter dose (convolution)
3) Add the resulting dose volumes to get the final dose per beamlet (superposition)



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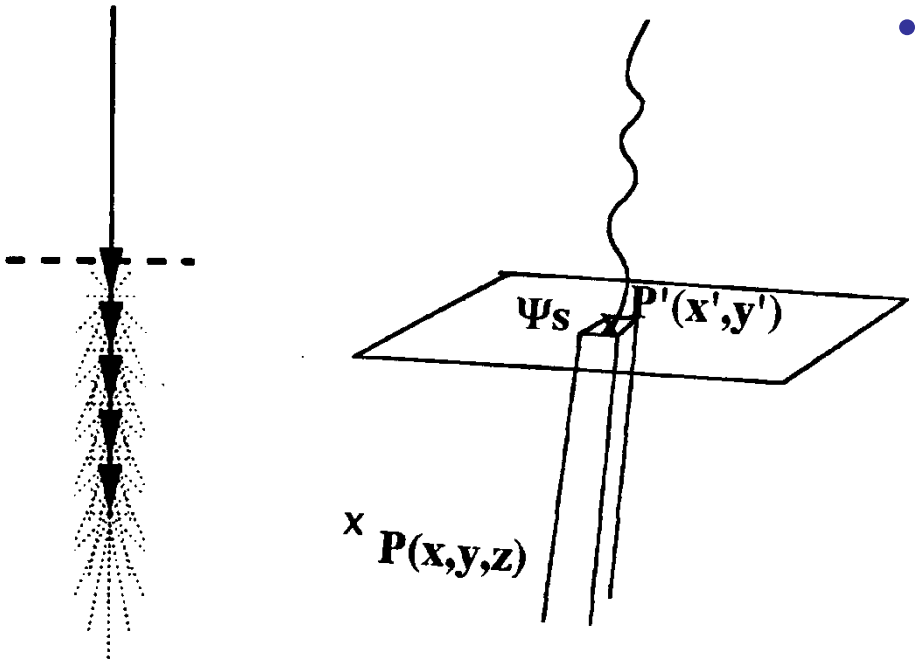
Practical Superposition/convolution

- To increase calculation speed
- Pre-convolve in depth: Pencil Beam
- Correction factor interpolation (Aspradakis and Redpath (1997)
- Collapsed cone convolution method: kernel represented by set of cones
- Ahnesjö, 1992: CCC algorithm of Helax, Masterplan
- Mackie et al 1985, Reckwerdt and Mackie, 1992: Pinnacle
- Fast Fourier transform: spatially invariant kernel (Wong et al 1997)
- AAA (Ulmer et al 2005): PB algorithm: additional degrees of freedom for lateral scatter kernels: inhomogeneities: lateral density scaling

Kernels : simplification 2D = "pencil beam"

- Pre convolution => “pencil beams”



- Faster calculation

➢Lateral scattering

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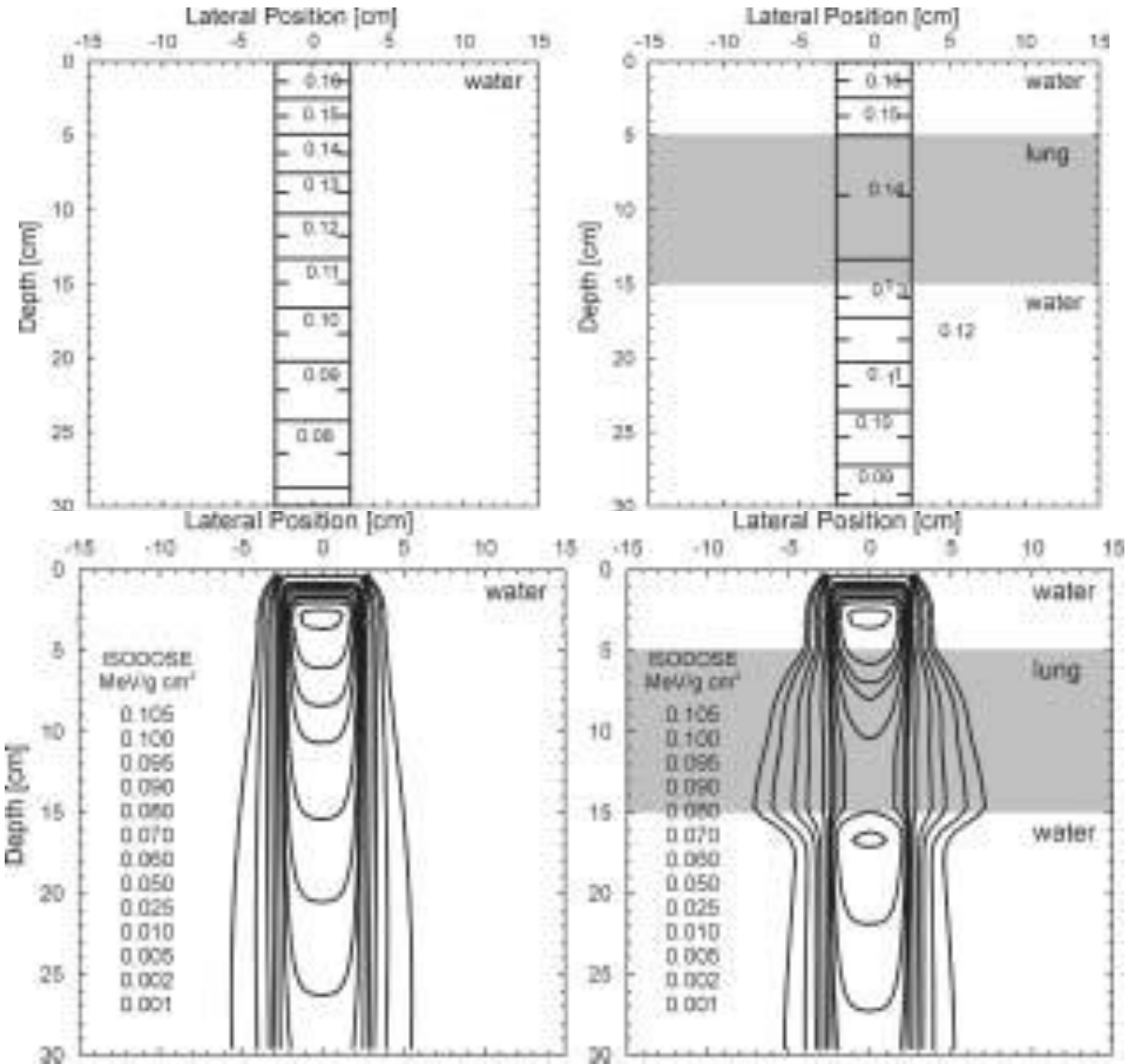
Superposition/convolution (Battista and Sharpe, 1992)



Dose calculations algorithms used in commercial TPSs

- Iplan (Brainlab): PB (category 3), Monte Carlo dose engine (based on XVMC, M. Fippel).
- Multiplan (Accuray): Ray-tracing of 1st category, Monte Carlo dose engine (based on MCSIM, C. Ma).
- GammaPlan: Ray-tracing of 1st category (only intracranial), Collapsed cone (category 4)
- Tomotherapy: superposition/convolution: category 4 (Lu et al 2005)
- Masterplan (Nucletron): PB (category 3), CCC (category 4) and MC for electrons (based on VMC++, Kawrakow)
- Xio (CMS, Elekta): superposition/convolution, Monaco: Monte Carlo (XVMC)
- Eclipse (Varian): Batho, Modified Batho (1st category), AAA (category 3-4) , Acuros XB (category 4)
- Dosisoft: Monte Carlo (based on Penelope, Salvat)
- ….

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Monte Carlo: the truth ???

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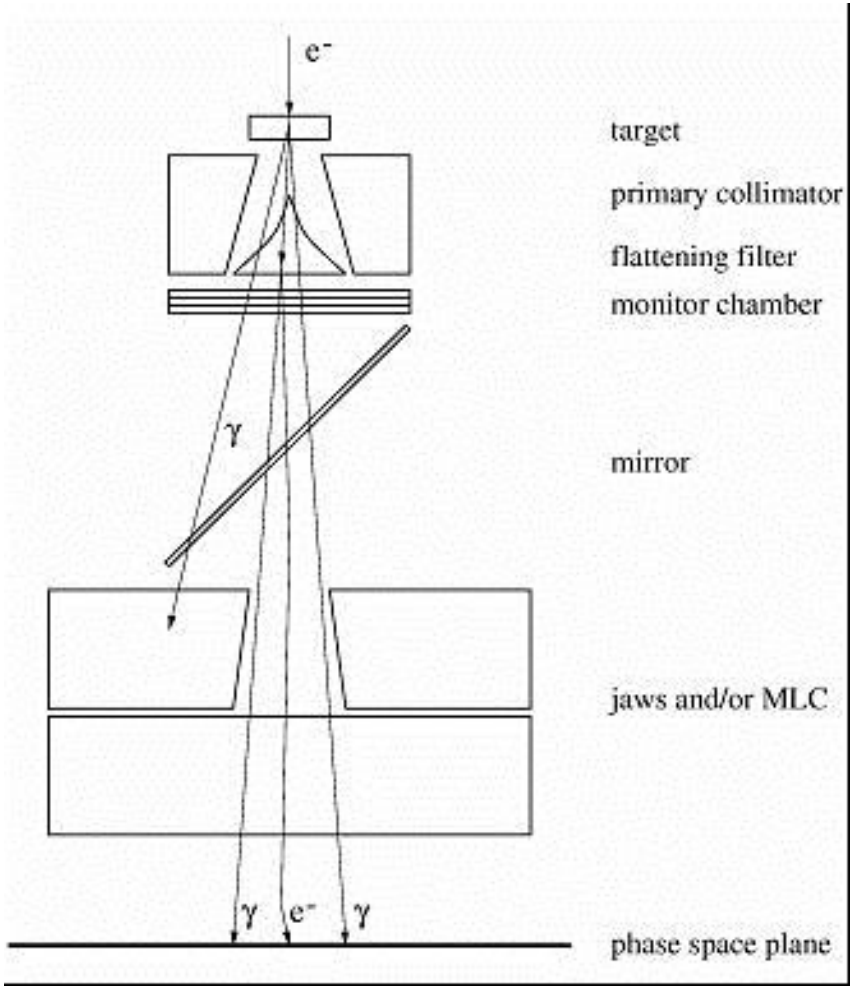
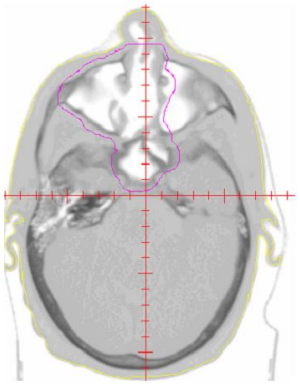
- ✓ Monte Carlo





MCTP: fundamentals

- Variance reduction and approximations
- CT conversion
- Dose to medium/dose to water
- Linac head modelling
- De-noising
- 4D treatment planning

Approximations

- Transport parameters:
  - PCUT
  - ECUT
- Region rejection: When electron is in less interesting region: stop transport
- Kerma approximation (ECUT ∞)

Bremsstrahlung and secondary electrons !!!

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Variance reduction techniques

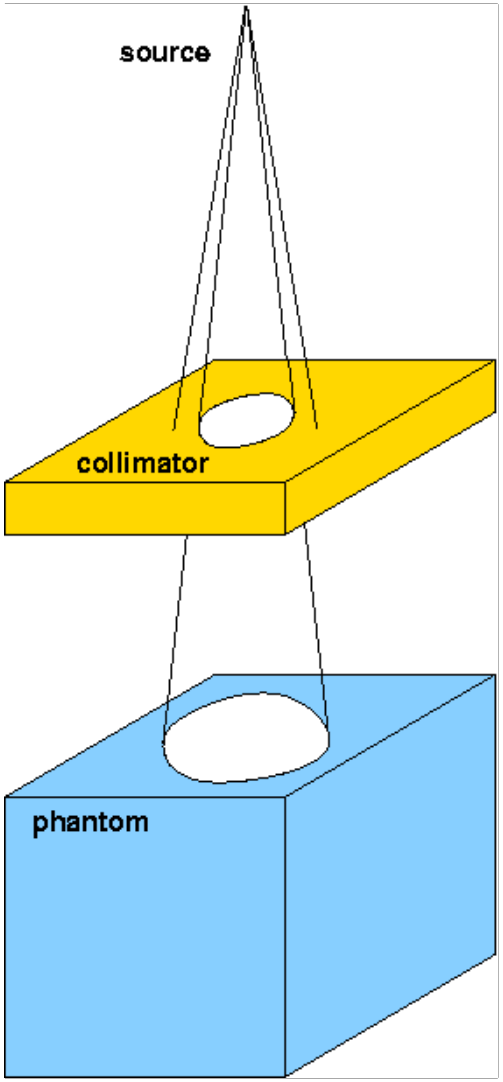
- Spend more calculation time on « interesting particles »
- « Does not introduce a bias »

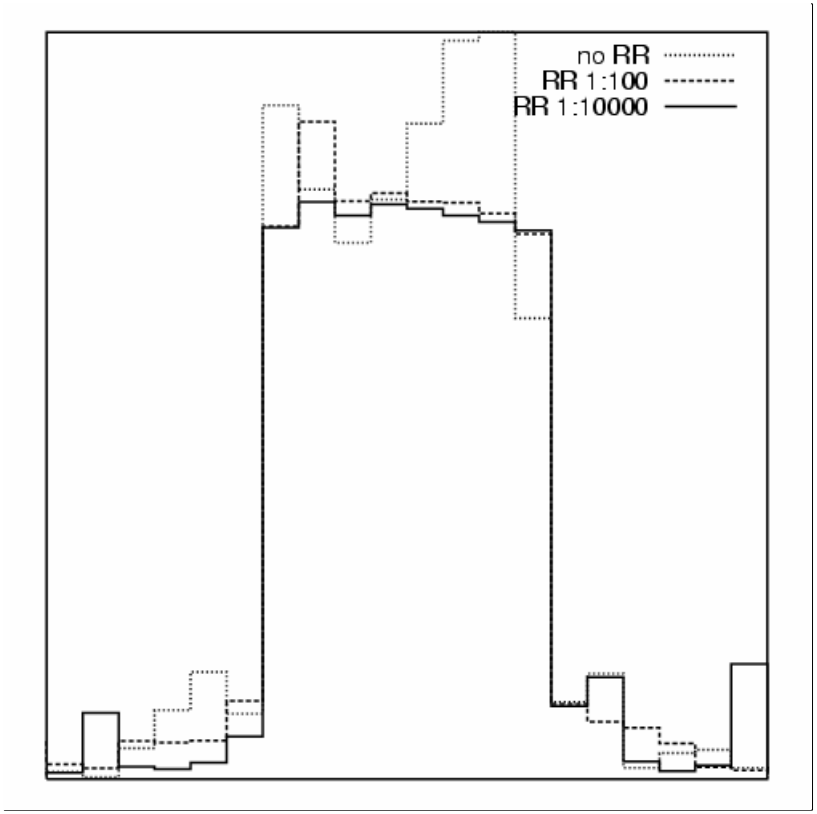
- Particle splitting
- Russian roulette
- Interaction forcing
- Woodcock tracing
- Importance sampling
- Stratified sampling (or quasi RNs)
- Correlated sampling

Example: Particle splitting

- Split particle in e.g. 10 sub-particles with a weight of 1/10
- e.g. Splitting of bremsstrahlung photons in target
- Risk: under-sampling

Example: under-sampling

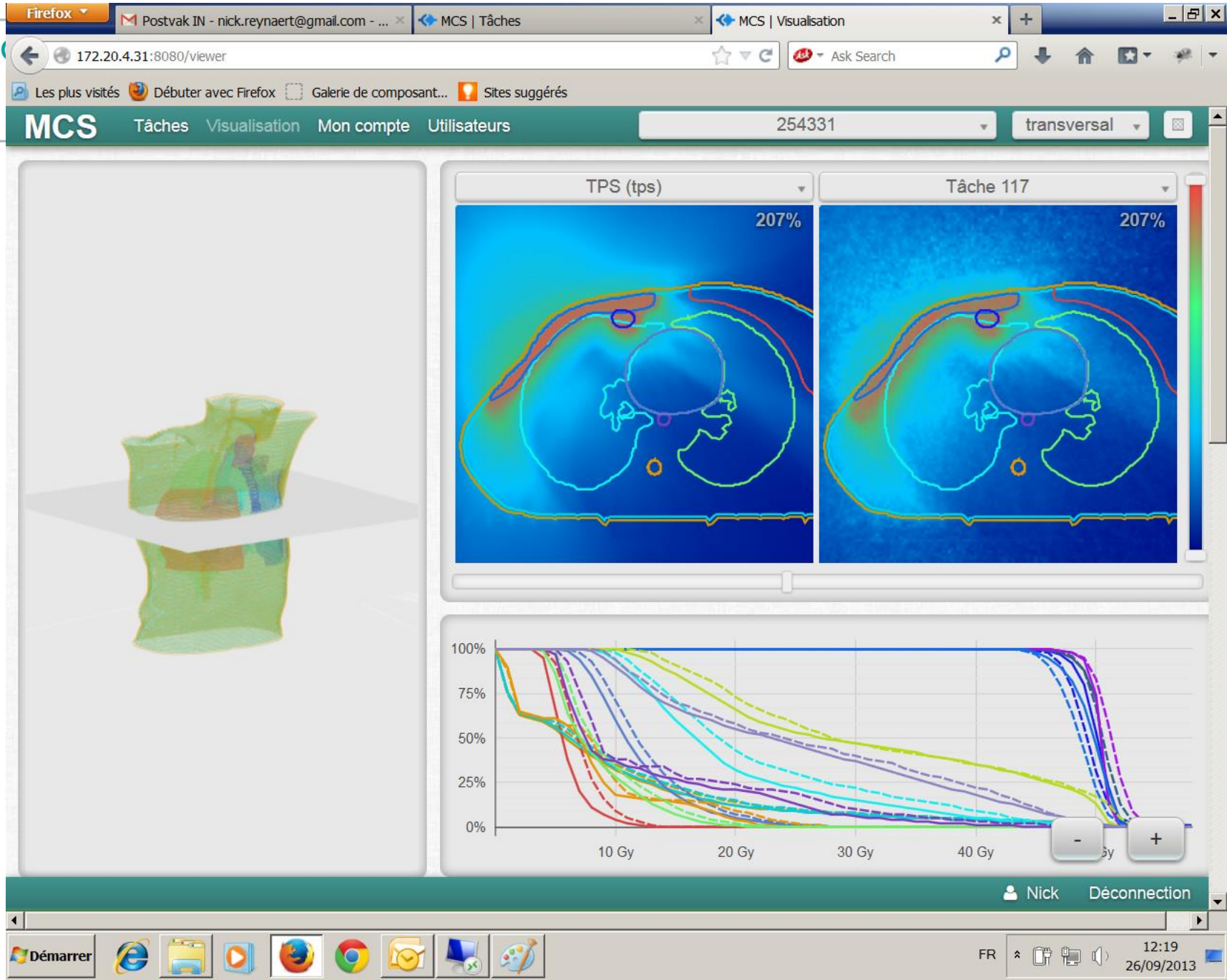




Denoising

- Smoothing of DVHs
- Denoising 3D distributions

✓ Factor 2 to 3. Otherwise smoothing (gaussian filter)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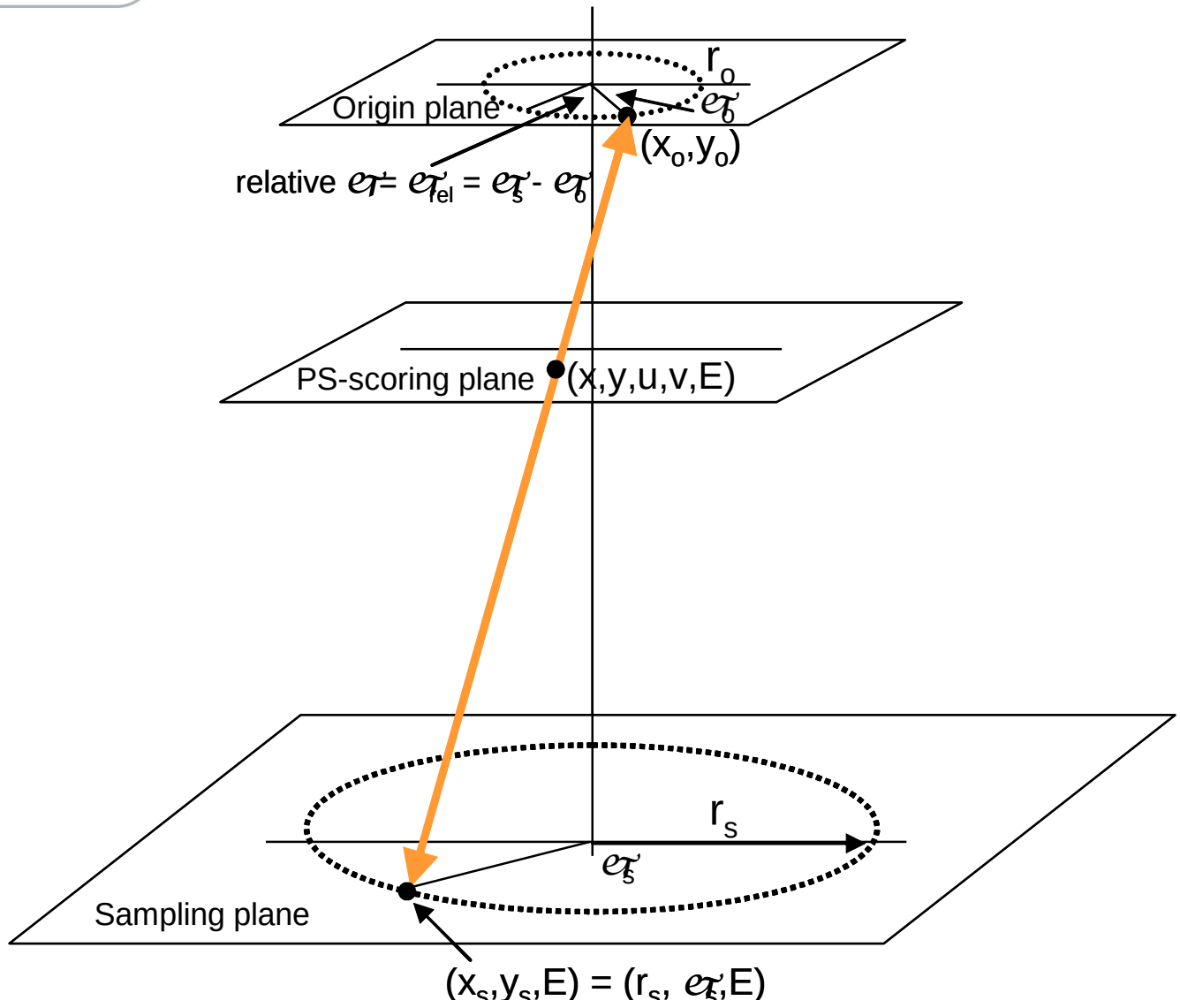
Linac head modelling for MCTP

- Fixed components → Multiple Source model
- Beam modifiers: ray tracing or other approximations

Virtual source model



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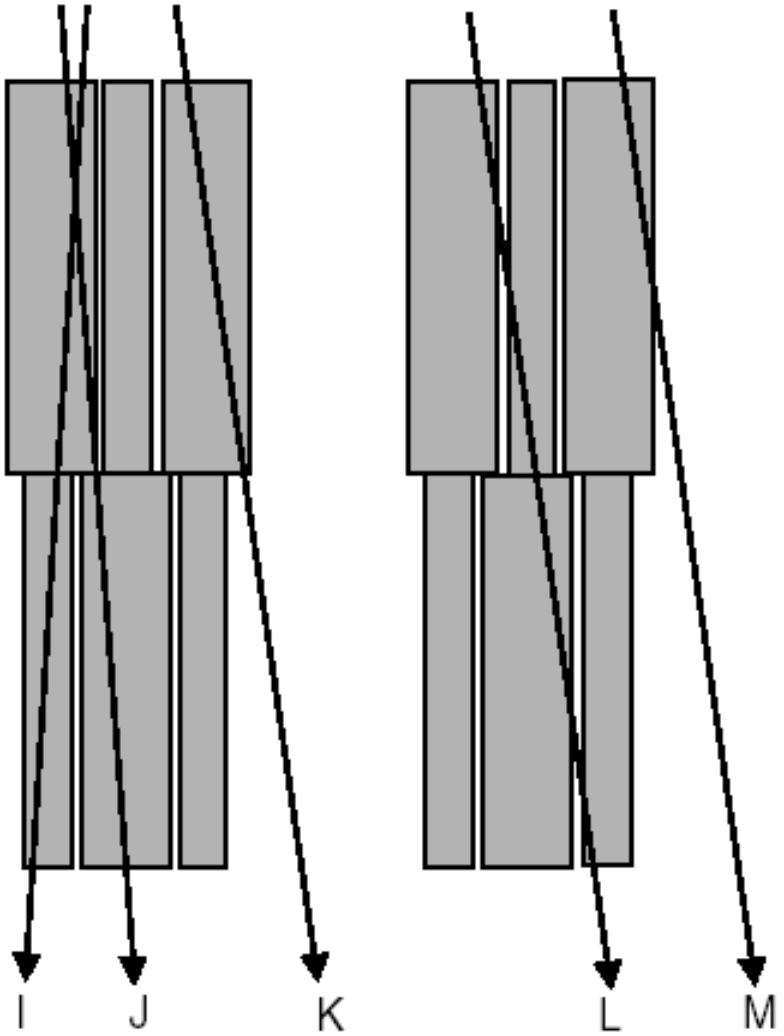
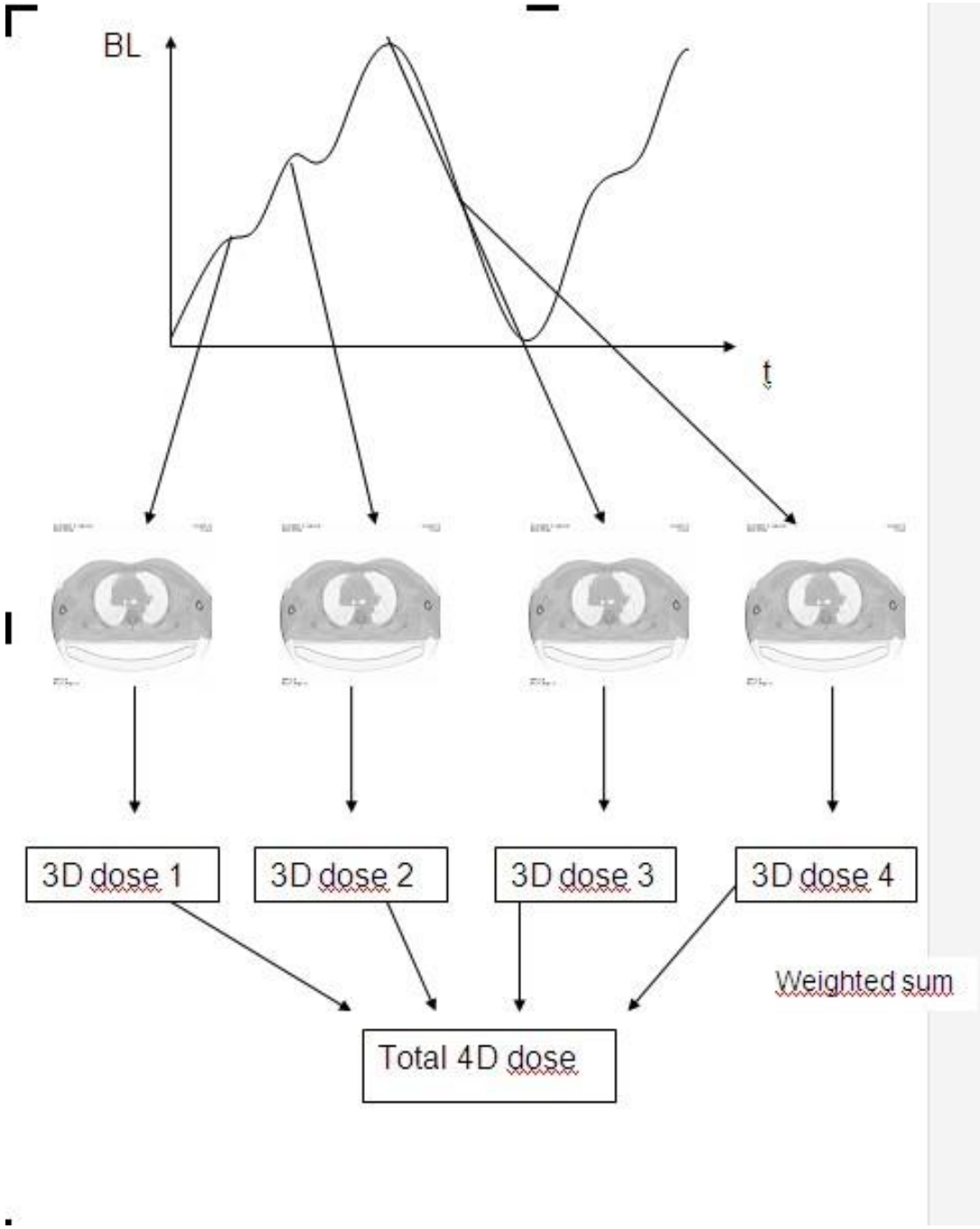
Beam modifiers



4D TP e.g. lung treatment

- MCTP ideal for 4D TP
- CT data at different time intervals breathing cycle
- Calculation time 4D = 3D (Keall et al)


BL
t
3D dose 1
3D dose 2
3D dose 3
3D dose 4
Weighted sum
Total 4D dose

MCTP dose engines

- ✓ For QA:
  - DOSXYZnrc/BEAMnrc engines
  - Engines based on MCNP, GEANT, Penelope
  - DPM (Sempau et al)
  - MCV (Siebers et al)

- ✓ Commercially used:
  - MCDOSE, MCSIM (Ma et al)
  - VMC, VMC++ (Kawrakow)
  - XVMC (Fippel)
  - Peregrine (Hartmann Siantar et al)

VMC, XVMC, VMC++

- HU →Cross sections
- Efficient Boundary crossing
- VRTs: particle splitting, russian roulette, history repitition
- Higher ECUT, transporting low energy e- with CSDA range
- Kerma approximation to higher order photons
- Directional brems splitting

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MCDOSE/MCSIM

- EGS4/BEAM
- Simplified virtual source model
- Ray tracing through beam modifiers
- VRTs

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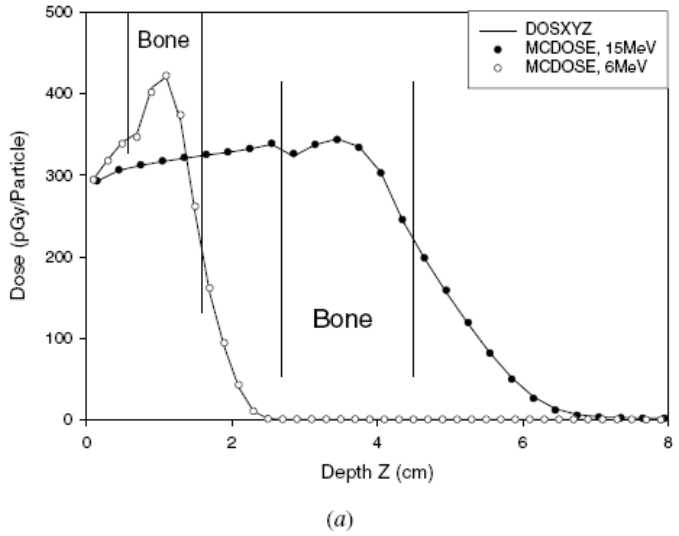
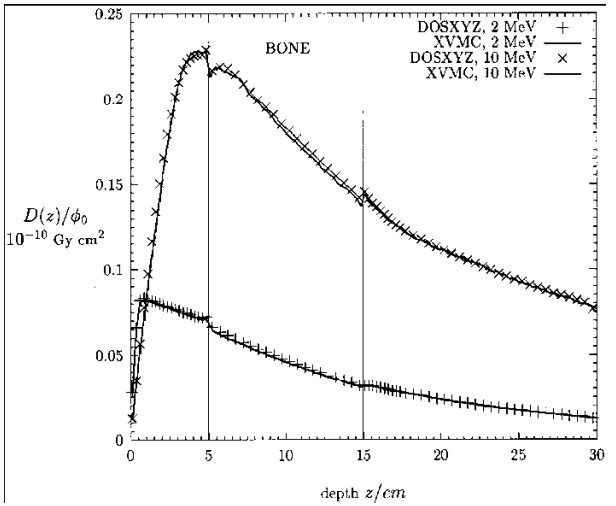
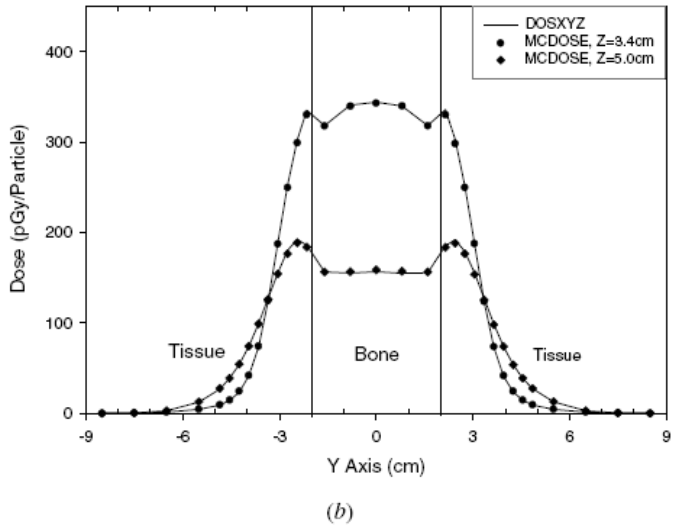
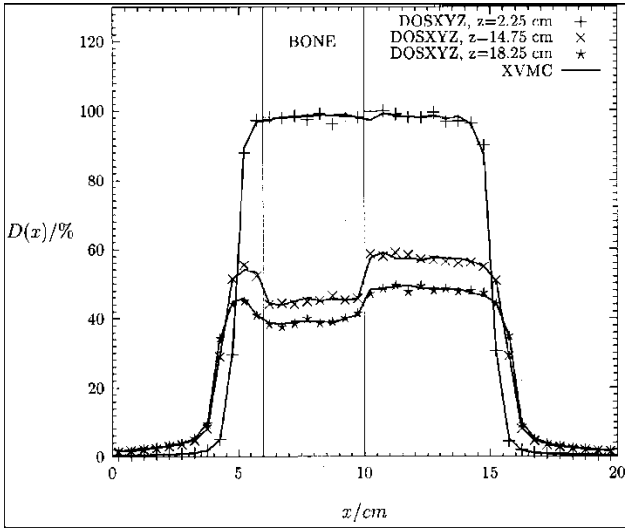
MCDOSE (Li et al, 2000)
XVMC (Fippel et al, 1999)

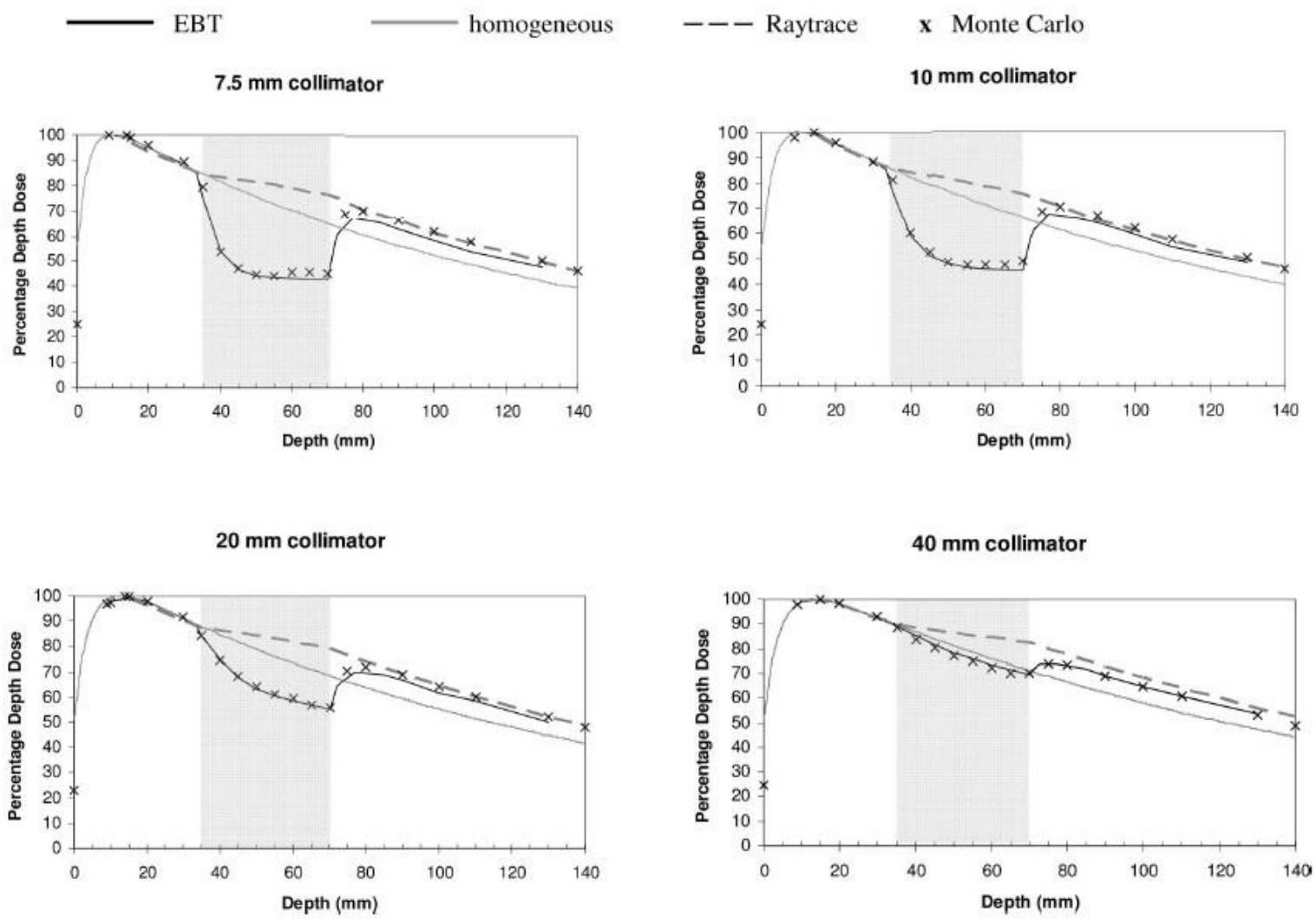








Multiplan (Accuray) (Wilcox and Daskalov 2008)



I.5 Why MCTP ?

- Overall uncertainty clinical dose delivery: 5 %; 3% on dose calculation
- State of the art non-MCTP: superposition/convolution: deviations above 5% due to hererogeneities; composition tissue not taken into account
- MC: Generally stated: within 2 %

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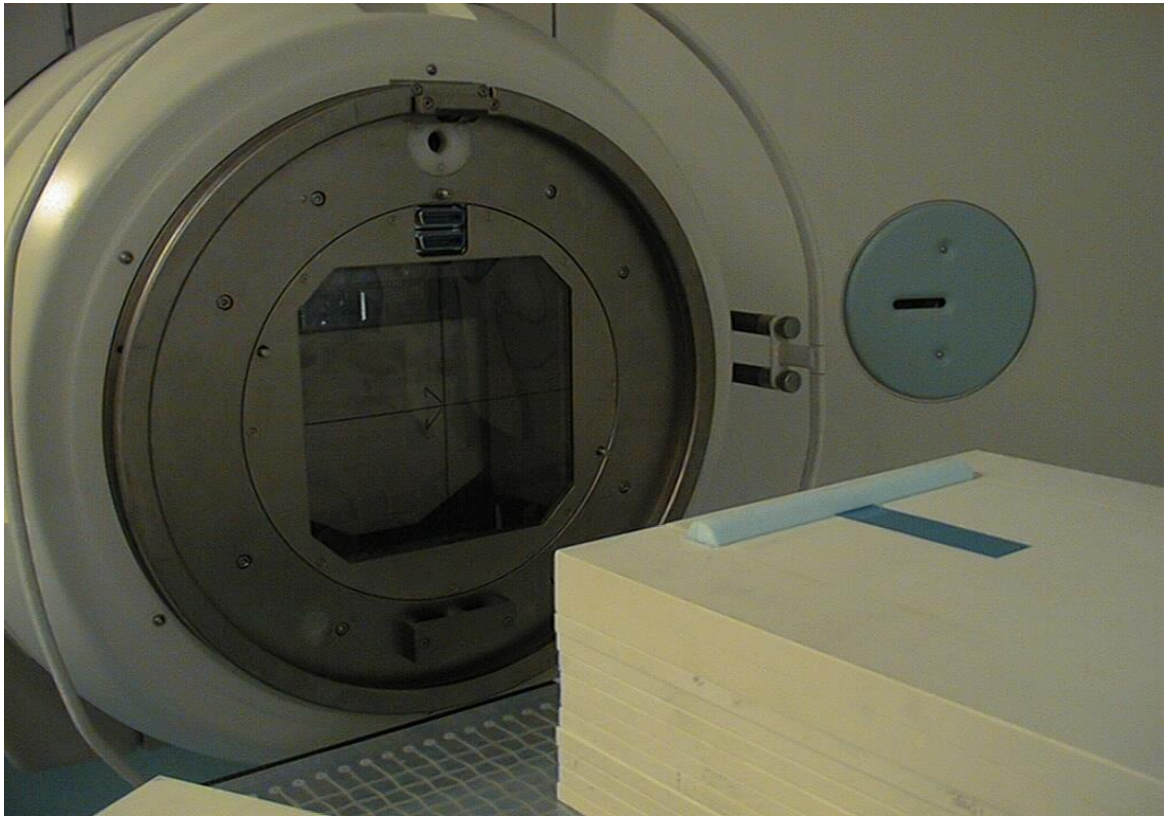
QA: Phantom studies



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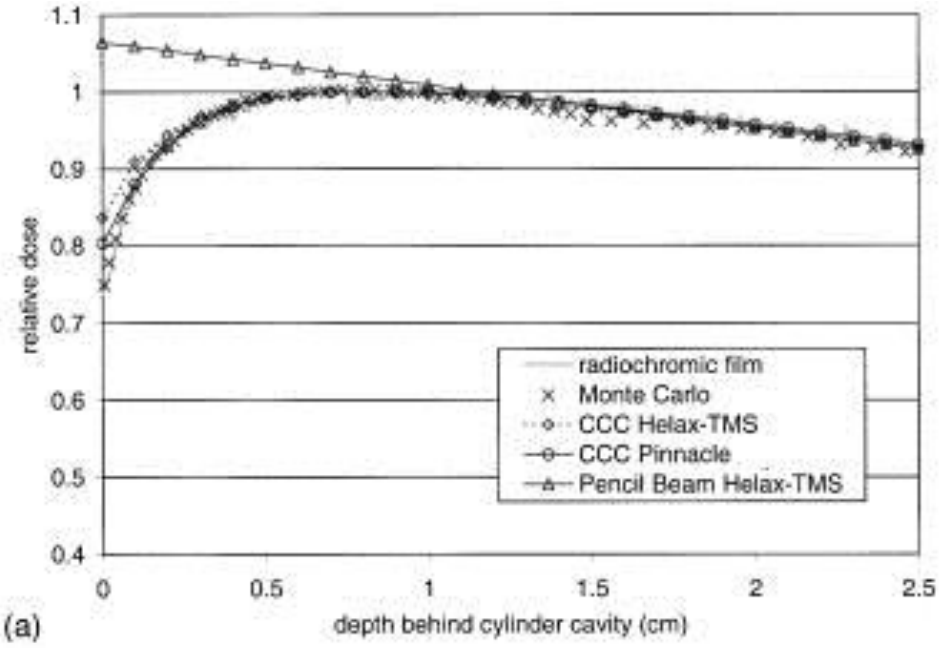

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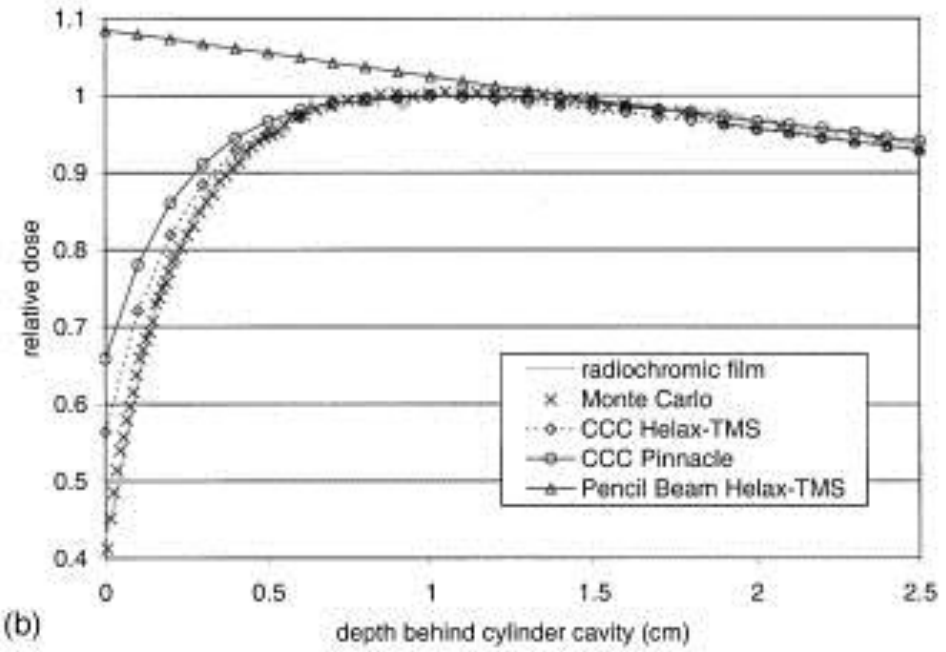

(b)

Martens et

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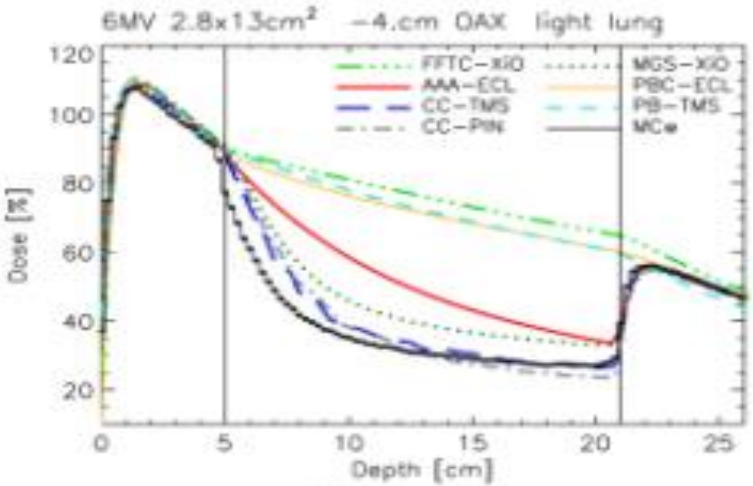
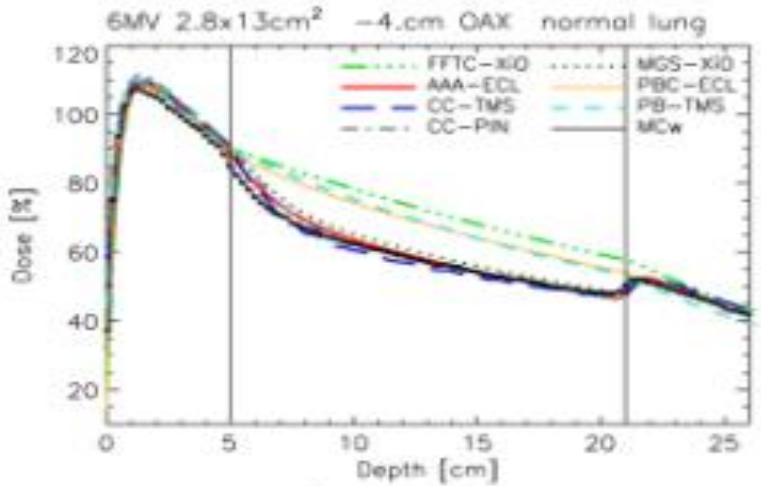
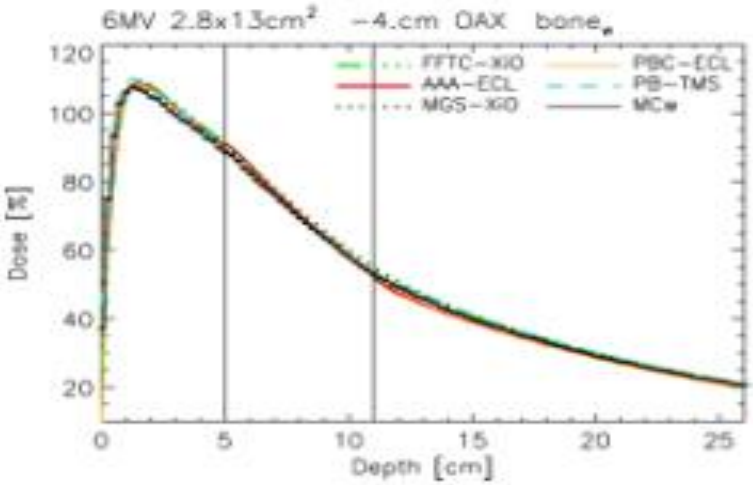
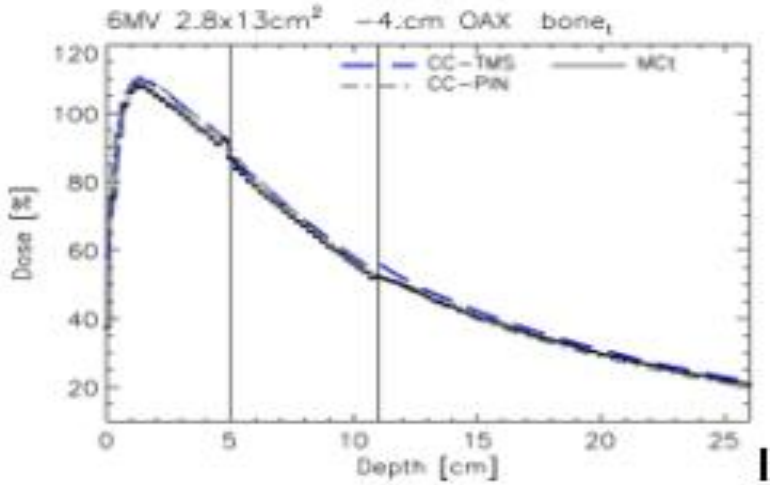
A. Fogliota et al. 2007

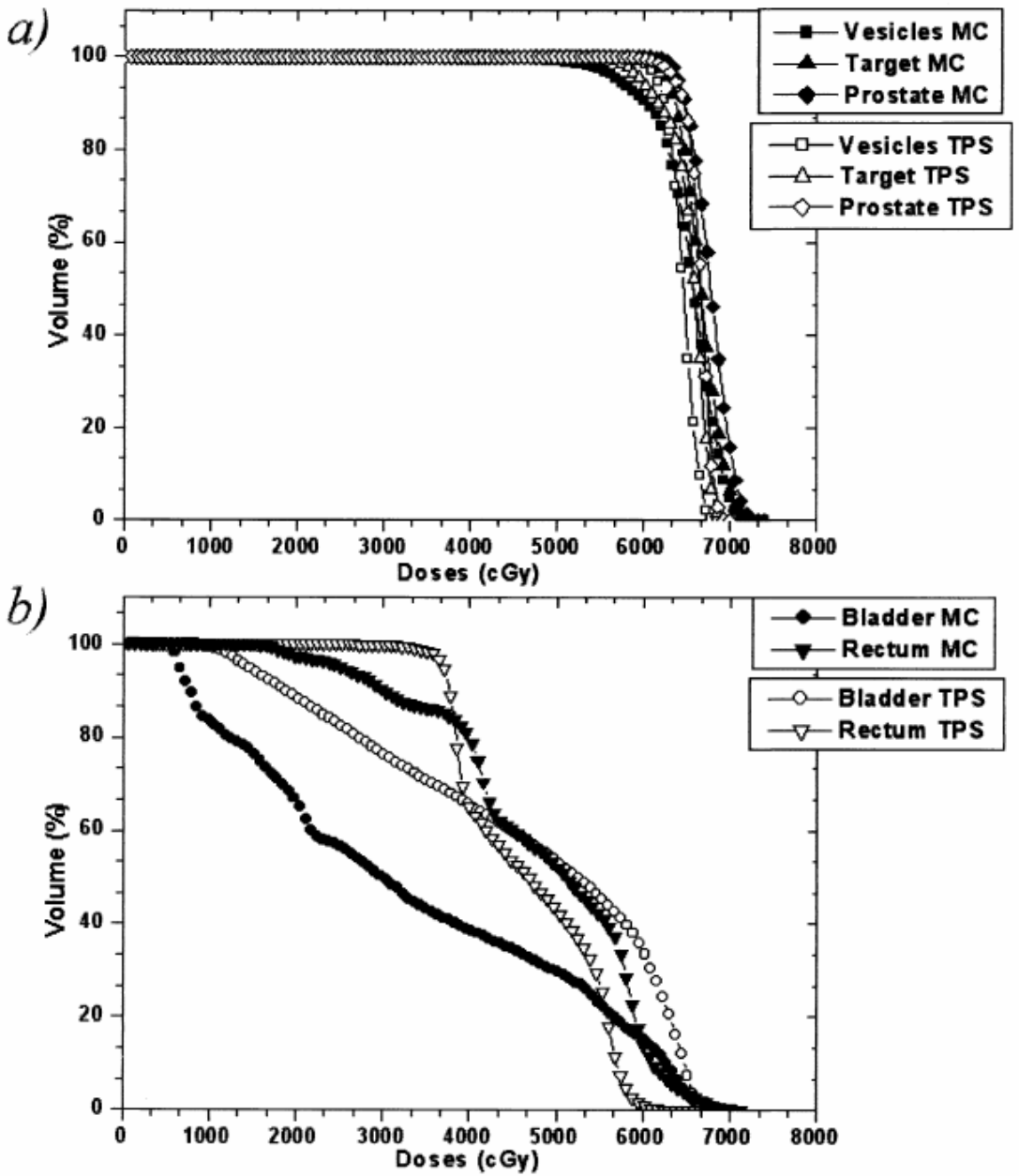




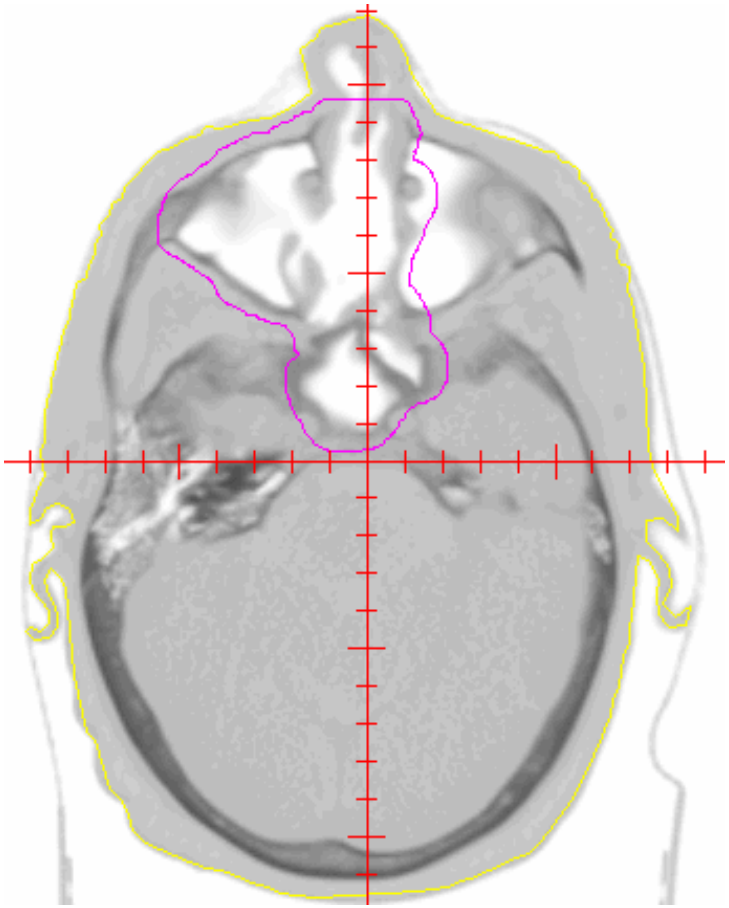


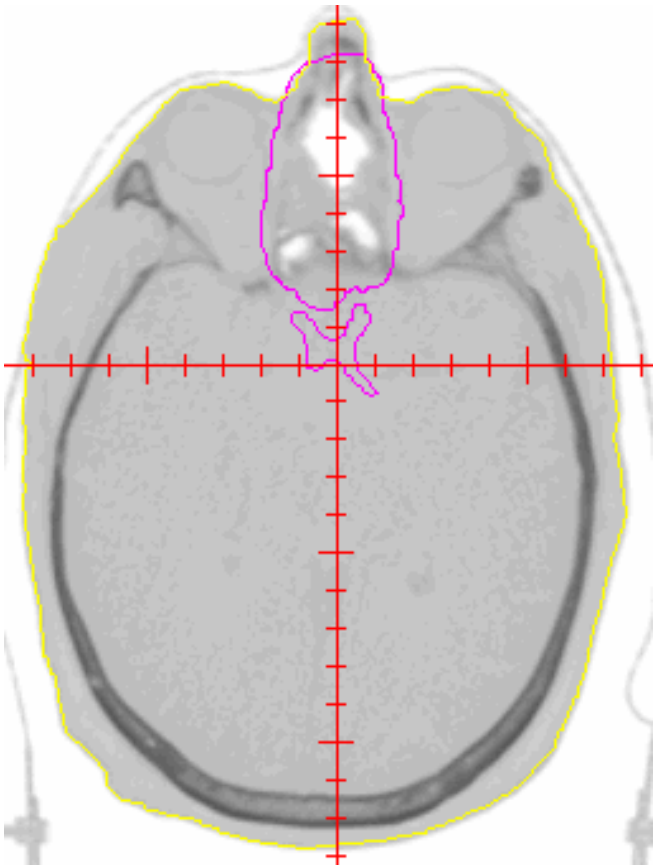


Leal et al, 2003:
PB/vs Monte
Carlo, prostate plan



MCDE/Peregrine (Reynaert et al, 2005)





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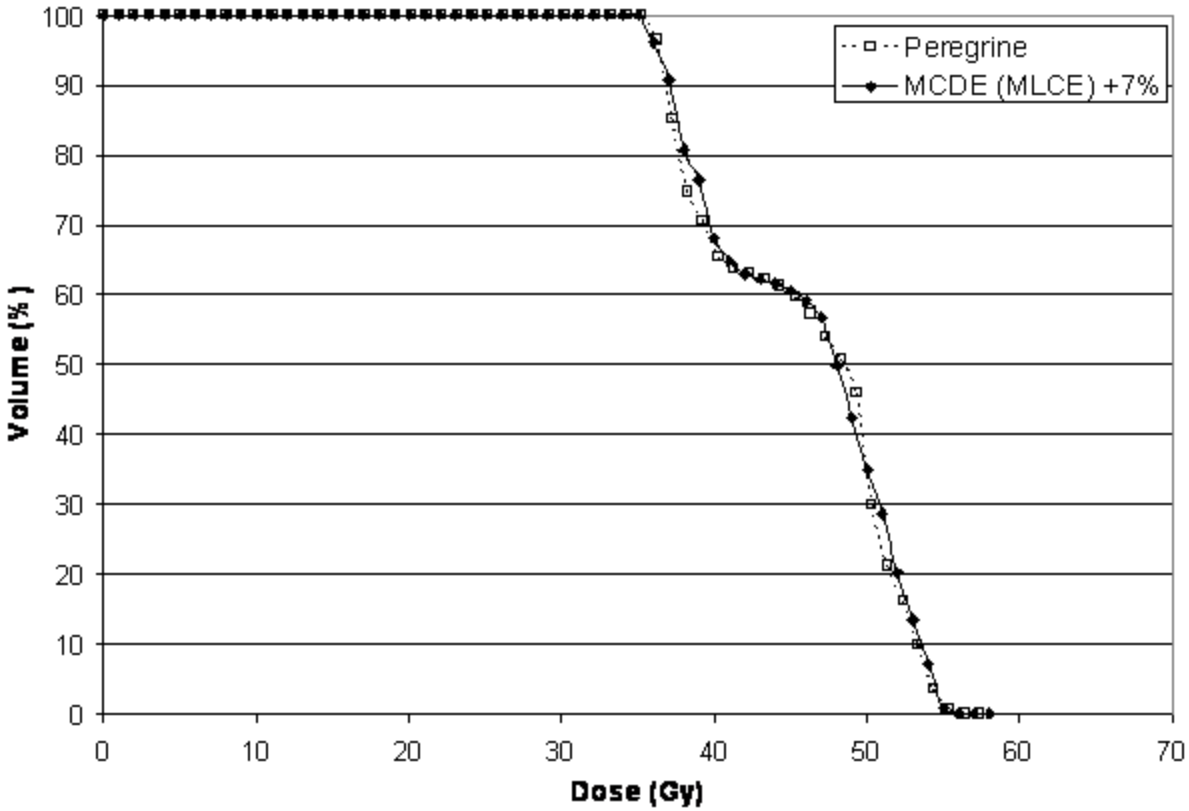
DVHs (MCDE/Peregrine)



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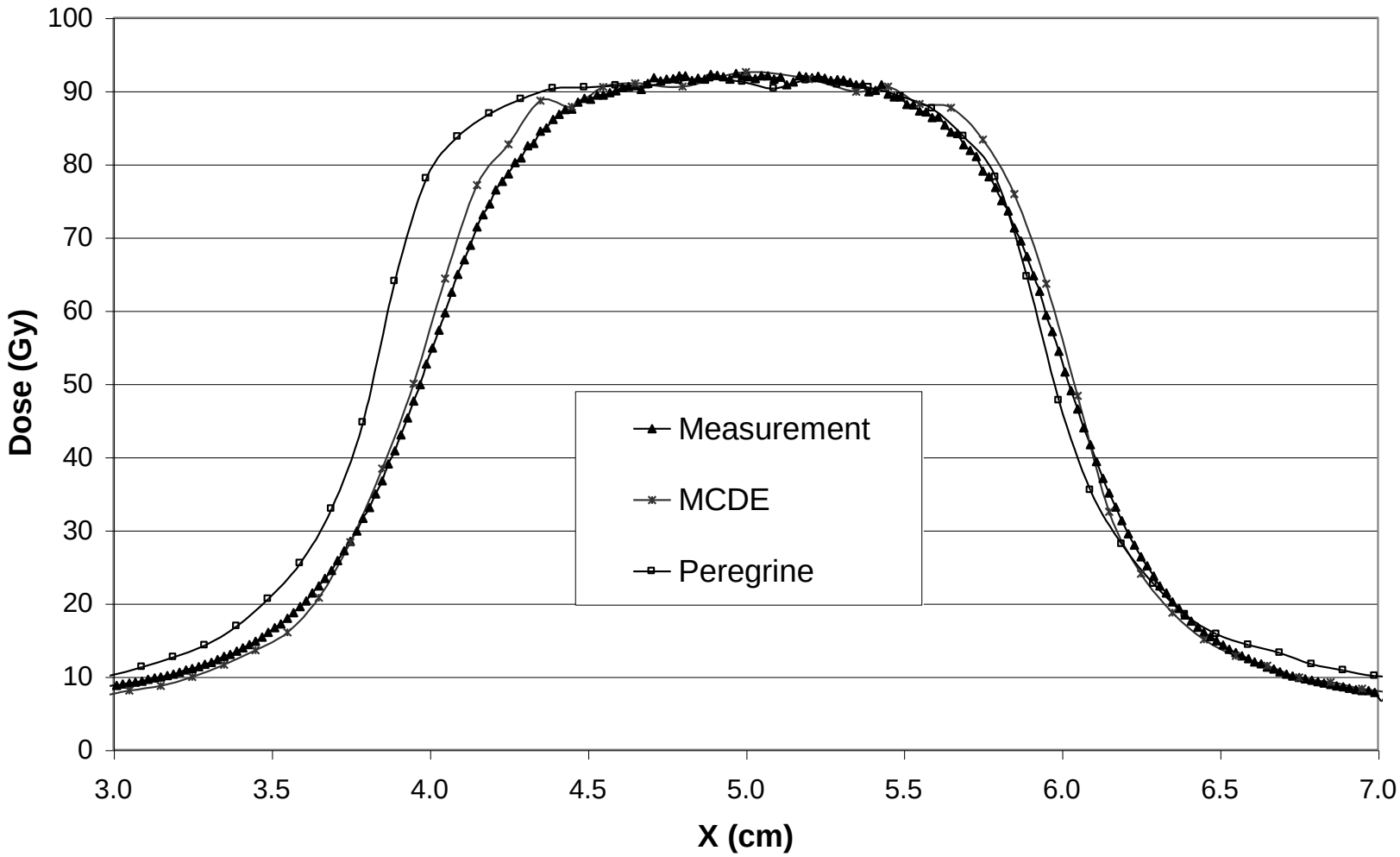
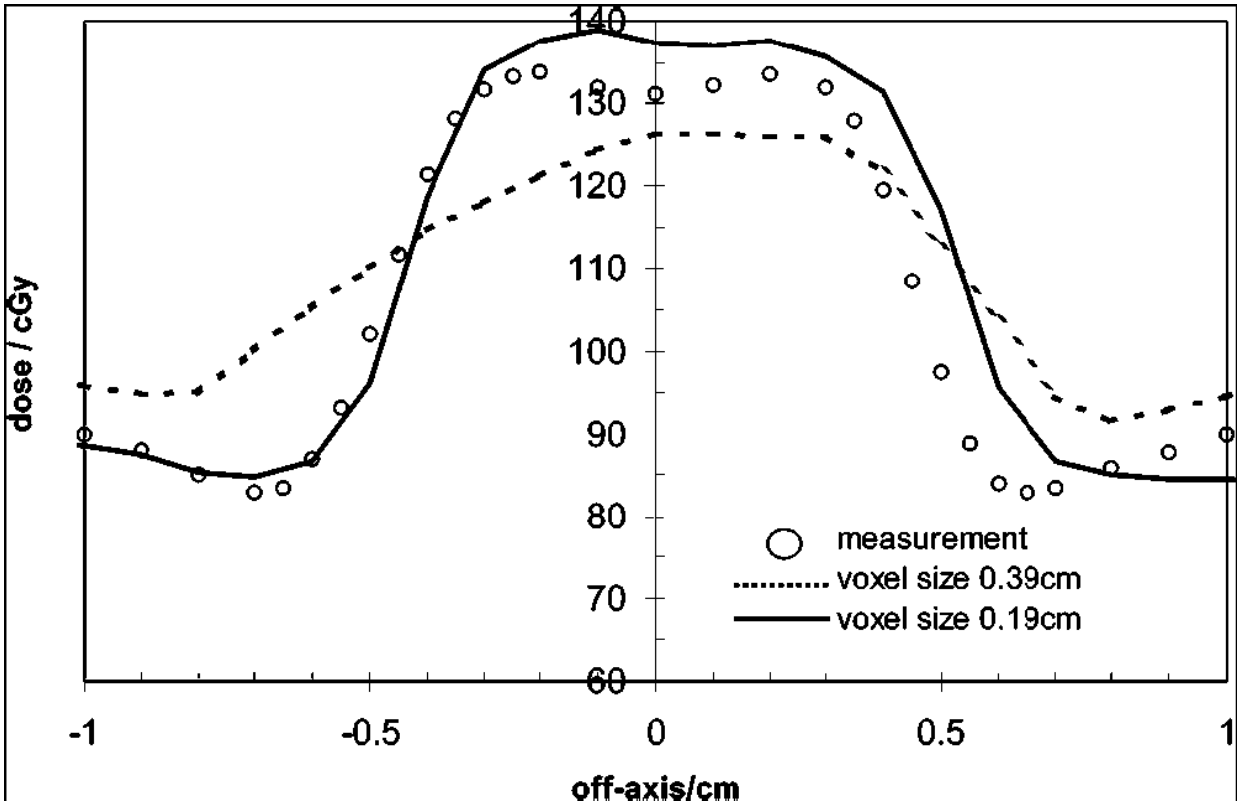
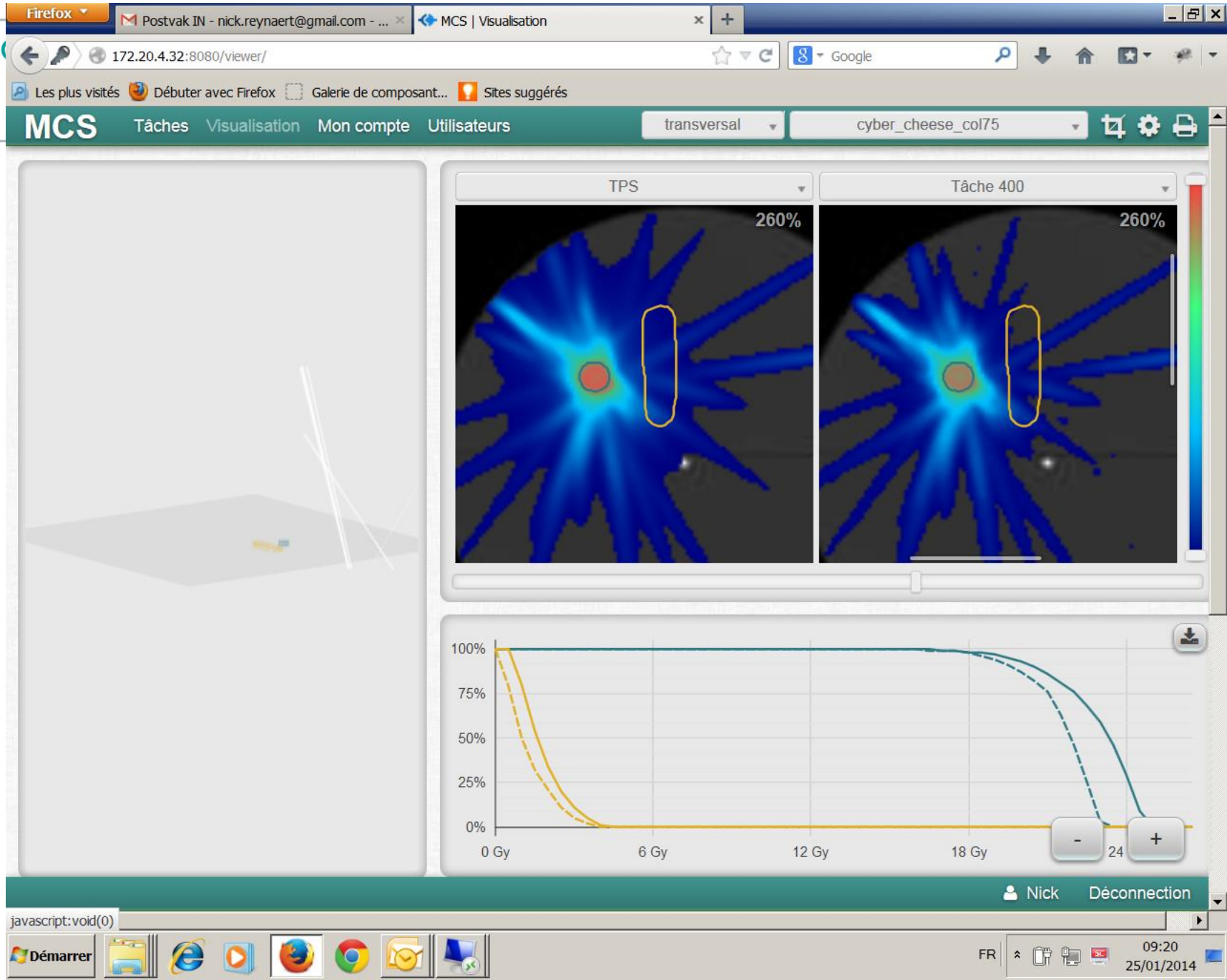
2x2 offset field: AB



VMC++ Masterplan (Nucletron), Cygler et al, 2004

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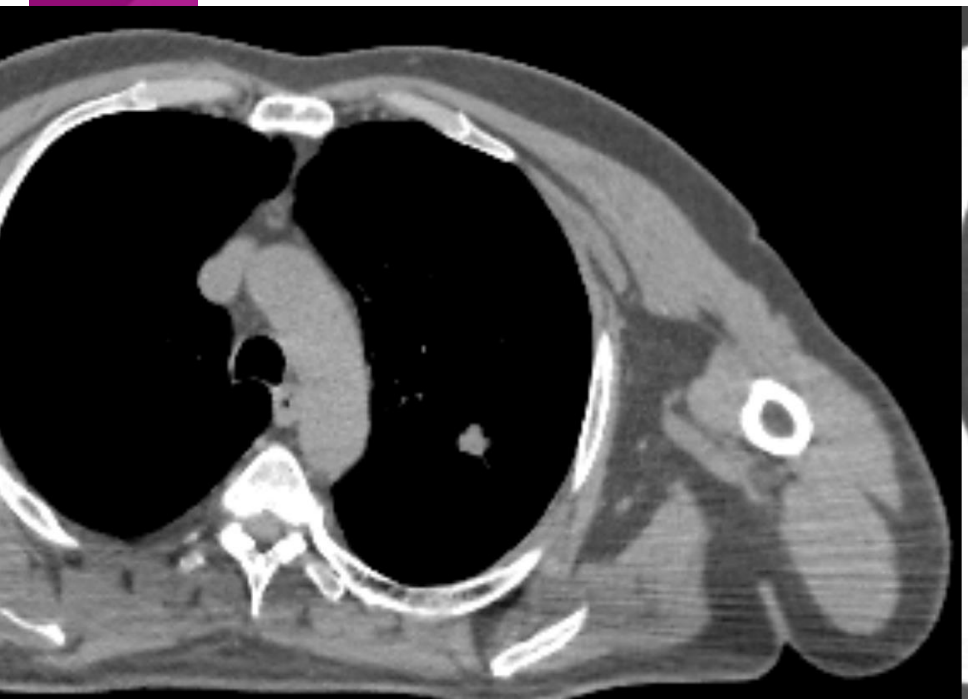
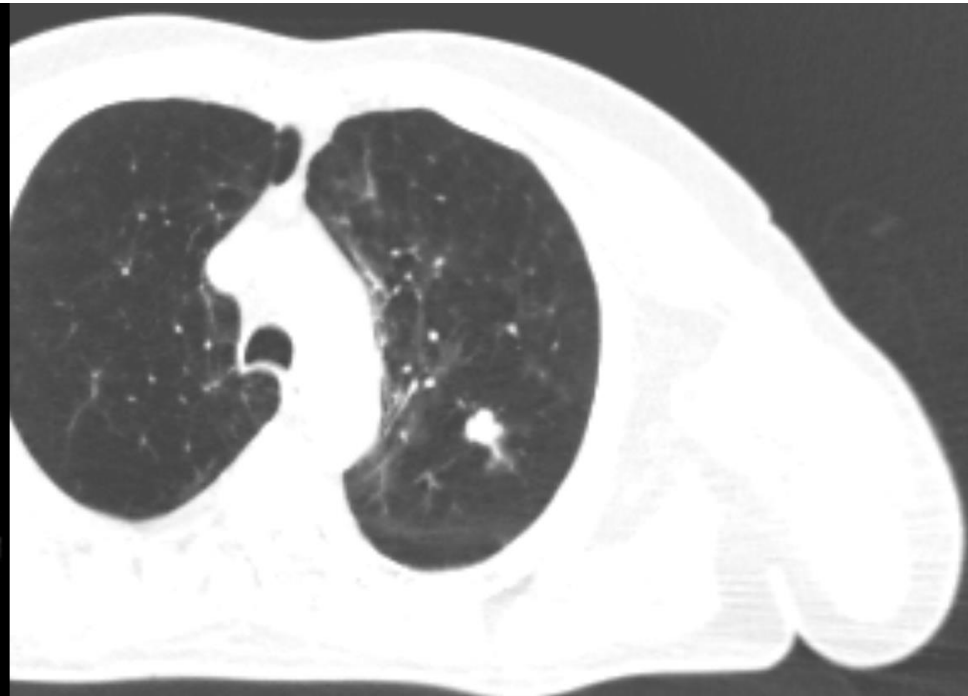
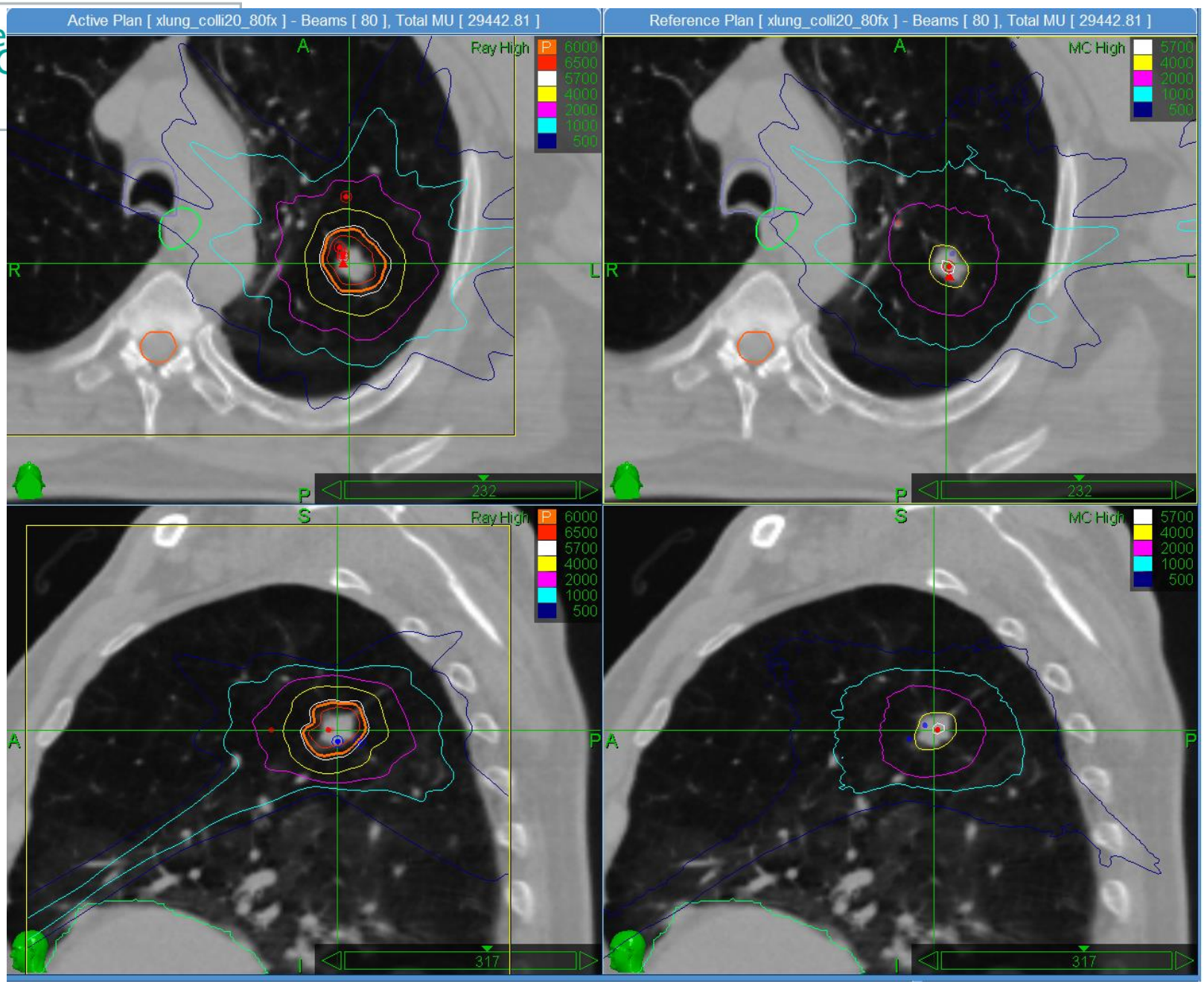
Extreme case: Cyberknife

- Small target (but tracking was possible)
- Extremely low lung density

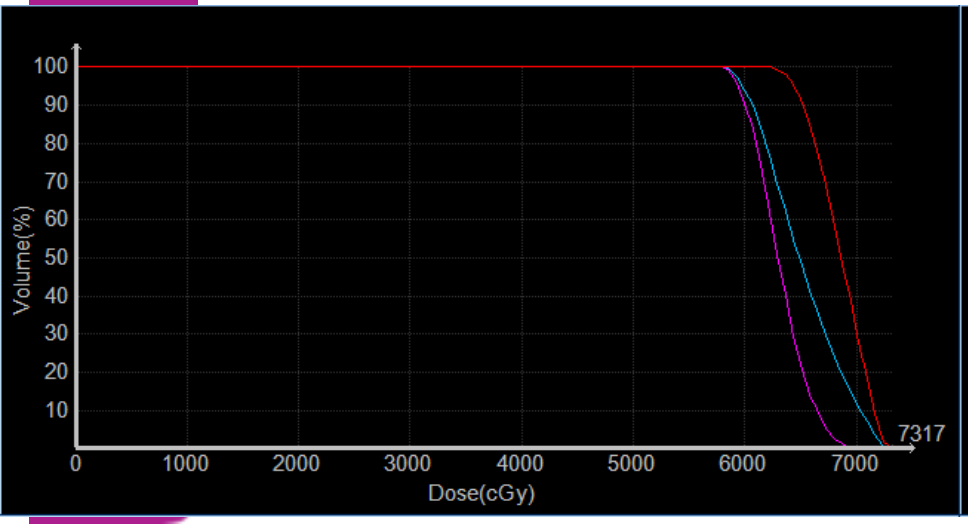


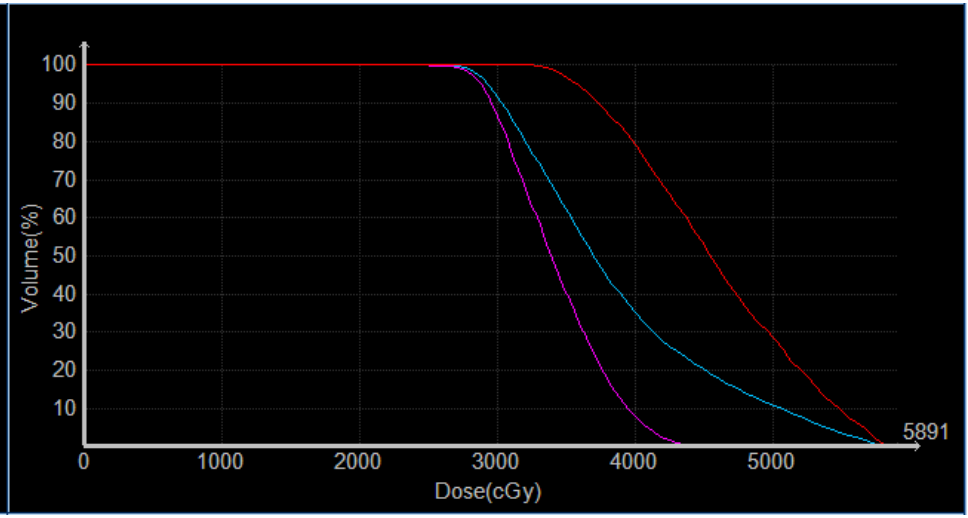


Ray- Tracing : 3 x 20 Gy **Monte-Carlo :**

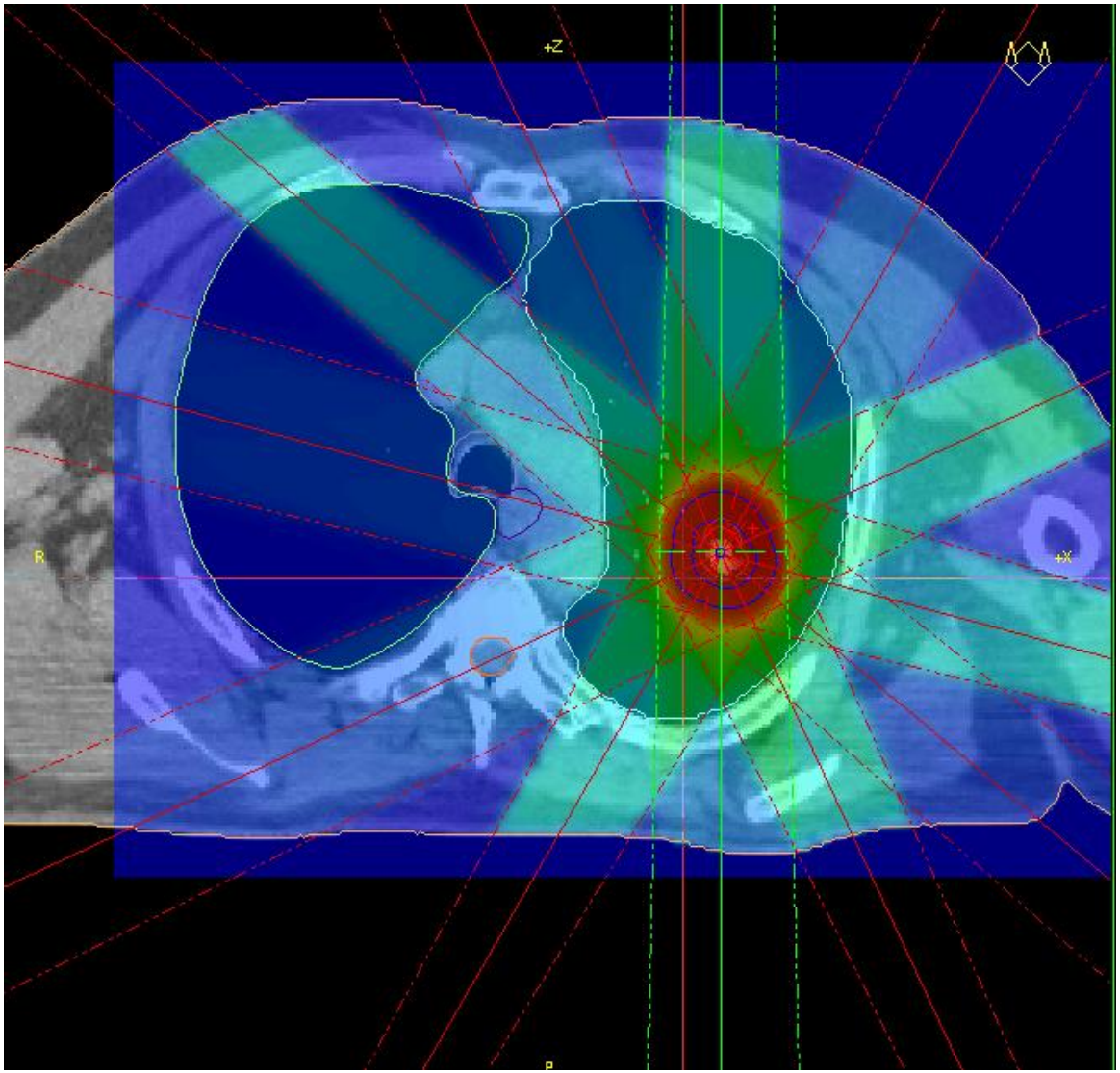


		Dose (Gy)		
	Ray-Tracing	MC	Ray-Tracing	MC
	GTV		PTV	
D2% (max)	72.4	57.7	72	56
D50%	68.5	45.3	64	36
D98% (min)	63.6	34.8	59.3	28.9





Same Patient: Masterplan (Nucletron)



- ✓ SBRT Plan for 6 MV Clinac

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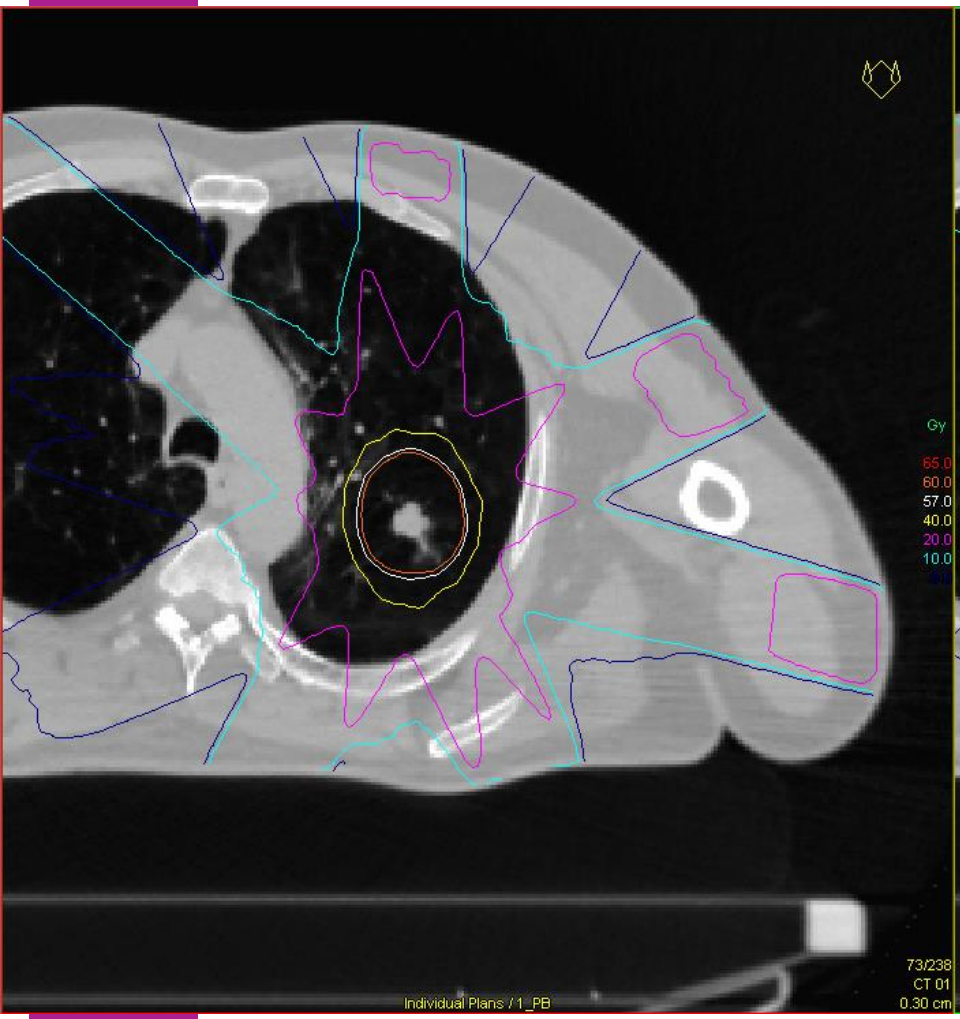
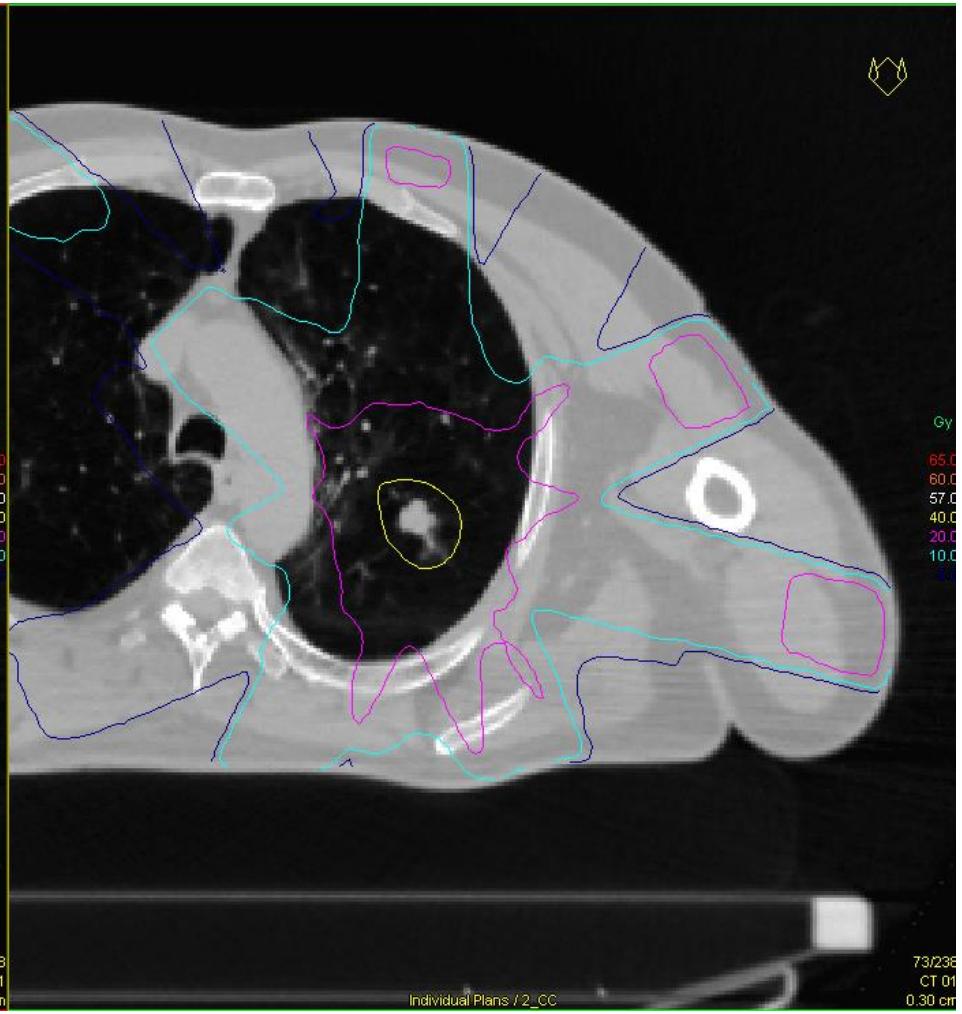
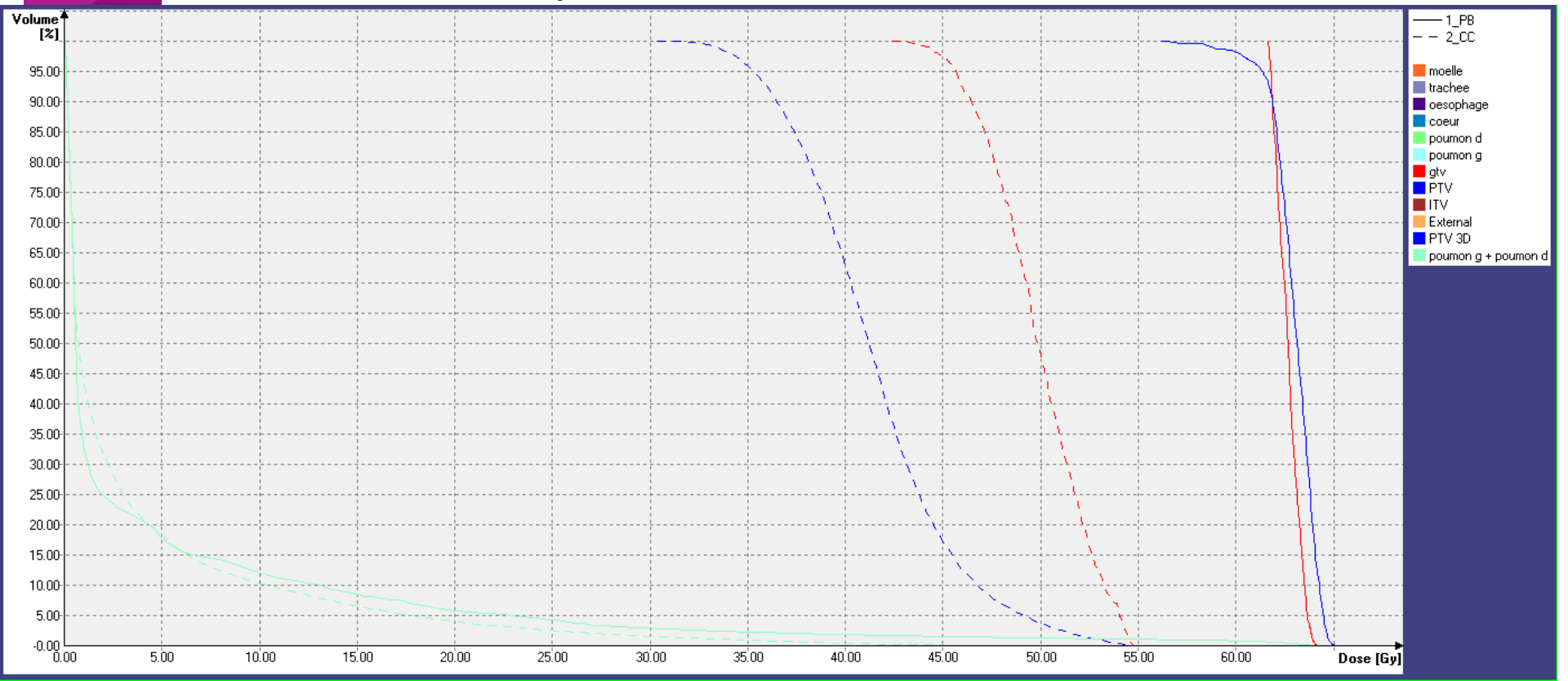
Pencil beam vs Collapsed cone





- Very important difference between algorithms of category 3 and 4
- Especially for the PTV (low density part)

-- Collapsed cone – Pencil Beam



Summary

- For SBRT lung treatment, a dose calculation of category 4 is required.
- Monte Carlo or superposition/convolution algorithms
- Prescription should be based on these algorithms to have less inter-patient differences (clinical trials e.g.)
- Even these 4th category dose calculation algorithms should be carefully benchmarked.
- For Monte Carlo algorithms: impact of noise, denoising, resolution, commissioning (output factors measurements, …)
- 4D optimization: Added value of MC algorithm
- Dose to water/Dose to medium ?

✓