Proton Monte Carlo Platforms
Treatment Planning and Latest Developments

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Conflicts of Interest

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- NCI / NIH
- Damon Runyon Foundation
- Brain Tumour Charity

Monte Carlo Introduction

- **Analytical Pencil Beam Algorithms:**

- For treatment planning and most clinical dose calculations
- Analytical calculations (approximations)
- Fast

Why do we need Monte Carlo ?

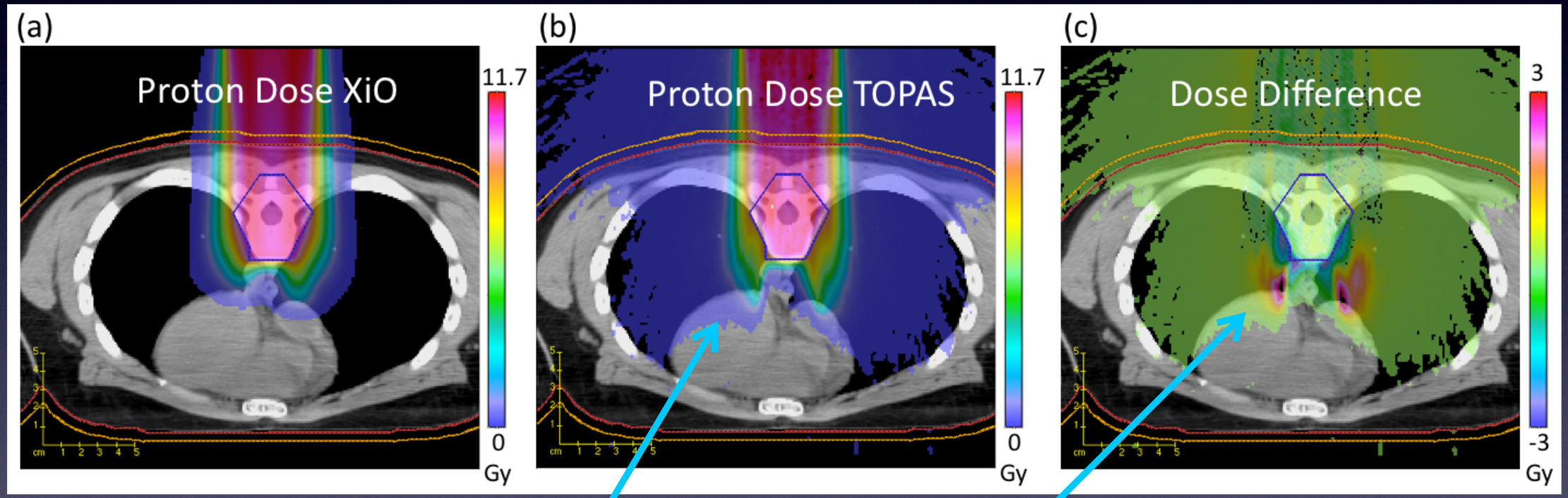
- **Monte Carlo** dose calculation serves as a **benchmark** for analytical dose calculation, in particular in complex geometries

- Monte Carlo can be used to calculate quantities in addition to dose (fluence, LET, …) for research, development and clinical applications

- **Differences** between Monte Carlo and analytical algorithms **more clinically significant in proton therapy** compared to photon therapy due to higher dose gradients and the end of range of proton beams

Monte Carlo Introduction

analytical MC Difference



range uncertainty for analytical dose calculations

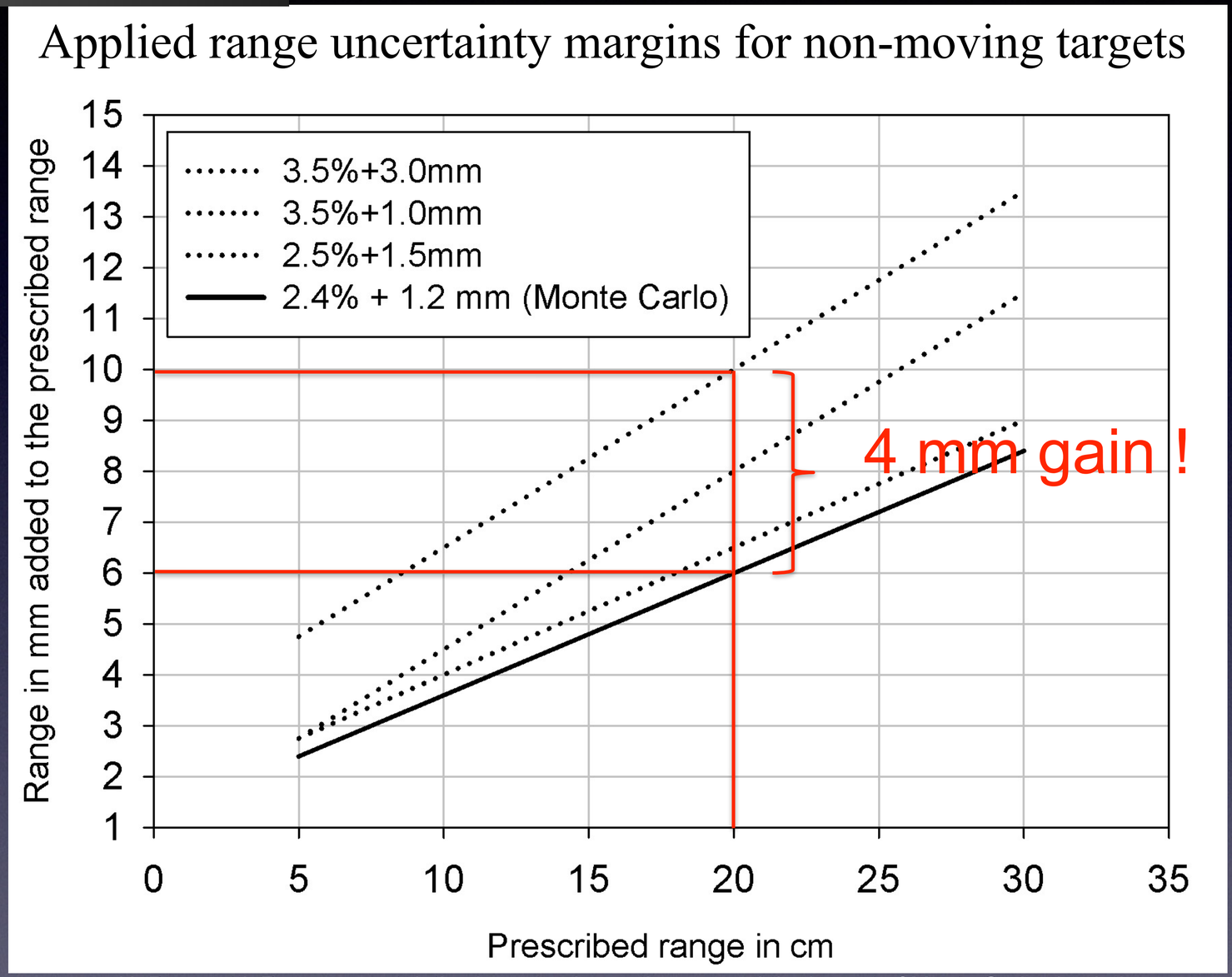
MASSACHUSETTS GENERAL HOSPITAL
RADIATION ONCOLOGY
HARVARD MEDICAL SCHOOL

Monte Carlo Introduction

Source of range uncertainty in the patient	Range uncertainty	With Monte Carlo
Independent of dose calculation:		
Measurement uncertainty in water for commissioning	± 0.3 mm	
Compensator design	± 0.2 mm	
Beam reproducibility	± 0.2 mm	
Patient setup	± 0.7 mm	
Dose calculation:		
Biology (always positive)	+ 0.8 %	
CT imaging and calibration	± 0.5 %	
CT conversion to tissue (excluding I-values)	± 0.5 % →	± 0.2 %
CT grid size	± 0.3 %	
Mean excitation energies (I-values) in tissue	± 1.5 %	
Range degradation; complex inhomogeneities	- 0.7 % →	± 0.1 %
Range degradation; local lateral inhomogeneities *	± 2.5 % →	± 0.1 %
Total (excluding *)	**2.7% + 1.2 mm**	**2.4 % + 1.2 mm**
Total	**4.6% + 1.2 mm**	

H. Paganetti: Range uncertainties in proton beam therapy and the impact of Monte Carlo simulations
Phys. Med. Biol. 57: R99-R117 (2012)

Monte Carlo Introduction



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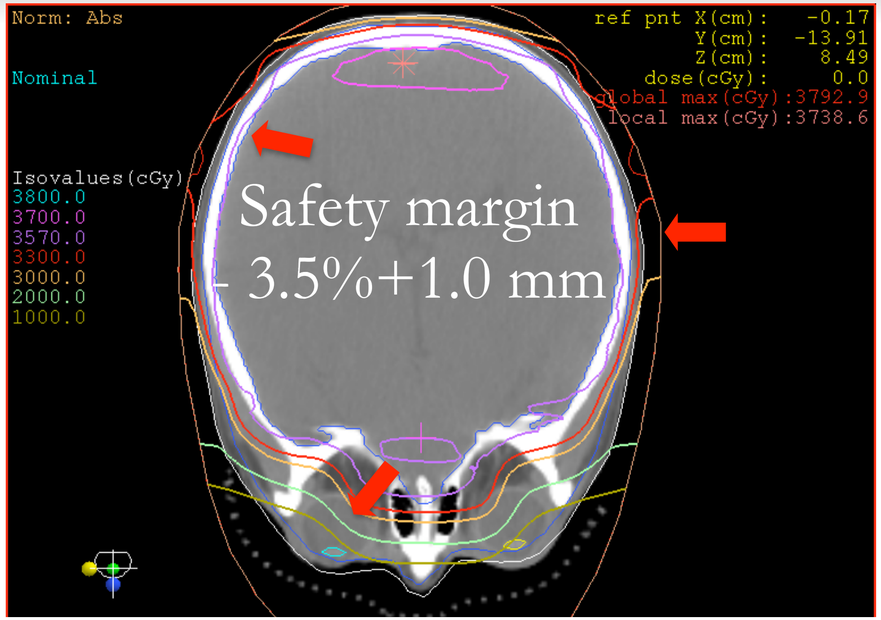
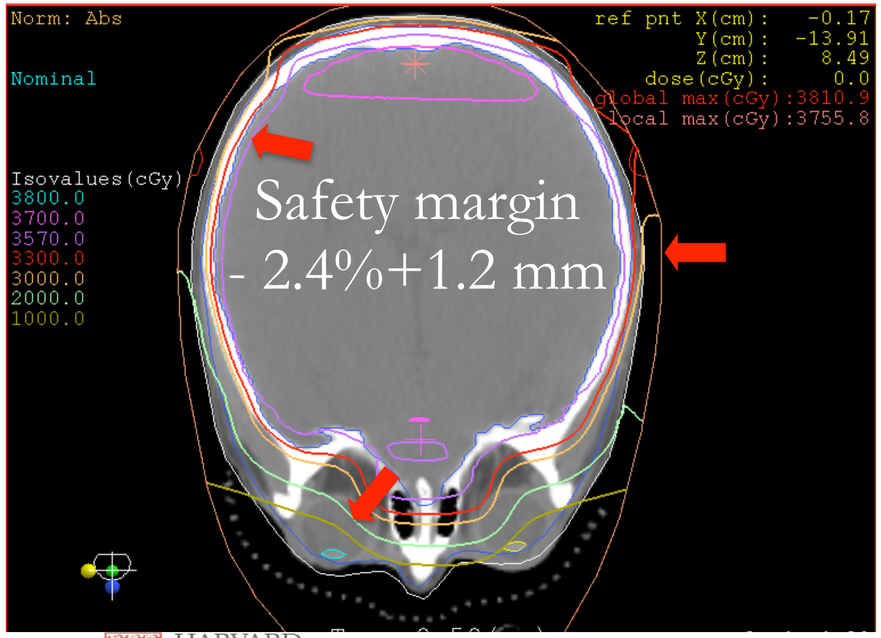
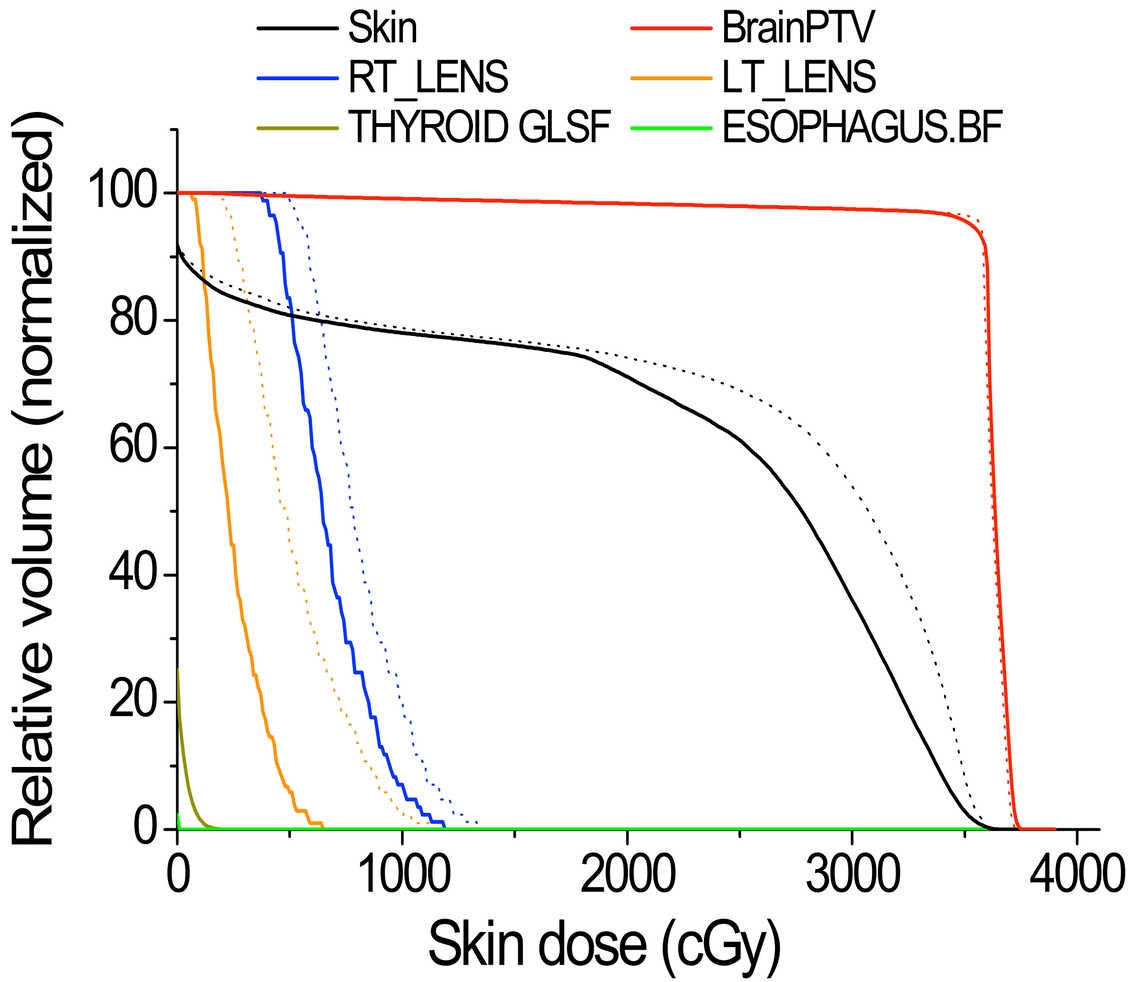
Effects of Margins





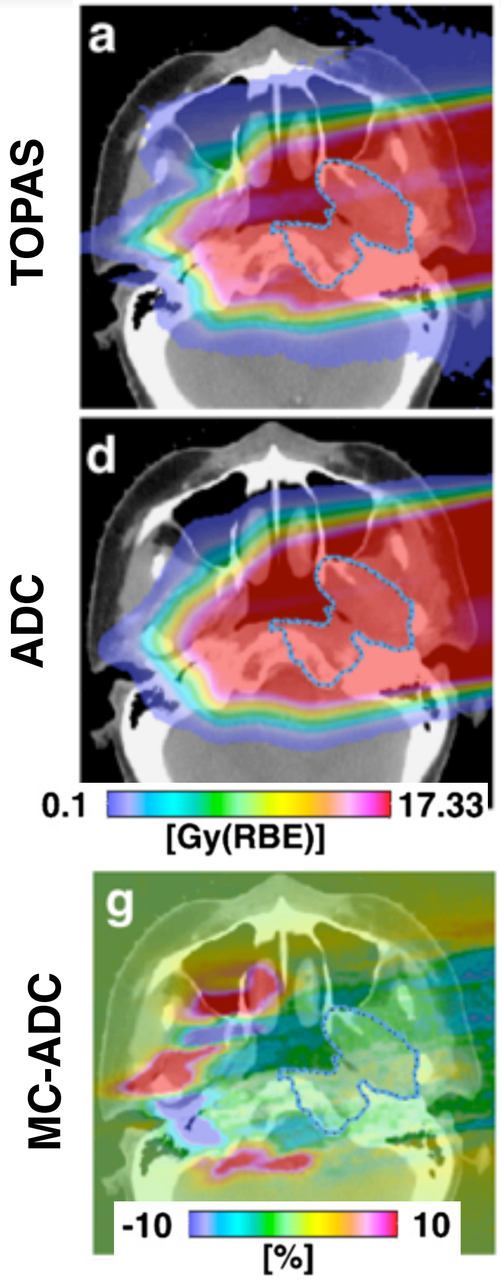
★ reduction of margins to 2.4% + 1.2 mm

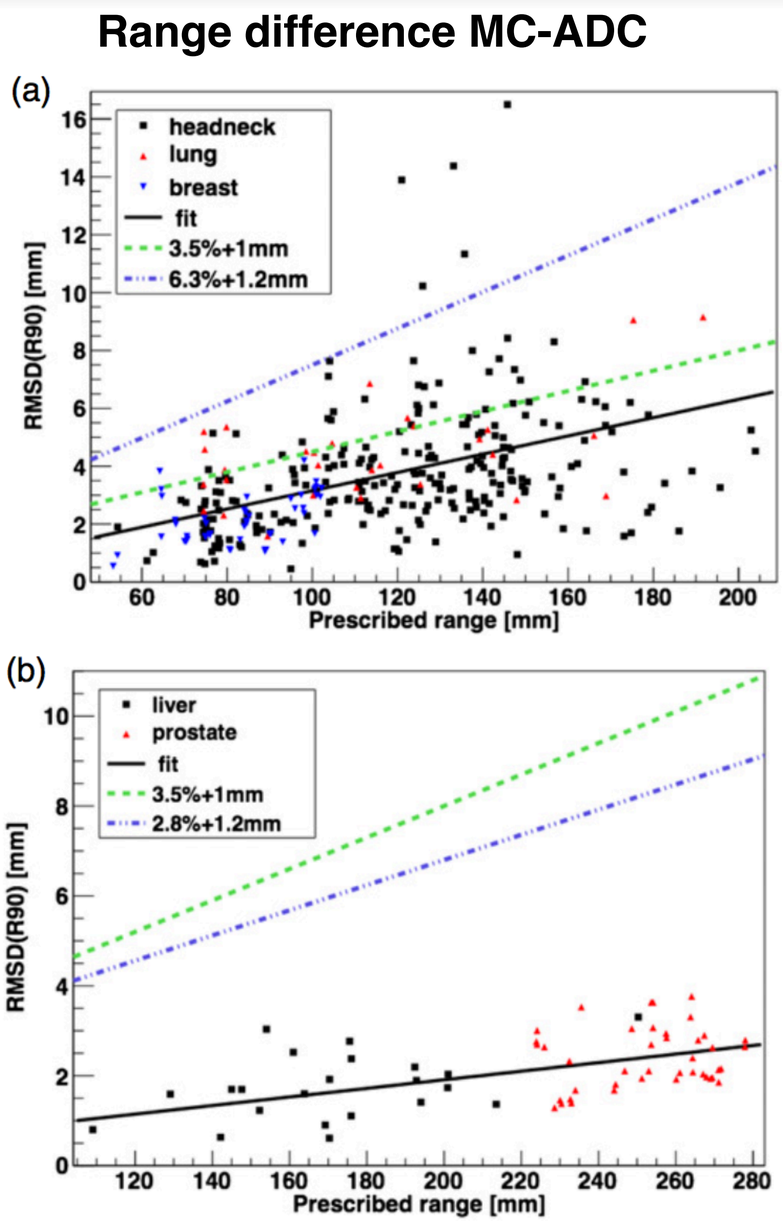
★ large effect on critical structures



Understanding uncertainties in treatment planning

- ★ MC considered to be gold standard of radiation transport calculations
- ★ Compare MC to treatment planning systems (TPS) based on analytical dose calculations (ADC)
- ★ Various studies comparing TPS to MC
- ★ Study effects of high density interfaces parallel to beam on analytical calculations



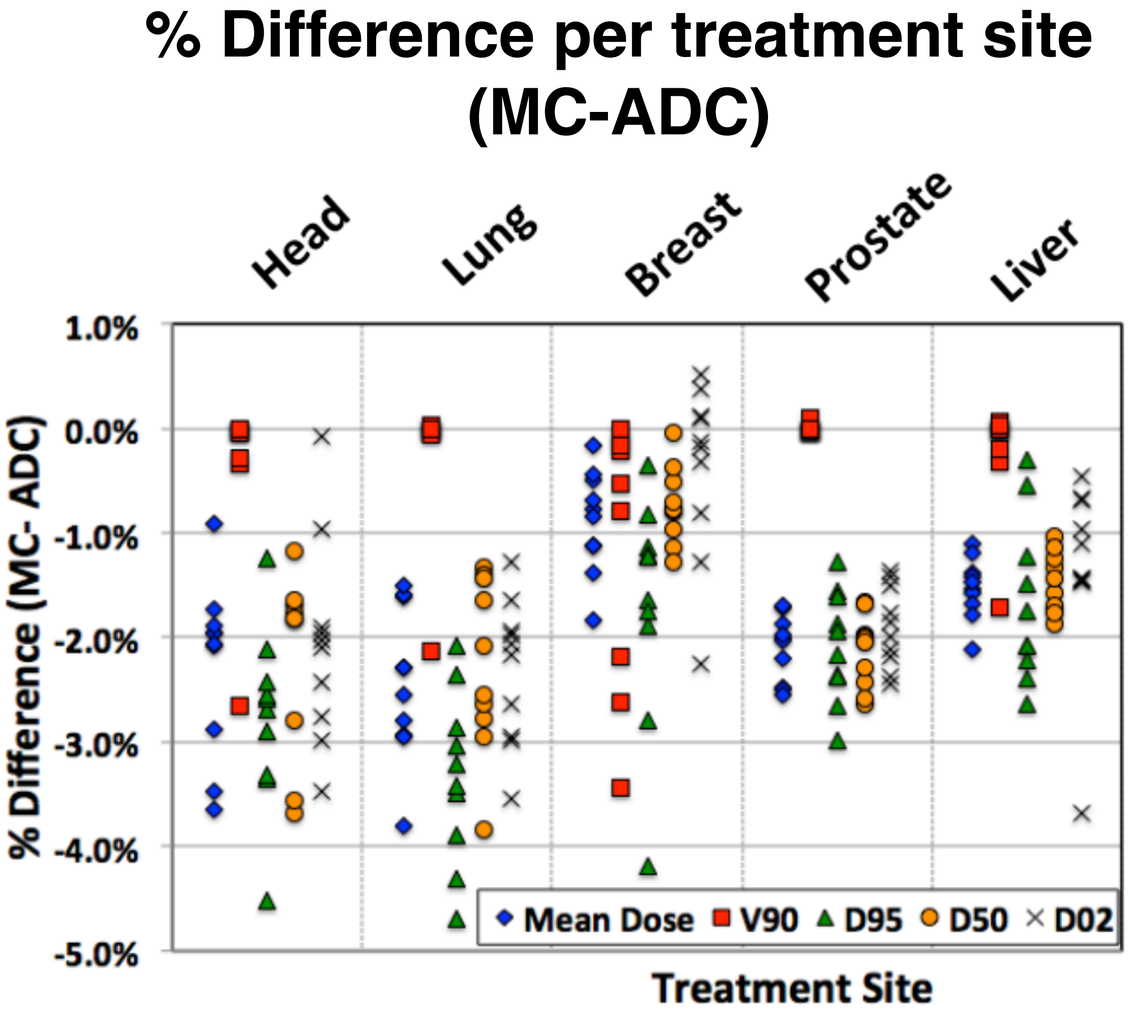


J. Schuemann et. al, PMB. 2014, IJROBP 2015

Comparing ADC and MC - DVH parameters

★ DVH comparison:

- ★ Multi-beam treatment fields
- ★ all differences between MC and ADC < 5%
- ★ largest variance for heterogeneous patient geometries
- ★ general underdosage (small fields + scattering effects)



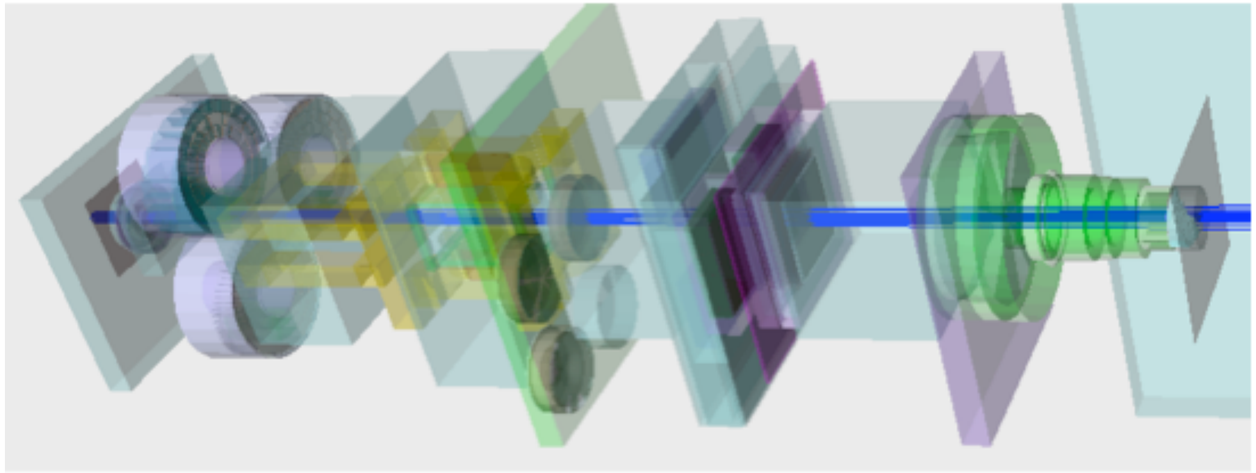
Schuemann et al, Red Journal (2015)

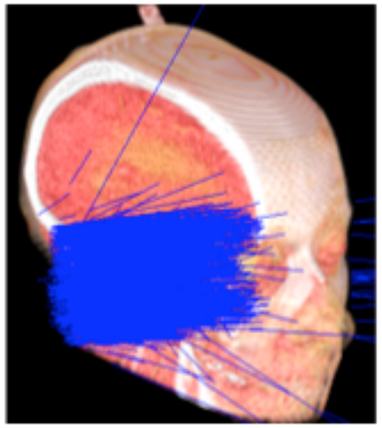
Many in house developments

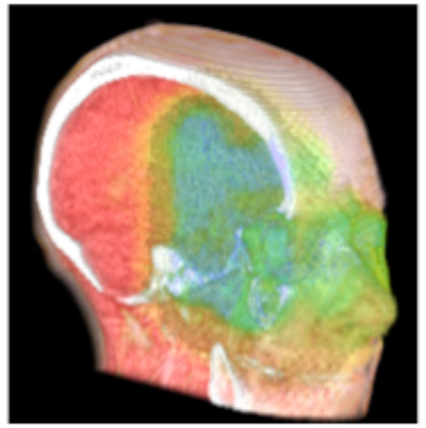
TOPAS: Tool for Particle Simulations

TOPAS:

Wraps the general purpose Geant4 Monte Carlo system for Particle Therapy







Clinical Routine Monte Carlo

Script actions:

- creates input files
  - scattering: range comp, aperture, beam current modulation
  - scanning: phase space input
- creates patient geometry from CT files
- includes absolute dose normalization
- submits simultaneous jobs to a cluster

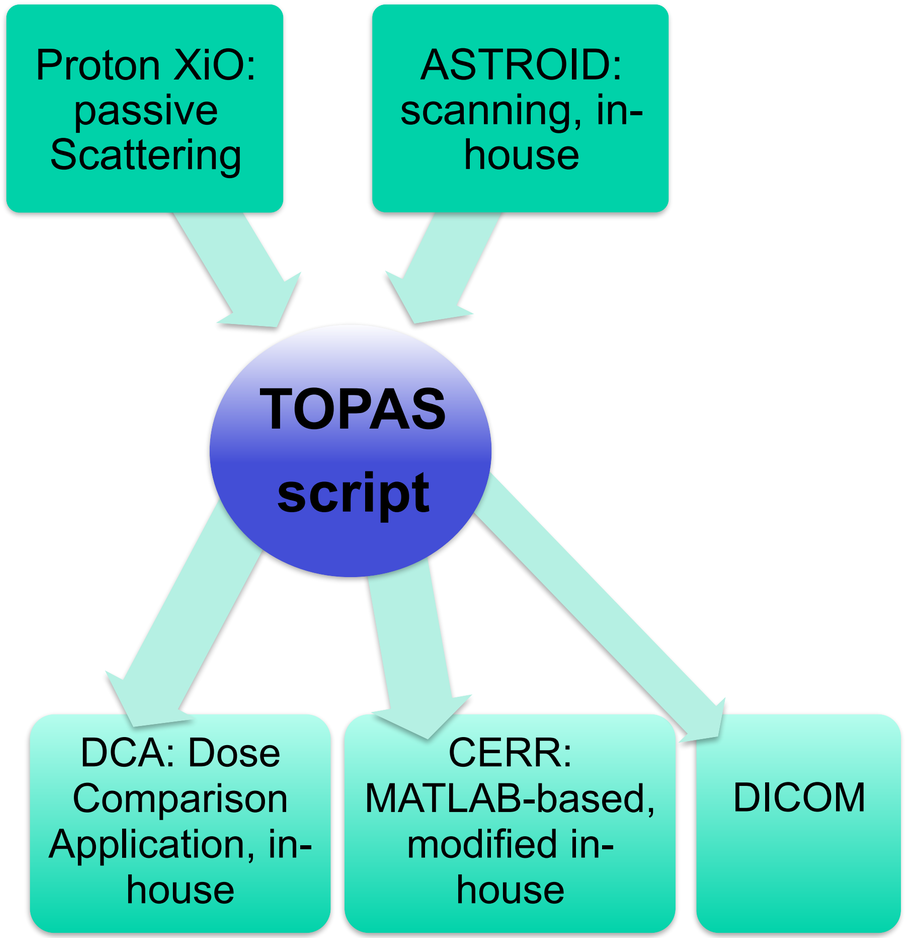
after the runs are finished:

- adds all fields
- outputs dose suitable for in-house and DICOM-compatible software
- reports dose-to-tissue / dose-to-water
- dose on planning grid and CT grid

full patient simulation:
~ 5 hrs on cluster
Total CPU time per field ~200 hours

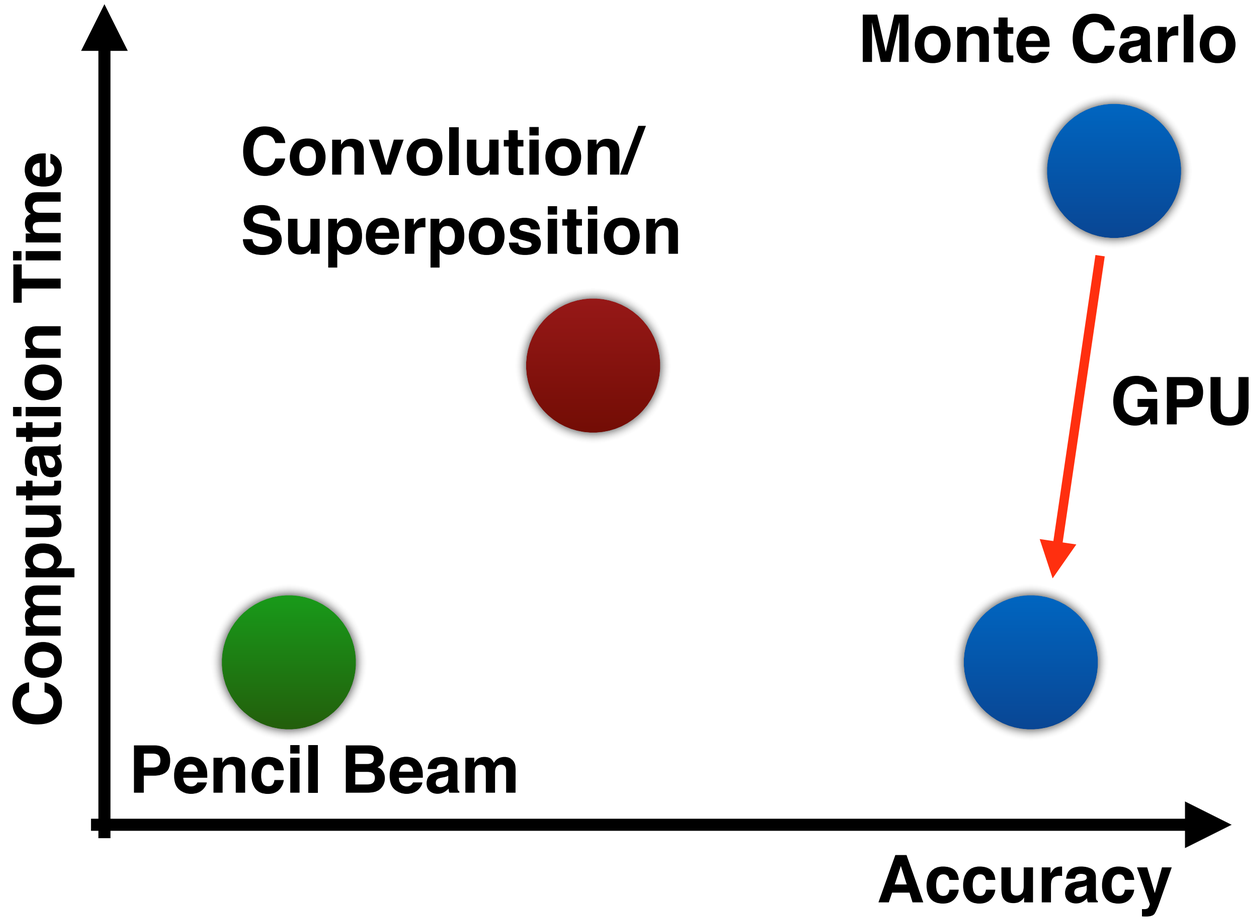
MC AUTO

J. Verburg, C. Grassberger, et al. Technol. Cancer Res. Treat., 2016



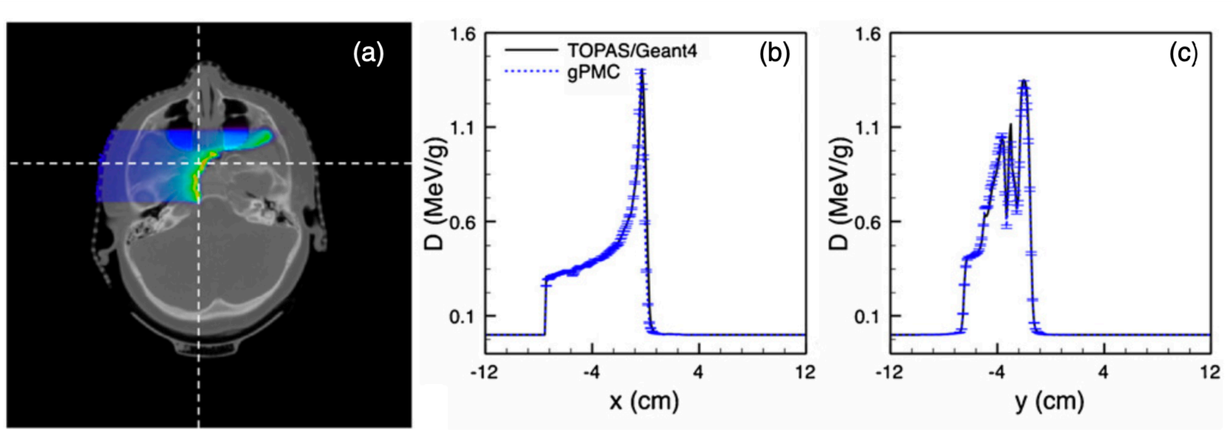
Challenges

- ★ Fast turnaround needed
- ★ Speed vs. accuracy
- ★ What is required?
  - ★ How accurate?
  - ★ How fast?

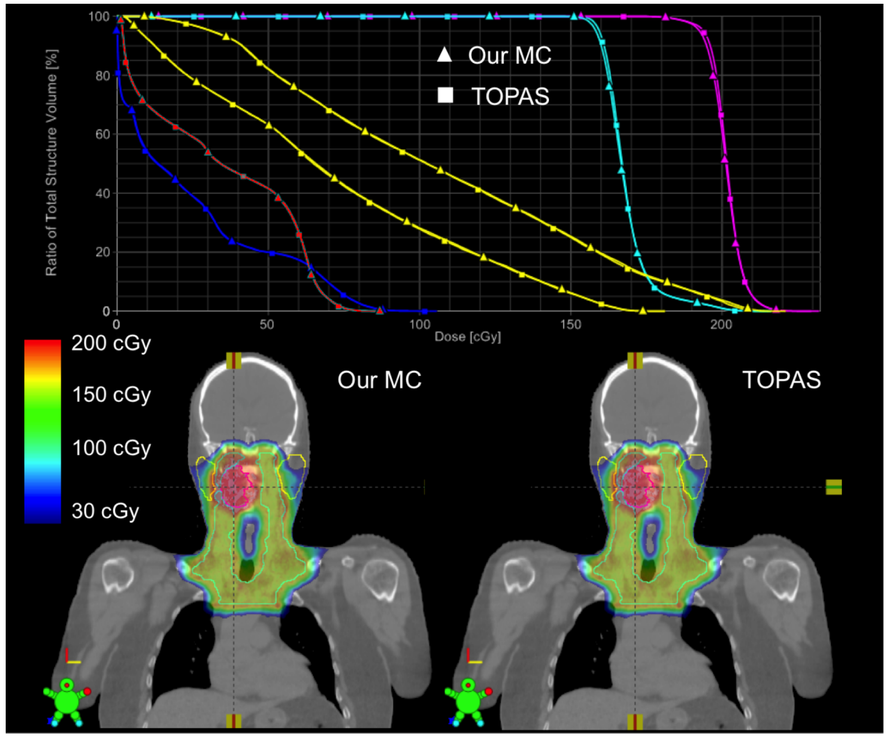


GPU Monte Carlo

- ★ GPUs offer faster MC simulations
- ★ Specialized applications
- ★ Some approximations
  - ★ No neutral particle transport
  - ★ Local deposition of electrons
- ★ Achieve few seconds dose calculations - similar to analytical codes!



Xun et al., PMB 2012

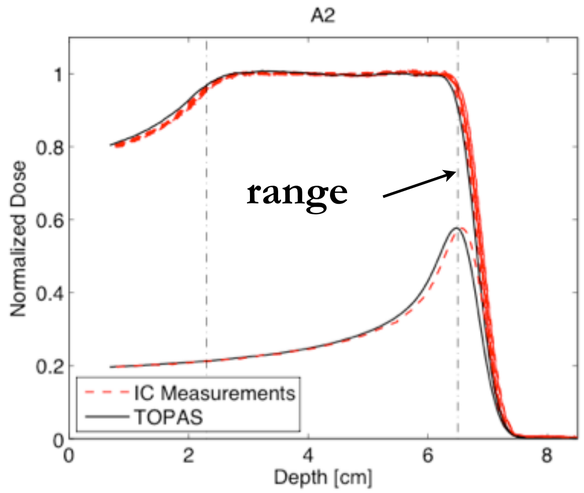


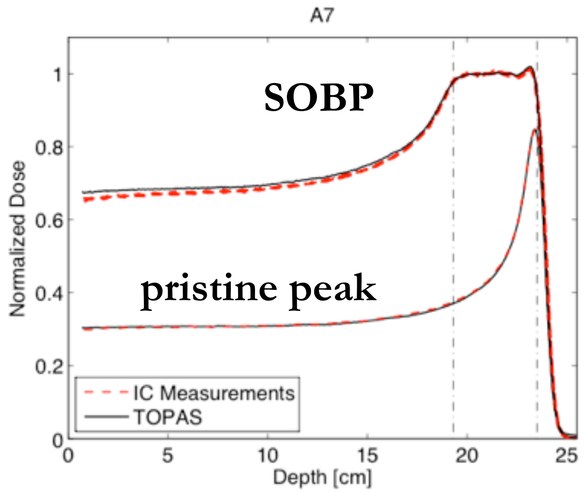
Tseung et al., Med. Phys 2015

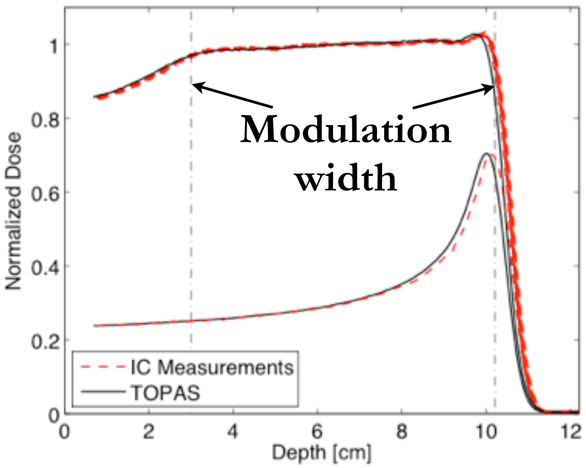
Important to validate / commission each MC

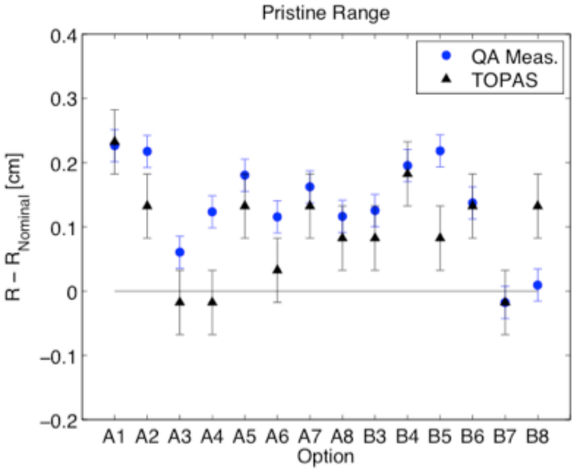
- ★ MC does not mean everything is automatically correct
- ★ Perform MC commissioning just like any other TPS
- ★ **New TG 349:** Commissioning of MC dose calculations in Proton Therapy

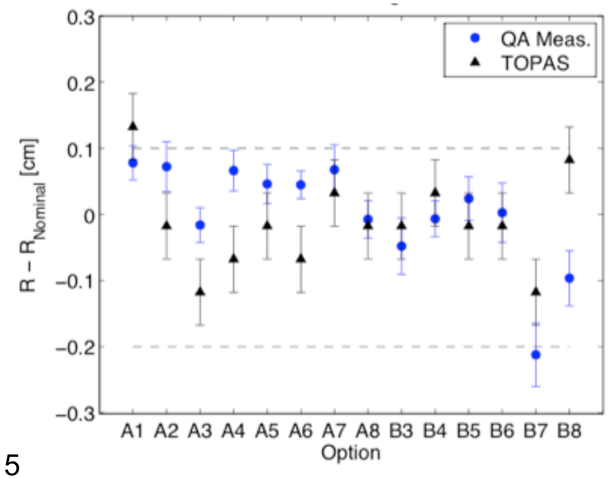
M. Testa et. al, Med. Phys. 2013

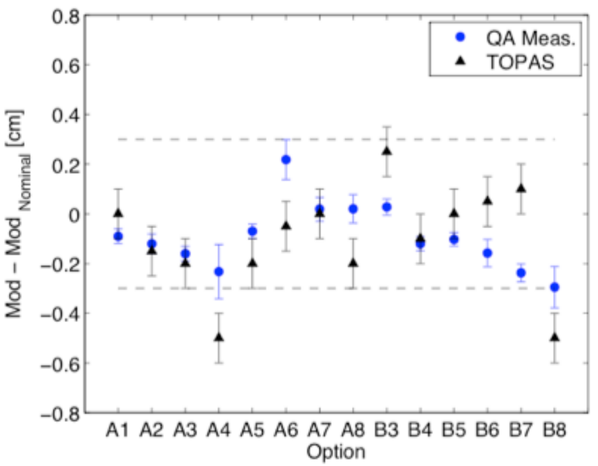












MC in commercial TPS

MC in TPS - pMC

RaySearch Laboratories

Information courtesy of
Martin Janson (RaySearch)

- ★ First clinical release of pMC in 2016
- ★ Final dose calculations and optimization dose computation
- ★ Migrated to the GPU in 2020, typical computation times of <5 seconds
  - ★ No more need for analytical dose calculations
- ★ Features:
  - ★ Transport of secondary p, D, and He
  - ★ Secondary electrons and neutral particles are not transported
  - ★ CT calibration (HU to mass density or HU to RSP)
  - ★ Single and double Gaussian in-air spot phase space supported
  - ★ Beam modeling explicitly considers the size of the Bragg peak chamber used to record the IDDs
  - ★ Includes Beam limiting devices (range shifters and patient specific apertures)

MC in TPS - GPUMCD

Information courtesy of Martin Soukup (Elekta)

- ★ Monaco 6.0 with GPUMCD is FDA approved
- ★ Handles photons, electrons, **protons**, magnetic fields
- ★ Calculation time per field < 5 seconds
- ★ Features
  - ★ Class II condensed history approach
  - ★ Includes: Ionizations, energy straggling, multiple-scattering, nuclear interactions
  - ★ Transport of delta electrons (optional)
  - ★ Stopping criteria (per spot)
  - ★ Spatial and angular distribution according to Fermi-Eyges theory
  - ★ Dose to water or dose to tissue
  - ★ Includes Beam limiting devices (ridge filter and patient specific apertures, not yet clinical), couch

MC in TPS - pMC

RaySearch Laboratories

Information courtesy of
Martin Janson (RaySearch)

★ In clinical operation at 50+ proton centers worldwide

ELEKTA

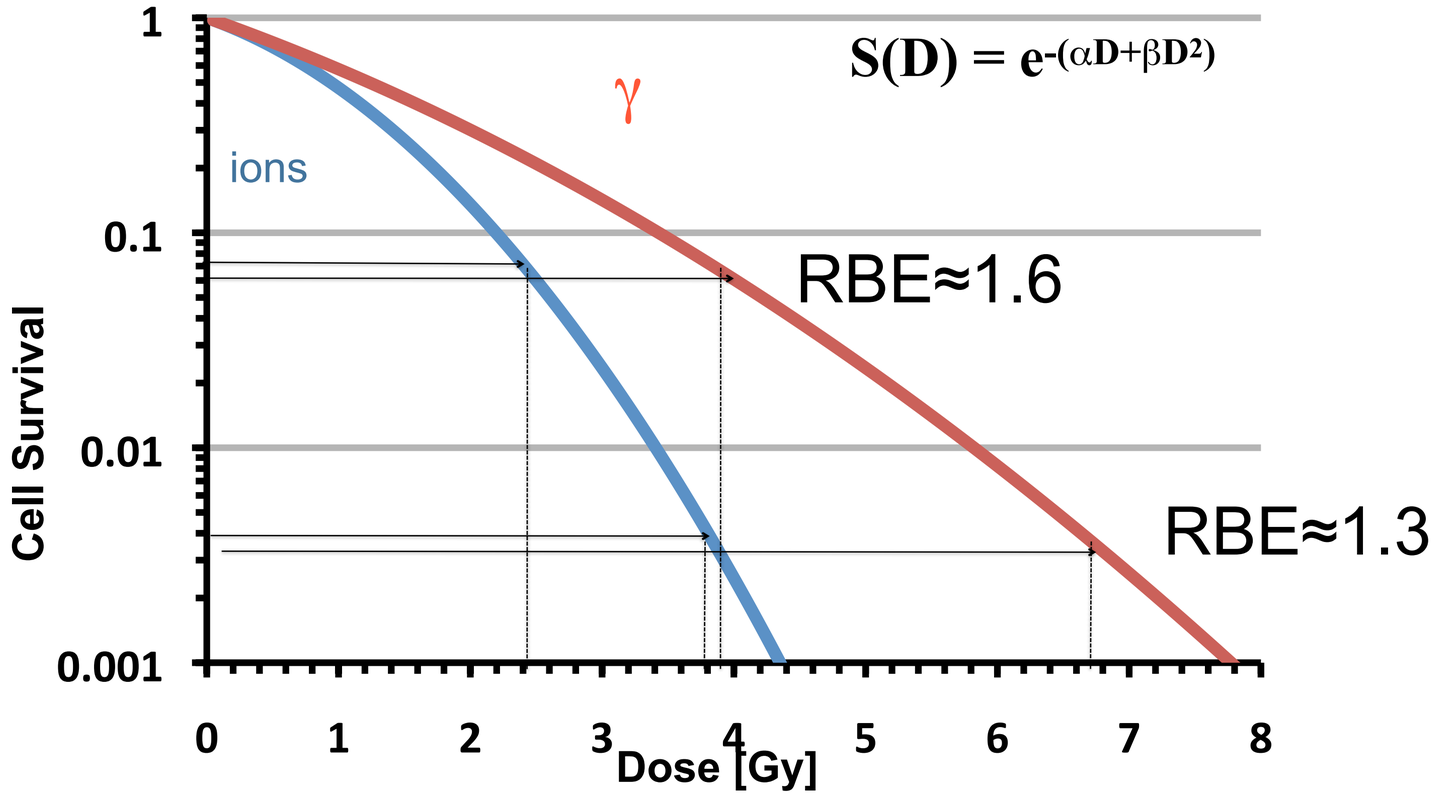
Information courtesy of
Martin Soukup (Elekta)

★ Clinical Proton MC is now standard for proton TPS.

★ Future features that are currently developed for clinical use include:

- ★ Computation of LET for evaluation and optimization
- ★ Support for more beam configurations (DS, ions, wobbling, etc.)

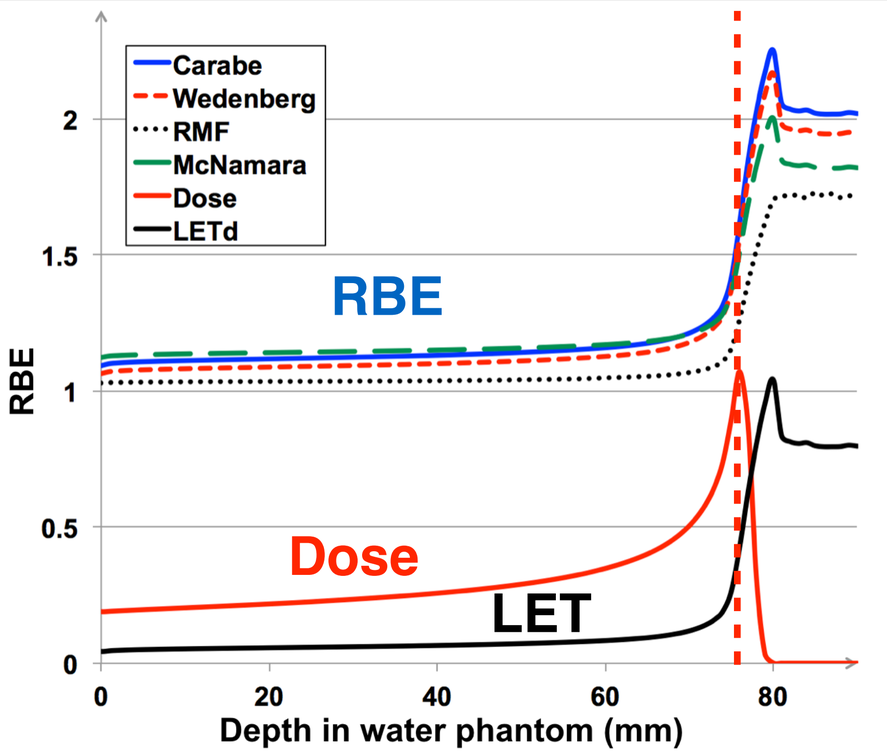
Including Biology: Relative Biological Effect - RBE



$$\text{RBE} = \text{Relative Biological Effect} = \frac{D_{\gamma}}{D_{protons}}\langle effect \rangle$$

Including Biology - RBE dependencies

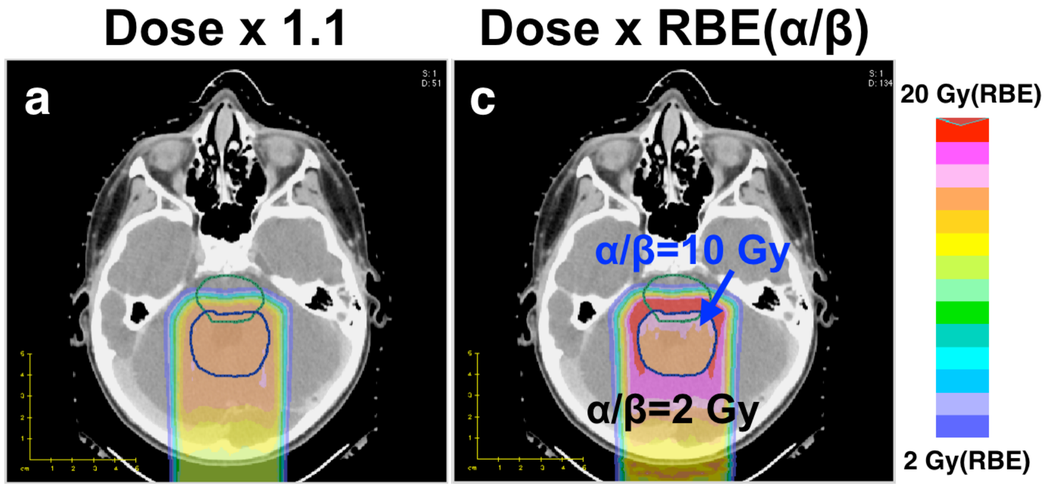
- ★ Protons assumed 10% more effective than photons:
  Clinically used RBE = 1.1, constant!
- ★ RBE depends on many factors:
  tissue, radiation quality, dose, endpoint, fractionation, …
- ★ Examples of RBE dependence:
  - ⋆ the modeling approach
  - ⋆ **α/β ratio**
  - ⋆ **Linear Energy Transfer (LET)**



Why do we like LET?

It is factor we can influence

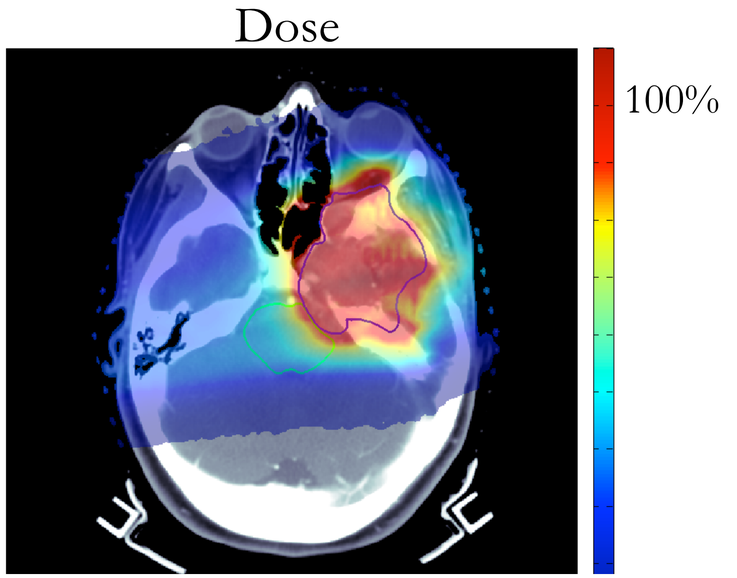
Independent of the model



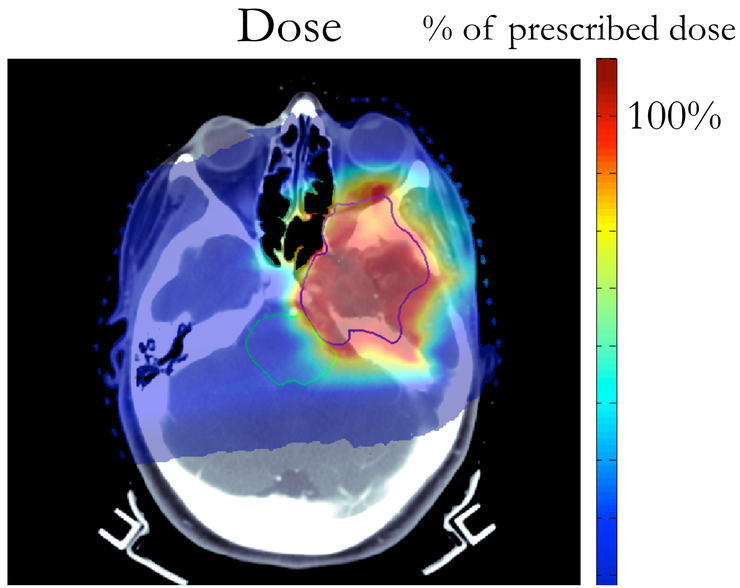
The effect of LET for biological optimization

3D

Grassberger et al
Int J Rad Biol Onc Phys
2011, 80:1559-1566



DET



Summary

★ Clinical Proton MC is now standard for proton TPS.

★ Comparable speed to analytical codes (GPU)

★ Comparable accuracy to full MC systems

★ Future of clinical MC:

- ★ More options, speed, devices
- ★ Including LET, biology, …

Thank you