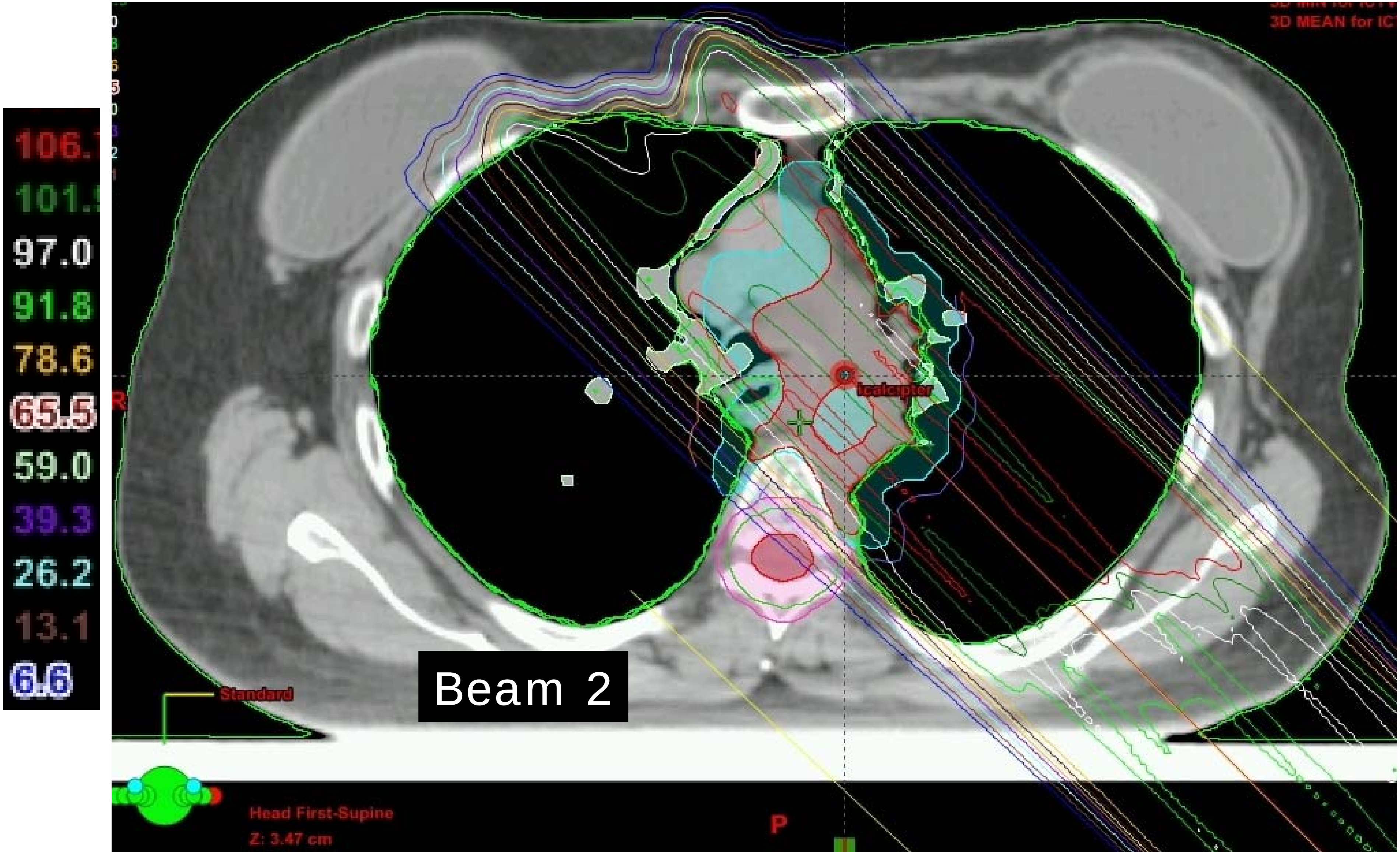
Degradation of the Distal Edge of Proton Dose Distributions by Low Density Heterogeneities

Uwe Titt, Narayan Sahoo, Yupeng Li, Xiaodong Zhang, Yuanshui Zheng, Phillip Taddei, Wayne Newhauser, Michael Gillin, <u>Radhe Mohan</u>

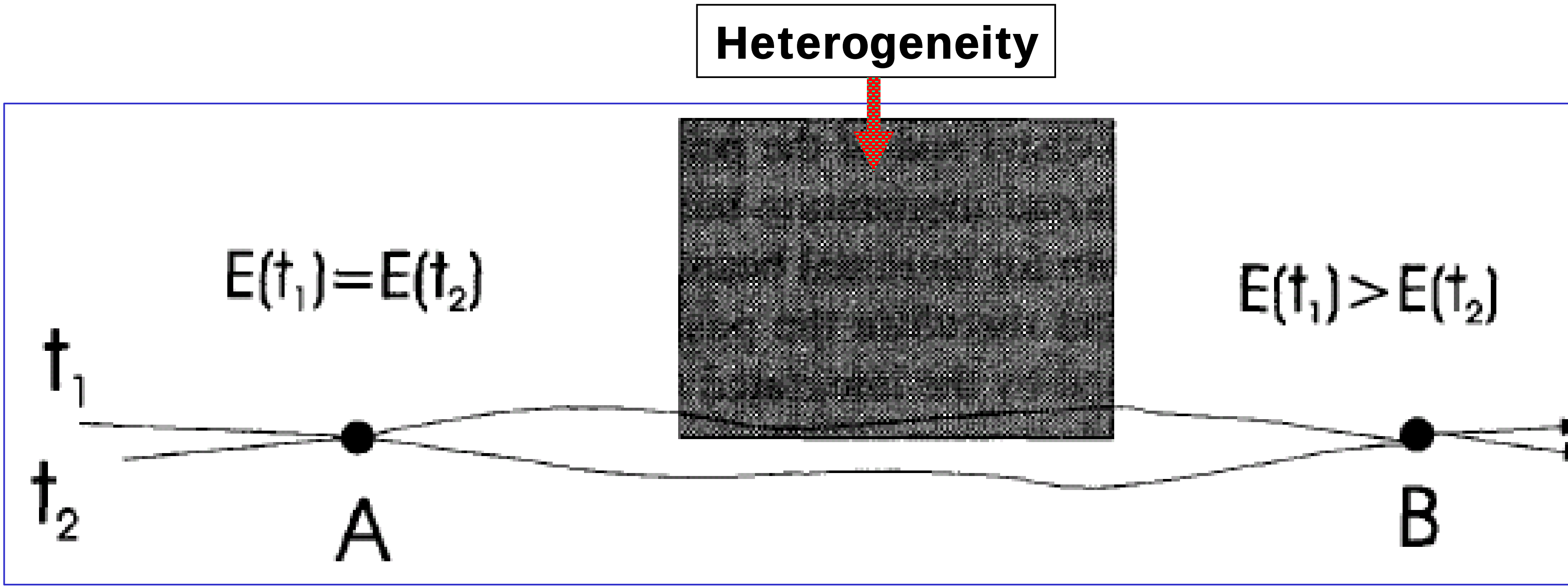
THE UNIVERSITY OF TEXAS
MD ANDERSON CANCER CENTER
Making Cancer History®

Thanks to
Those Who Got Us Where We Are Today

- Dr. James Cox
- Mr. Mitch Latinkic
- Dr. Alfred Smith and his team
  - Martin Bues, George Ciangaru, James Yang, Jerimy Polf, …
- Dr. Michael Gillin and his team
  - Richard Amos, Jim Lii, Narayan Sahoo, Richard Wu, Ron Zhu, …
- Many other creative physicists
  - Peter Balter, Lei Dong, Wayne Newhauser, Uwe Titt, Xiaodong Zhang, …

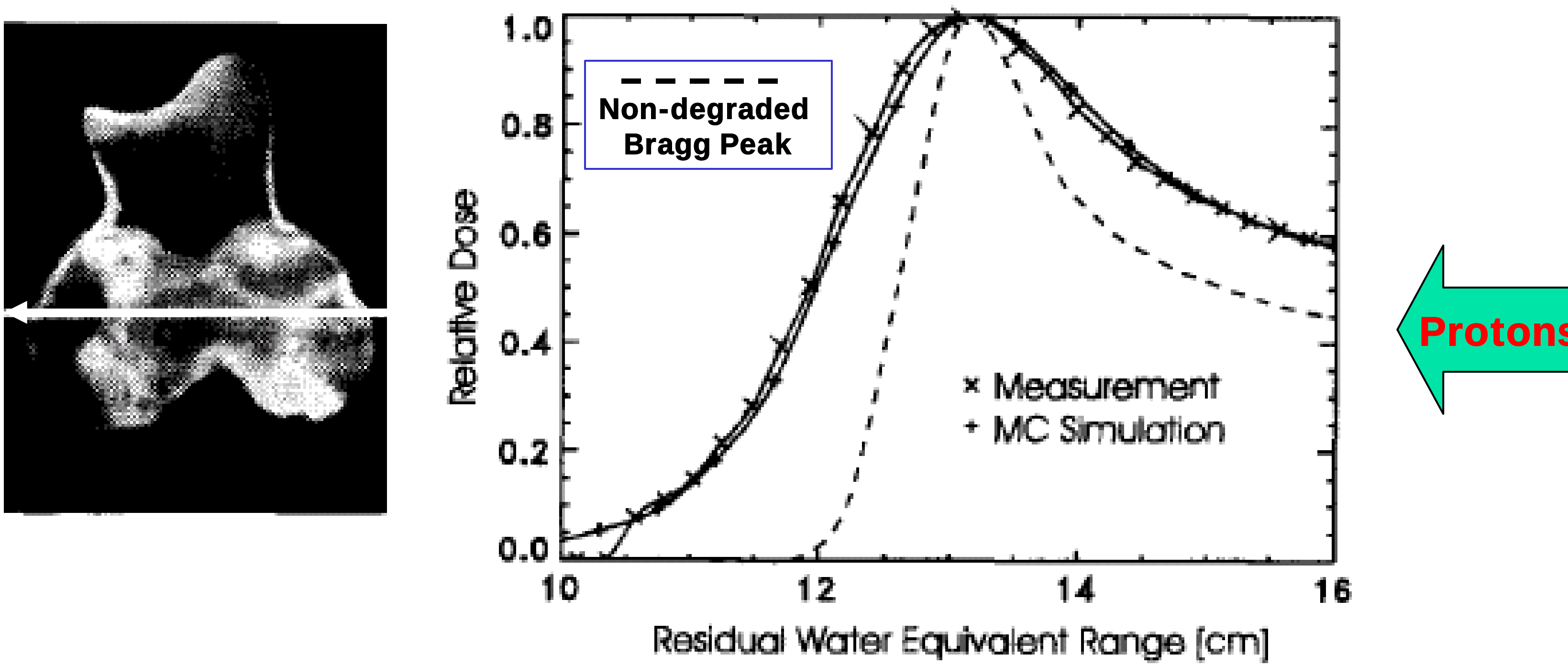

97.0
91.8
78.6
65.5
59.0
39.3
26.2
13.1
6.6
R
Standard
Beam 2
Head First-Supine
Z: 3.47 cm
P

Range Degradation Caused By Heterogeneities

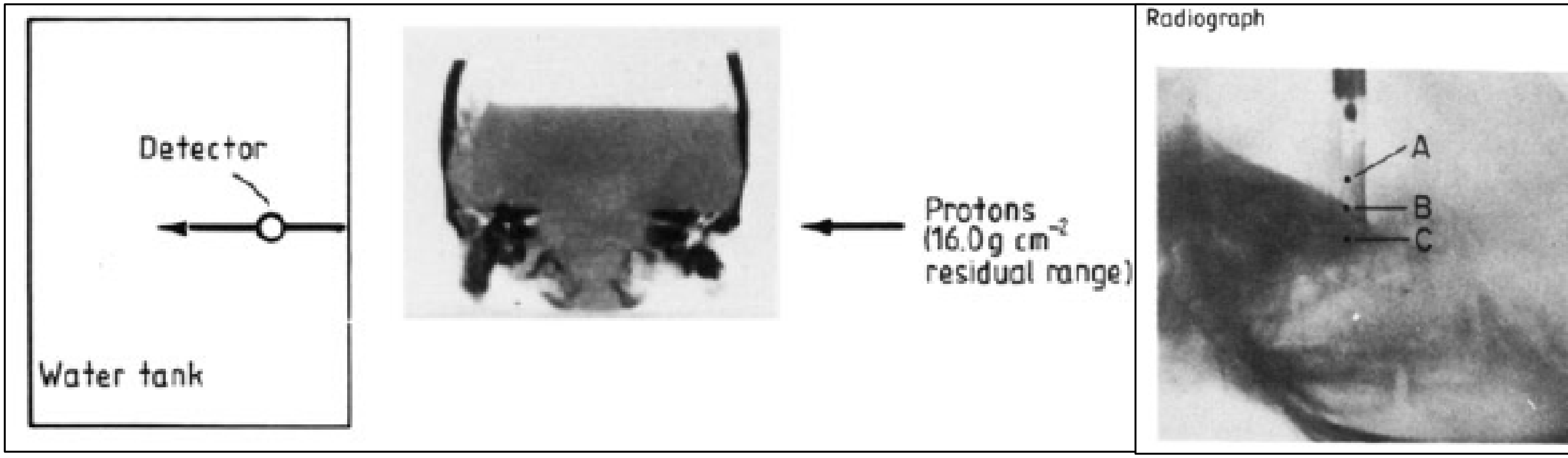


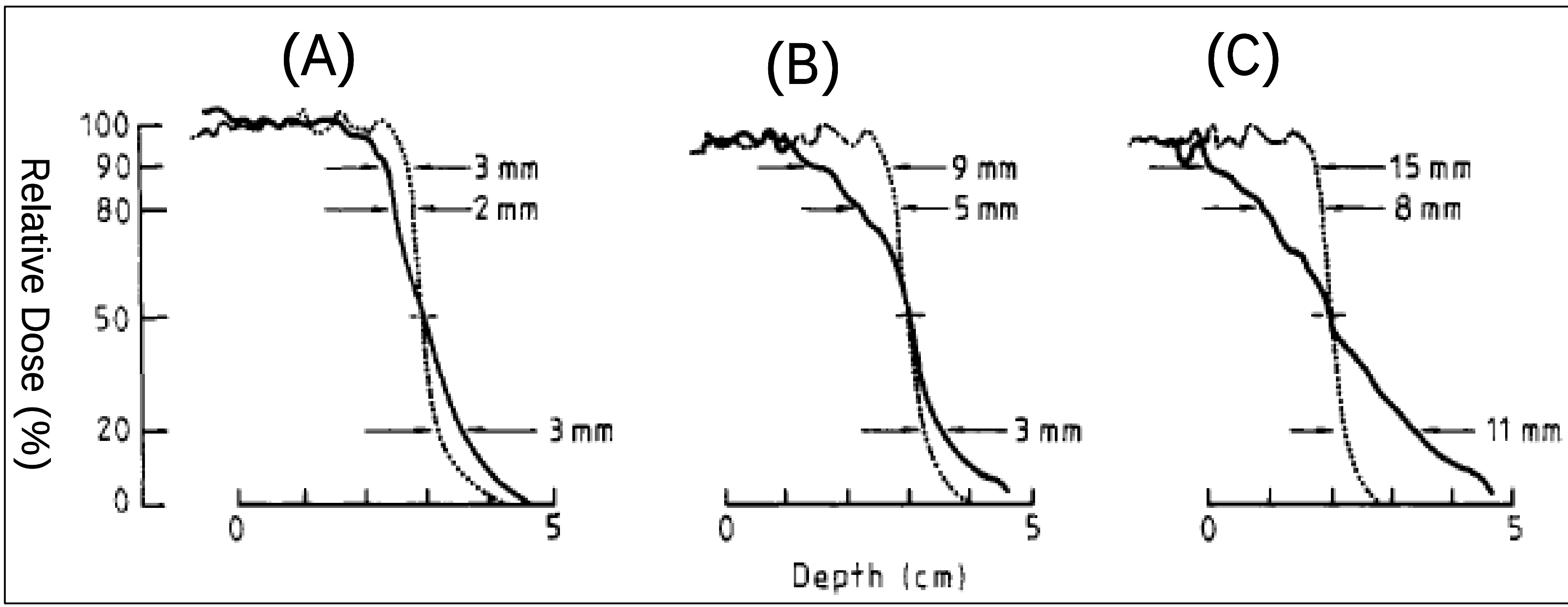
Schaffner dissertation, 1997

Degradation of Distal Fall-Off Caused By Complex Heterogeneities



Schaffner dissertation, 1997



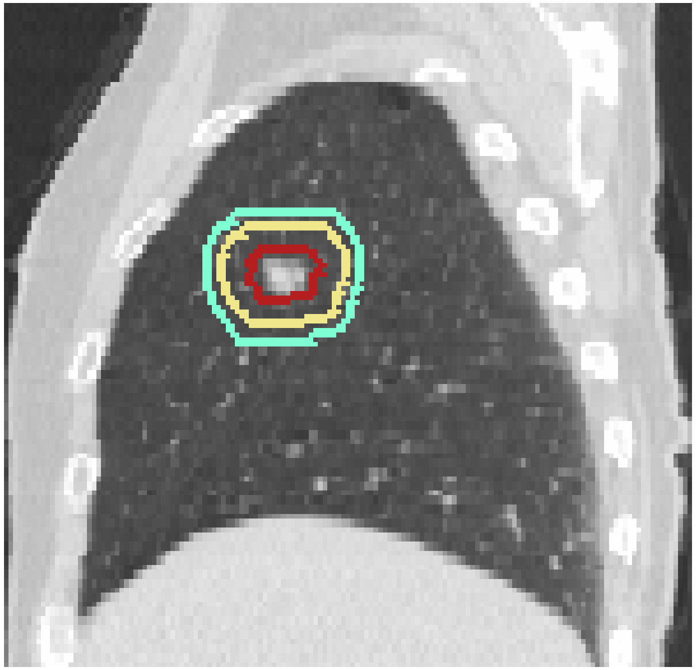


Protons Through Base of Skull: 90 to 20 % fall of increases from 6 to 32 mm

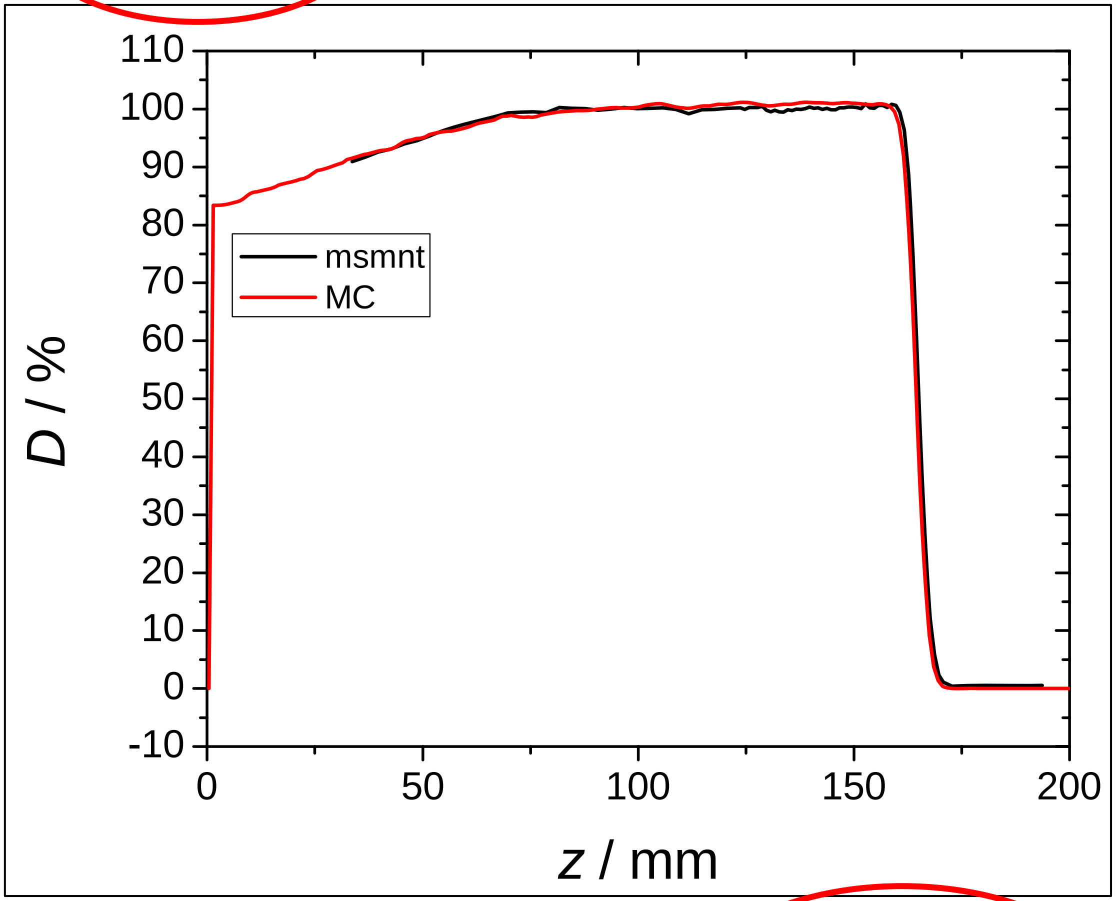
Urie, et al, Phys. Med. Biol., 1986, Vol. 31, No. 1, 1-15.

Overall Purpose

- Assess through measurements and MC simulations
  1. The perturbation and degradation of dose distributions by complex and low density regions in the path of proton beams before and after the GTV for thoracic cancers
  2. The limitations of dose calculation algorithms implemented in TPS's



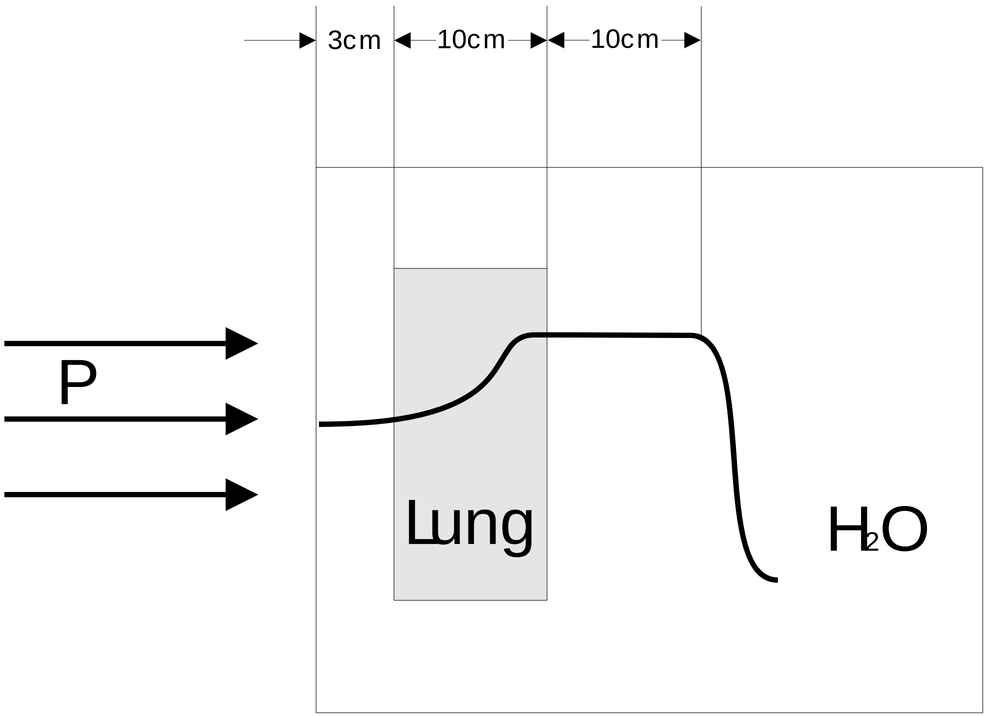
Benchmark of Monte Carlo vs. Measurements 180 MeV Passively Scattered Protons



SOBP (90- 90%): 11 cm
Field Size: 10x10 cm^2

	R90 (cm)	90-20% Falloff mm	80-20% Falloff mm
Monte Carlo	16.25	4.60	3.74
Measurements	16.17	4.45	3.68

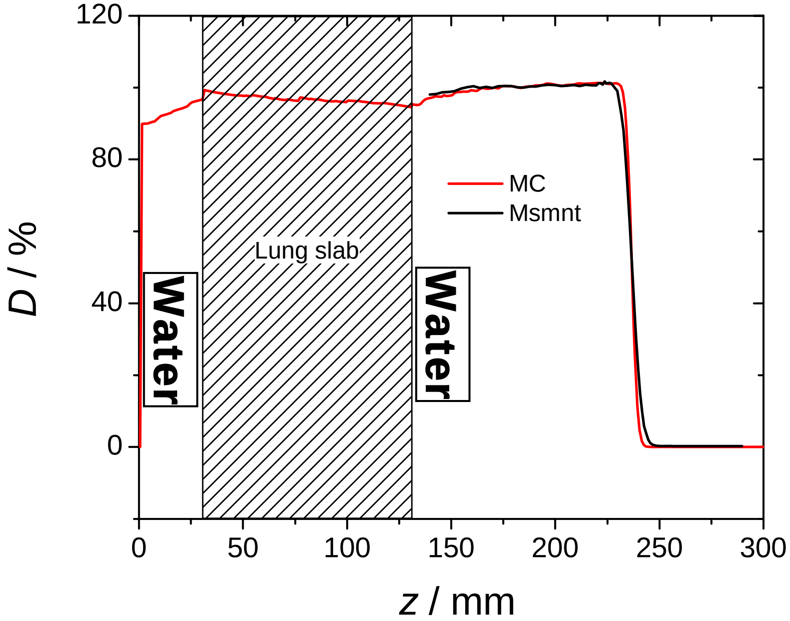
Monte Carlo Benchmark 2

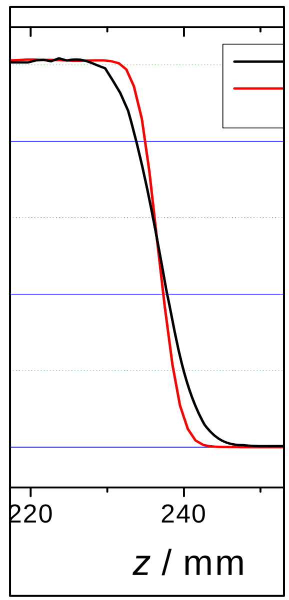


Commercial Lung Equivalent Material, Density = 0.28 gm / cc

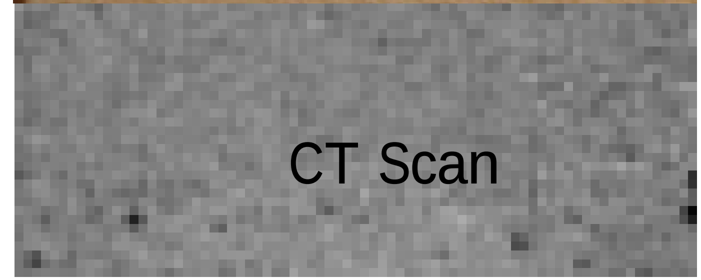
(Actual Lung Density Lower)

Monte Carlo Benchmark 2





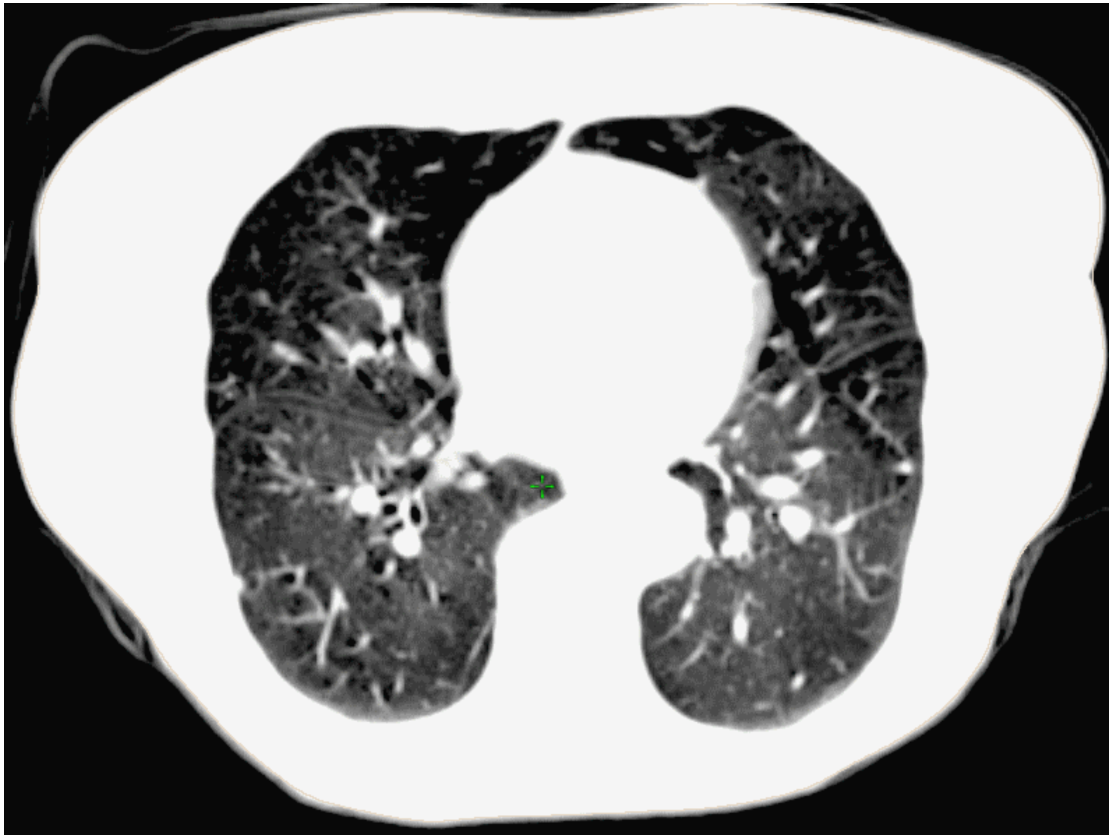
MC Calculations Assumed Homogeneous Lung



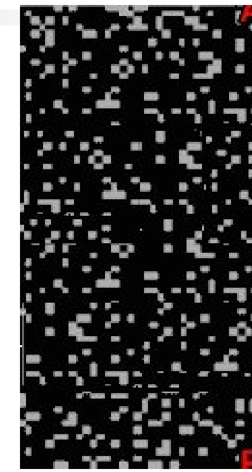
	90-20% Falloff mm	80-20% Falloff mm
Monte Carlo	4.66	3.74
Measurements	7.75	6.2

Real Lung

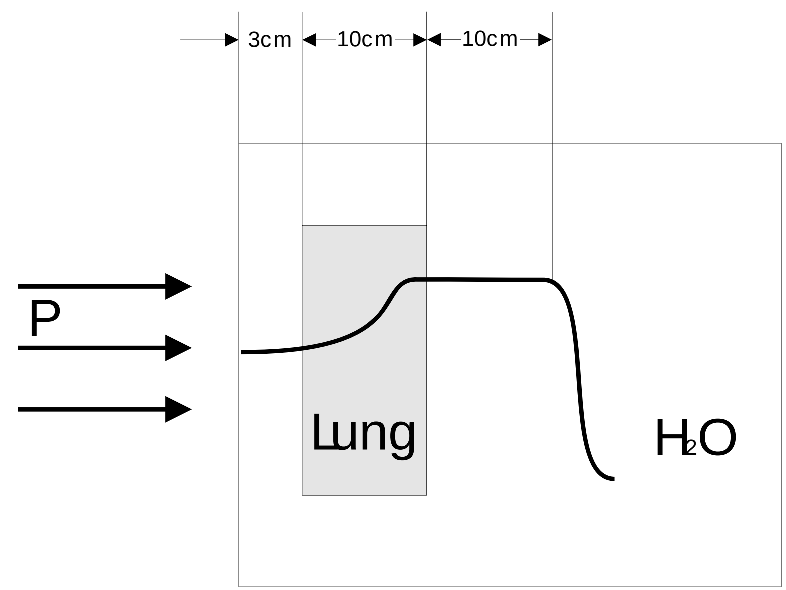
- Density lower ~0.1 to 0.2
- Inhomogeneous



“Texturized” Lung Equivalent Material
Monte Carlo Simulations vs. TPS

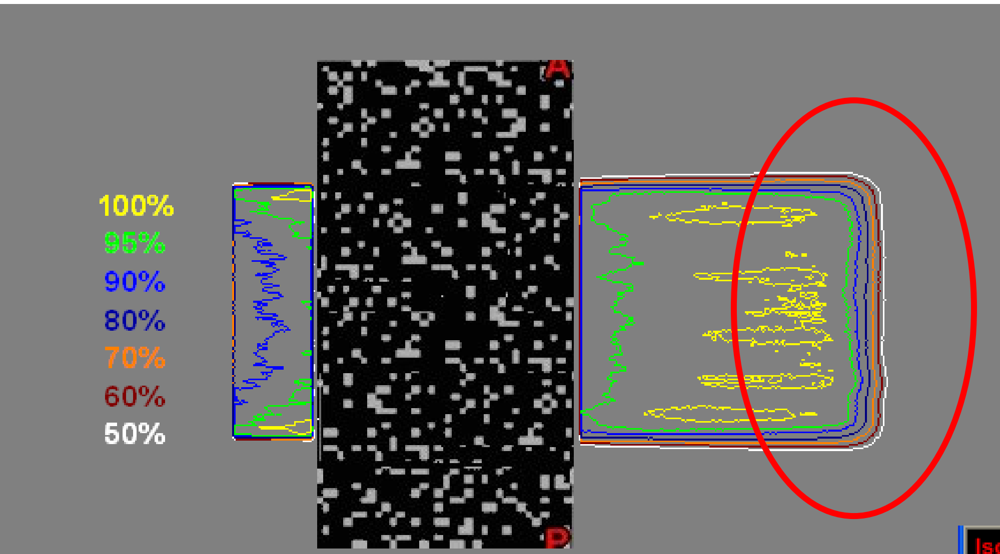


- **Digital Texturized (Voxelized) Phantom**
  - **$3 \times 3 \times 3$ mm^3**
  - **$\rho_{\text{lung material}} = 1$ gm / cc (20% of voxels randomly)**
  - **$\rho_{\text{lung material-average}} = 0.2$ gm / cc**
- **Homogeneous slab, $\rho = 0.2$ g cc**

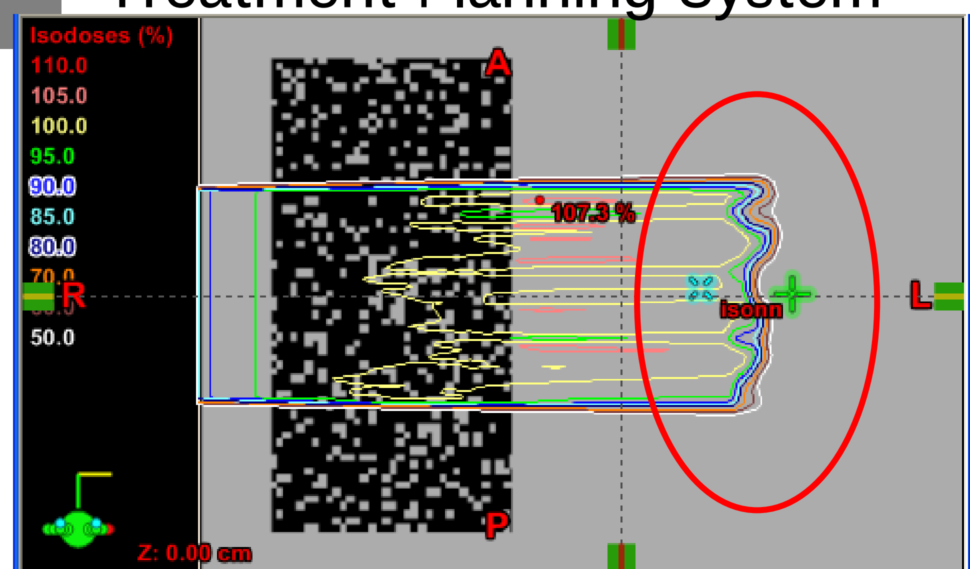


“Texturized” Lung Equivalent Material Monte Carlo vs. TPS Dose Calculations

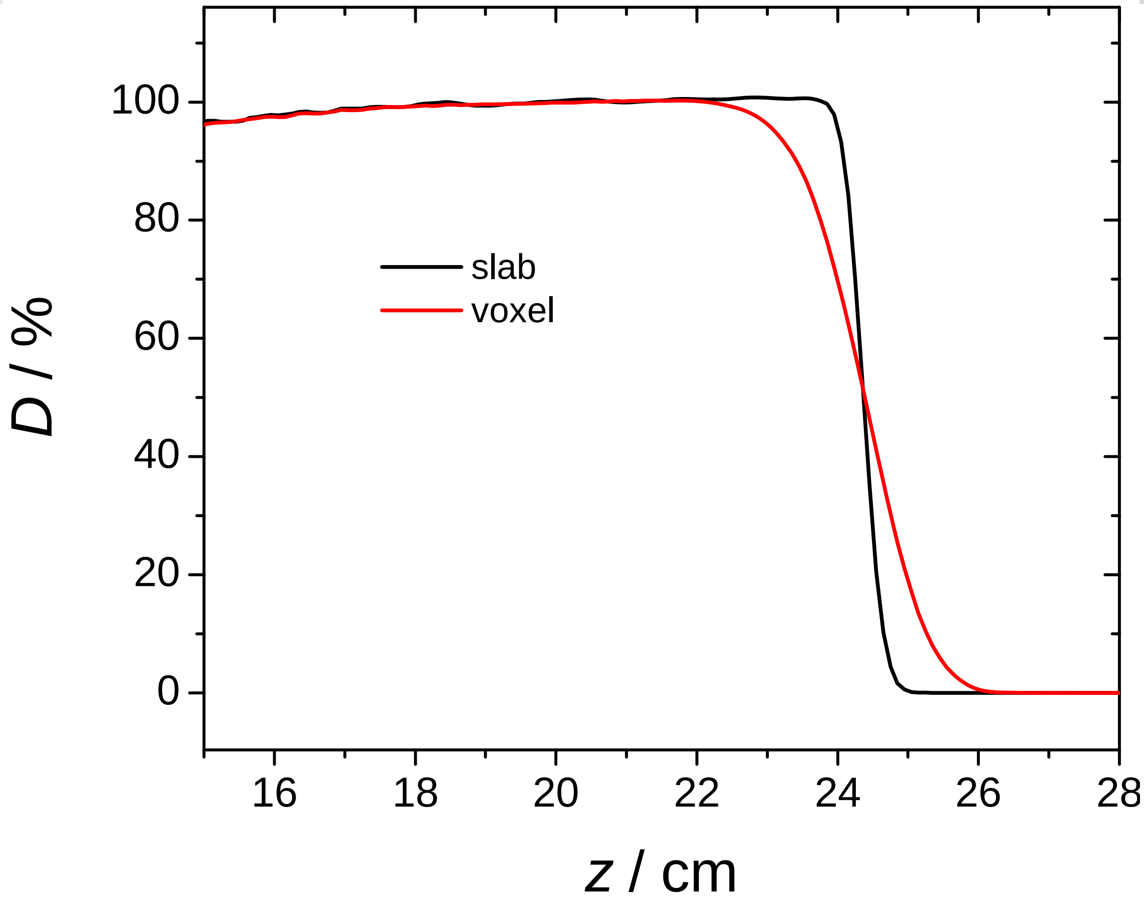
Monte Carlo



Treatment Planning System

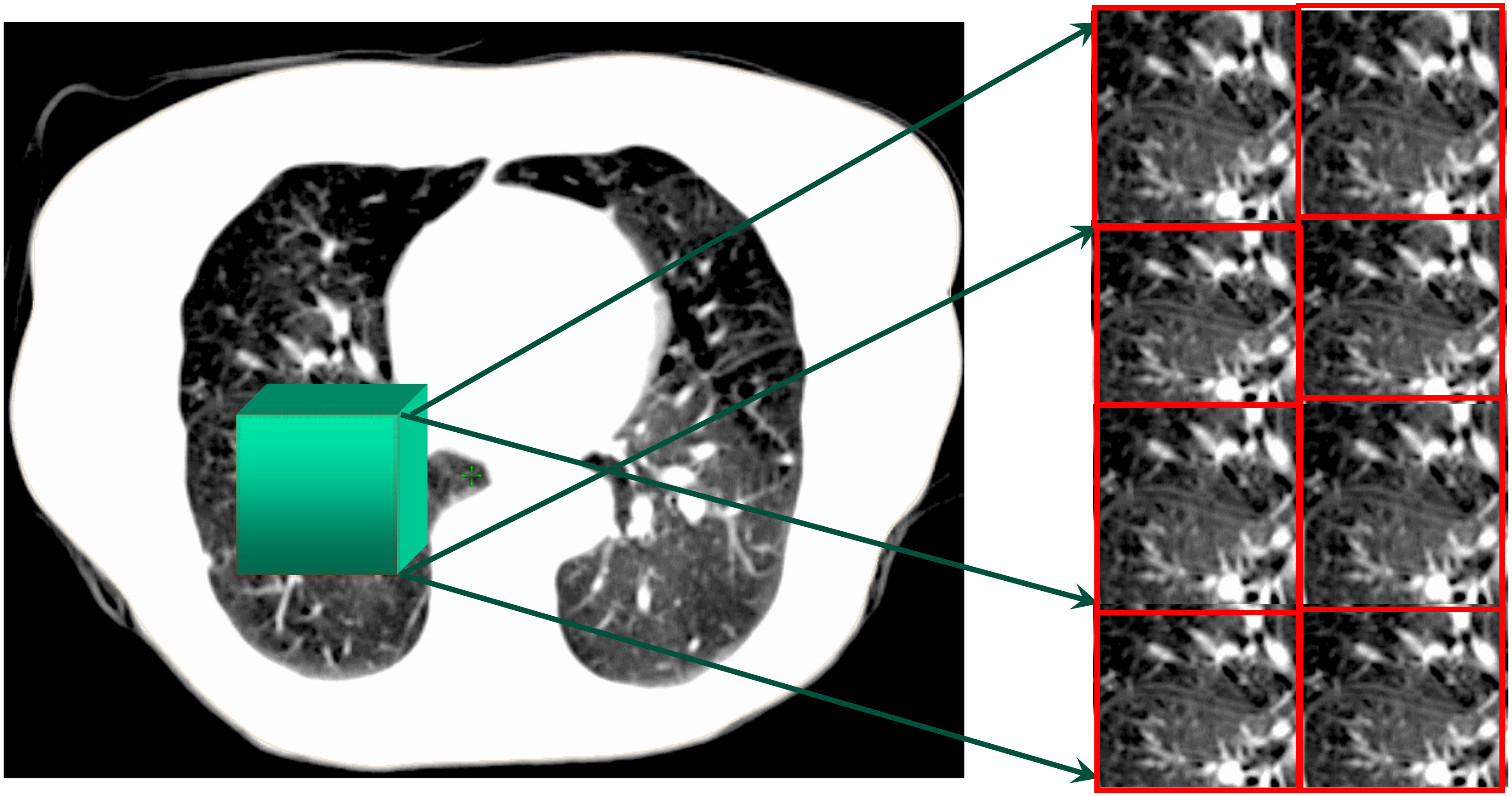


MC Dose Calculations
Homogeneous Slab vs. Texturized Lung Material

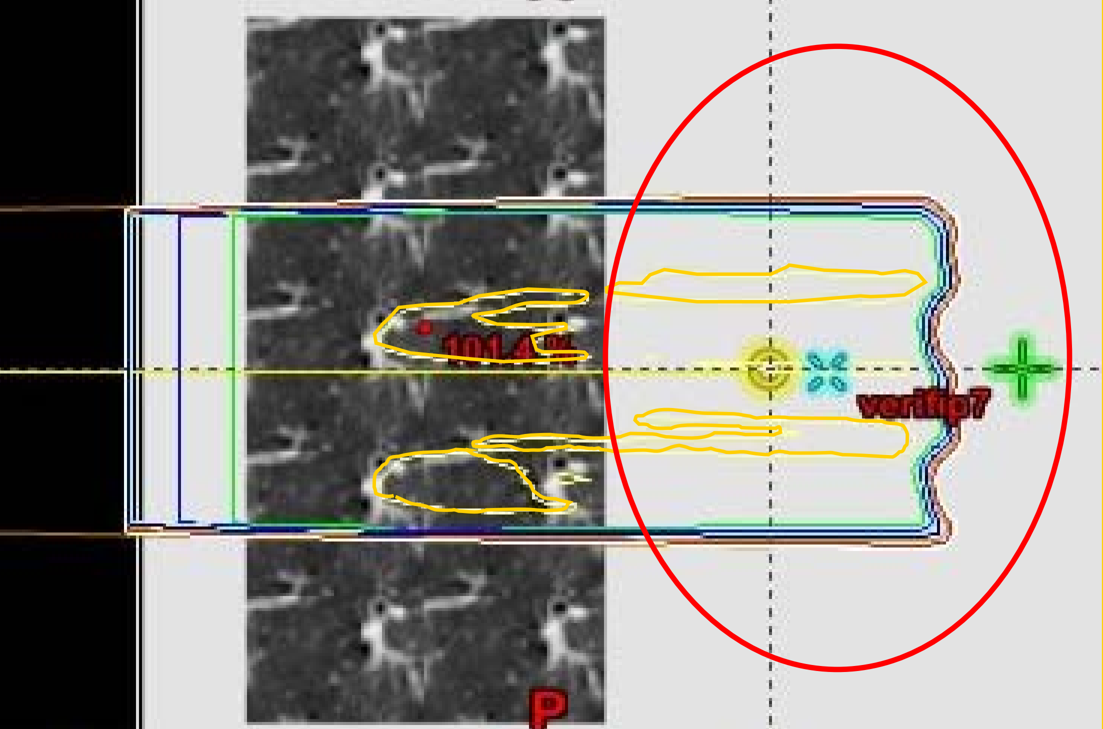


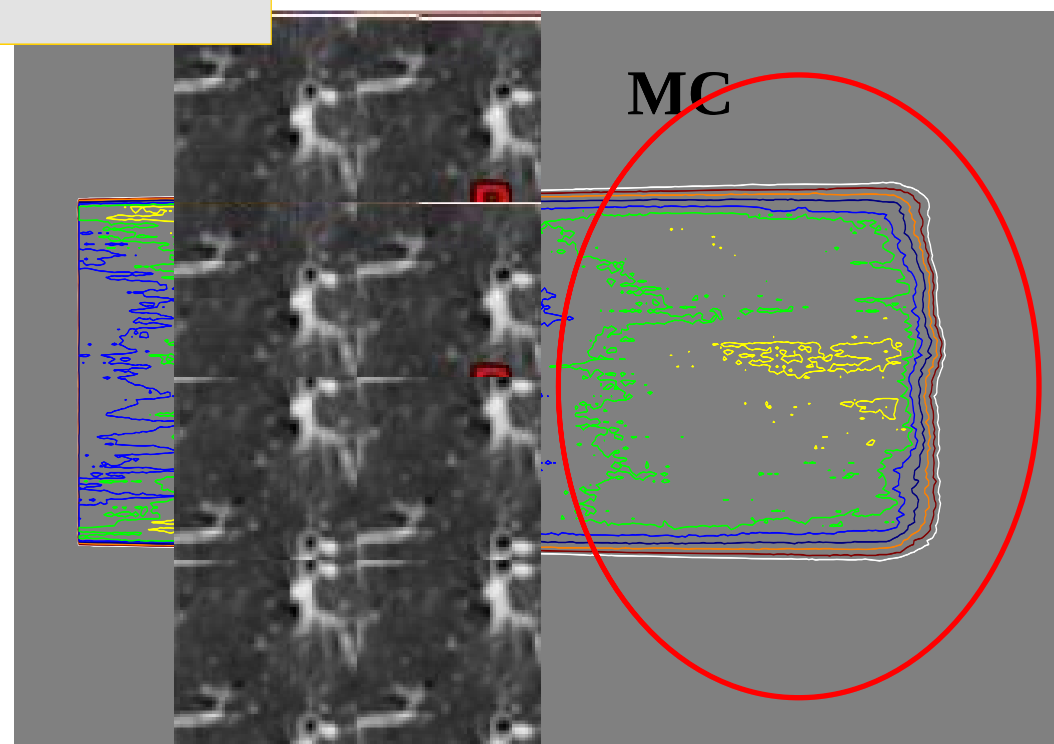
	90-20% Falloff mm	80-20% Falloff mm
Homogeneous Slab	4.5	3.6
Texturized voxels	15.6	12.1

A "Real Lung Slab"
Schematic Example

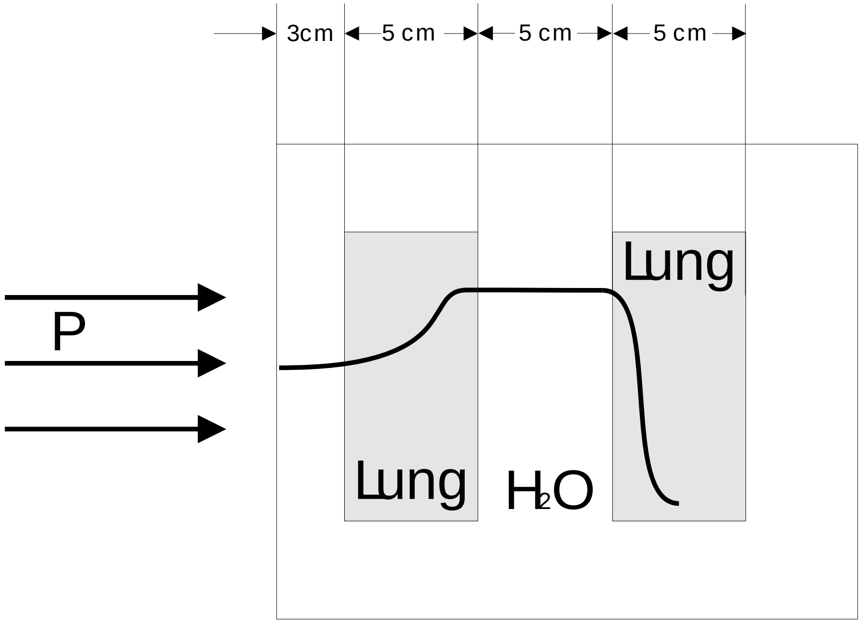


MC vs. TPS for the Real Lung Slab

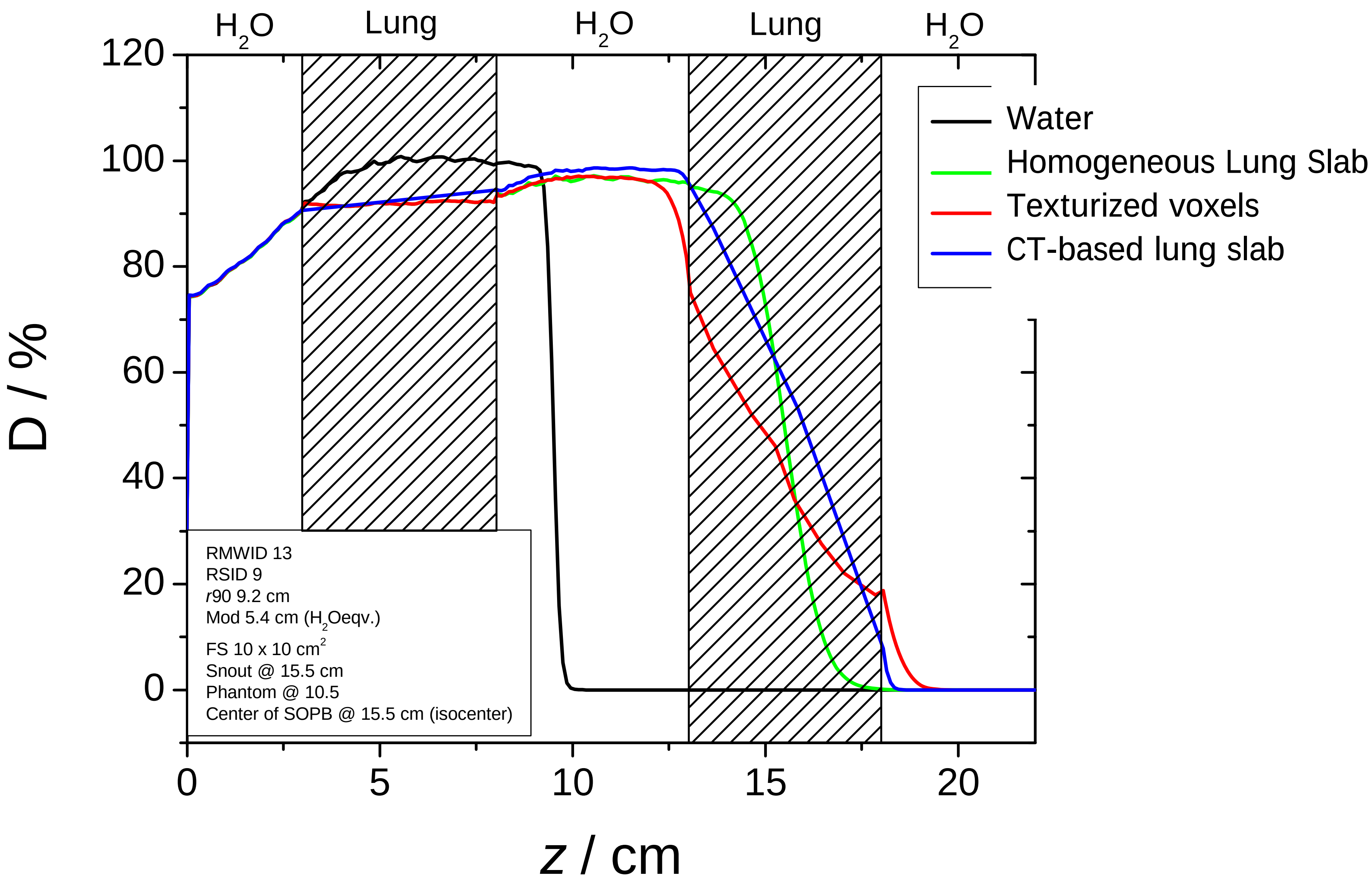




Tumor Surrounded by Lung



Tumor Surrounded by Lung
Monte Carlo Dose Calculations (140 Mev Protons)



Tumor Surrounded by Lung
Distal Falloff [mm] (140 MeV Protons)

	Water	Homogeneous Lung Slab (Density .2)	Texturized Voxels (Av. Density .2)	CT-based Lung Slab
90%-20%	3.4	17.5	47.4	39.7
80%-20%	2.6	13.4	44.4	33.2

Summary and Conclusions

- Complex heterogeneities in the path of protons to the tumor and beyond may perturb dose distributions significantly and degrade the distal edge
- Residual range of protons in lung distally to the tumor may be many times longer
- Degraded beam has a greater lower energy component
  - Could the biological effect by higher in the degraded beam?

Summary and Conclusions

- Dose computation models implemented on current treatment planning systems are limited in their ability to adequately account for proton scattering
- Accuracy of computed dose is important to correctly estimate perturbation and degradation
- Monte Carlo techniques would help
  - Too slow today but could be applied to selected situations

Summary and Conclusions

- **Questions to be answered regarding degradation and perturbation of dose distributions caused by complex heterogeneities:**
  - **How do they affect distal and proximal margins?**
  - **Are biological and clinical consequences significant?**
- **Possible mitigation remedies**
  - **Increase the number of beams**
  - **Optimize beam angles**

Degradation and perturbation caused by heterogeneities cannot be considered in isolation

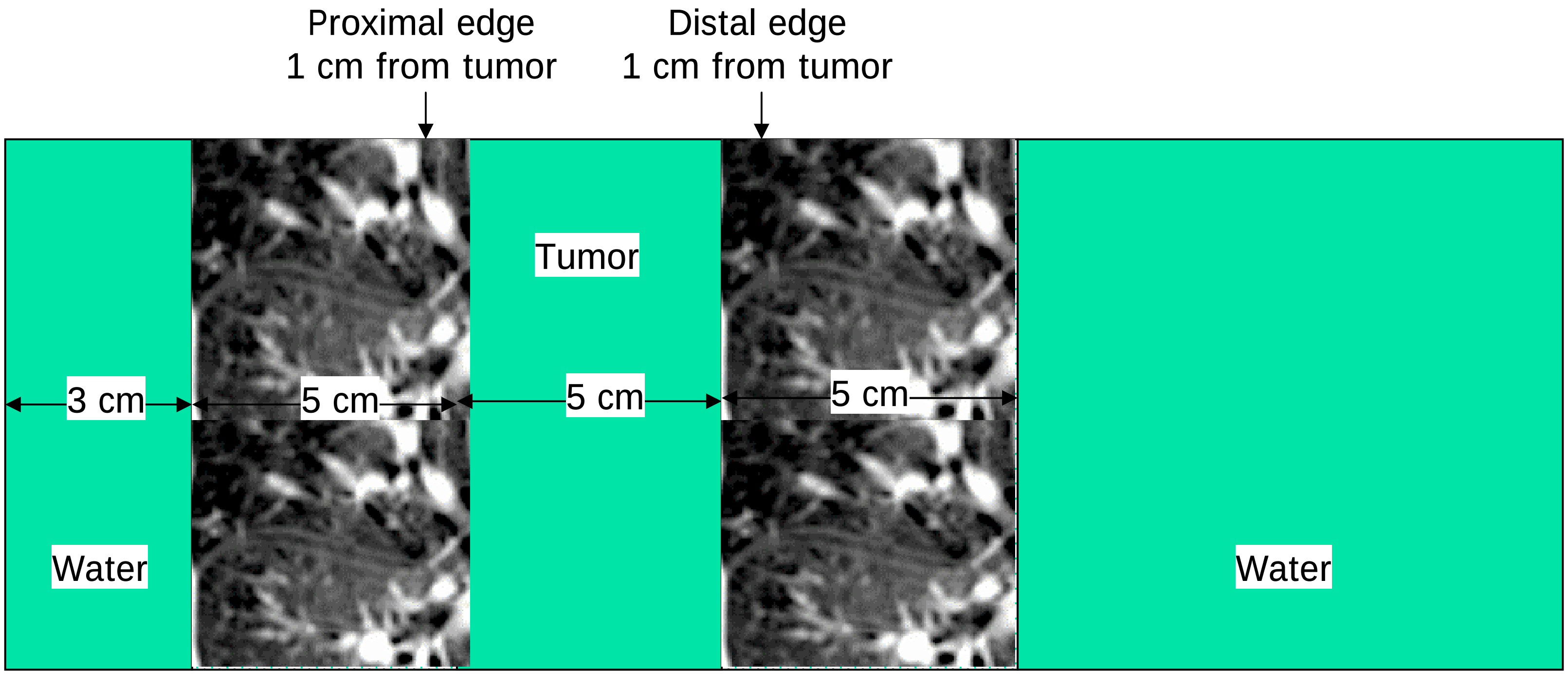
Combined effect of heterogeneities, motion and other sources of uncertainties must be considered

Thank You

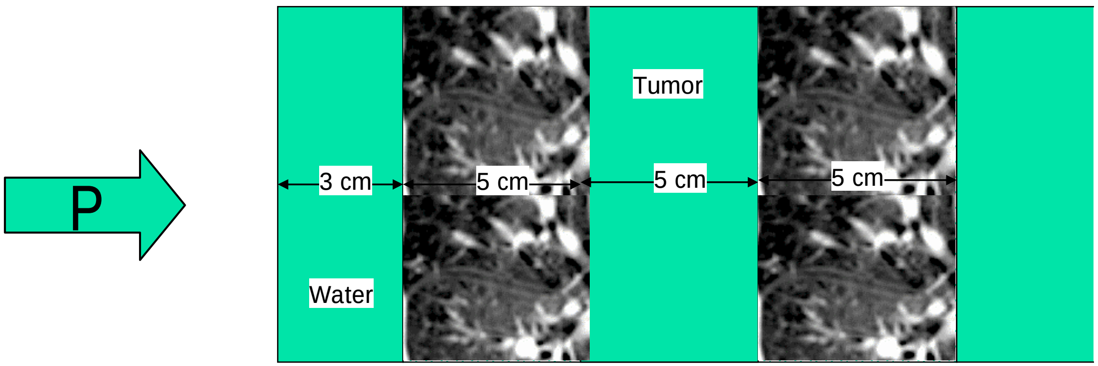
Longer Term Objectives

- Studies involving a population of thoracic patients to answer the following:
  - How much do the distal falls of differ from the ideal fall off?
  - How much does this degradation and perturbation contribute to the distal and proximal margins?
  - Are their any biological and clinical consequences?
  - Does the accuracy of current dose computation models have clinically significant ramifications?
  - Is there anything we can do to mitigate the consequences of degradation?

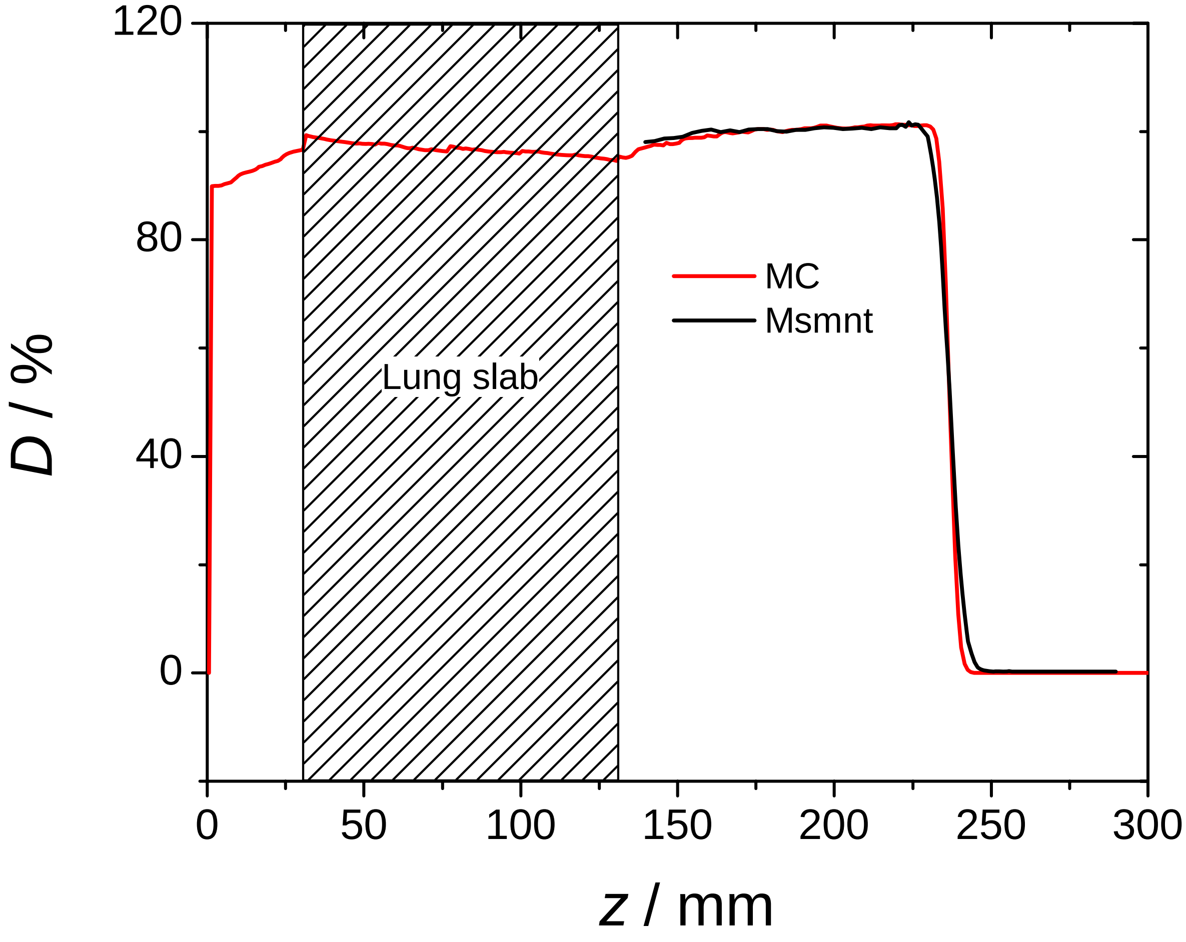
Monte Carlo vs Eclipse Calculations in Patients (Optional if actual patient cannot be Voxelized for MC Calculations



Lung may be replaced by lung cropped from actual patient image

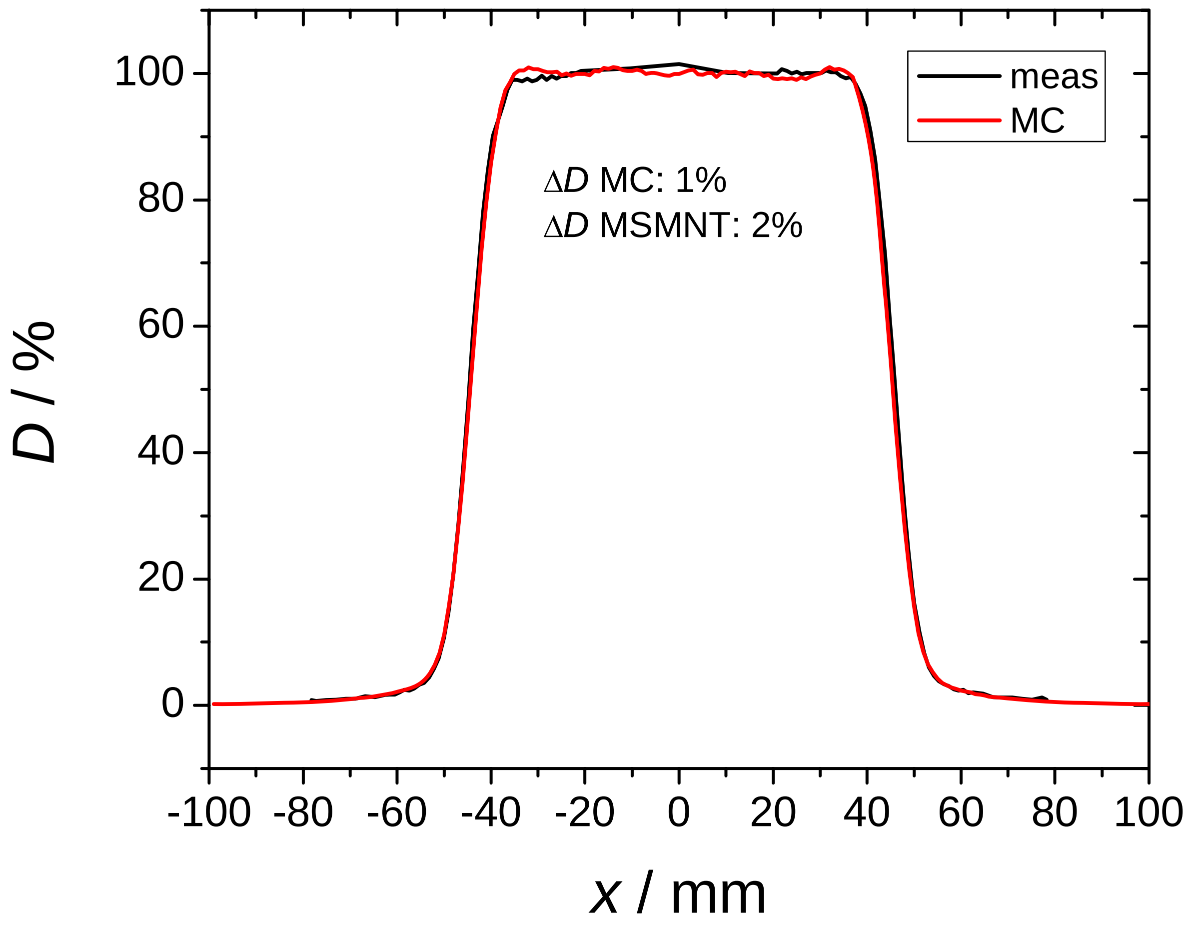

P
Tumor
3 cm
5 cm
5 cm
5 cm
Water

Benchmark



Benchmark

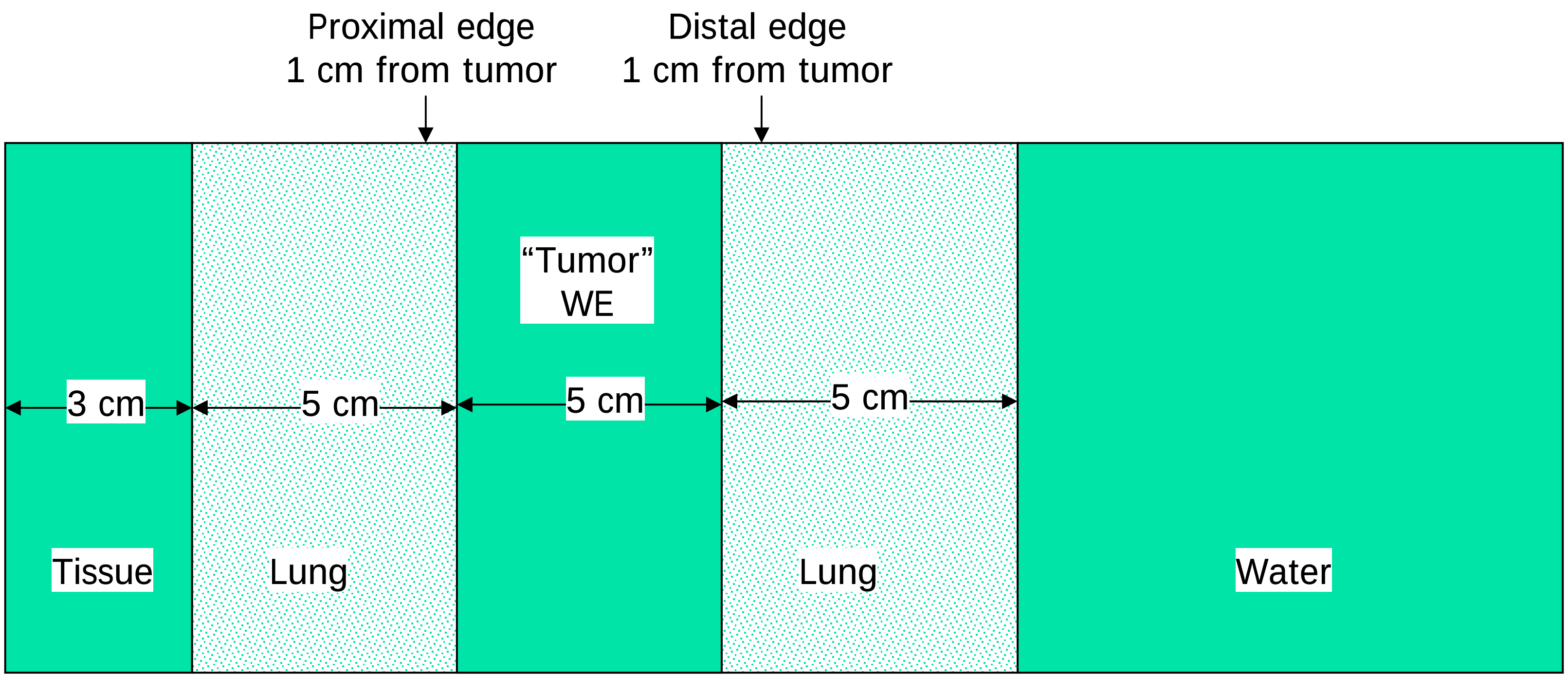
Lateral profile at isocenter



Benchmark

- Monte Carlo vs. Measurements (with 10 cm lung slab)
  - Lateral penumbras:
    - Monte Carlo: 8.99 mm (90%-20%)
    - Measurement: 8.51 mm (90%-20%)
    - Monte Carlo: 7.71 mm (80%-20%)
    - Measurement: 6.72 mm (80%-20%)
  - Field size (50-50%)
    - Monte Carlo: 8.99 cm
    - Measurement: 9.07 cm

Thicknesses and Densities are Changeable Depending on the Commissioned Energy Available

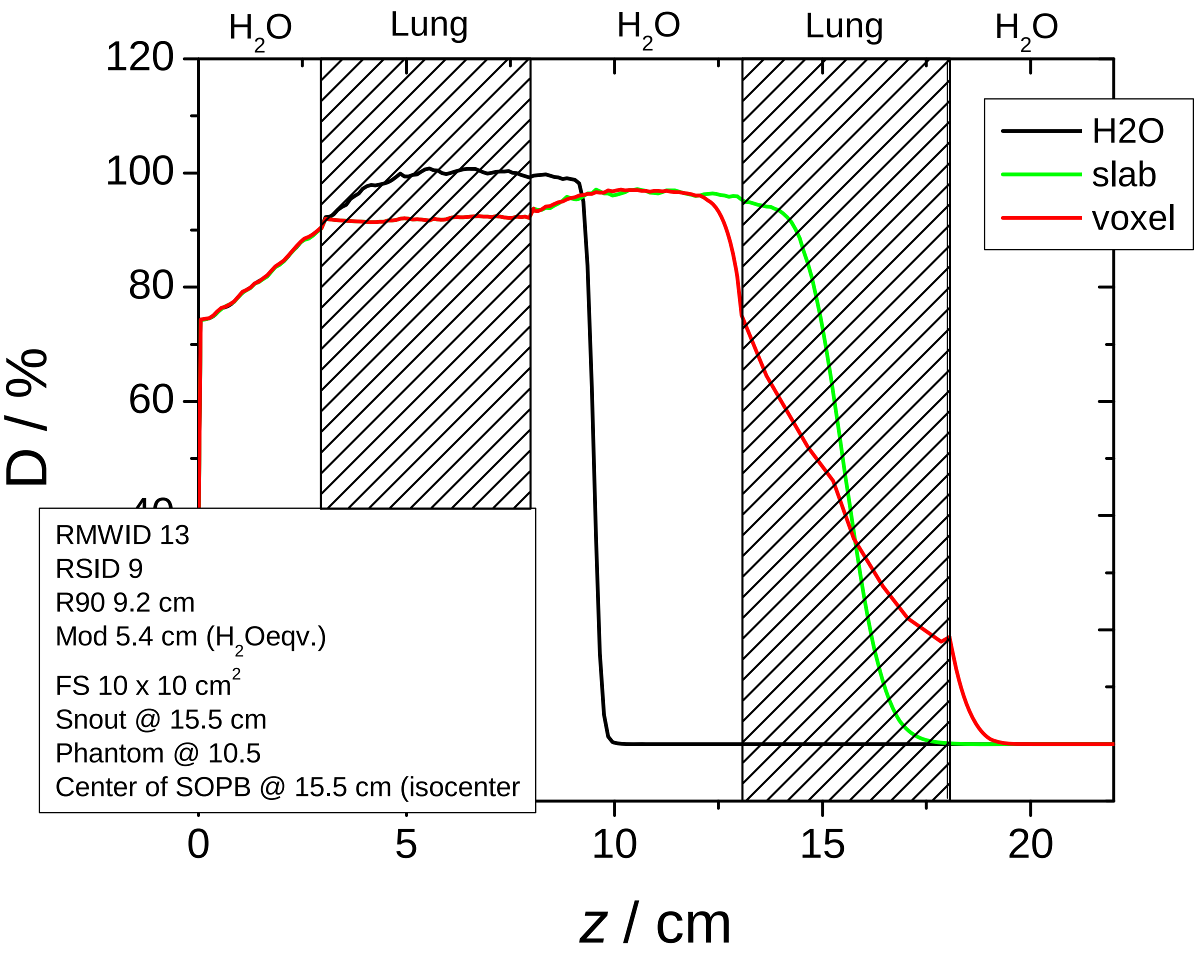


Lung density = 0.2 homogeneous, 0.2 inhomogeneous (i.e.20% of pixels are water)

Beam Parameters

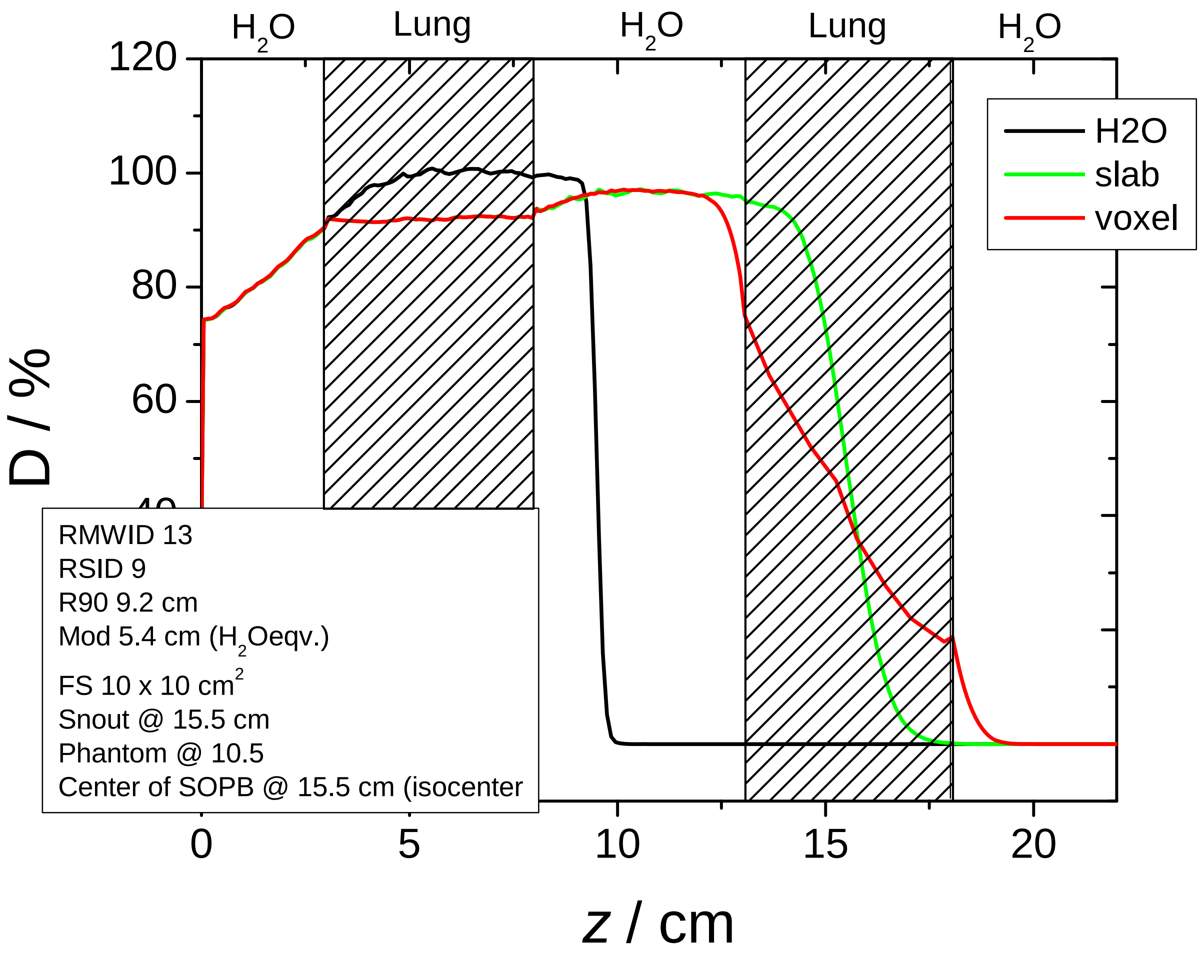
- **Setup B:**
  - **RMW-ID 13 (E_p = 140 MeV)**
  - **RS-ID 9 (r_{90} = 9.2 cm)**
  - **Modulation 5.5 cm**
  - **FS 10 × 10 cm^2**
  - **Snout position 15.5 cm**
  - **Upstream phantom position at 10.5 cm**
  - **Center of SOBP at isocenter**

Setup B

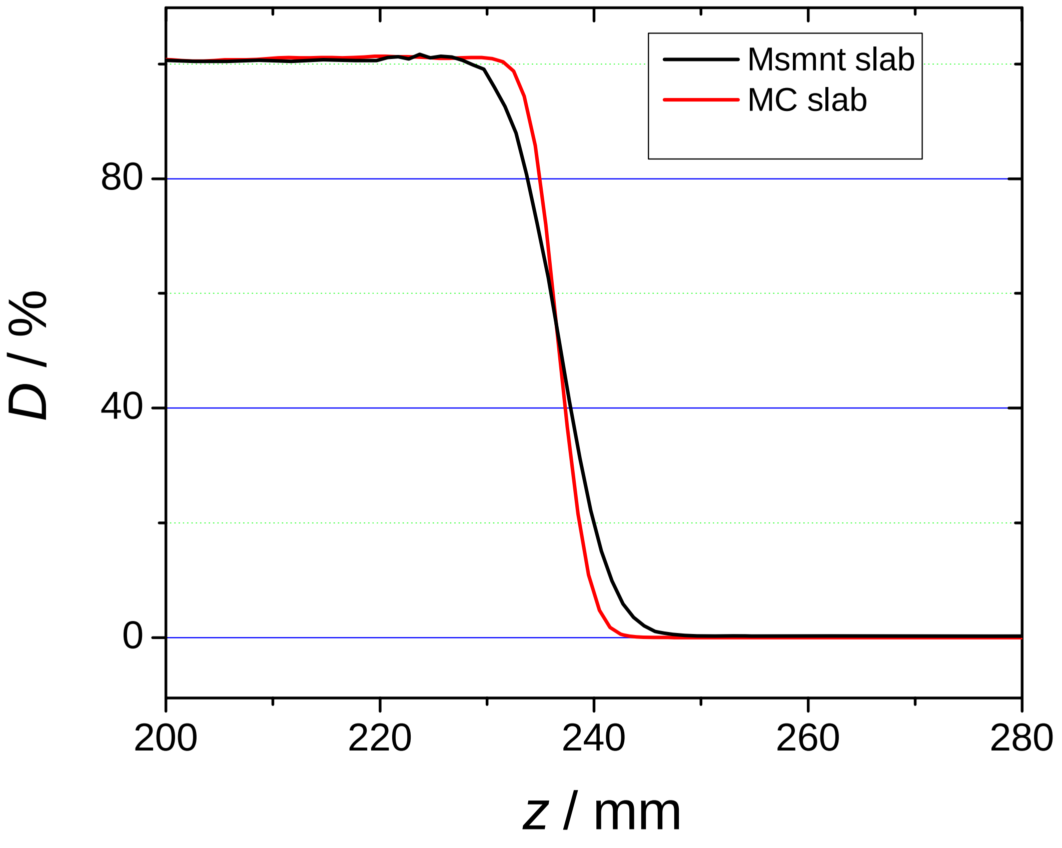


H2O
Lung
H2O
Lung
H2O
120
100
80
60
40
D / %
0
5
10
15
20
z / cm
H2O
slab
voxel
RMWID 13
RSID 9
R90 9.2 cm
Mod 5.4 cm (H2Oeqv.)
FS 10 x 10 cm2
Snout @ 15.5 cm
Phantom @ 10.5
Center of SOPB @ 15.5 cm (isocenter

Setup A – MC
voxel vs slab geometry

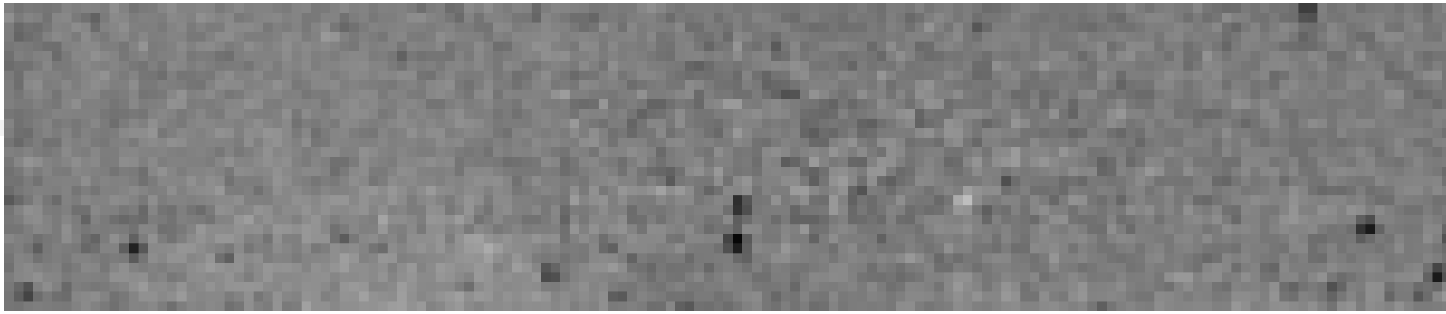


Setup A
Distal Falloff
MC vs measurement



Benchmark

- **Monte Carlo vs. Measurements (with 10 cm lung slab)**
  - **r_{90} measured: 23.40 cm**
  - **r_{90} Monte Carlo: 23.23 cm**
  - **Distal falloff**
    - **Monte Carlo: 4.66 mm (90%-20%)**
    - **Measurement: 7.75 mm (90%-20%)**
    - **Monte Carlo: 3.74 mm (80%-20%)**
    - **Measurement: 6.20 mm (80%-20%)**



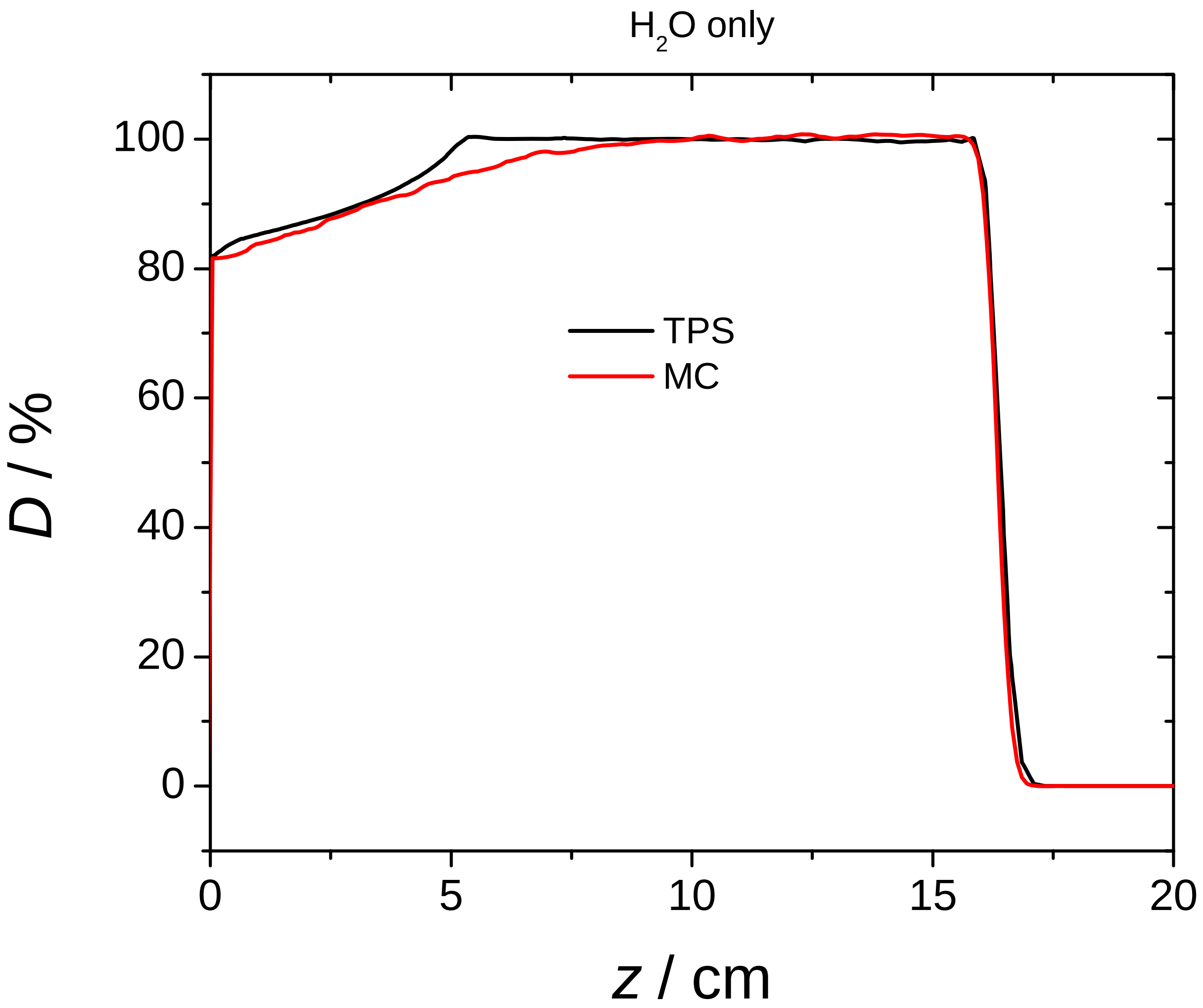
Benchmark

- Monte Carlo vs. measurements
  - Beam for setup A
    - In pure water
    - With a 10 cm slab of lung equivalent plastic
    - Aperture physical size 8.2 cm × 8.2 cm

Benchmark

- **Monte Carlo vs. TPS (with 10 cm lung slab)**
  - r_{90} **TPS: 23.37 cm**
  - r_{90} **Monte Carlo: 23.23 cm**
  - **Distal falloff**
    - **Monte Carlo: 4.66 mm (90%-20%)**
    - **TPS: 5.10 mm (90%-20%)**
    - **Monte Carlo: 3.74 mm (80%-20%)**
    - **TPS: 4.30 mm (80%-20%)**

Benchmark



Benchmark

- Monte Carlo vs. ECLIPSE (H_2O only)
  - Range
    - r_{90} MC : 16.11 cm
    - r_{90} MC : 16.02 cm
  - Falloff:
    - MC : 5.2 mm (90-20%)
    - Measurement : 5.0 mm (90-20%)
    - MC : 4.1 mm (80-20%)
    - Measurement : 3.9 mm (80-20%)

Comparison MC vs. ECLIPSE
Setup A

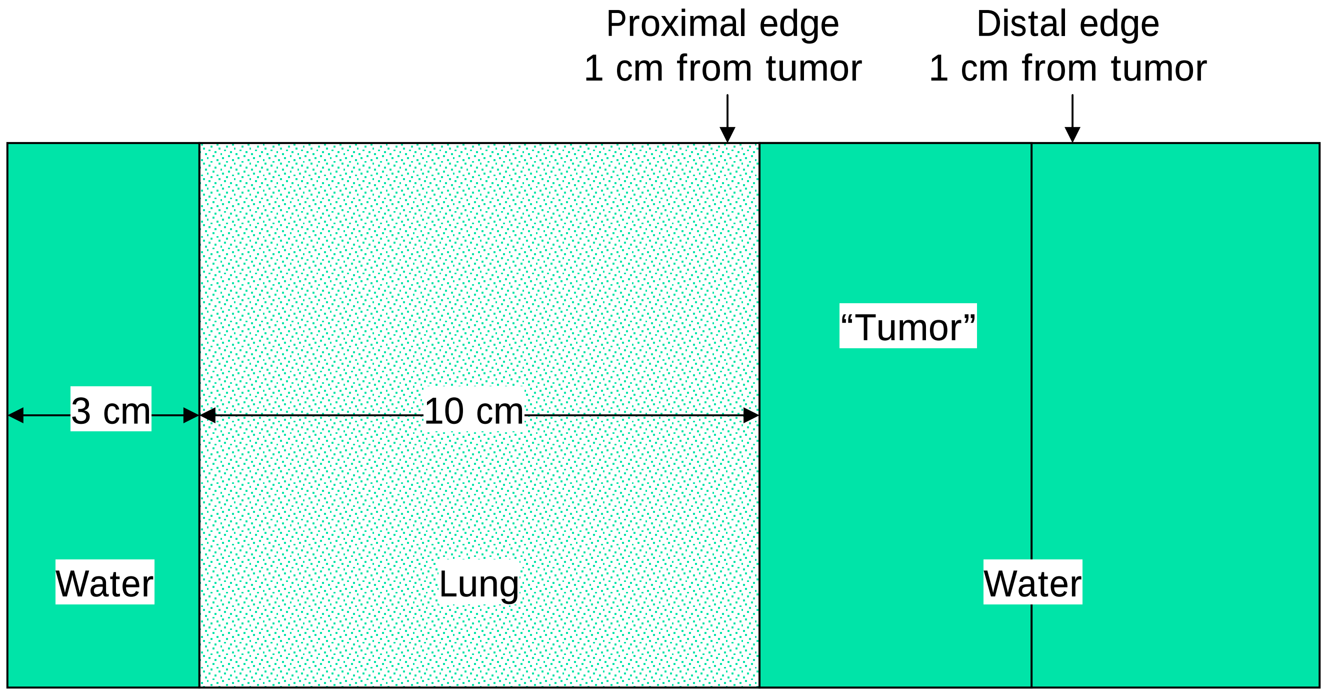
Distal Falloff in cm (TPS)		Distal Falloff in cm (MC)	
90%-20%	80%-20%	90%-20%	80%-20%
2.30	1.90	1.67	1.27
1.32	1.03	1.59	1.27
1.57	0.98	1.58	1.21
1.40	1.20	1.54	1.23
1.32	1.18	1.44	1.15
1.07	0.85	1.50	1.19
1.08	0.83	1.59	1.24

	90-20% Falloff mm	80-20% Falloff mm				
Homogeneous Slab	4.5	3.6				
Texturized voxels	15.6	12.1				

	R90 (cm)	90-20% Falloff mm	80-20% Falloff mm			
Monte Carlo	16.25	4.60	3.74			
Measurements	16.17	4.45	3.68			

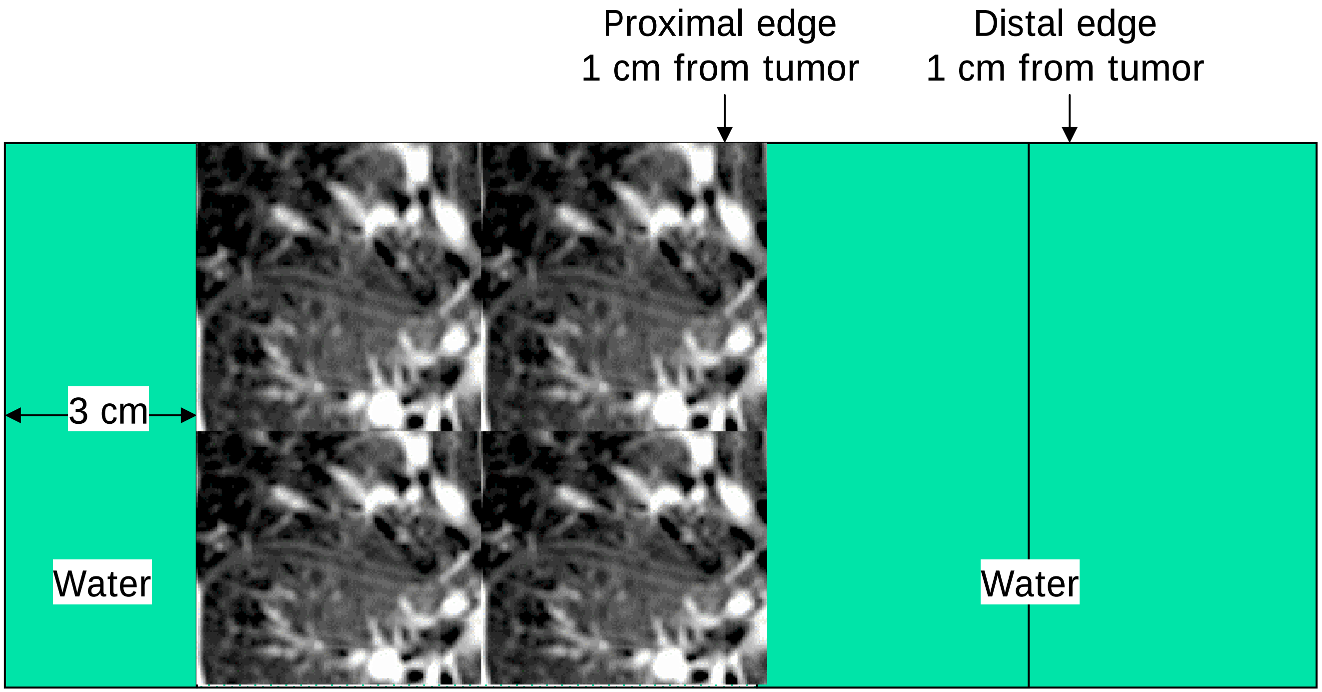
	R90 (mm)	90 - 20% Fall-off mm	80 - 20% Fall-off mm
Monte Carlo	16.25	4.60	3.74
Measurements	16.17	4.45	3.68

Setup A1



Lung density = 0.2 homogeneous, 0.2 inhomogeneous (i.e.20% of pixels are water)

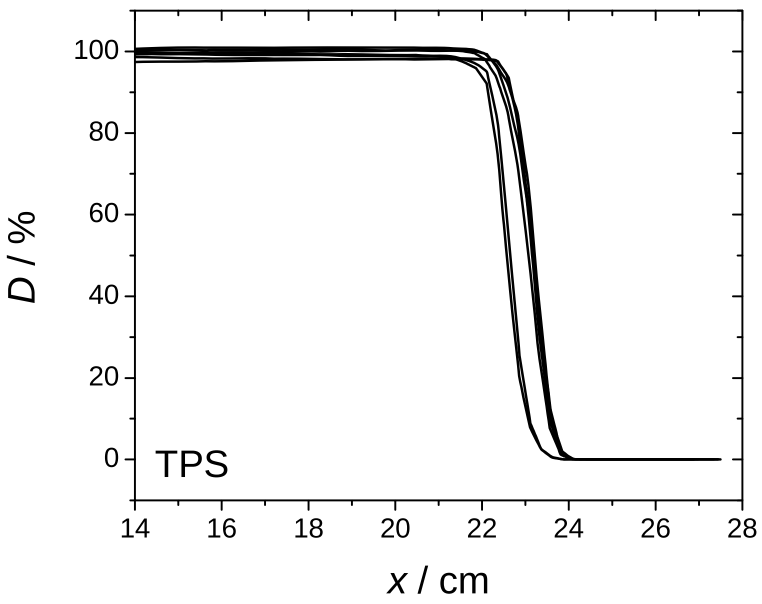
Setup A2



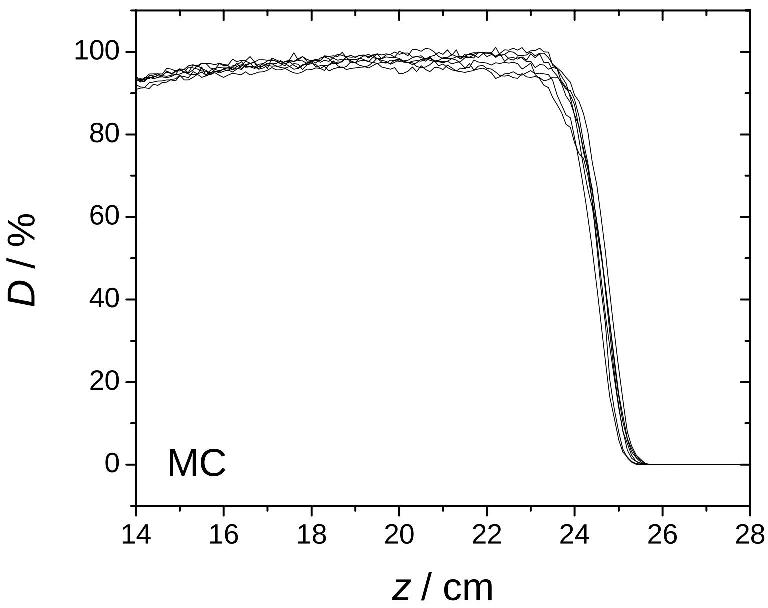
Lung may be replaced by lung cropped from actual patient image

Comparison MC vs. TPS
Setup A - CT geometry

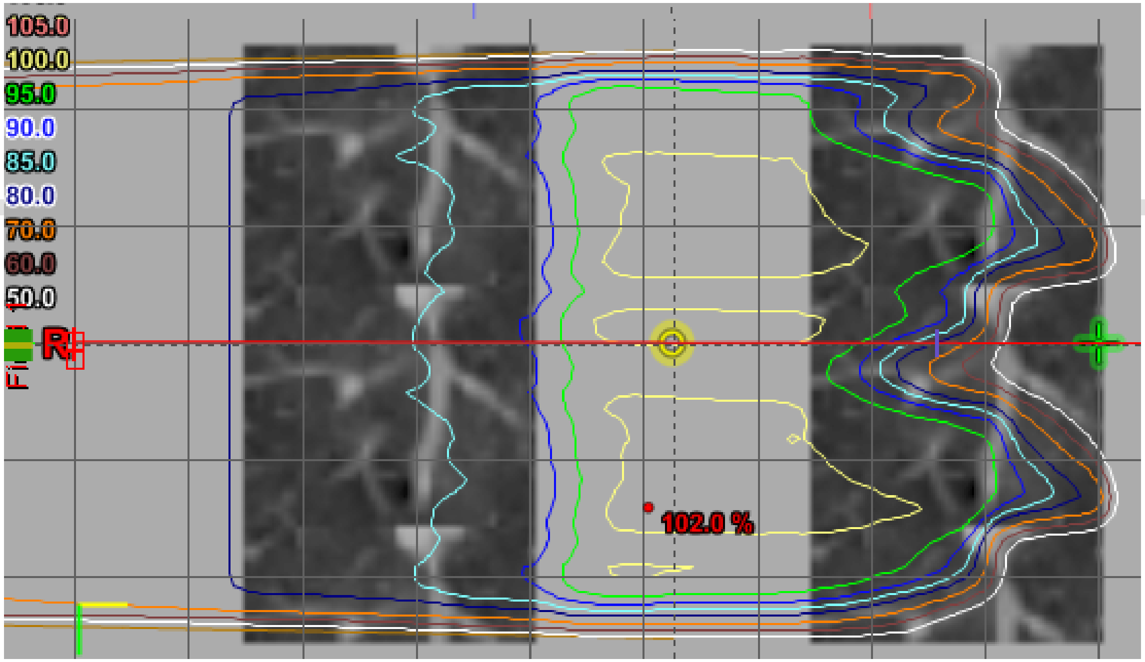
- **Range variations:**

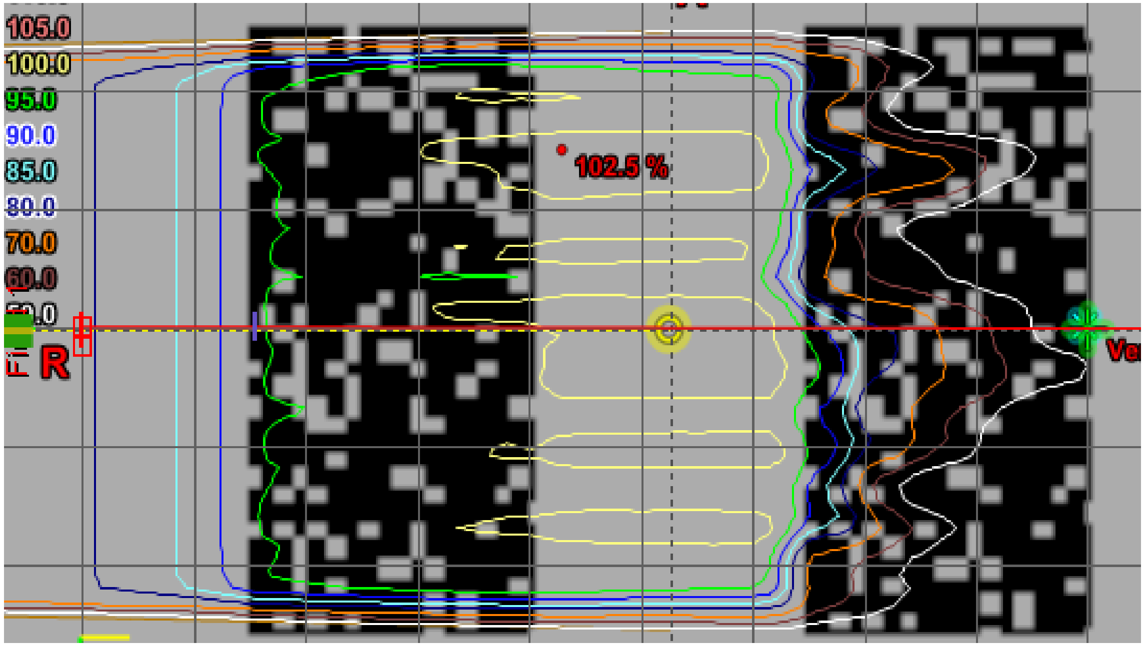


22.13 cm – 22.69 cm

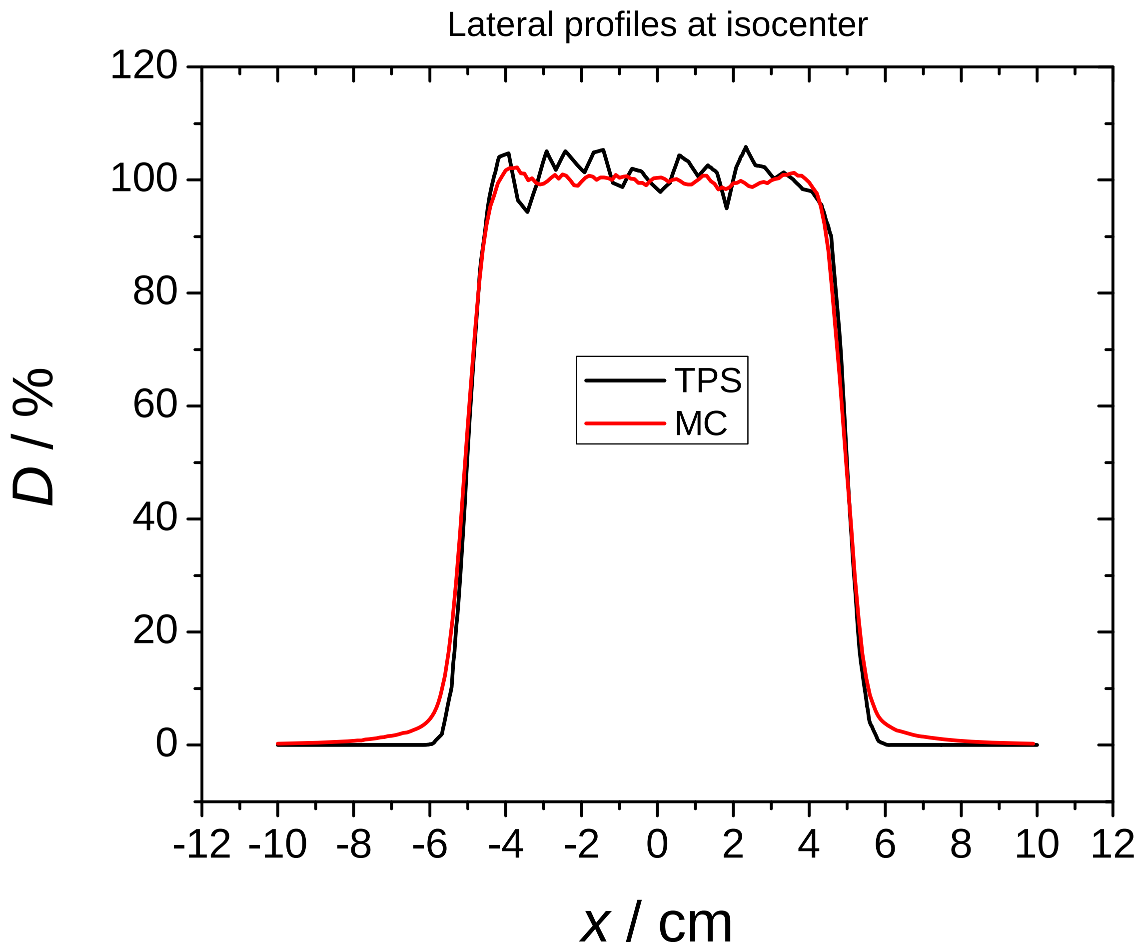


23.44 cm – 24.00 cm


105.0
100.0
95.0
90.0
85.0
80.0
70.0
60.0
50.0
R
102.0 %


105.0
100.0
95.0
90.0
85.0
80.0
70.0
60.0
102.5 %
R

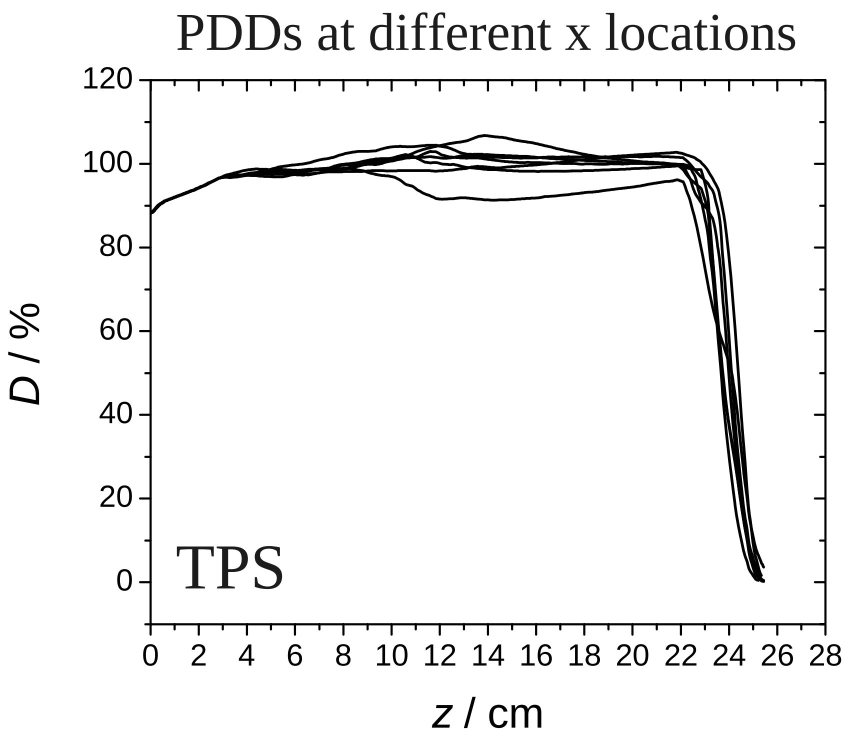
Comparison MC vs. ECLIPSE
Setup A



Comparison MC vs. ECLIPSE Setup A

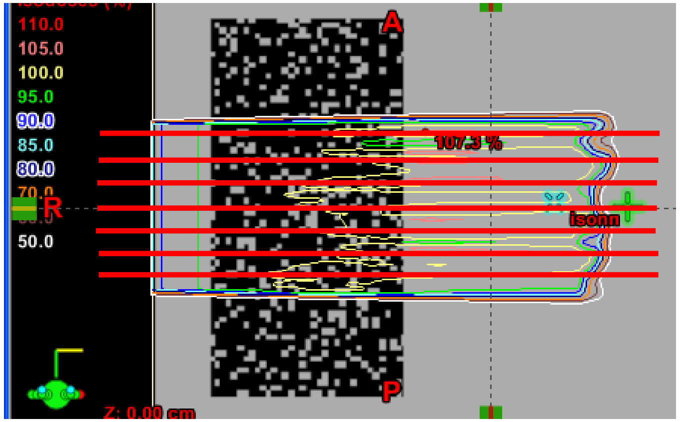
- **Penumbra (80% - 20%)**
  - **MC: 7.2 mm**
  - **TPS: 5.9 mm**
- **Dose variations in field**
  - **MC: 2.2%**
  - **TPS: 5.7 %**
- **Dose below 20% underestimated by TPS (known issue)**

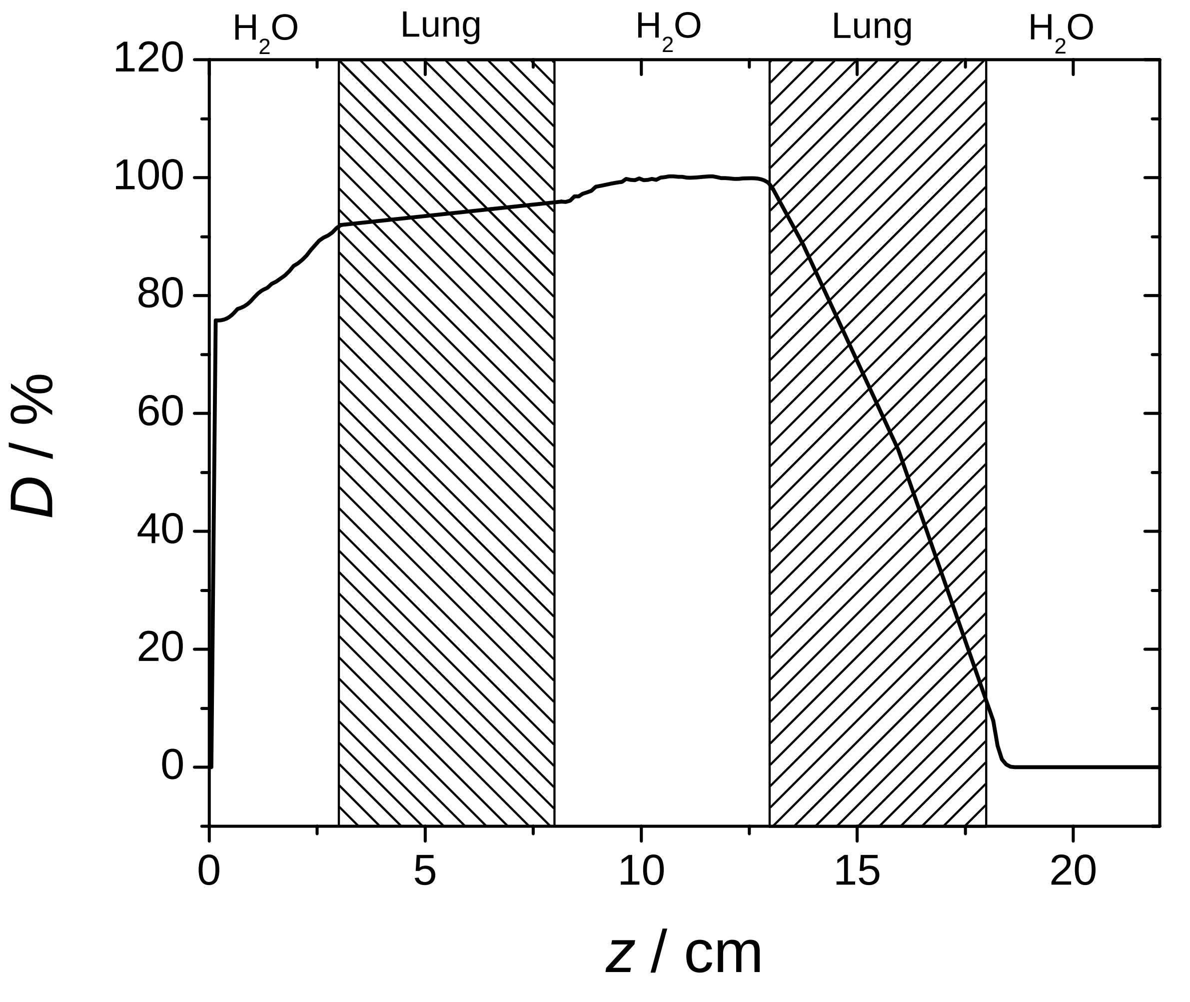
Comparison MC vs. ECLIPSE
Setup A



Variations in range:

22.42 cm - 23.72 cm

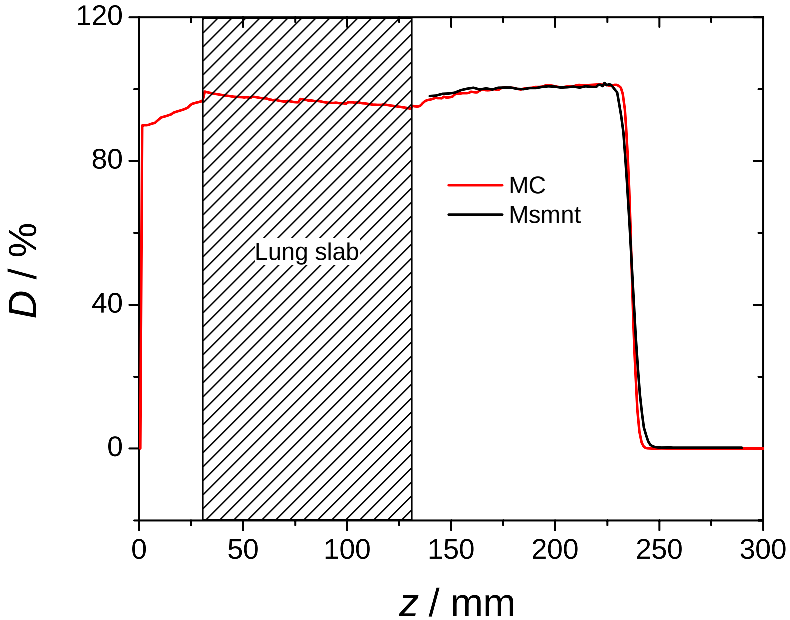


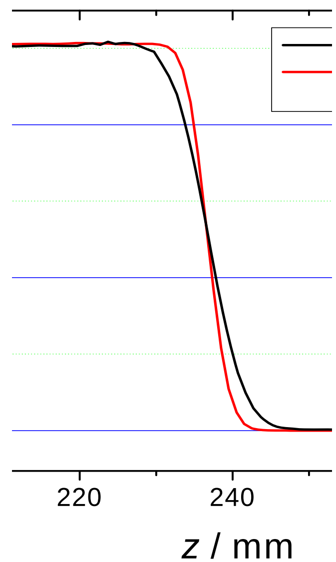

H2O
Lung
H2O
Lung
H2O
120
100
80
60
40
20
0
D / %
0
5
10
15
20
z / cm

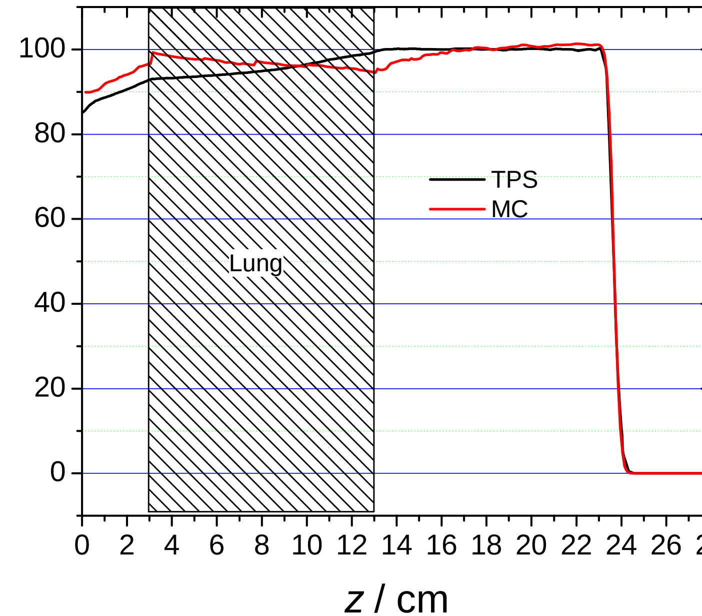
Comparison MC vs. TPS
Setup A - CT geometry

Distal Falloff in cm (TPS)		Distal Falloff in cm (MC)	
90%-20%	80%-20%	90%-20%	80%-20%
0.67	0.53	1.51	1.02
0.73	0.56	1.17	0.77
0.94	0.70	1.05	0.84
0.90	0.67	1.14	0.78
0.84	0.60	0.94	0.68
0.78	0.59	1.01	0.77
0.79	0.60	1.06	0.96

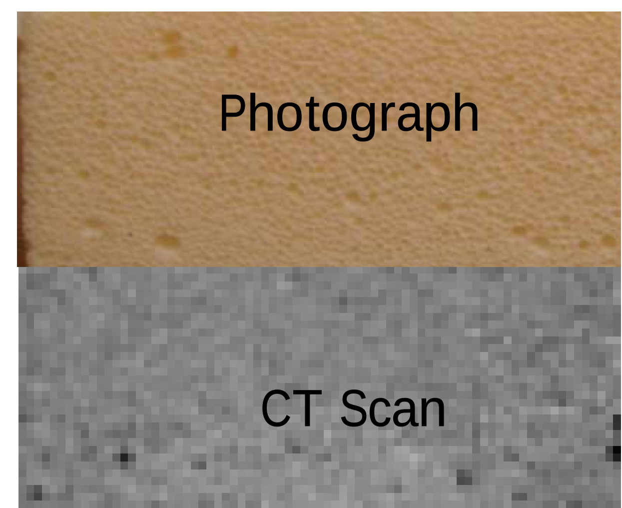
Monte Carlo Benchmark 2



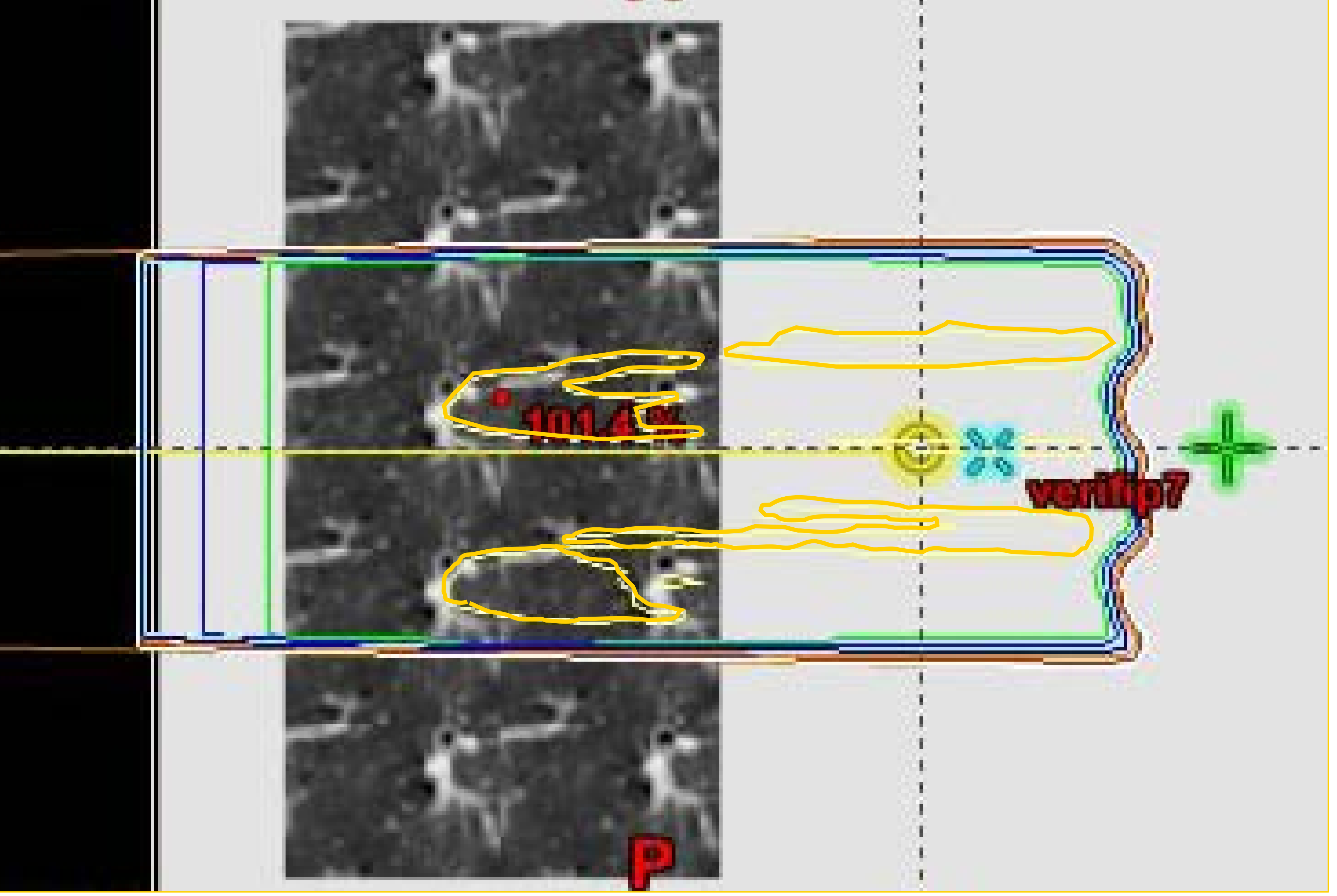


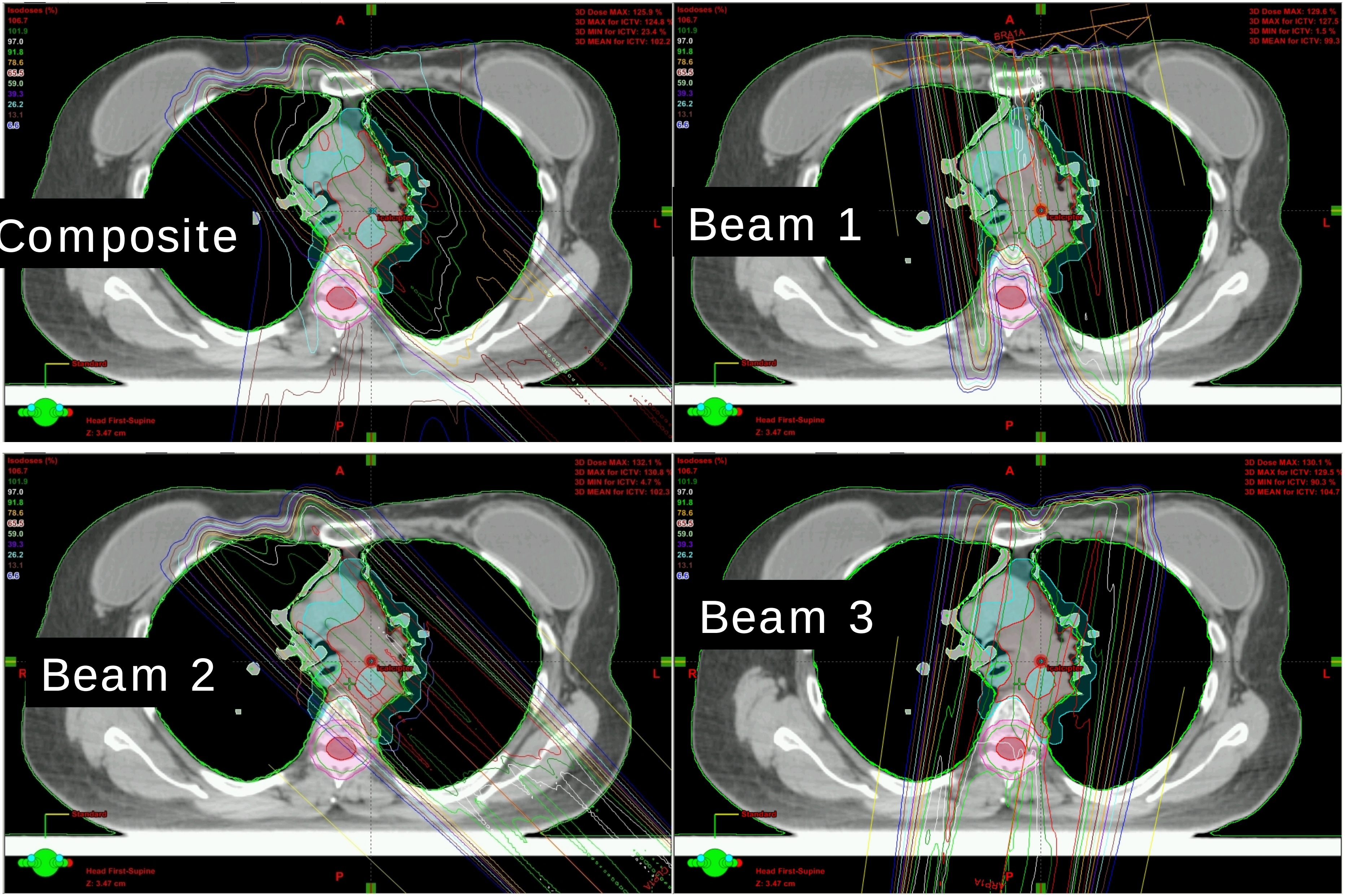


	90-20% Falloff mm	80-20% Falloff mm
Monte Carlo	**4.66**	**3.74**
Measurements	**7.75**	**6.2**



MC Calculations Assumed Homogeneous Lung


101.4 %
verifip7
P


Composite
Isodoses (%)
106.7
101.9
97.0
91.8
78.6
65.5
59.0
39.3
26.2
13.1
6.6
3D Dose MAX: 125.9 %
3D MAX for ICTV: 124.8 %
3D MIN for ICTV: 23.4 %
3D MEAN for ICTV: 102.2
A
P
L
Standard
Head First-Supine
Z: 3.47 cm
Beam 1
3D Dose MAX: 129.6 %
3D MAX for ICTV: 127.5
3D MIN for ICTV: 1.5 %
3D MEAN for ICTV: 99.3
Beam 2
3D Dose MAX: 132.1 %
3D MAX for ICTV: 130.8 %
3D MIN for ICTV: 4.7 %
3D MEAN for ICTV: 102.3
Beam 3
3D Dose MAX: 130.1 %
3D MAX for ICTV: 129.5 %
3D MIN for ICTV: 90.3 %
3D MEAN for ICTV: 104.7