Update on proton therapy research at the University of Texas, M. D. Anderson Cancer Center

Uwe Titt

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Uwe Titt
(Monte Carlo guy)

THE UNIVERSITY OF TEXAS

MD Anderson ~~Cancer~~ Center

Making Cancer History®

Global Map of Sister Institutions

MDACC

Divisional Structure

The Division of Radiation Oncology comprises the Departments of Radiation Oncology, Radiation Physics, and Experimental Radiation Oncology.

Division of Radiation Oncology

Division Head................................ Bruce Minsky, M.D.
Division Head *ad interim*

Deputy Division Head and
Clinical Research Director .... Bruce Minsky, M.D.

Executive Director and
Division Administrator .... Robin Famiglietti, M.B.A., F.A.C.H.E., Ph.D.

Department of Radiation Oncology

Chair: Bruce Minsky, M.D., *ad interim*

Employees: 513

Department of Radiation Physics

Chair: Geoffrey Ibbott, Ph.D.

Employees: 211

Department of Experimental Radiation Oncology

Chair: Junjie Chen, Ph.D.

Employees: 130

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KEY COMPONENTS

The Department of Radiation Physics provides research-driven, safe, accurate and high-quality patient care in collaboration with radiation oncologists. Faculty members in Radiation Physics conduct research and drive technology development to advance the delivery of radiation therapy. In conjunction with The University of Texas Graduate School of Biomedical Sciences, the department provides master's and Ph.D. degrees in medical physics. The Radiation Oncology Medical Physics Residency Program is a two-year clinical training program for medical physicists.

Radiation Physics is home to the National Cancer Institute-funded Radiological Physics Center. The center supports clinical trials and cooperative research groups to ensure that institutions participating in clinical trials deliver prescribed radiation doses that are clinically comparable and consistent.

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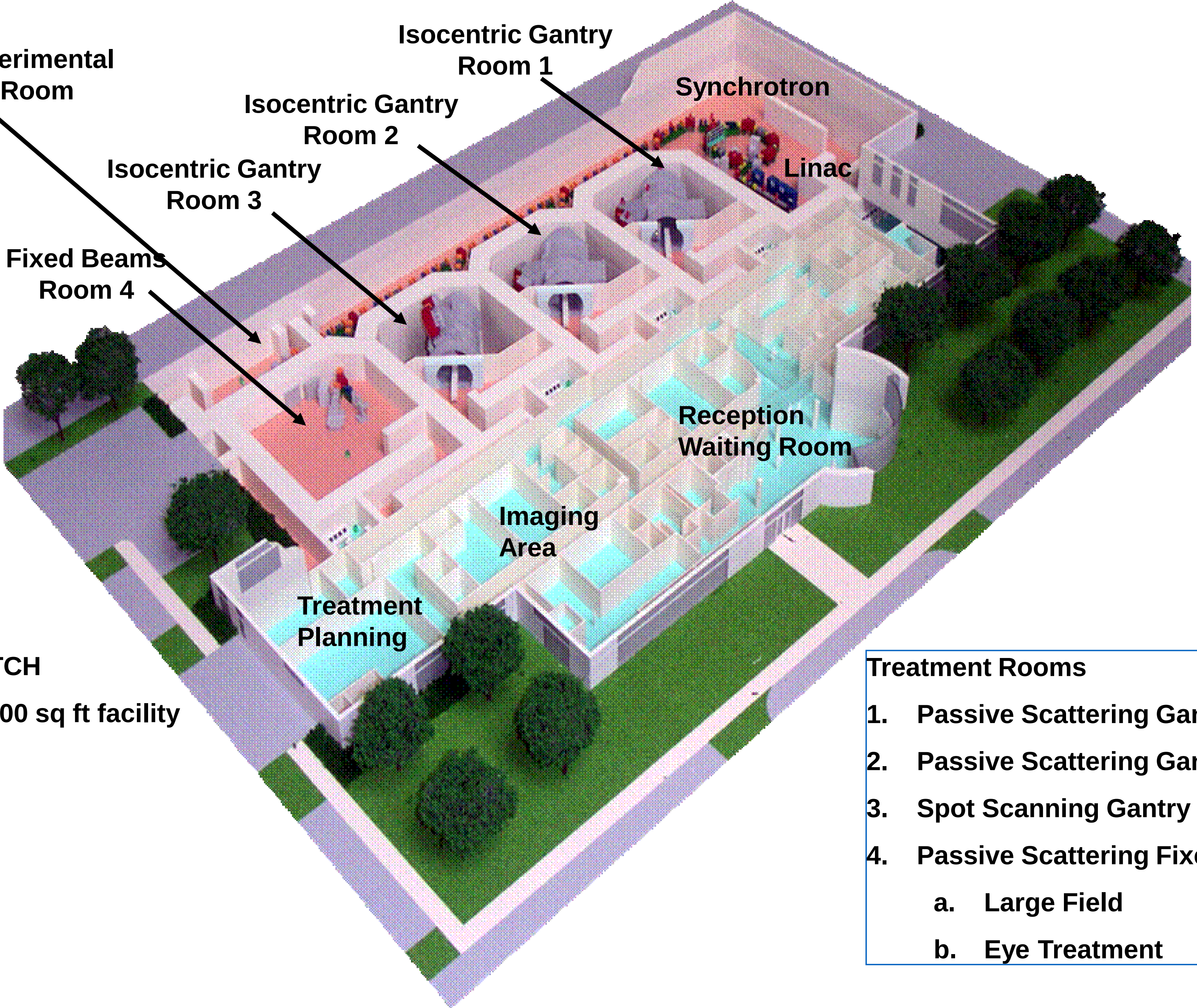
Proton Therapy



PTCH

9300 sq ft facility

Treatment Rooms

1. Passive Scattering Gantry
2. Passive Scattering Gantry
3. Spot Scanning Gantry
4. Passive Scattering Fixed
    a. Large Field
    b. Eye Treatment

Hitachi Synchrotron

Hitachi Synchrotron - Characteristics

- **7 Mev horizontal multi-turn injection**
- **Rotating freq. = 1.6-8 MHz**
- **70 – 250 MeV extraction energy**
- **0.4 MeV resolution**
- **2 – 6.7 sec/cycle**
- **0.5 - 5 sec/spill**
- **> 8 x 10^{10} p/pulse**
- **2 Gy/min for 14x14x16 cc**
- **Pulse to pulse energy change**

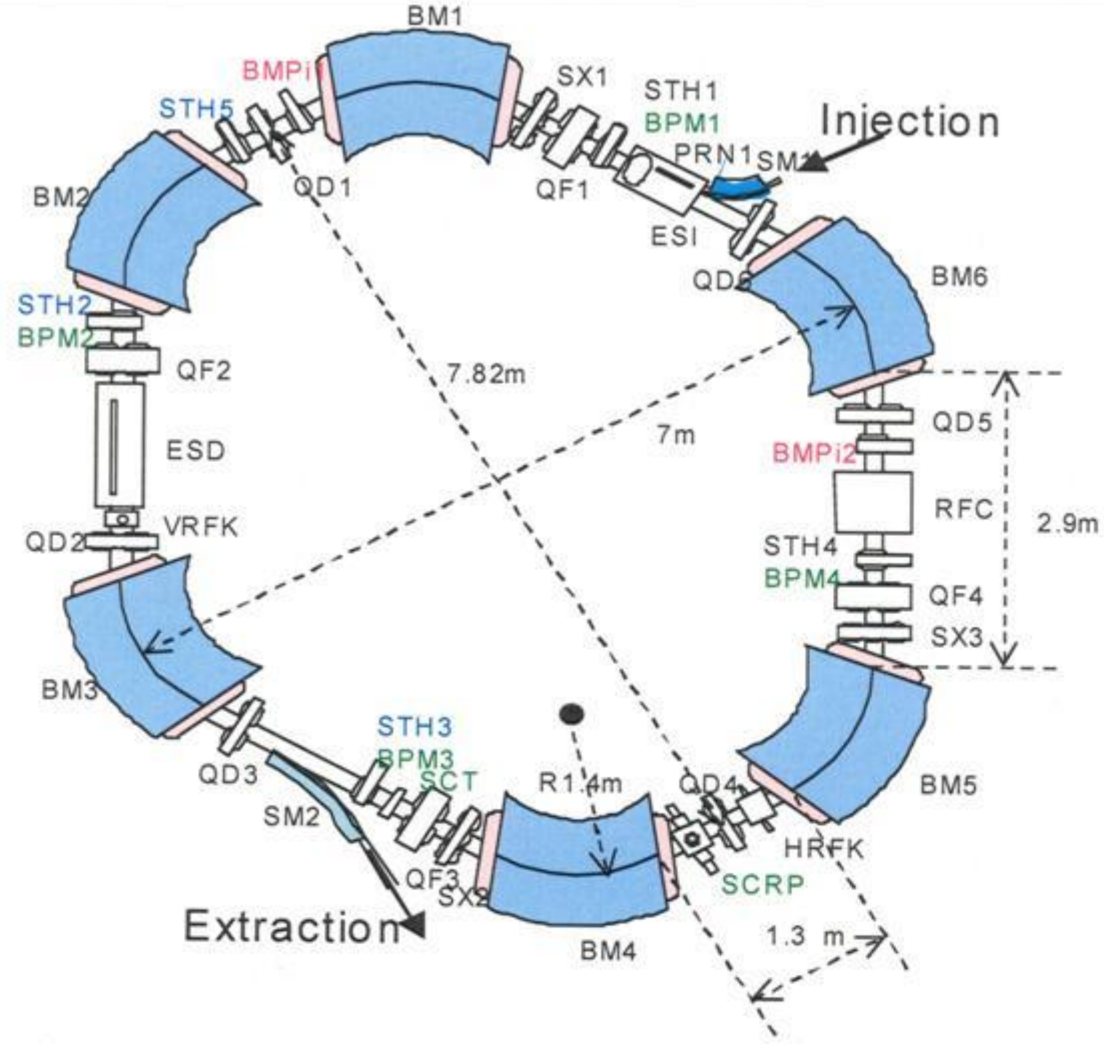


Figure 3.1.4-1 Configuration of Synchrotron Accelerator

Research

Overview – Proton Therapy

- There are two ways of delivering proton therapy
  - With passive scattering (PSPT)
  - With scanned narrow beamlets) whose intensities are optimally adjusted to produce intensity-modulated proton therapy (IMPT)

- In principle, proton therapy has significantly greater therapeutic potential
  - IMPT has even greater potential

Overview - Challenges

- There are numerous unresolved problems and gaps in our knowledge that could limit the exploitation of the full potential of PT
  - Protons are more vulnerable uncertainties
  - Examples of uncertainties:
    - Inter- and intra-fractional anatomic variations
    - Dosimetric
      - Approximations in dose computation algorithms
      - CT data
      - CT to stopping power ratio conversion
    - Biological

Overview - Challenges

- Dose distributions seen on treatment plans may be significantly different from what the patient gets
  - (Robustness of treatment plans uncertain)
  - IMPT is even more vulnerable to uncertainties
- Distal edge of proton beams may be degraded significantly by heterogeneities
- Optimization systems insufficiently advanced
  - Quality is not as high as it can be

Overview – Research Opportunities

- Knowledge gaps to be filled and problems to be solved present opportunities for research

- Examples
  - Studies of the impact of and reduction in intra- and inter-fractional uncertainties
  - Incorporation of uncertainties in plan optimization (robust optimization)
  - Improving dose computation accuracy

Overview – Research Opportunities

- More examples

  - Optimization - PSPT
    - Beam directions
    - Compensators
  - Optimization - IMPT - beyond intensities
    - Beam parameters - angles, spot positions, …
    - Robust optimization
  - Robustness quantification
  - Biology

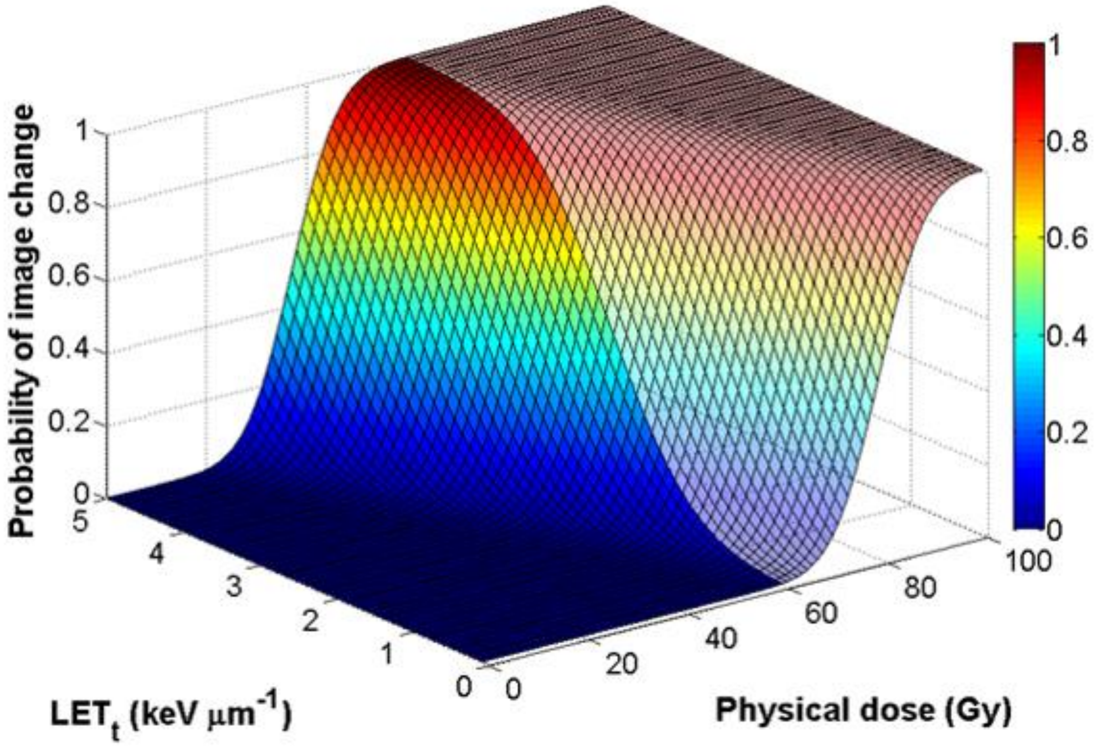
NCI-Funded Joint Program Project Grant (MGH and MDACC)

Improving the Clinical Effectiveness and Understanding of the Biophysical Basis of Proton Therapy

- Project 1: Assessment of Effectiveness of IMPT vs. IMRT through Phase II Randomized Clinical Trials
- Project 2: Exploratory Phase I/II Clinical Studies to Improve the Therapeutic Ratio of Proton Radiation Therapy
- Project 3: Assessing and understanding the impact of physical and biological factors on outcomes of proton therapy
- Project 4: Improving Outcomes by Optimally Exploiting Physical and Biological Characteristics of Protons

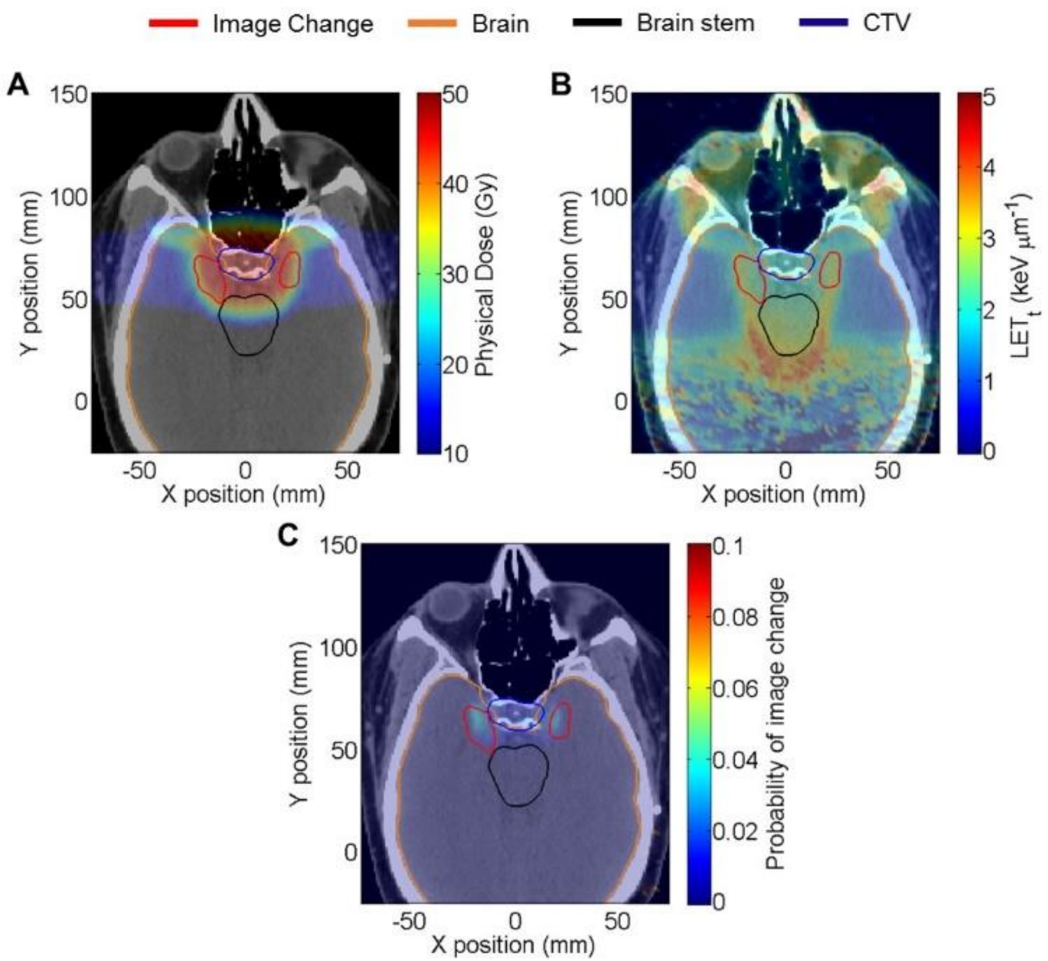
Christopher Peeler:

- Application of Monte Carlo dose calculation techniques for studies of proton relative biological effectiveness
- Analysis of retrospective data to determine correlations between proton dose and LET and imaged outcomes
- Development of models to describe in vivo biological effects of protons
- Analysis of outcomes data with respect to traditional linear-quadratic models of proton relative biological effectiveness



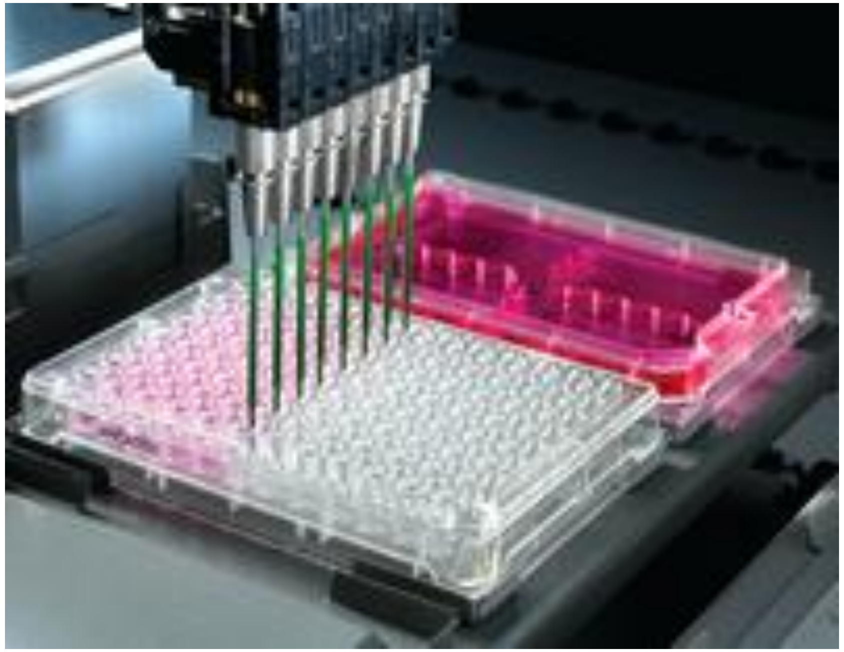
A generalized linear model which describes probability of normal tissue image changes in brain as a function of proton dose and LET.

(A) Physical dose, (B) track-averaged LET, and (C) probability of image change for an example patient case

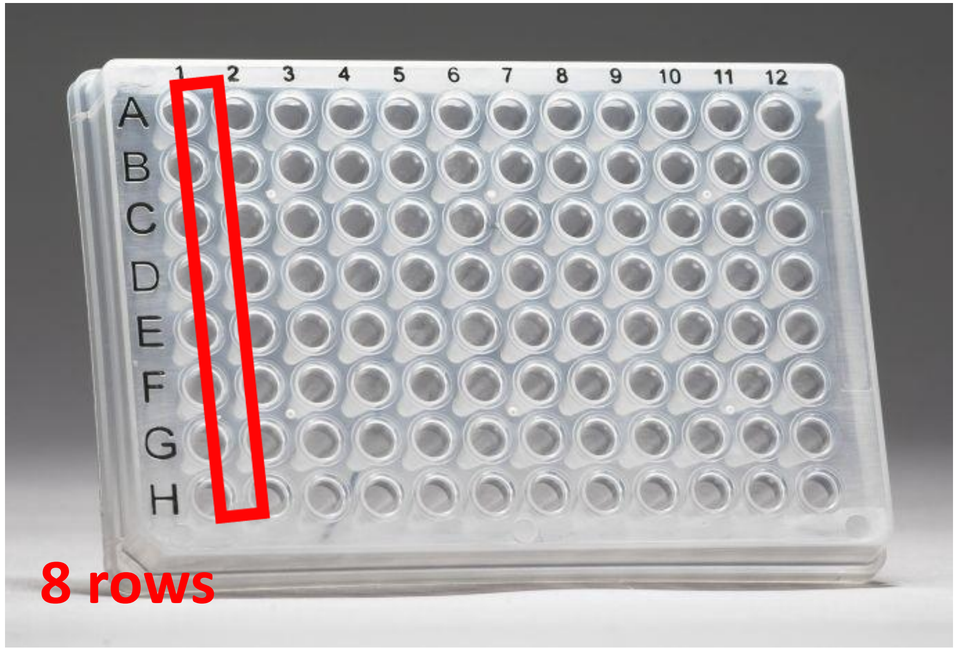


Fada Guan & Lawrence Bronk:
Spatial Mapping of the Biological Effectiveness of Scanned Proton Beams

12 columns



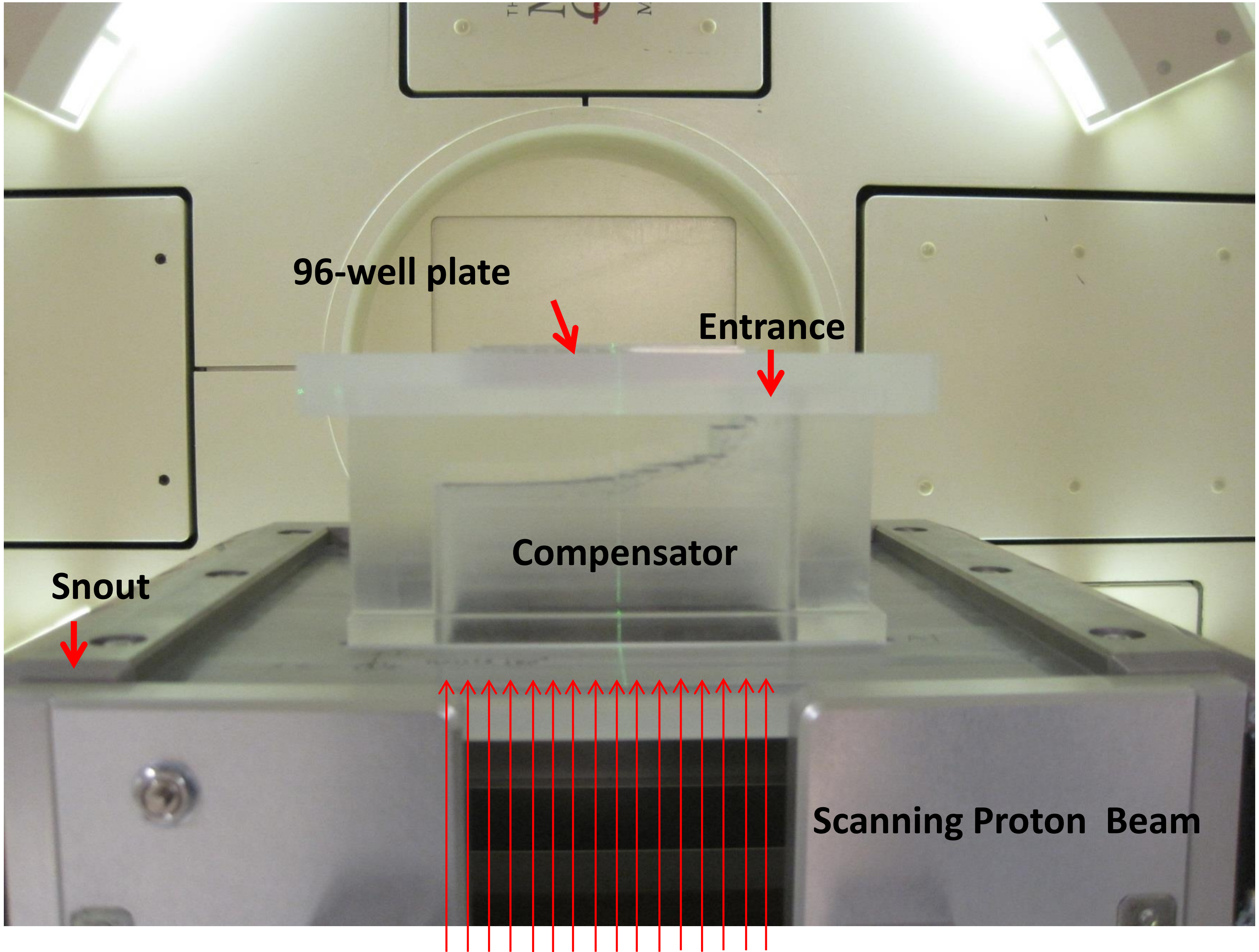
Solution: RPMI 1640 medium



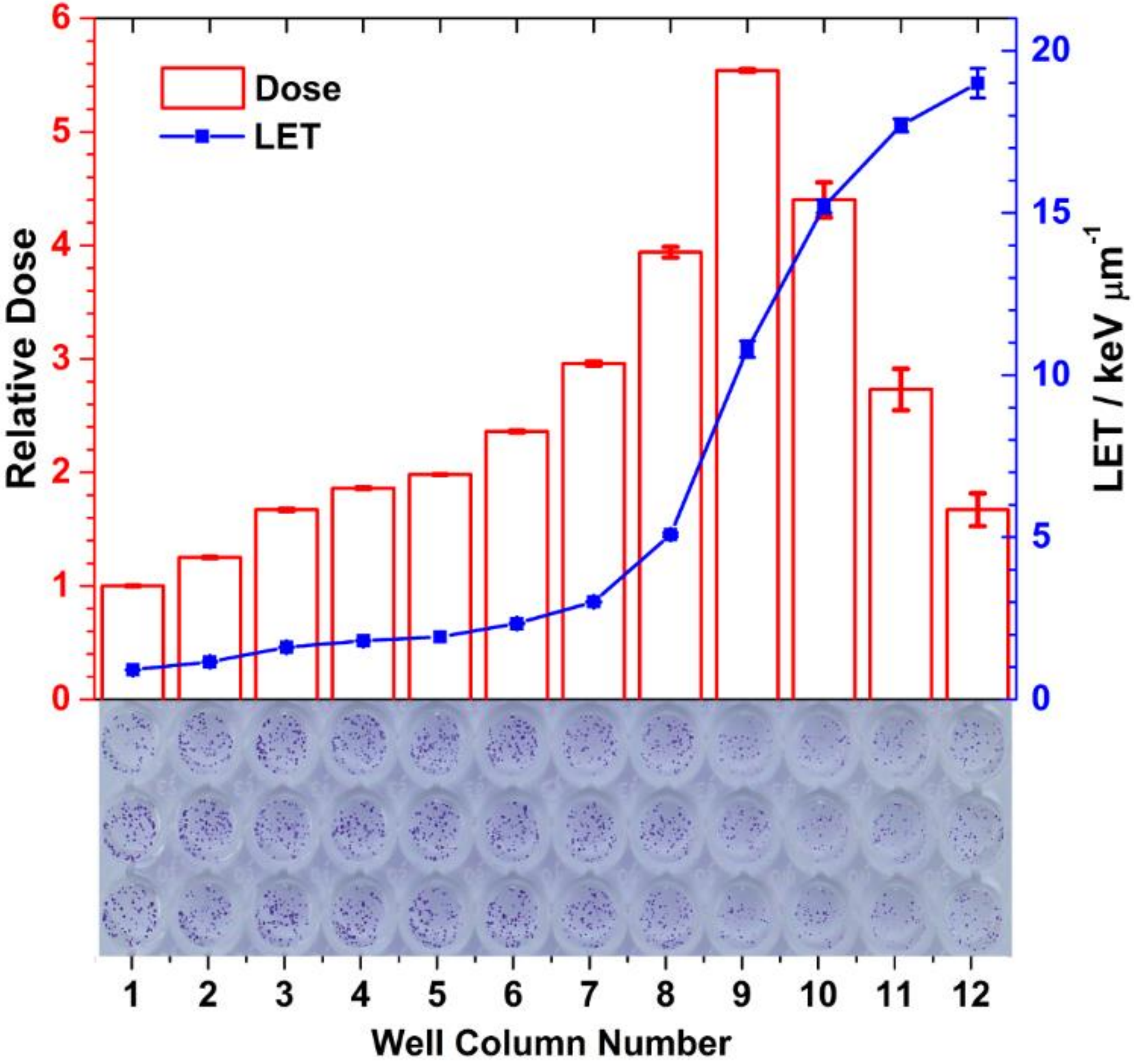
96-well plate

High-throughput Cell Culture

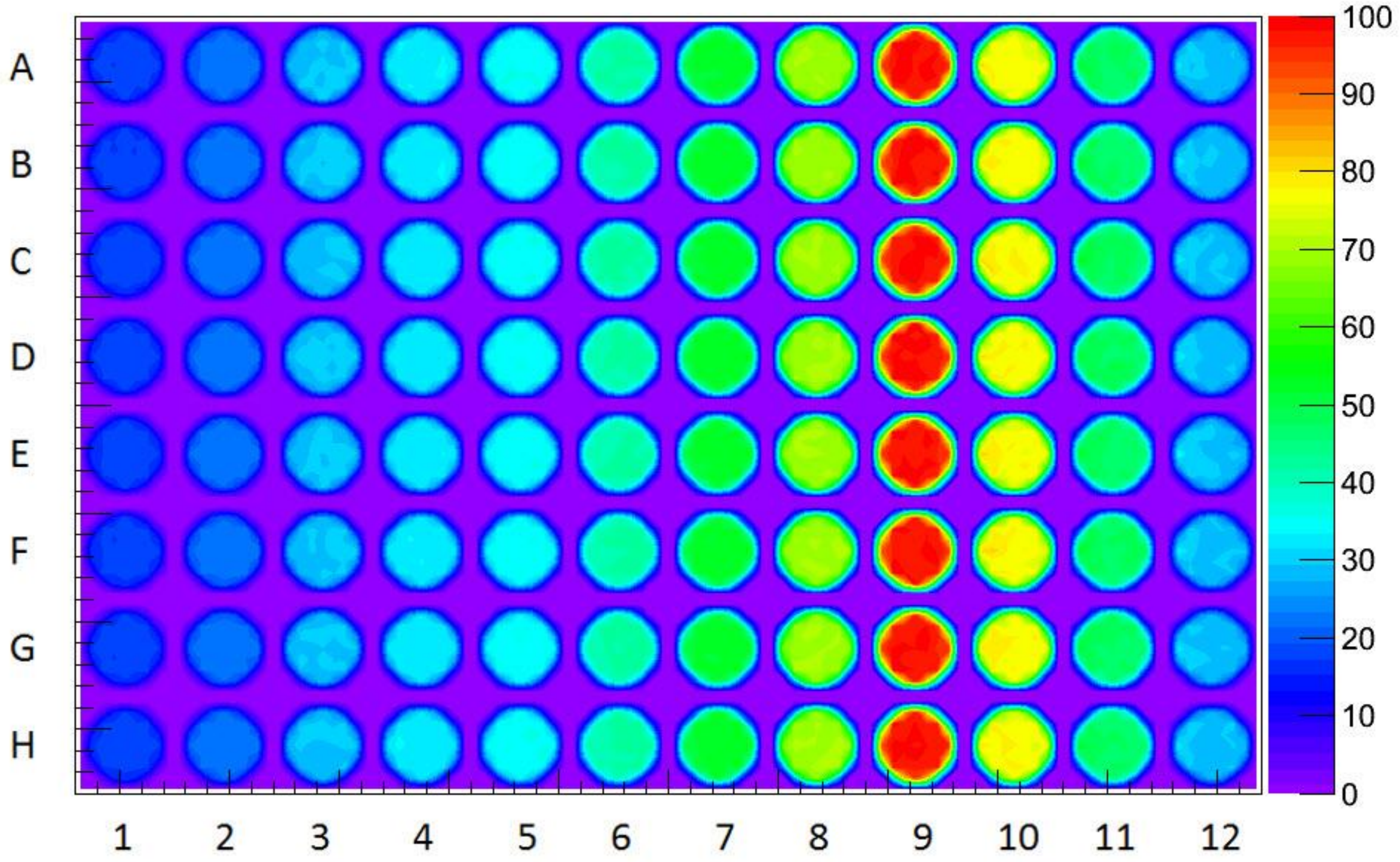
Cell Irradiation



LET Effect in Cell Kill

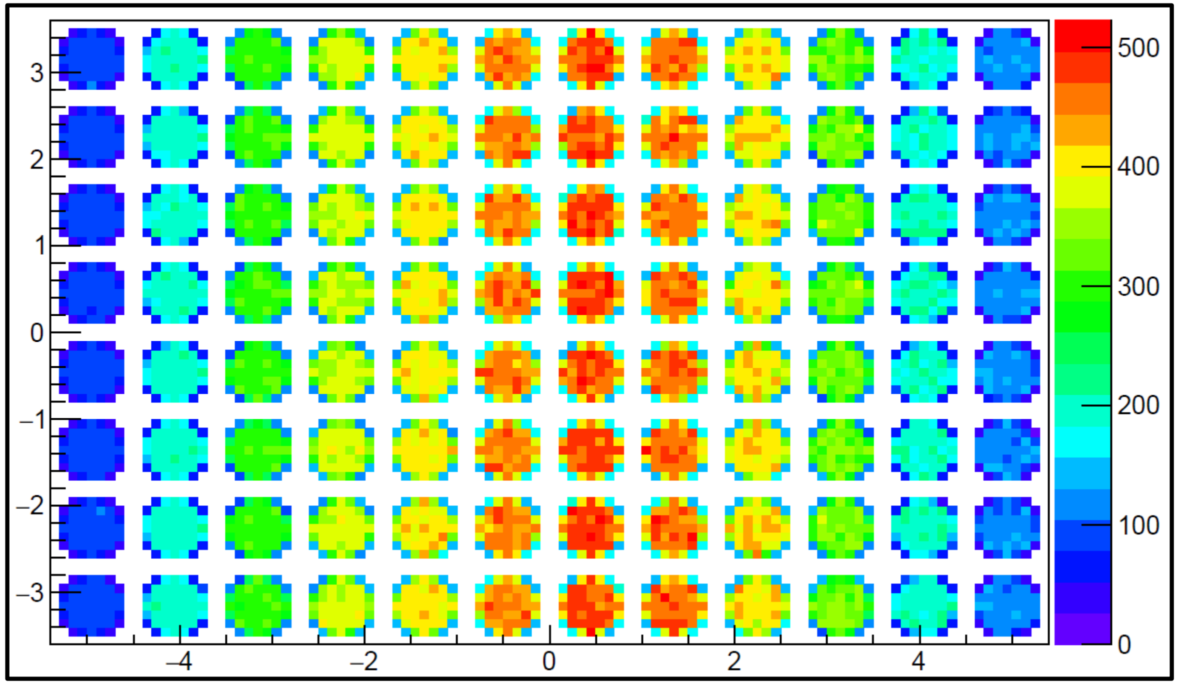


Dose Map in the 96-Well Plate (from MC)

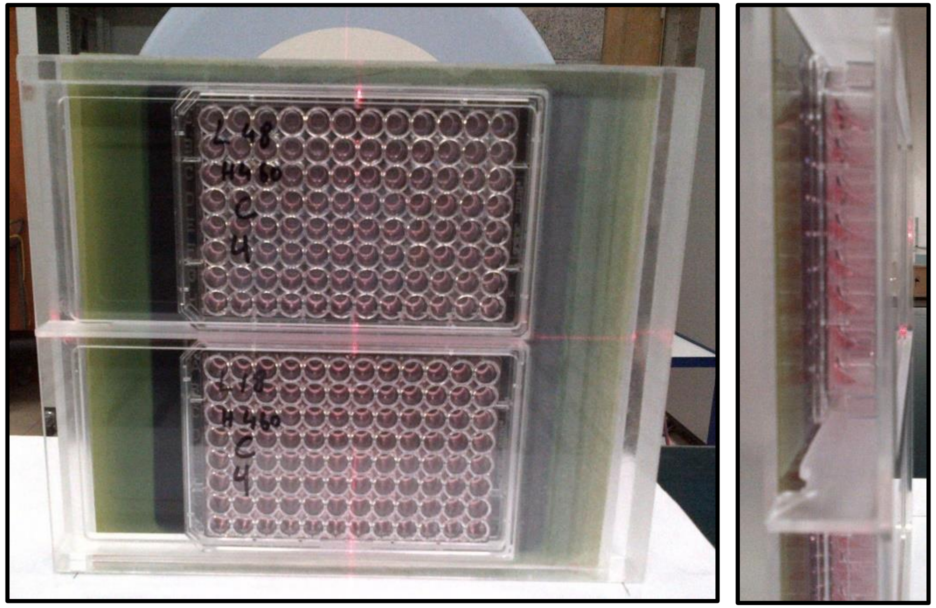


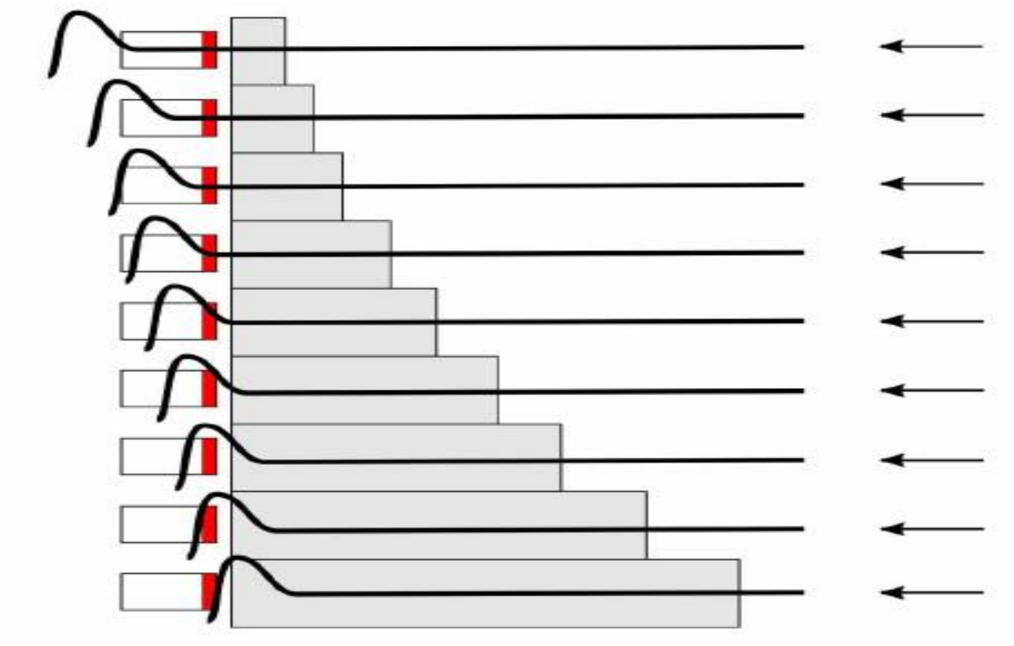
Darshana Patel & Lawrence Bronk:

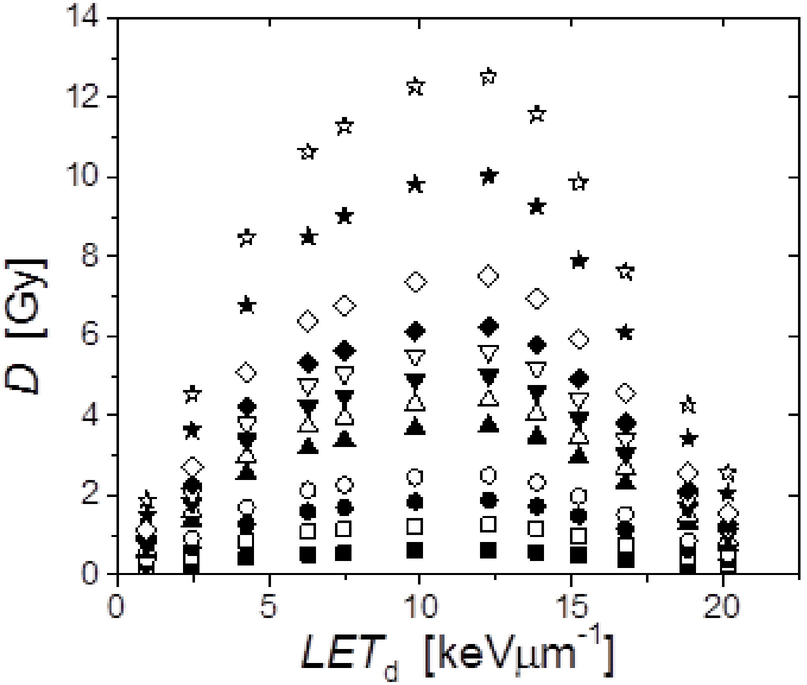
Relative Biological Effectiveness (RBE) of Heavy Ion Beams



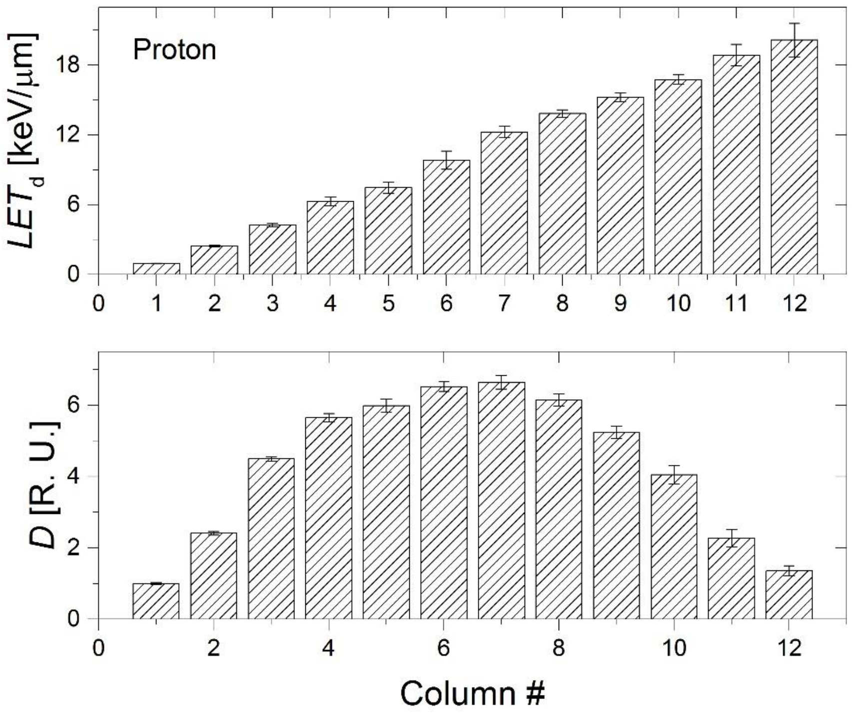
3
2
1
0
−1
−2
−3
−4
−2
0
2
4
500
400
300
200
100
0

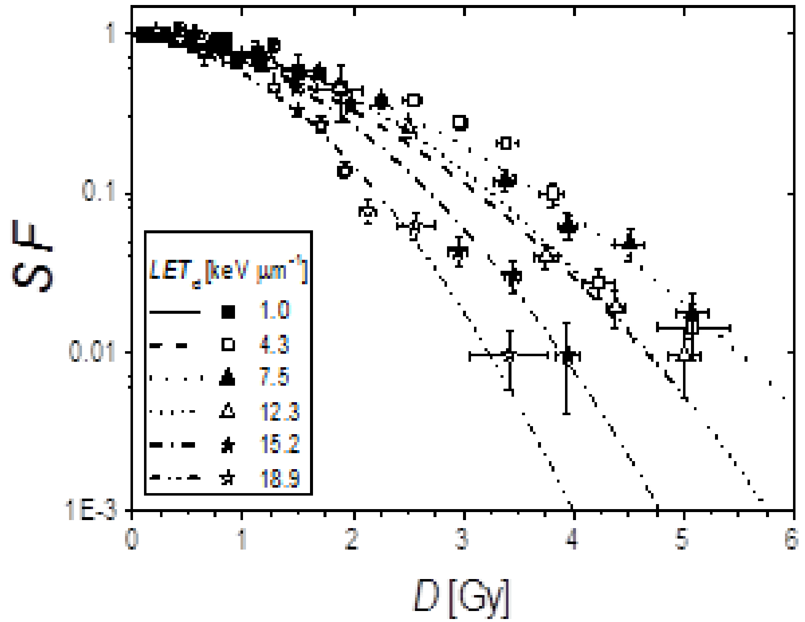


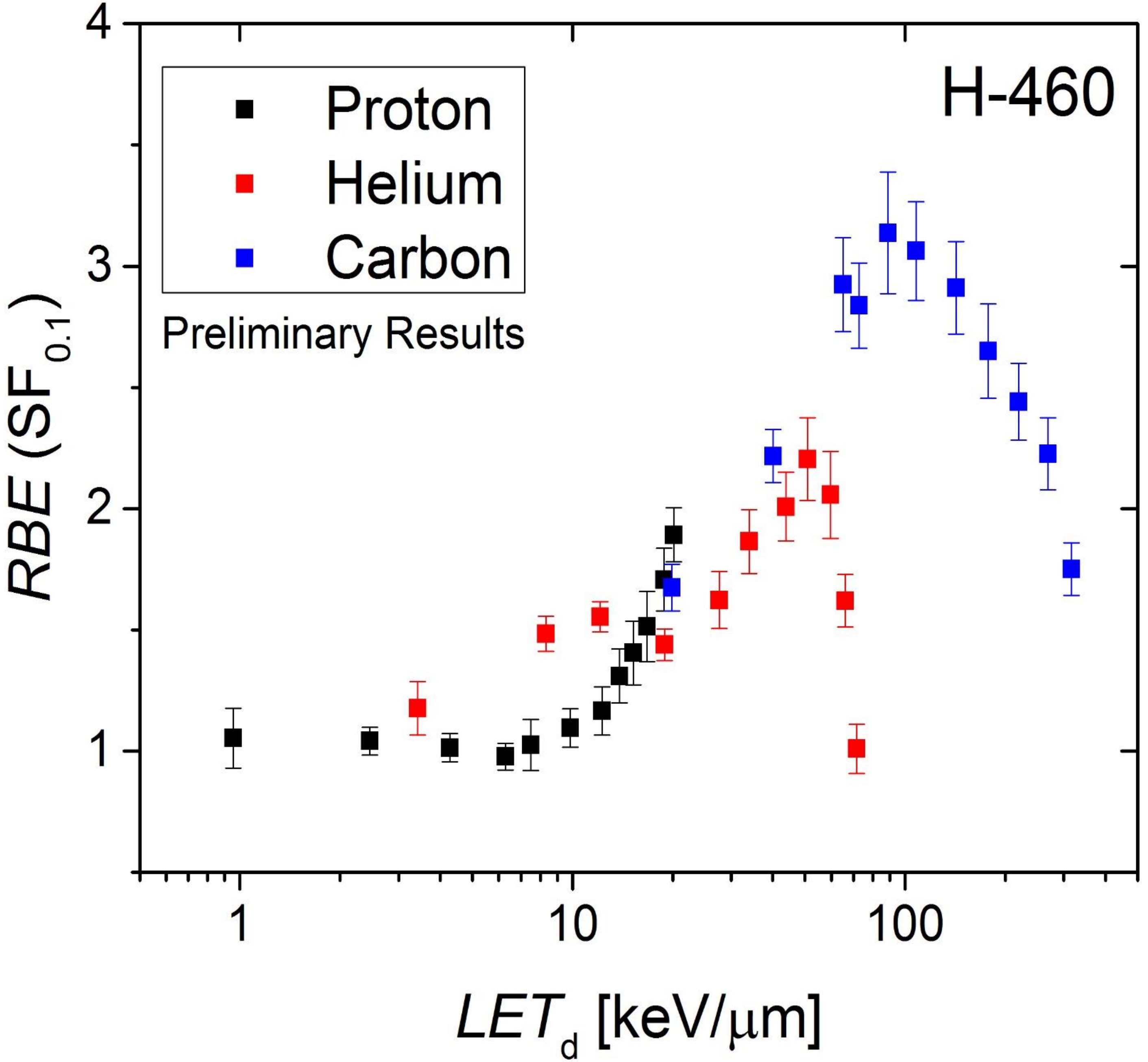




14
12
10
8
6
4
2
0
0
5
10
15
20
D [Gy]
LET_d [keVμm^{-1}]


Proton
LETd [keV/µm]
0
6
12
18
0 1 2 3 4 5 6 7 8 9 10 11 12
D [R. U.]
0
2
4
6
0 2 4 6 8 10 12
Column #


SF
1
0.1
0.01
1E-3
0 1 2 3 4 5 6
D [Gy]
LETd [keV µm-1]
1.0
4.3
7.5
12.3
15.2
18.9

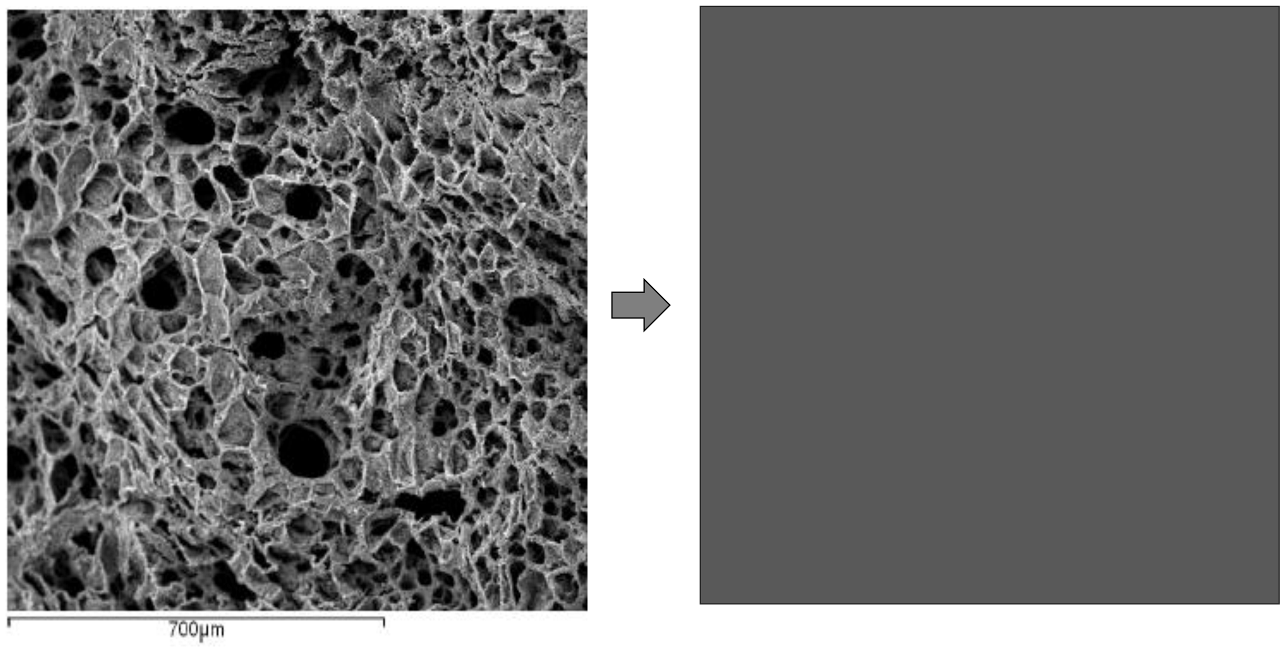

RBE (SF0.1)
1
2
3
4
Proton
Helium
Carbon
Preliminary Results
H-460
1
10
100
LETd [keV/µm]

Dragan Mirkovic:

- Lung Heterogeneity correction for protons
- Analysis of patient outcomes:
  - Lung toxicities vs. doses delivered
  - Lung recurrences vs. doses delivered
  - Brain imaging changes in proton therapy patients
  - Head and neck toxicities vs. doses delivered

Lung heterogeneity correction

- Current CT based models use volume averaging and replace highly heterogeneous lung tissue with a homogeneous model
- This can have adverse effects on dose calculation in lung

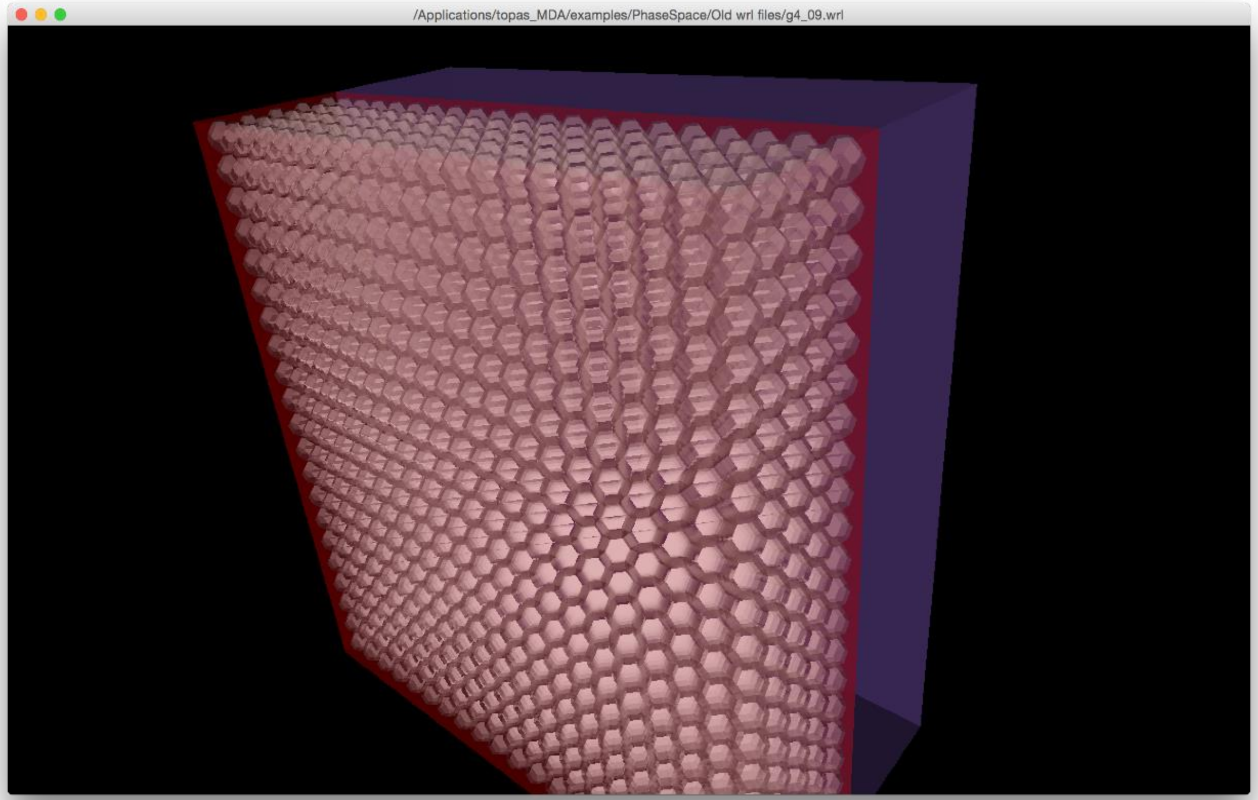


- Microscopic model possible?
  - Correctly models microscopic structure of lung tissue
  - 2 mm^3 volumes of the lung tissue parameterized by density
  - Microscopic structure of the lung approximated with a grid of truncated octahedra

Zayne Belal:

Heterogeneity correction for proton beams in lung tissue

•Compare proton transport through homogeneous and heterogeneous lung tissue using TOPAS. Goal is to develop a heterogeneity correction factor that can be used to resolve issues with volume averaged CT of lung tissue.



•Picture: Heterogeneous lung phantom with alveolar-like sacs (red), phasespace (purple)

•Commission a model of a Passive Scattering Proton therapy (PSPT) treatment head developed MCNPX. Goal is to create a dose approximation model that recreates the dose measured during quality assurance.

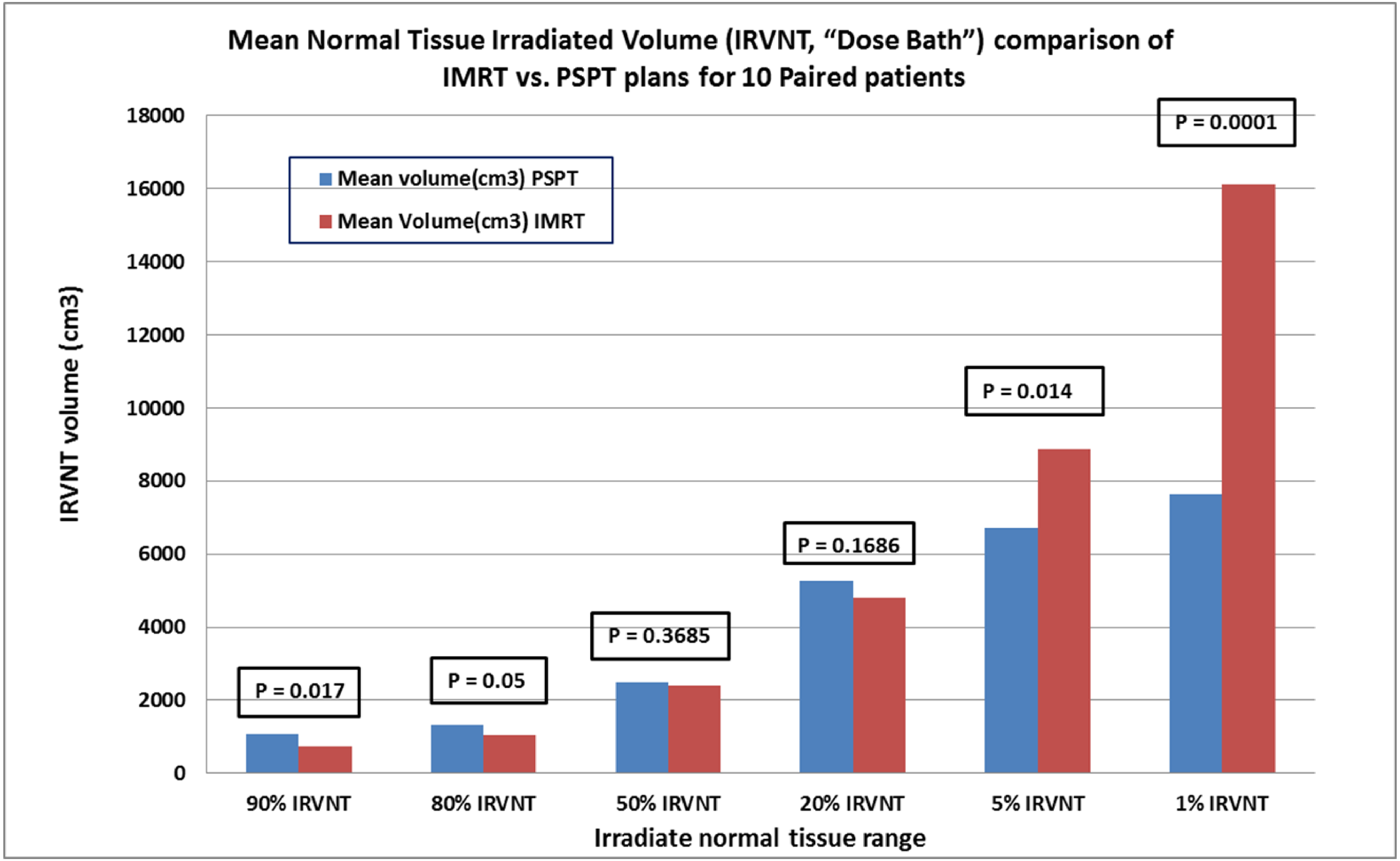
Ryosuke Kono:

Evaluation of Potential Impact of RBE Variations in IMPT Planning

- IMPT planning study for brain tumors
- Evaluation of potential impact of RBE variations (using FDC)
- Analysis of the effects of the number and the directions of proton beams in IMPT planning
- Goal: find optimal beam arrangement in clinical applications of a variable RBE for IMPT planning.

Amy Liu: Comparing normal tissue irradiated volumes for proton vs. photon treatment plans on PO1 lung patients

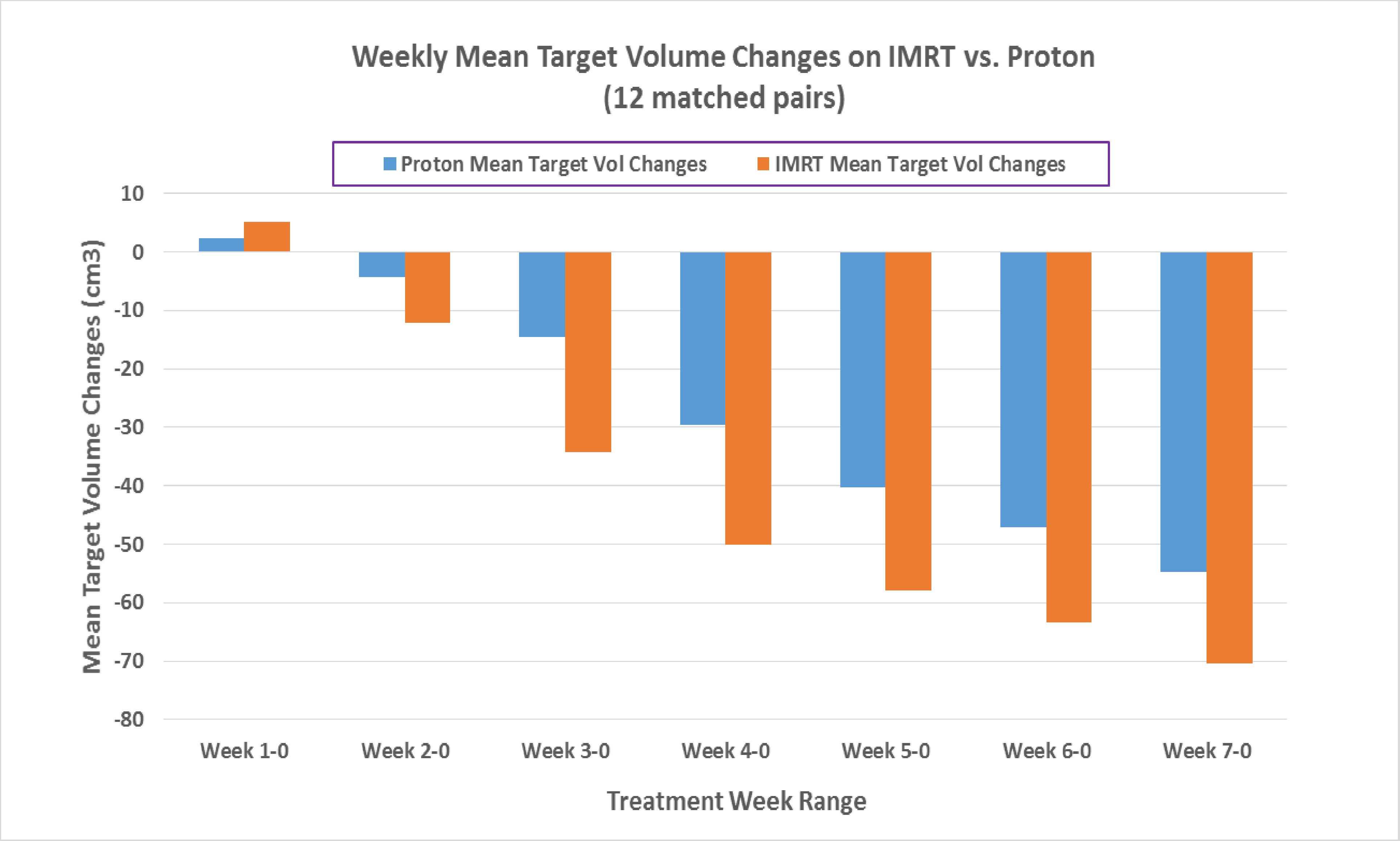
Purpose: The aim of this work is to compare the "irradiated volume" (IRV) of normal tissues receiving 1, 5, 20, 50, 80 and 90% or higher of the prescription dose with passively scattered proton therapy (PSPT) vs. IMRT of lung cancer patients. The overall goal of this research is to understand the factors affecting outcomes of a randomized PSPT vs. IMRT lung trial.



Mean Normal Tissue Irradiated Volume (IRVNT, "Dose Bath") comparison of IMRT vs. PSPT plans for 10 Paired patients
Mean volume(cm3) PSPT
Mean Volume(cm3) IMRT
IRVNT volume (cm3)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
P = 0.017
P = 0.05
P = 0.3685
P = 0.1686
P = 0.014
P = 0.0001
90% IRVNT
80% IRVNT
50% IRVNT
20% IRVNT
5% IRVNT
1% IRVNT
Irradiate normal tissue range

GTV CT number, volume and mass changes with IMRT vs. passively scattered proton therapy (PSPT) for locally advanced NSCLC patients

Purpose: To investigate and compare changes in CT number (CTN), volume and mass of gross tumor volume (GTV) derived from the weekly CTs for NSCLC patients on an IMRT vs. PSPT randomized trial.

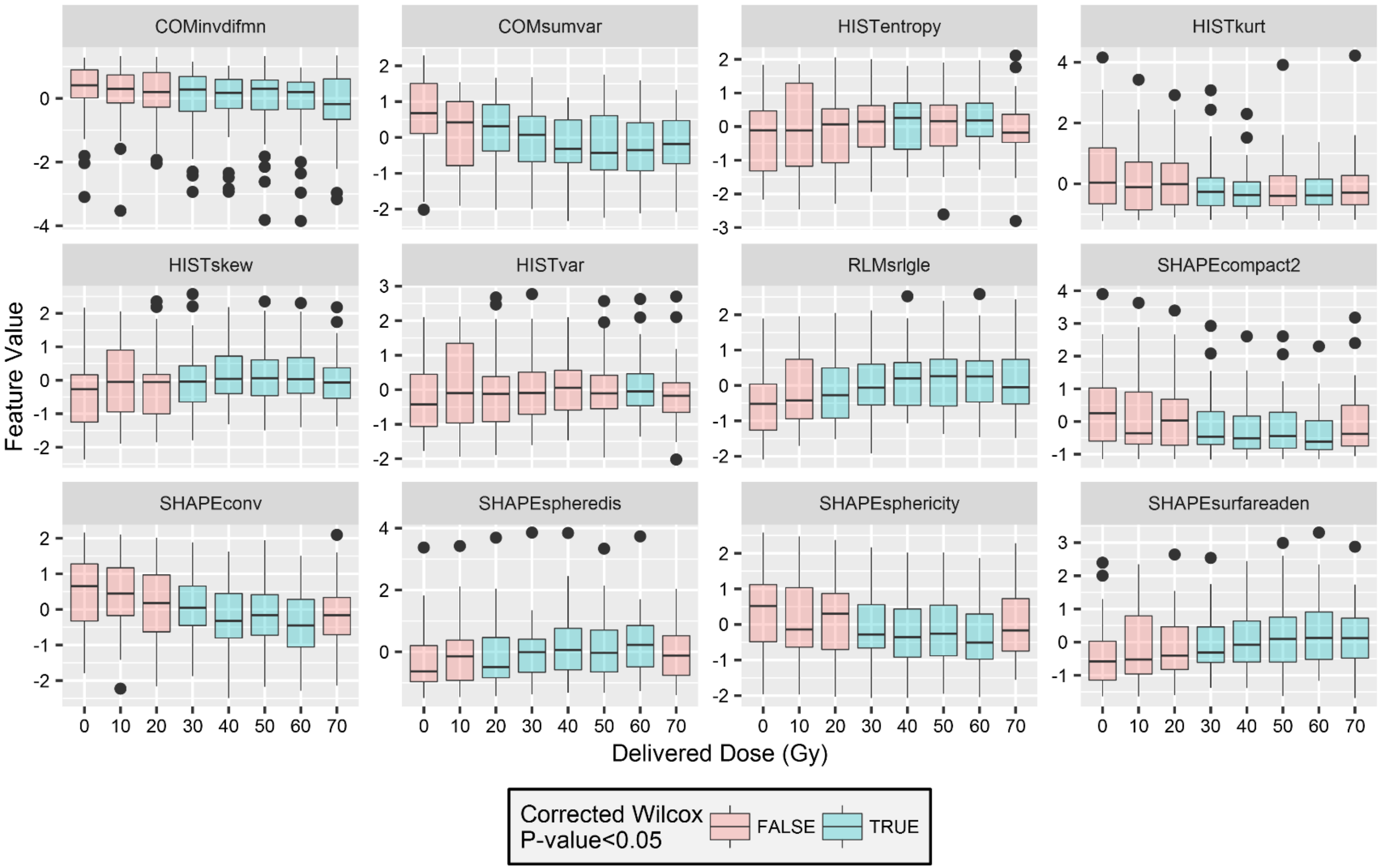

Weekly Mean Target Volume Changes on IMRT vs. Proton
(12 matched pairs)
Proton Mean Target Vol Changes
IMRT Mean Target Vol Changes
Mean Target Volume Changes (cm3)
10
0
-10
-20
-30
-40
-50
-60
-70
-80
Week 1-0
Week 2-0
Week 3-0
Week 4-0
Week 5-0
Week 6-0
Week 7-0
Treatment Week Range

Laurence Court:
Radiomics features change during radiation TX

- These summarize the delta radiomics work we did. No difference between protons and photons found.

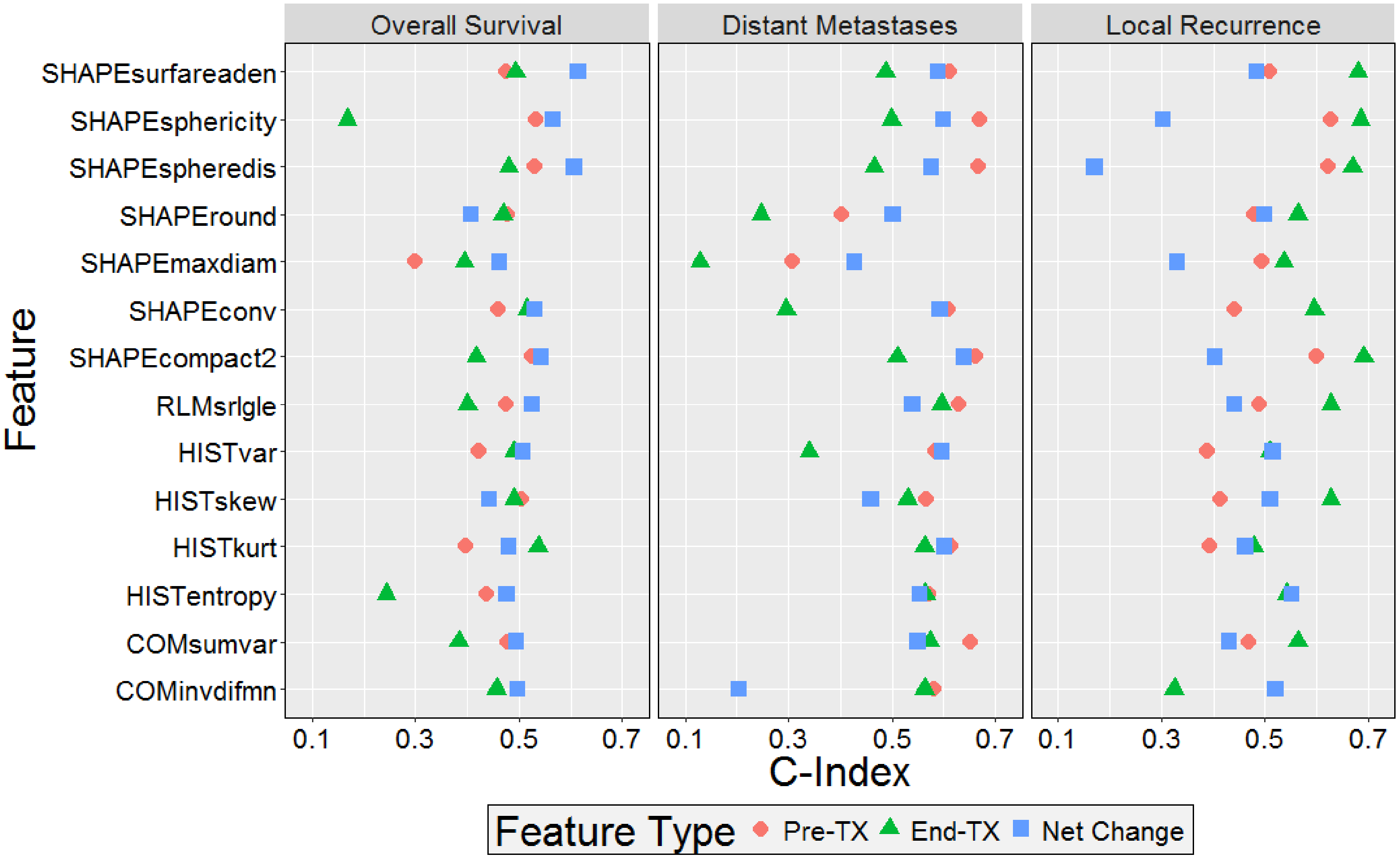
Radiomics features change during radiation TX

- Used a wilcox sign rank test to compare patients radiomics values during treatment to their values at the beginning of treatment.
- P-values were corrected using Bonferroni method
- Changes in radiomics features are significant as early as 10-15 fractions (after 20-30 Gy has been delivered)
- Feature changes were not impacted by treatment group (Proton versus IMRT)



Univariate and multivariate models using radiomics features

- Univariate Results (in figure)
  - Overall Survival: net changes were most prognostic
  - Distant Metastases: pre-TX values are most prognostic
  - Local Recurrence: end of TX values were most prognostic
- Multivariate Results:
  - Overall Survival & Distant Mets: only clinical factors and one pre-TX feature were prognostic
  - Local Recurrence: only one end of TX feature was prognostic.



Gabriel Sawakuchi:
Basic and translational radiobiology

Research Focus/Funded Projects:

- DNA damage response induced by particle beams
- Gold nanoparticle sensitization (chemo/radiation)
- Dosimetry in the presence of magnetic fields

Our lab works in the interface of physics, instrument development and biology.

Live cell imaging in therapeutic beam lines

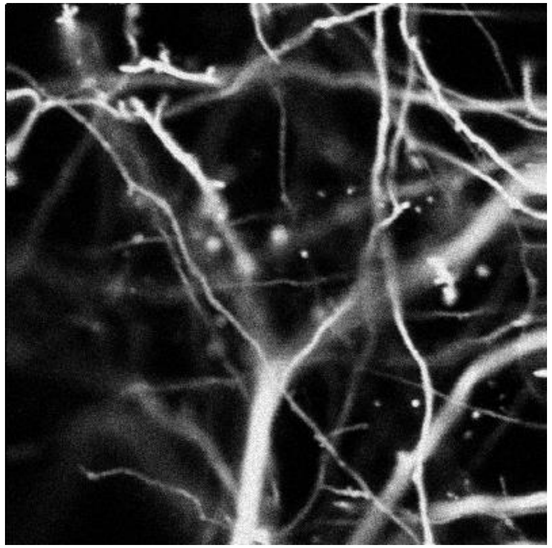
- Designed and constructed a portable open frame confocal microscope

- Flexible configuration

- Can be shipped to any place

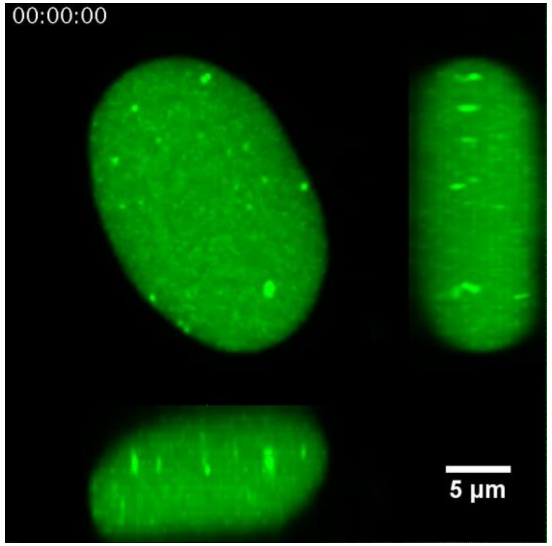
- Can be used in any beam line
  - horizontal beams
  - vertical beams

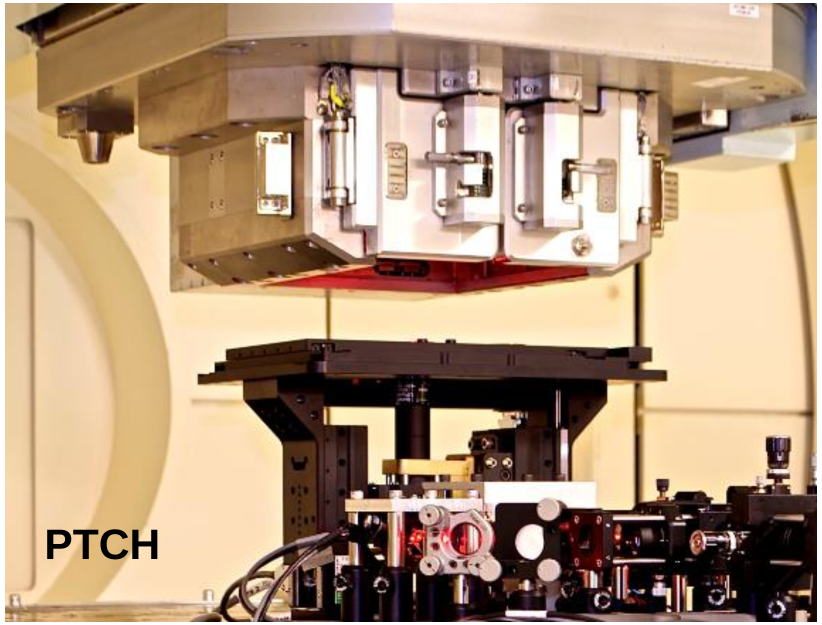
Live cell imaging in therapeutic beam lines



Live neurons from rats imaged for 30 min after x-ray exposure

Single strand break DNA damage from 60 MeV protons

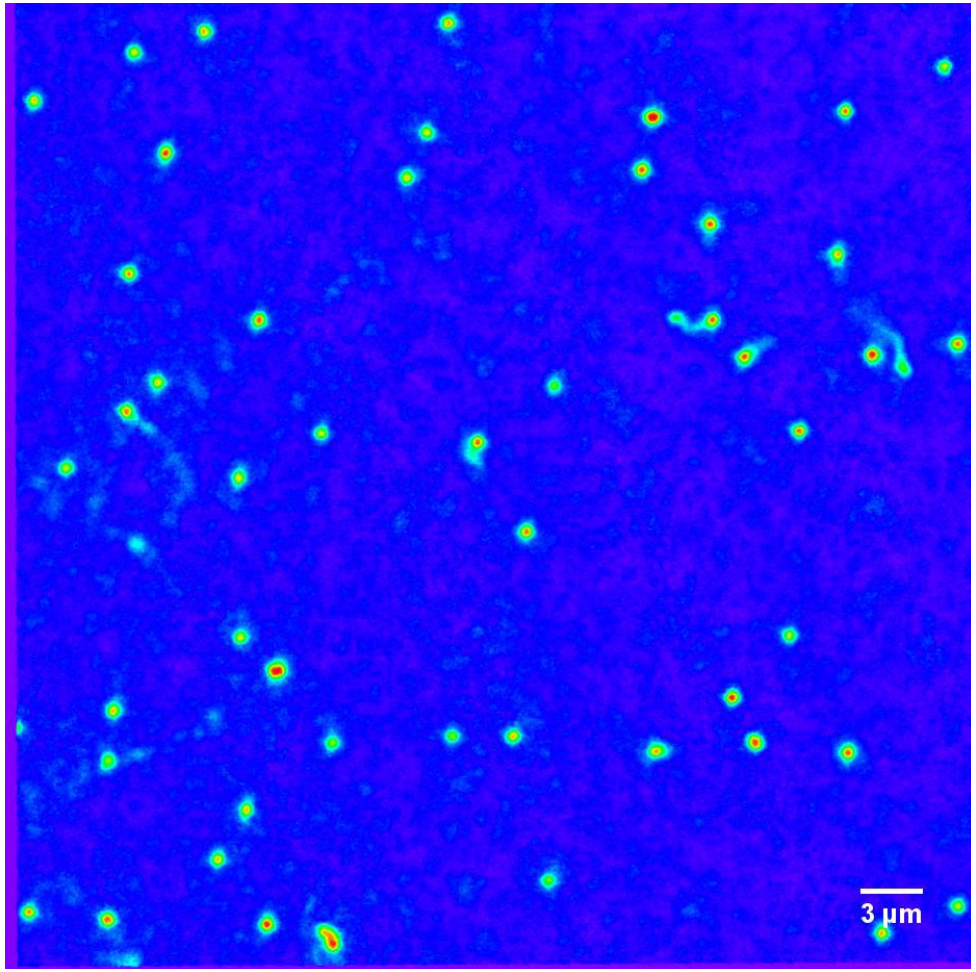




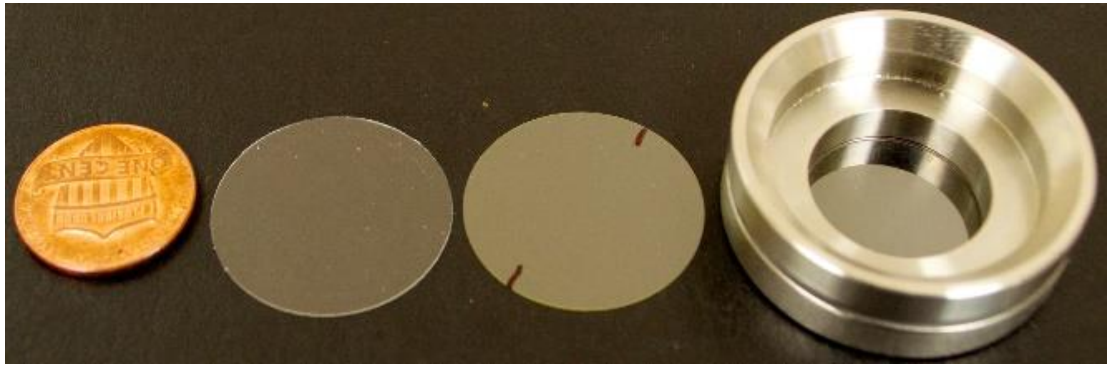
Nanoscale radiation measurements in live cells

- Fluorescence nuclear track detectors (FNTDs) **(Al_2O_3:C,Mg)**
- Can be read out using confocal microscopy
- 3D reconstruction of tracks
- Resolution limited by diffraction (~ **300 nm**)
- Can be cut into coverslips
- **Biocompatible!**

Protons, ~65 MeV, ~1 keV/μm in H_2O



Sawakuchi et al 2016, Med. Phys. 43, 2485

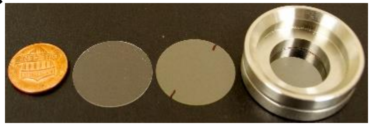


Nanoscale radiation measurements in live cells

FNTD

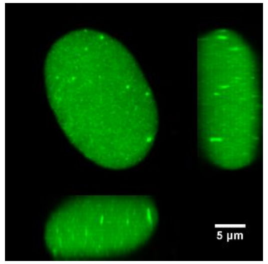
+

FNTD coverslip



+

Live cell imaging



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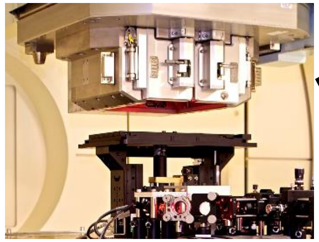
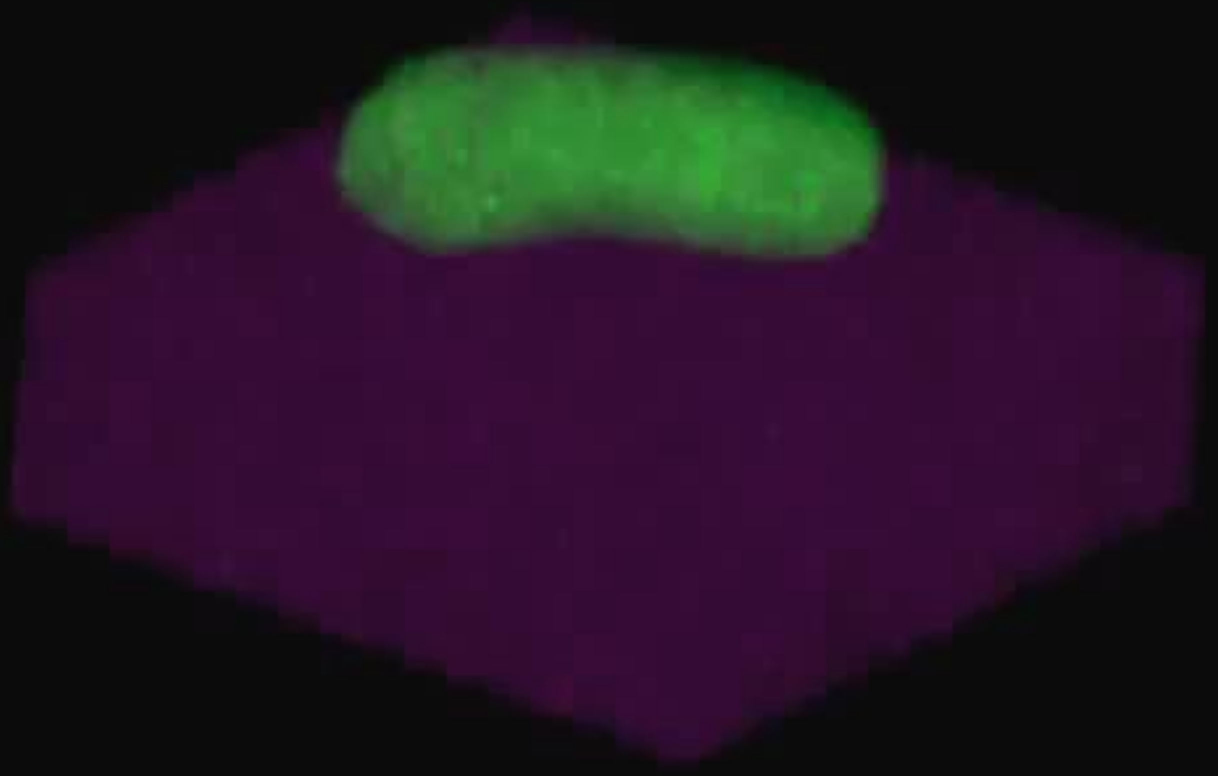
Beamline microscopy



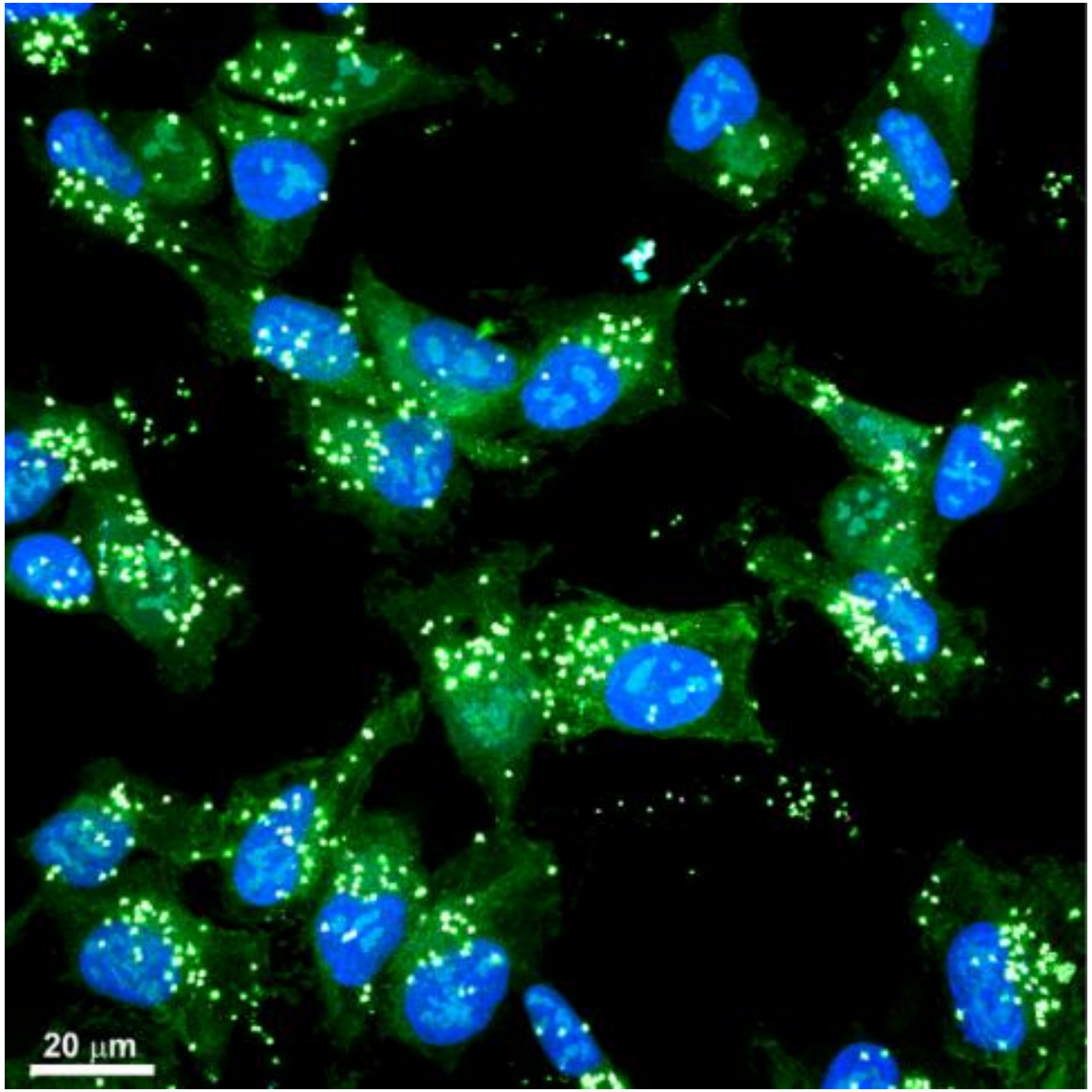
McFadden et al 2016, IJROBP 96, 221



HT1080-eGFP-XRCC1 + Protons (~65 MeV, ~1 keV/µm in H_2O)
Single strand breaks

Gold-nanoparticles sensitization

- What are the causes of gold-nanoparticle sensitization?
  - Monte Carlo simulations to understand physical mechanisms
  - Lice cell experiments to understand biological mechanisms

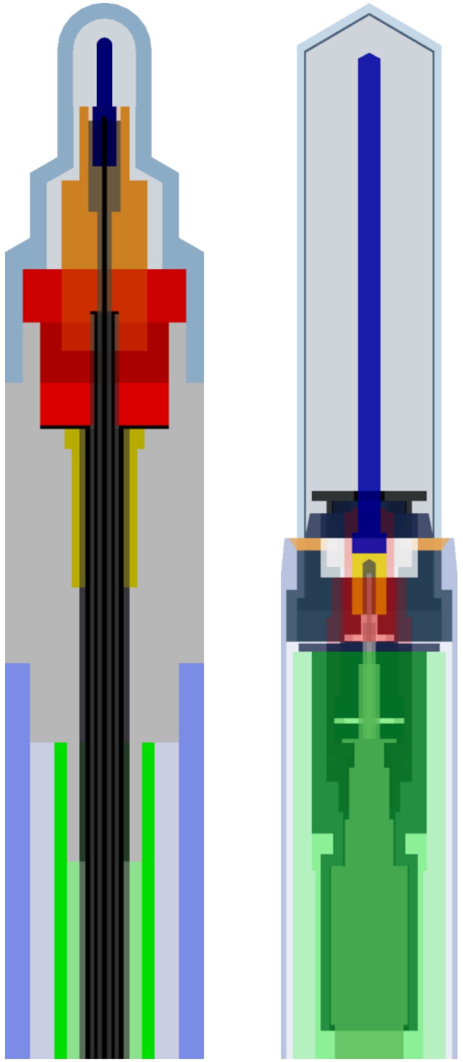


Fibrosarcoma cells treated with gold-nanoshells. Blue: nucleus; green: cytoplasm; and white: gold-nanoshells.

Dosimetry in the presence of magnetic fields

- Develop and validate formalism to calibrate MRI-guided radiotherapy units
  - B-field affects the response of ionization chambers that are used to calibrate radiotherapy units
  - Use Monte Carlo and measurements to determine correction factors to use ionization chambers in B-fields

Exradin A1 **PTW 30013**



Detailed models of ionization chambers implemented in the Monte Carlo code Geant4. These models are used to study how B-fields affect the response of the chambers.

Reference dosimetry in magnetic fields: formalism and ionization chamber correction factors

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G. S. Ibbott
Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, Houston, Texas 77030

G. O. Sawakuchi[b]
Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, Houston, Texas 77030 and Graduate School of Biomedical Sciences, The University of Texas, Houston, Texas 77030

O'Brien et al 2016, Med. Phys. 43, 4915

My current clinical research

5d Doses (Monte Carlo simulations)

Goal: Compute the best representation of cumulative Biologically-Effective Dose Distribution actually delivered

Or: Compare Eclipse 3d lung cancer treatment dose distributions with MC 5d (weekly repeat 4d)

And: Assess the differences

Current Status

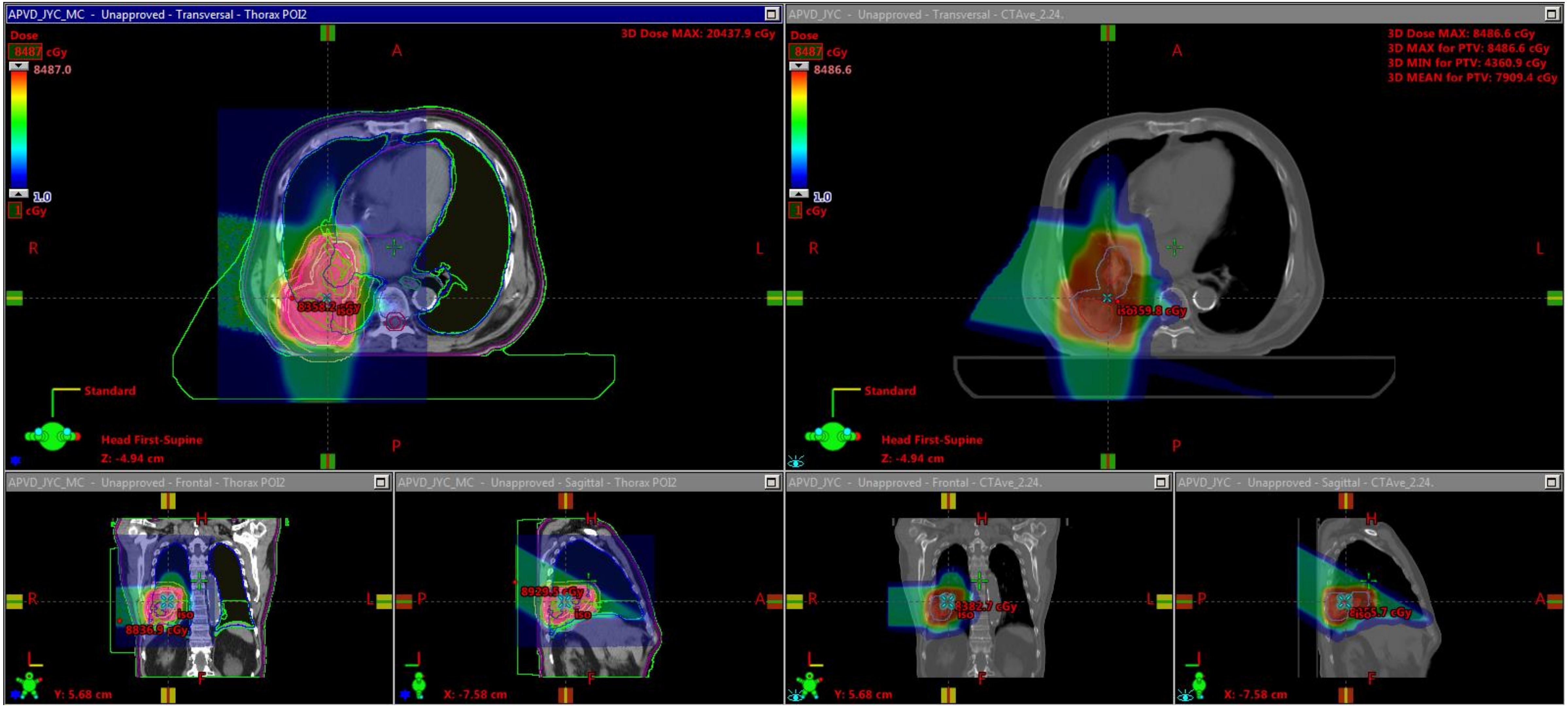
- 3 patients fully computed
  - Analysis in progress
- 2 more in progress
  - Computations underway
- 2 more prepared for MC sims

Patient 1

- RLL Lung case
- Treated in 2010 with PSPT
- 74 Gy CGE in 37 fx

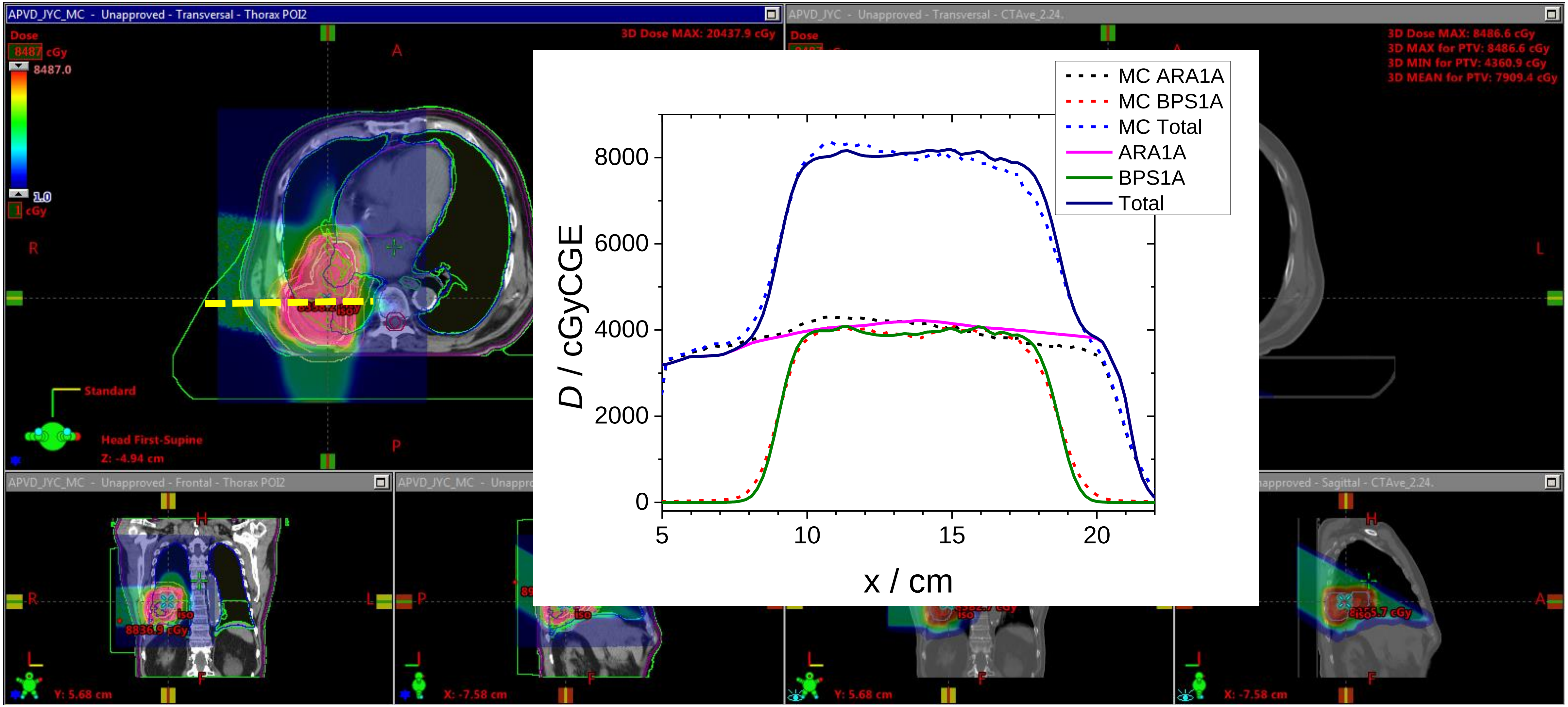
Validation

MC²　　　　　　　　　　ECLIPSE



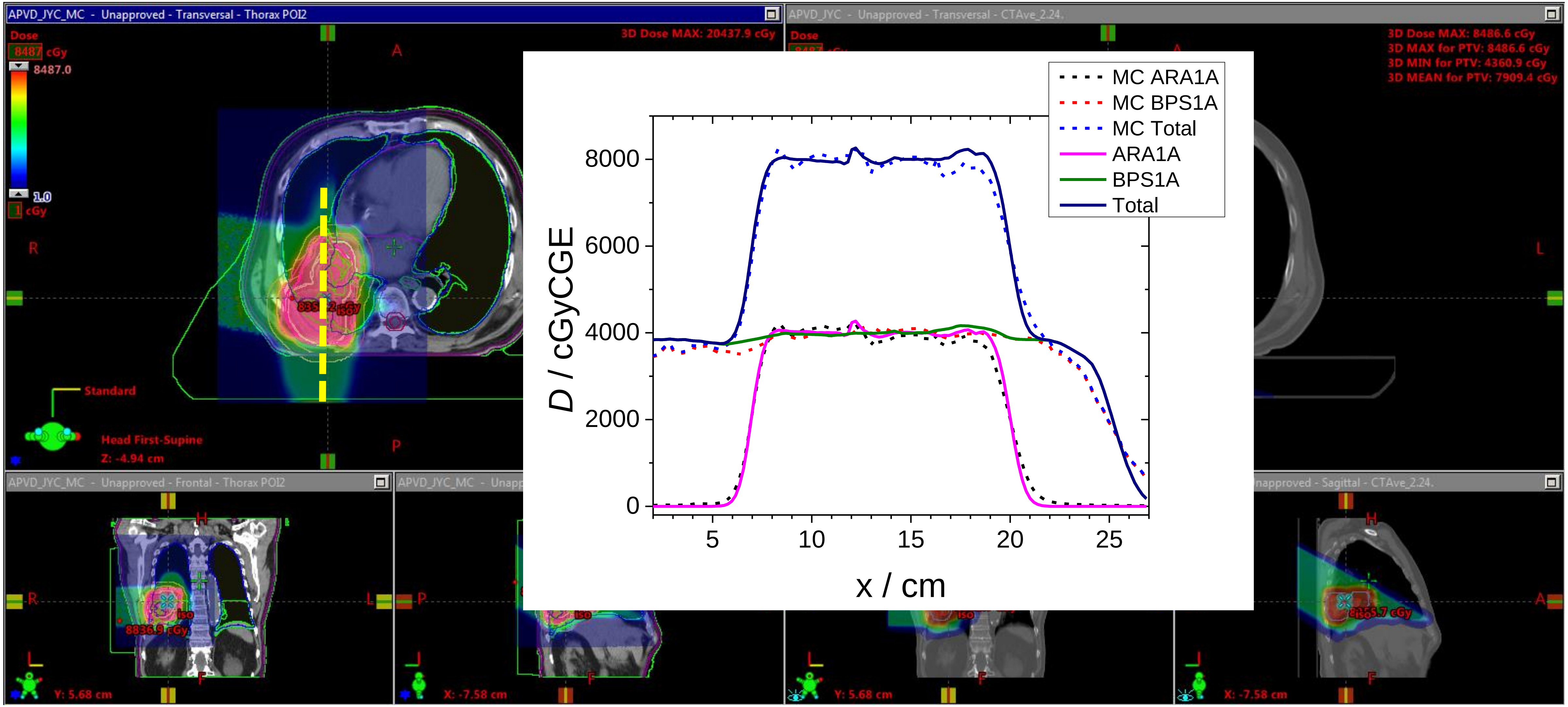
Validation

MC^2 ECLIPSE



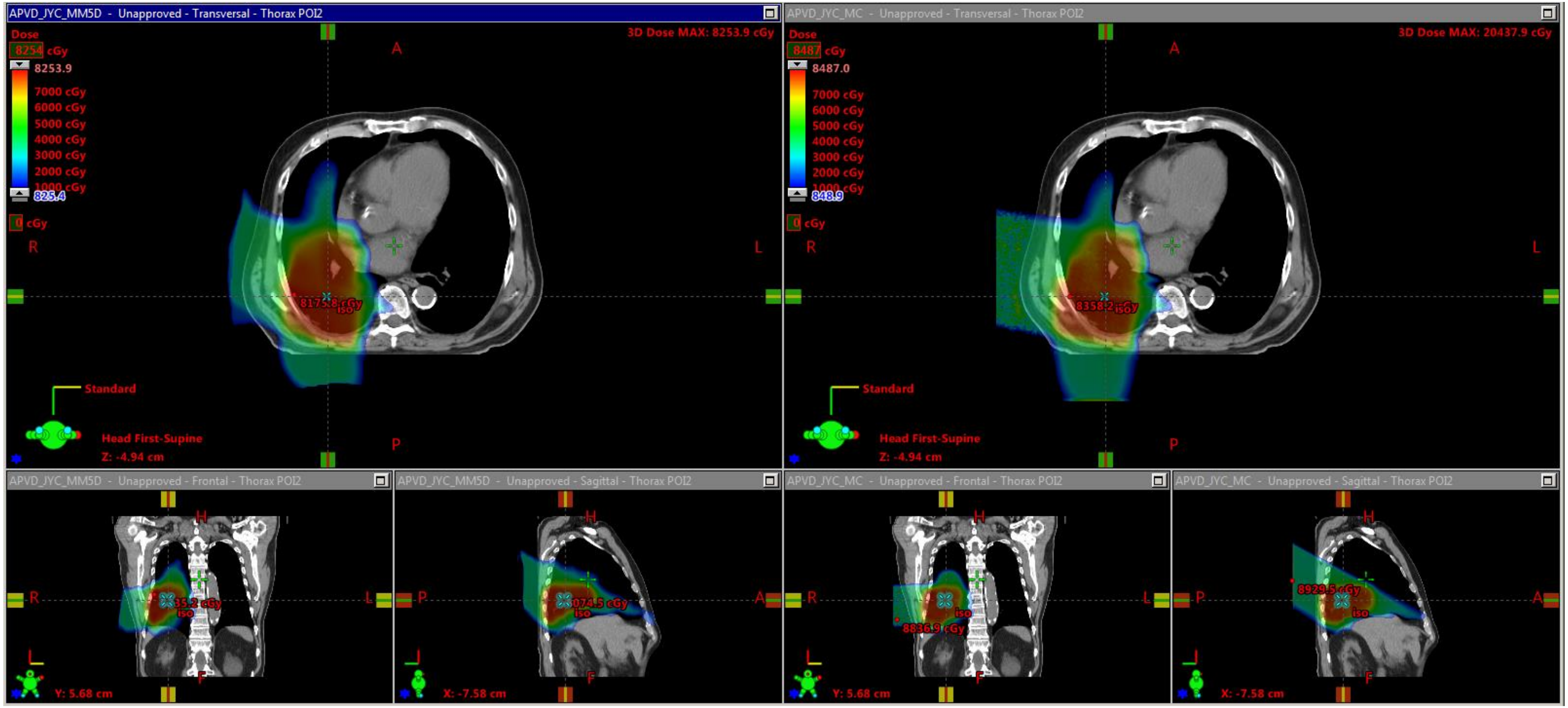
Validation

MC² ECLIPSE



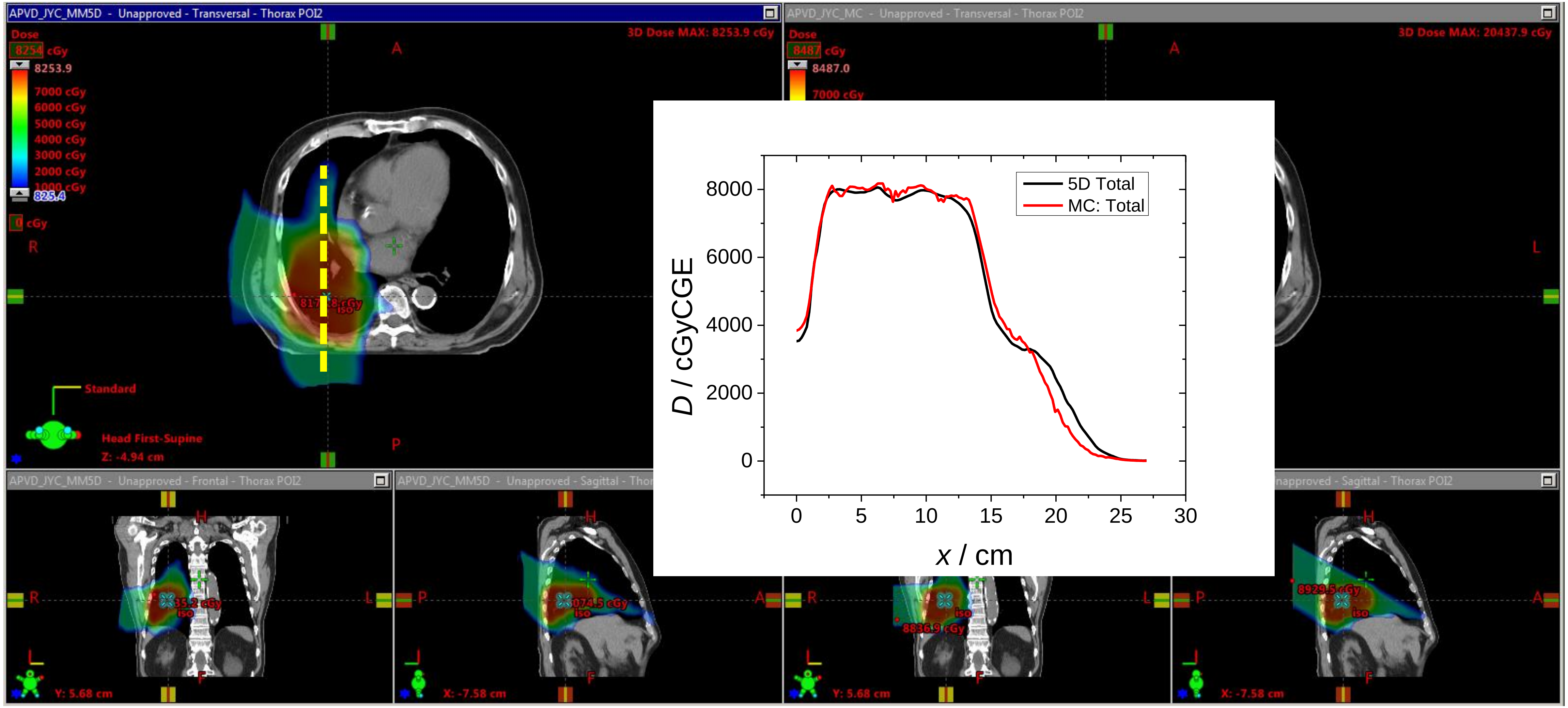
Importing 5d doses…

MC² ECLIPSE

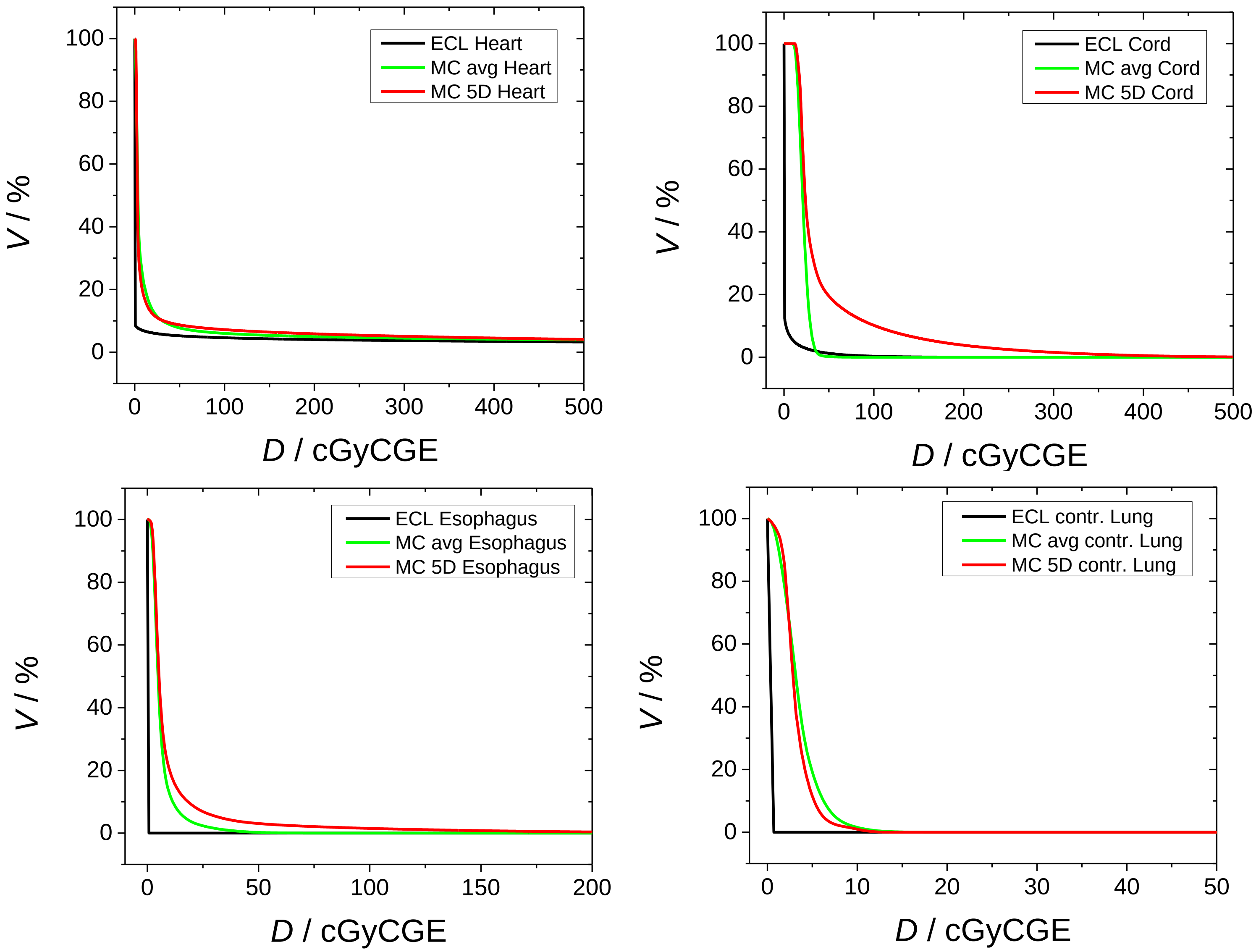


Importing 5d doses...

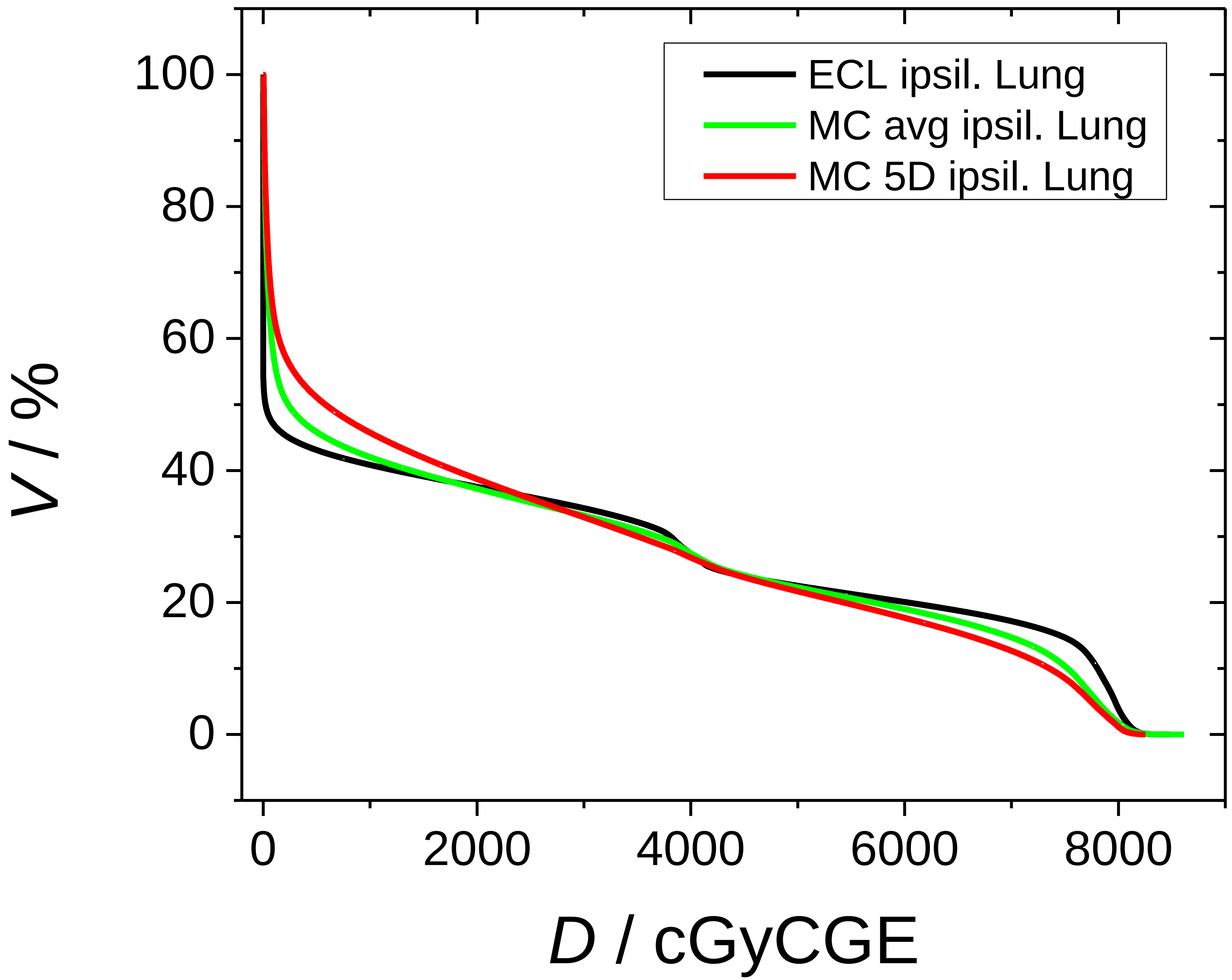
MC^2 ECLIPSE



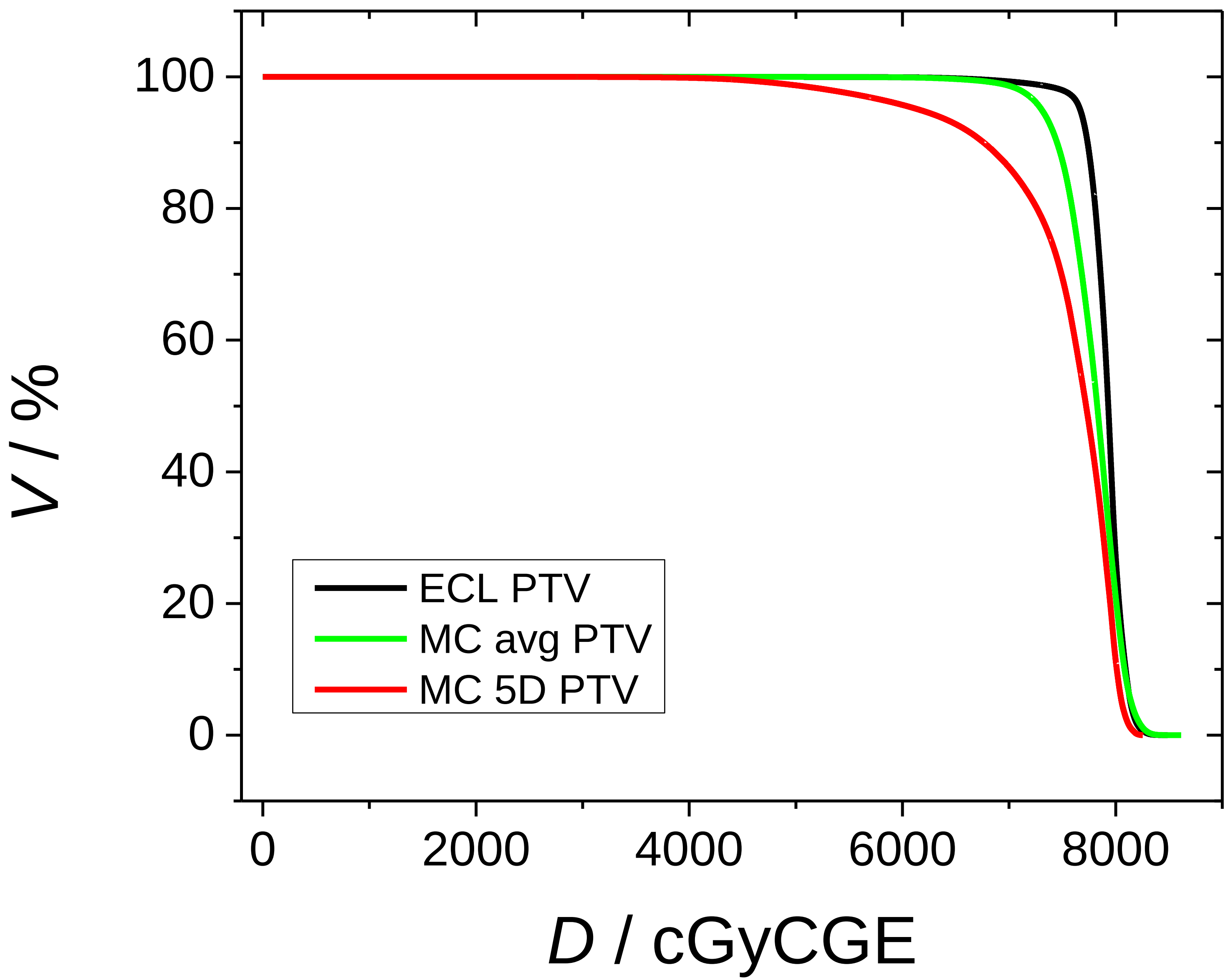
DVHs: heart, cord, esoph., contr. lung



DVHs: ipsilateral lung

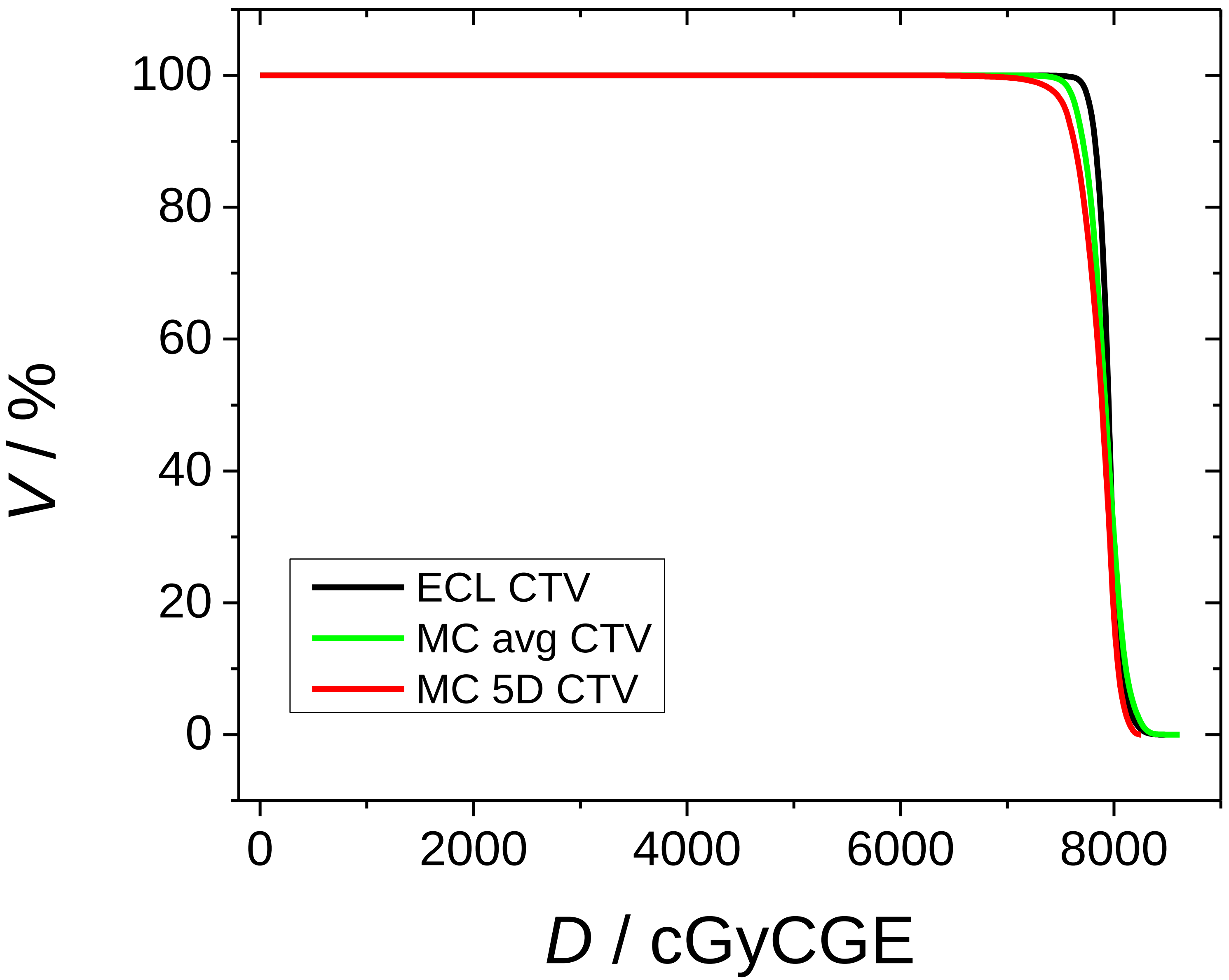


DVHs: PTV



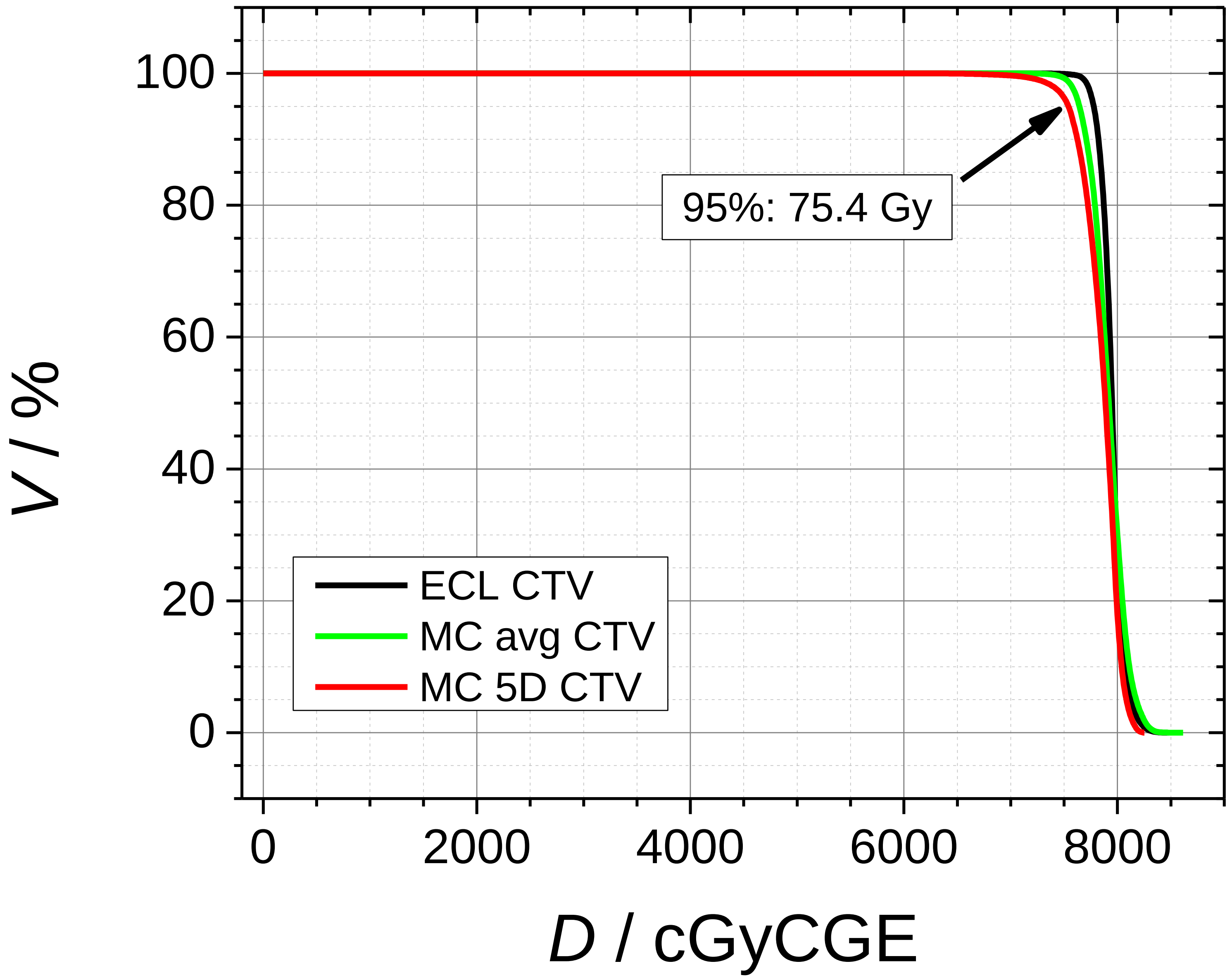
100
80
60
40
20
0
V / %
0
2000
4000
6000
8000
D / cGyCGE
ECL PTV
MC avg PTV
MC 5D PTV

DVHs: CTV



V / %
100
80
60
40
20
0
ECL CTV
MC avg CTV
MC 5D CTV
0
2000
4000
6000
8000
D / cGyCGE

DVHs: CTV

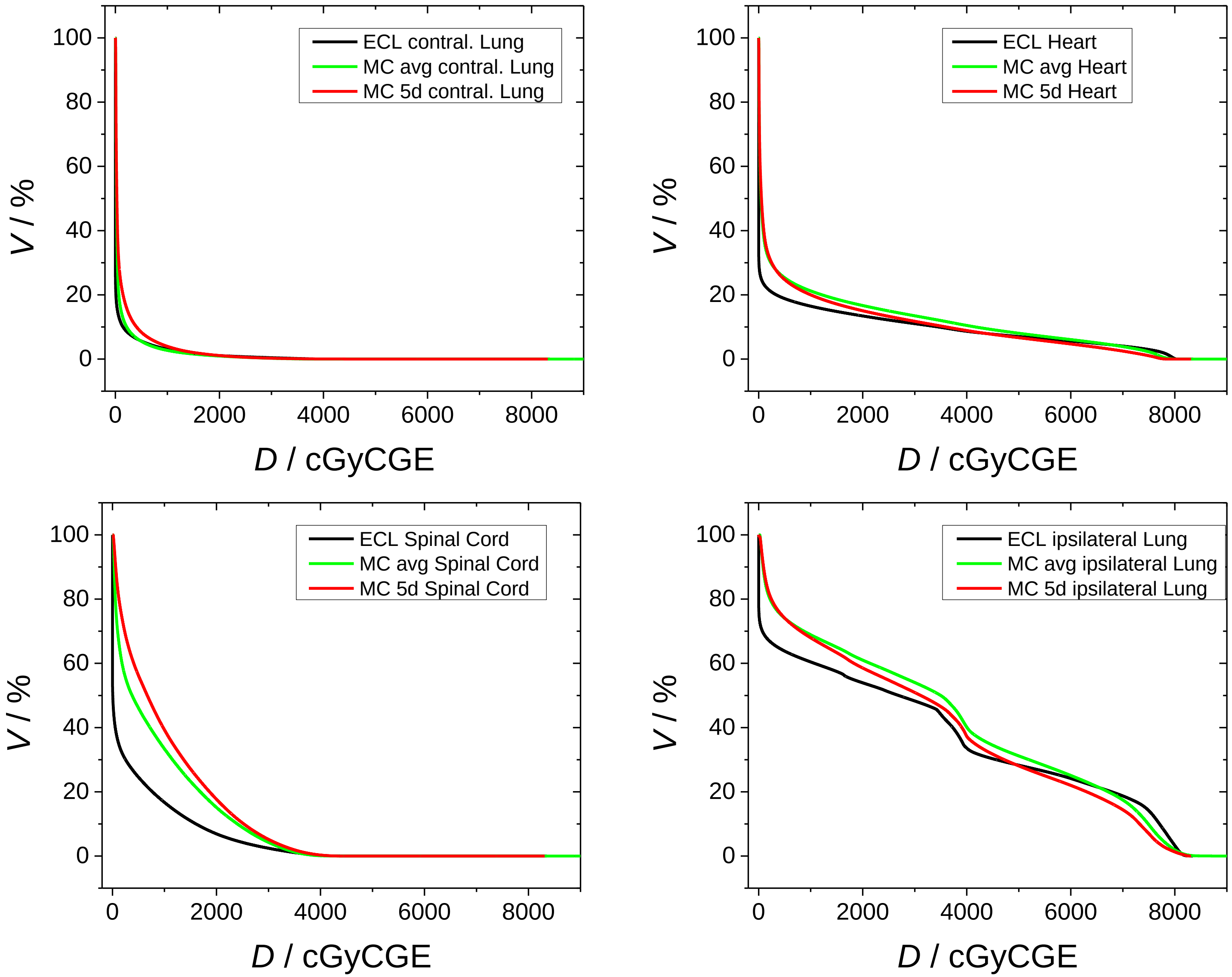


100
80
60
40
20
0
V / %
0
2000
4000
6000
8000
D / cGyCGE
95%: 75.4 Gy
ECL CTV
MC avg CTV
MC 5D CTV

Patient 2

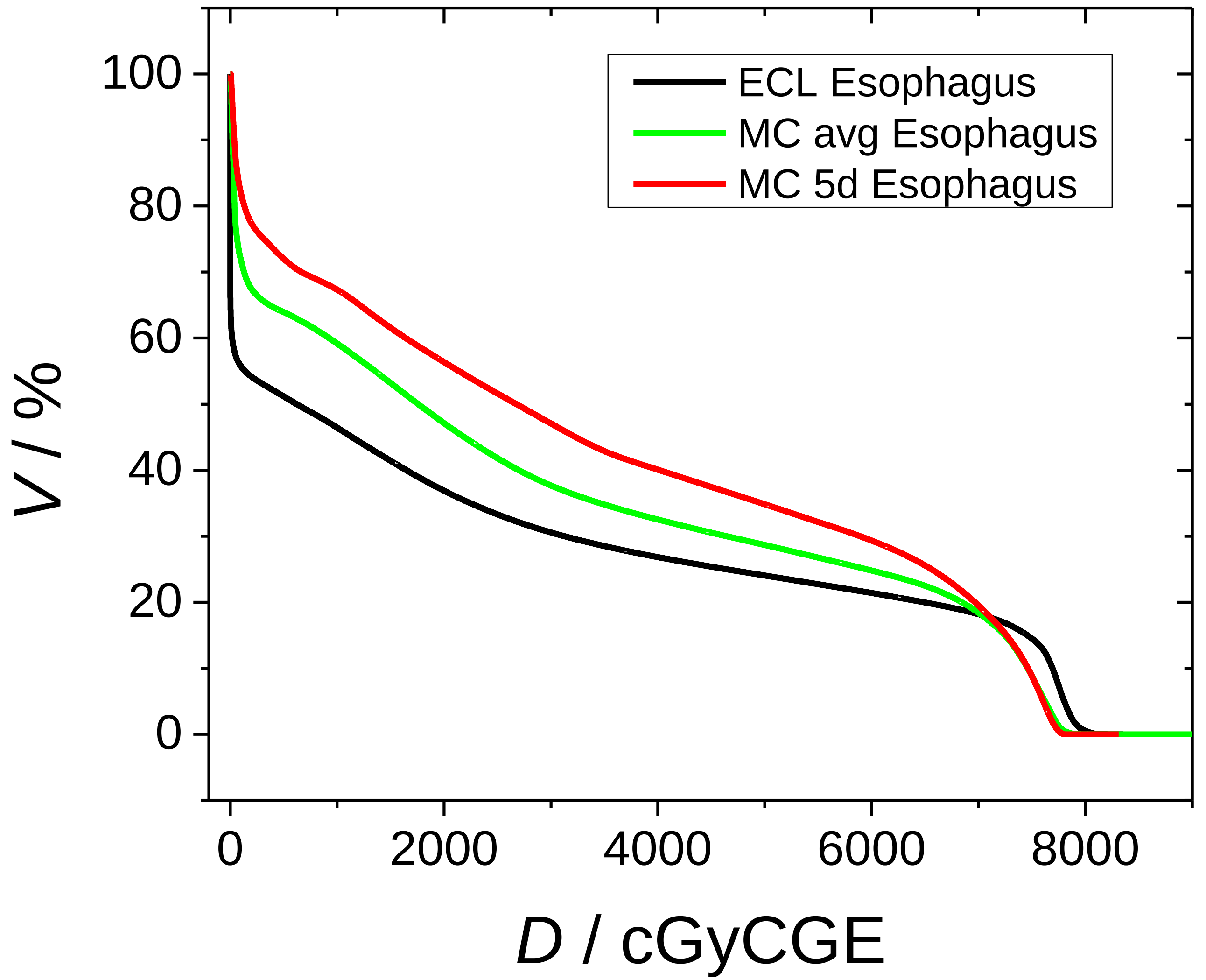
- Right upper recurrent lung tumor
- Treated in 2010 with PSPT
- 74 Gy CGE in 37 fx

DVHs

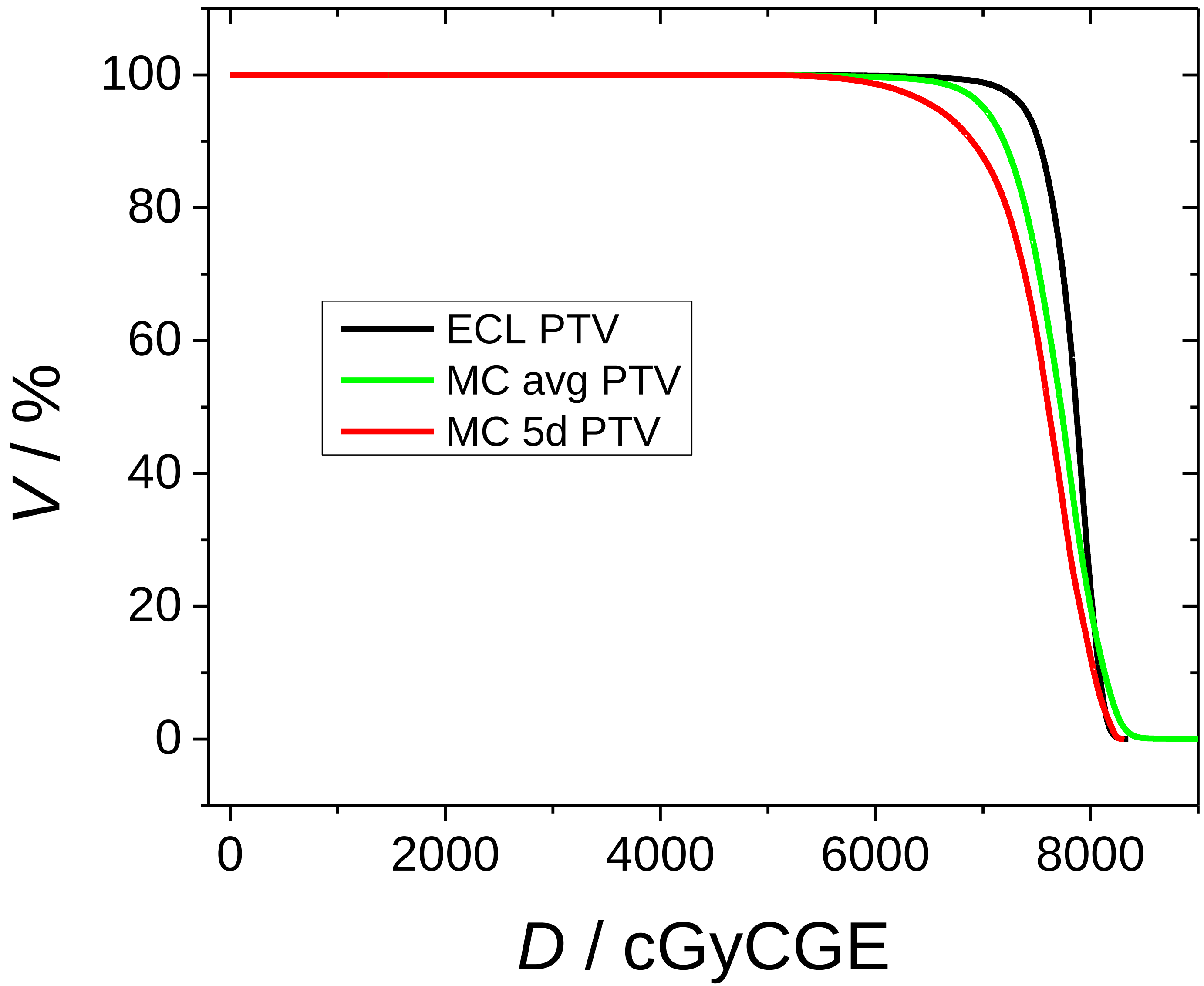


ECL contral. Lung
MC avg contral. Lung
MC 5d contral. Lung
ECL Heart
MC avg Heart
MC 5d Heart
ECL Spinal Cord
MC avg Spinal Cord
MC 5d Spinal Cord
ECL ipsilateral Lung
MC avg ipsilateral Lung
MC 5d ipsilateral Lung
V / %
D / cGyCGE
0
20
40
60
80
100
2000
4000
6000
8000

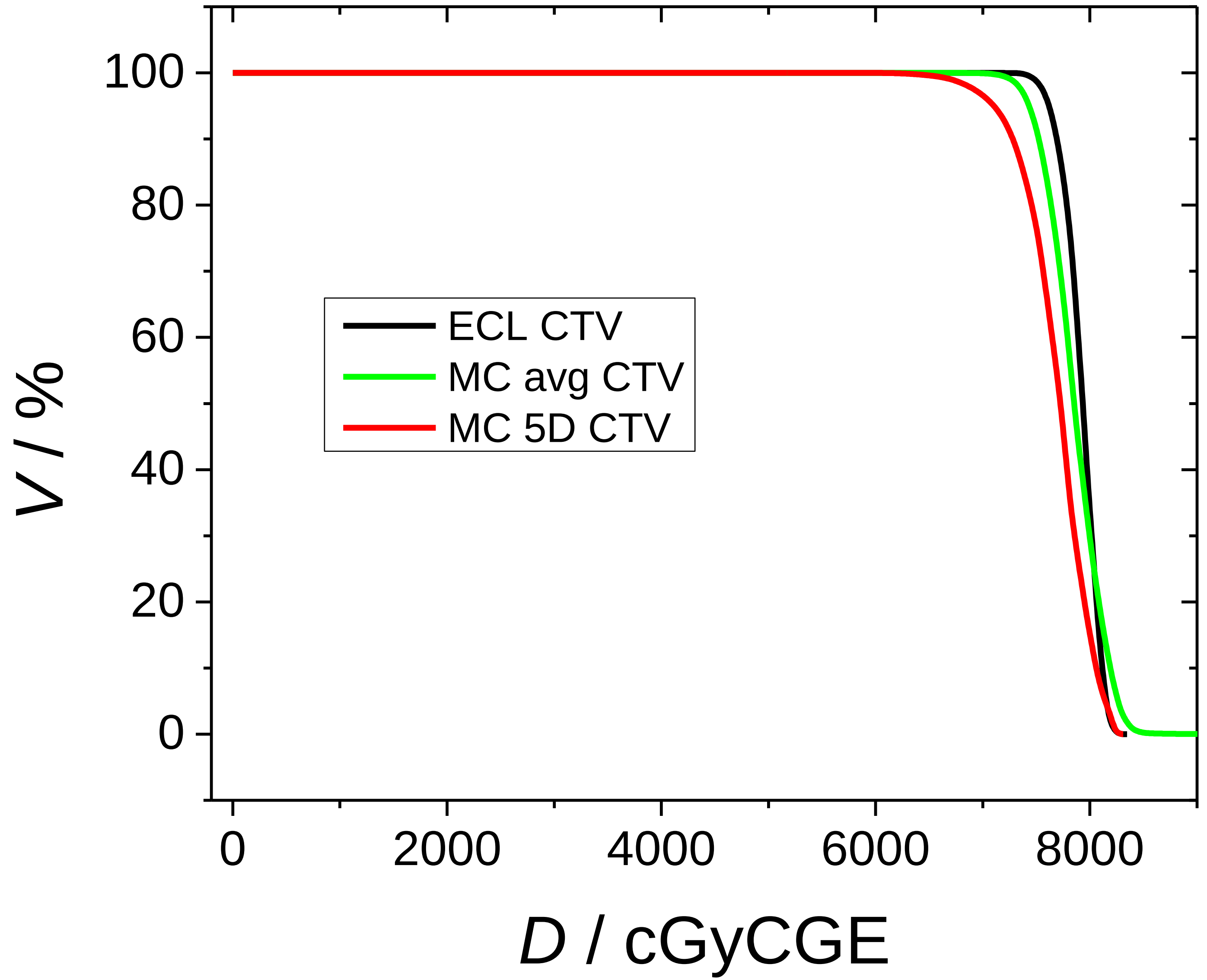
DVHs Esophagus



DVHs PTV

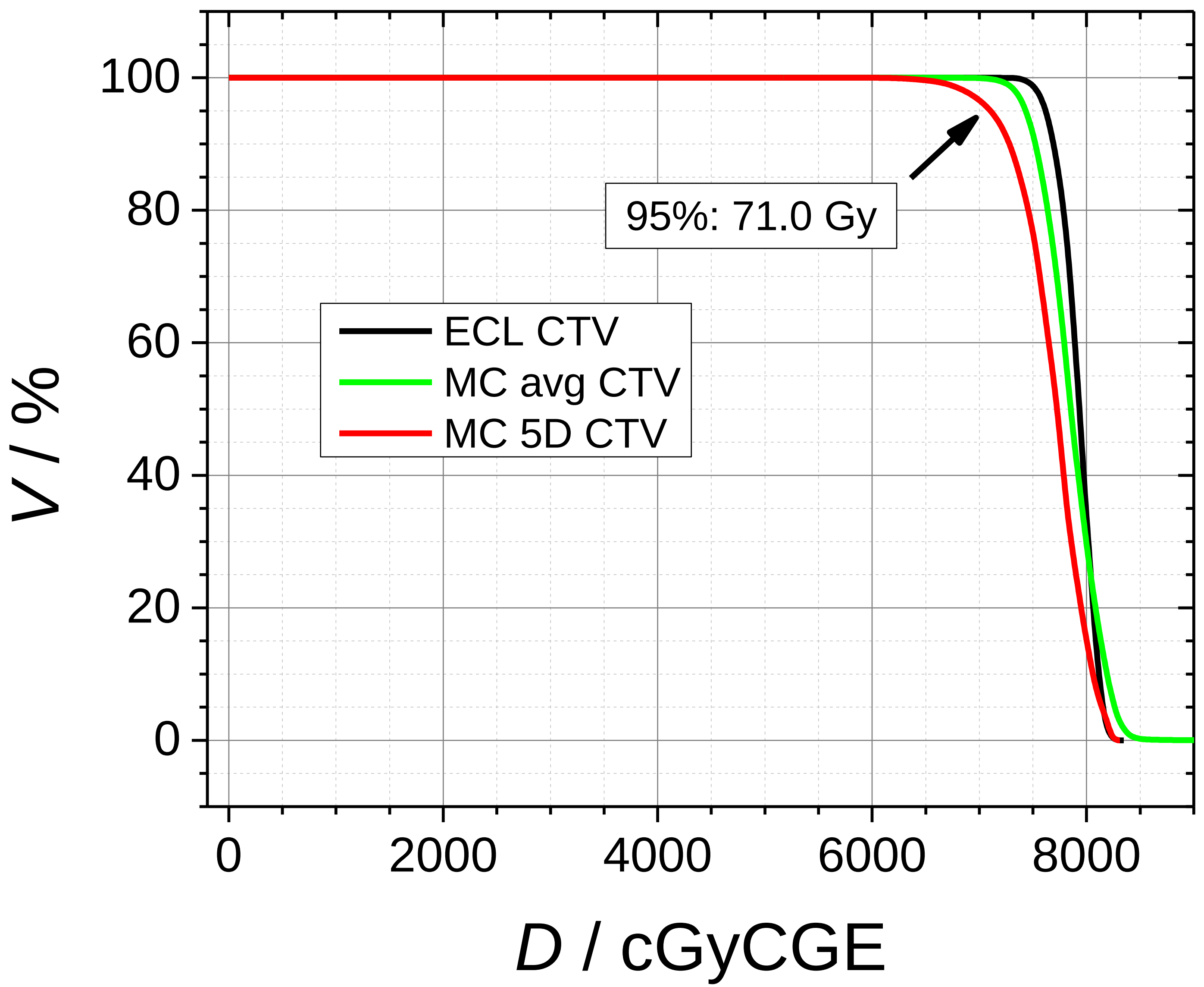

ECL PTV
MC avg PTV
MC 5d PTV
100
80
60
40
20
0
V / %
0
2000
4000
6000
8000
D / cGyCGE

DVHs CTV



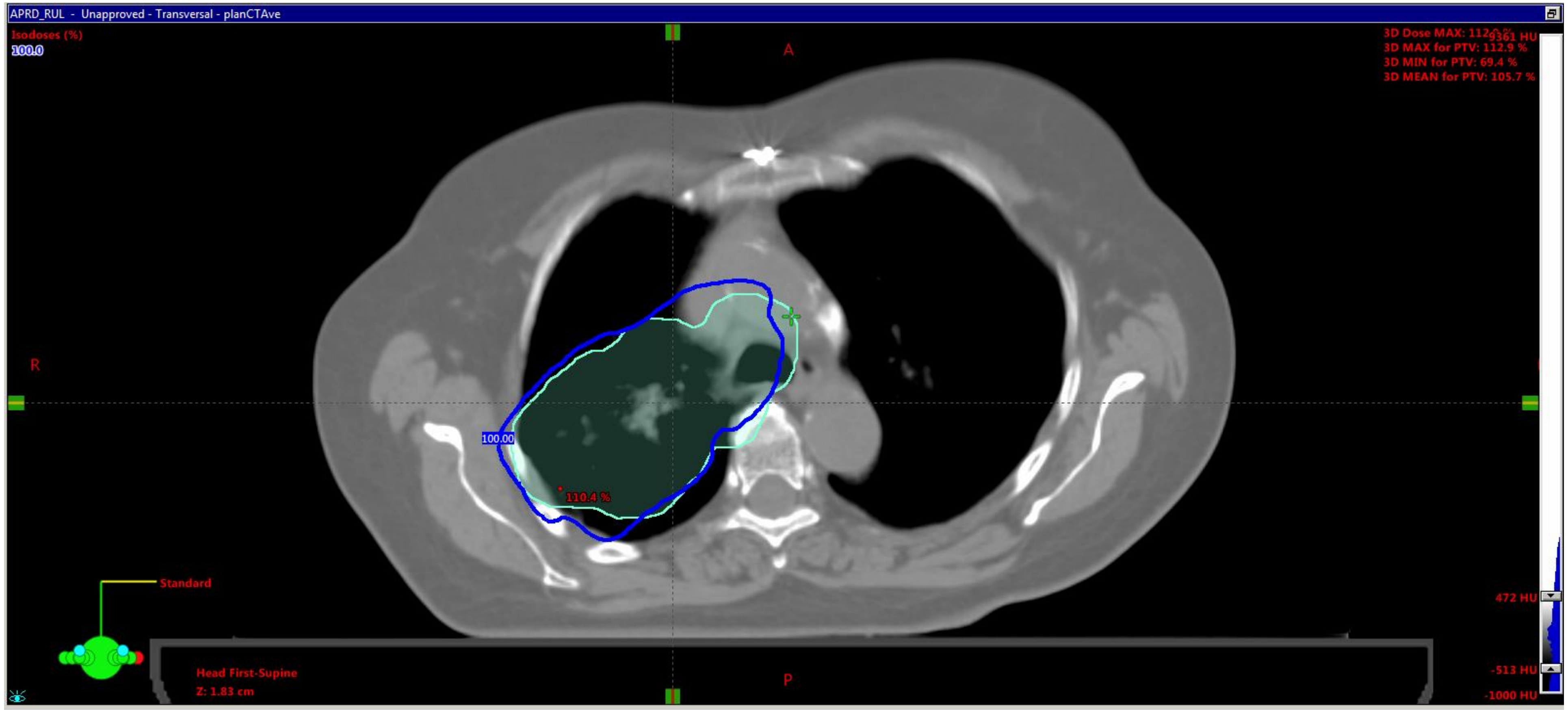
100
80
60
40
20
0
0
2000
4000
6000
8000
V / %
D / cGyCGE
ECL CTV
MC avg CTV
MC 5D CTV

DVHs CTV

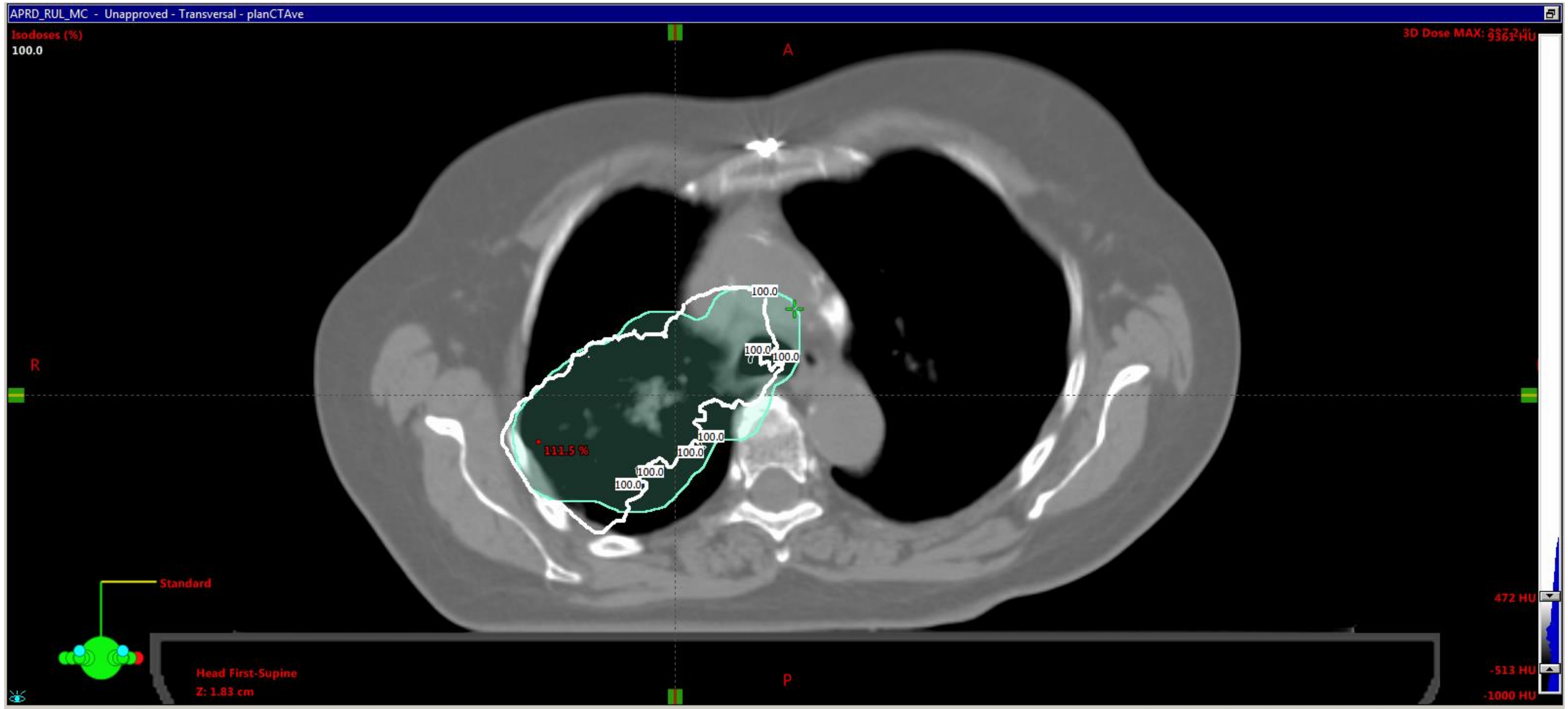


95%: 71.0 Gy
ECL CTV
MC avg CTV
MC 5D CTV
V / %
100
80
60
40
20
0
0
2000
4000
6000
8000
D / cGyCGE

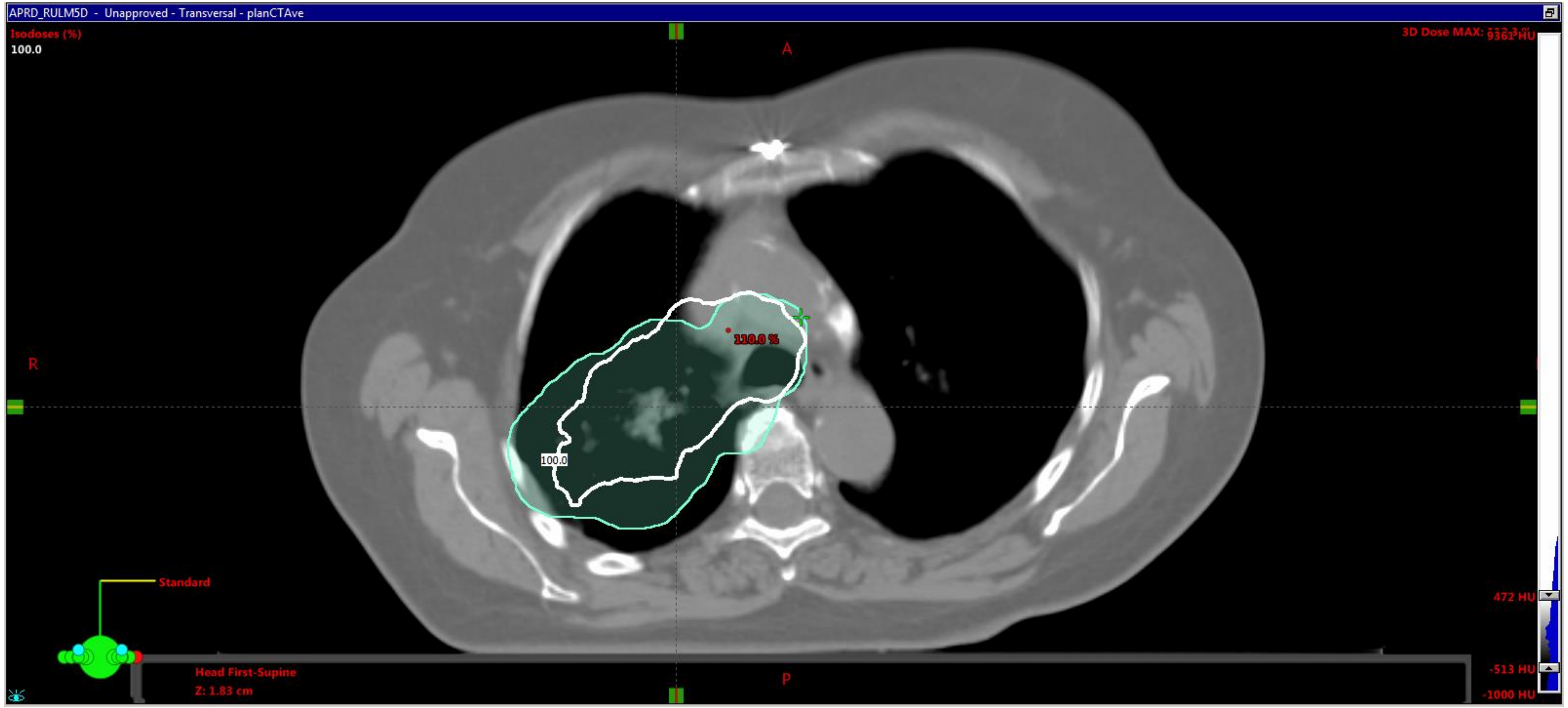
ECLIPSE PTV and 100% line



MC avg. PTV and 100% line



MC 5d PTV and 100% line



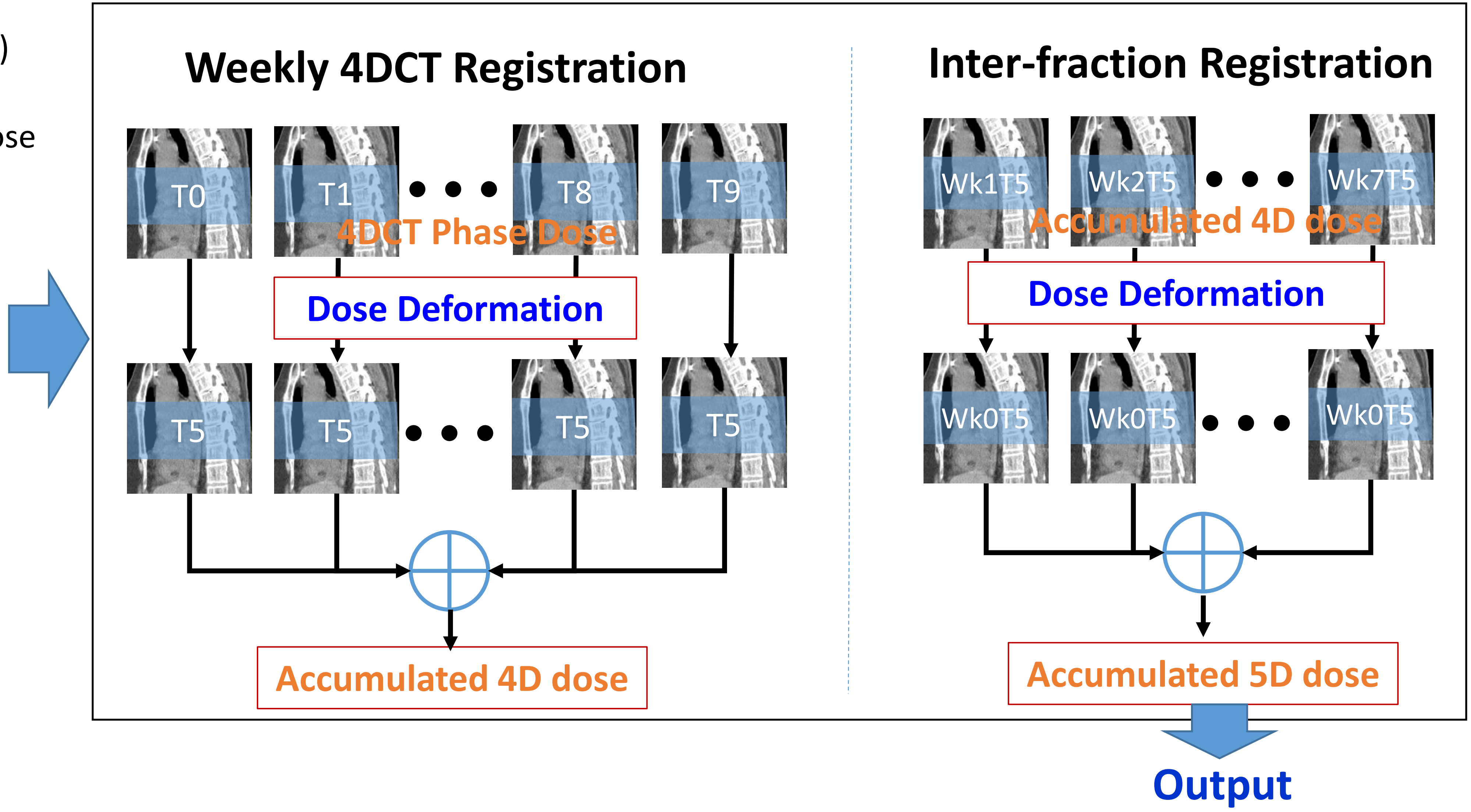
What did we learn?

- DVHs show the expected differences between ECLIPSE doses and MC (avg) doses
  - Low dose regions enhanced
  - High dose regions slightly reduced
- Comparing both to the doses from the 5d computations show larger differences in PTV
- CTV shows small deviations from predictions
- Needs to be investigated further!
- Achtung! So far we used an RBE of 1.1 only !!!

Jinzhong Yang: A Fully Automated 5D Dose Accumulation Tool

Input: (Uwe, Dragan)

- Weekly 4DCT
- Calculated phase dose



MC cpu time requirements

- Example:
  - 1 patient
  - 3 beams
  - Each beam 33 runs
  - Each run on 64 cpus needs (n+1) hours
  - n = 1, …, 23

- That's a lot of computing…

High Performance Computing

- Institutional cluster
  - Nautilus (>8000 cpus, my “reservation”: 2300)
  - Shark (~1800 cpus)
  - Eagle (?? Cpus)

- Departmental cluster
  - Martin2
  - >2500 cpus

My current (not so clinical ???) research

The Proton-Expansion-Project

- New HITACHI proton facility
- 4 rotational gantries
- All scanning beam

The Proton-Expansion-Project

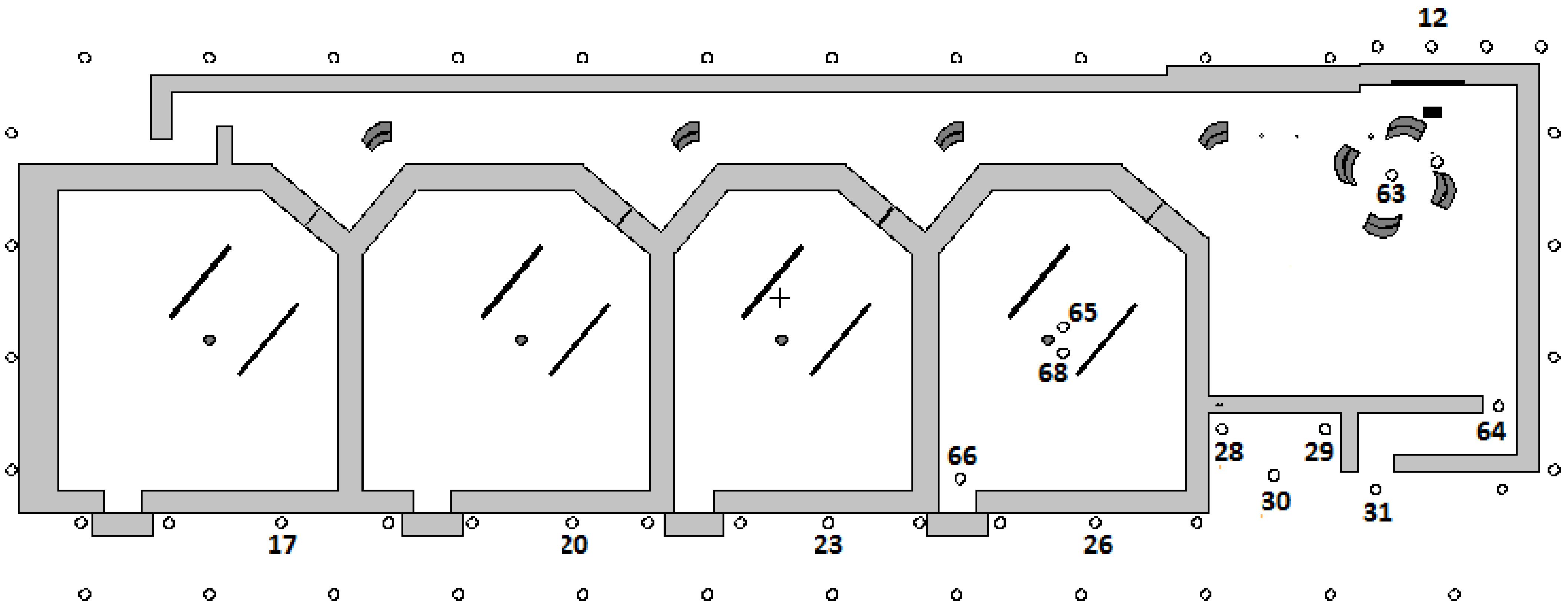
- My interest:
  - Radiation Protection
    - Members of the public: 5 mSv / y and 0.02 mSv in any one hour
    - Occupational: 50 mSv / y
  - Facility Features
    - Straight doors / no mazes
    - Straight conduits
    - Alignment holes

The Proton-Expansion-Project

- Monte Carlo
  - Model
  - Simulations

- Evaluation of shielding
  - Estimate Facility usage
  - Estimate Fluence
  - Conversion of Fluence to Ambient Dose Equivalent
  - Results

Monte Carlo Model



161 sources (1 injector and 40 locations at 4 Energies)

Each run with 5×10^8 protons (runtime ~ 60 hours +)

Estimate Facility Usage

#of protons/year

source #	description		E / MeV	clinical	commissioning	MEE operation			
0	Injector		7	1.236E+16	6.941E+15	1.236E+16			
						230 MeV	200 MeV	170 MeV	50 MeV
1	Acc magnet 1		75	4.070E+15		5.618E+14	1.124E+15	5.618E+14	5.743E+15
2	Acc magnet 1		75	4.070E+15		5.618E+14	1.124E+15	5.618E+14	5.743E+15
3	Acc magnet 1		75	4.070E+15		0.000E+00	0.000E+00	0.000E+00	0.000E+00
4	Acc magnet 2		75	4.070E+15		5.618E+14	1.124E+15	5.618E+14	5.743E+15
5	Acc magnet 2		75	4.070E+15		5.618E+14	1.124E+15	5.618E+14	5.743E+15
6	Acc magnet 2		75	4.070E+15		0.000E+00	0.000E+00	0.000E+00	0.000E+00
7	Acc magnet 3		75	4.070E+15		5.618E+14	1.124E+15	5.618E+14	5.743E+15
8	Acc magnet 3		75	4.070E+15		5.618E+14	1.124E+15	5.618E+14	5.743E+15
9	Acc magnet 3		75	4.070E+15		0.000E+00	0.000E+00	0.000E+00	0.000E+00
10	Acc magnet 4		75	4.070E+15		5.618E+14	1.124E+15	5.618E+14	5.743E+15
11	Acc magnet 4		75	4.070E+15		5.618E+14	1.124E+15	5.618E+14	5.743E+15
12	Acc magnet 4		75	4.070E+15		0.000E+00	0.000E+00	0.000E+00	0.000E+00
13	scraper		75	1.006E+17					5.535E+16
14	extraction		230	2.022E+15		4.994E+14	1.024E+15	4.994E+14	
15	FFC		230	1.948E+15	2.647E+15	2.497E+14	4.744E+14	2.497E+14	
16	damper		230	0		4.245E+14	8.489E+14	4.245E+14	
17	ISO	270 deg	230	1.030E+15	1.074E+15	2.497E+14	5.306E+14	2.497E+14	
18	ISO	0 deg	230	1.030E+15	6.816E+15	2.497E+14	5.306E+14	2.497E+14	
19	ISO	90 deg	230	1.030E+15	6.741E+15	2.497E+14	5.306E+14	2.497E+14	
20	ISO	180 deg	230	1.030E+15	9.738E+14	2.497E+14	5.306E+14	2.497E+14	
21	ISO	270 deg	230	1.030E+15	1.074E+15	2.497E+14	5.306E+14	2.497E+14	
22	ISO	0 deg	230	1.030E+15	6.816E+15	2.497E+14	5.306E+14	2.497E+14	
23	ISO	90 deg	230	1.030E+15	6.741E+15	2.497E+14	5.306E+14	2.497E+14	
24	ISO	180 deg	230	1.030E+15	9.738E+14	2.497E+14	5.306E+14	2.497E+14	
25	ISO	270 deg	230	1.030E+15	1.074E+15	2.497E+14	5.306E+14	2.497E+14	
26	ISO	0 deg	230	1.030E+15	6.816E+15	2.497E+14	5.306E+14	2.497E+14	
27	ISO	90 deg	230	1.030E+15	6.741E+15	2.497E+14	5.306E+14	2.497E+14	
28	ISO	180 deg	230	1.030E+15	9.738E+14	2.497E+14	5.306E+14	2.497E+14	
29	ISO	270 deg	230	1.030E+15	1.074E+15	2.497E+14	5.306E+14	2.497E+14	
30	ISO	0 deg	230	1.030E+15	6.816E+15	2.497E+14	5.306E+14	2.497E+14	
31	ISO	90 deg	230	1.030E+15	6.741E+15	2.497E+14	5.306E+14	2.497E+14	
32	ISO	180 deg	230	1.030E+15	9.738E+14	2.497E+14	5.306E+14	2.497E+14	

C / As	#######	protons
nC	#######	protons
uC	#######	protons
mC	#######	protons

during commissioning, 3 months are ~590 hours of beam on!

factor 171.6 — hourly values

clinical

Sa1	injector	495	uC/3M		7 MeV	5999
Sa2	Acc Mags	489	uC/3M	each	<50 MeV	
Sa3	Scraper	4030	uC/3M		<50 MeV	5998
Sa4	Extraction	81	uC/3M		230 MeV	5997
Sh1	FCC	78	uC/3M		230 MeV	5996
	damper					5995
	ISOs	41.25	uC / 3M		230 MeV	each angle

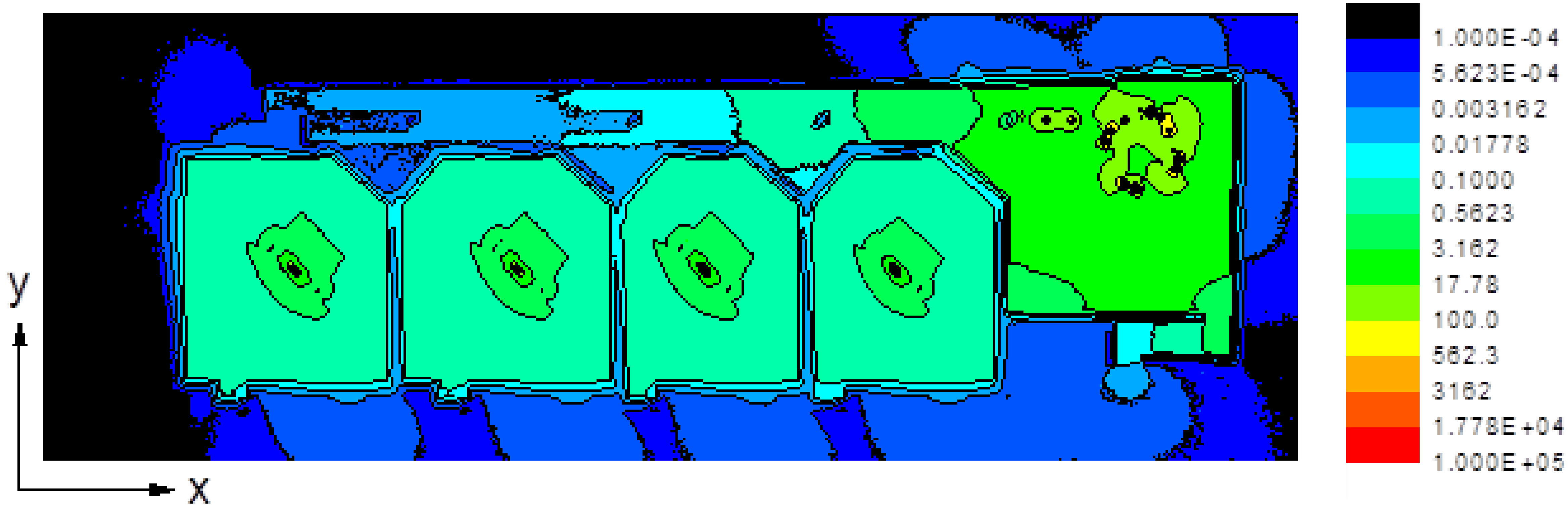
commissioning

							hourly values	
Sa1	injector	278	uC/3M		7 MeV	5999	1.62	uC/h
Sa2	Acc Mags	128	uC/3M	each	<50 MeV		0.7459	uC/h
Sa3	Scraper	1548	uC/3M		<50 MeV	5998	9.021	uC/h
Sa4	Extraction	79	uC/3M		230 MeV	5997	0.4604	uC/h
Sh1	FCC	106	uC/3M		230 MeV	5996	0.6177	uC/h
	damper					5995		
	ISOs	273	uC / 3M			0 deg	1.5909	uC/h
		270	uC / 3M			90 deg	1.5734	uC/h
		39	uC / 3M			180 deg	0.2273	uC/h
		43	uC / 3M			270 deg	0.2506	uC/h

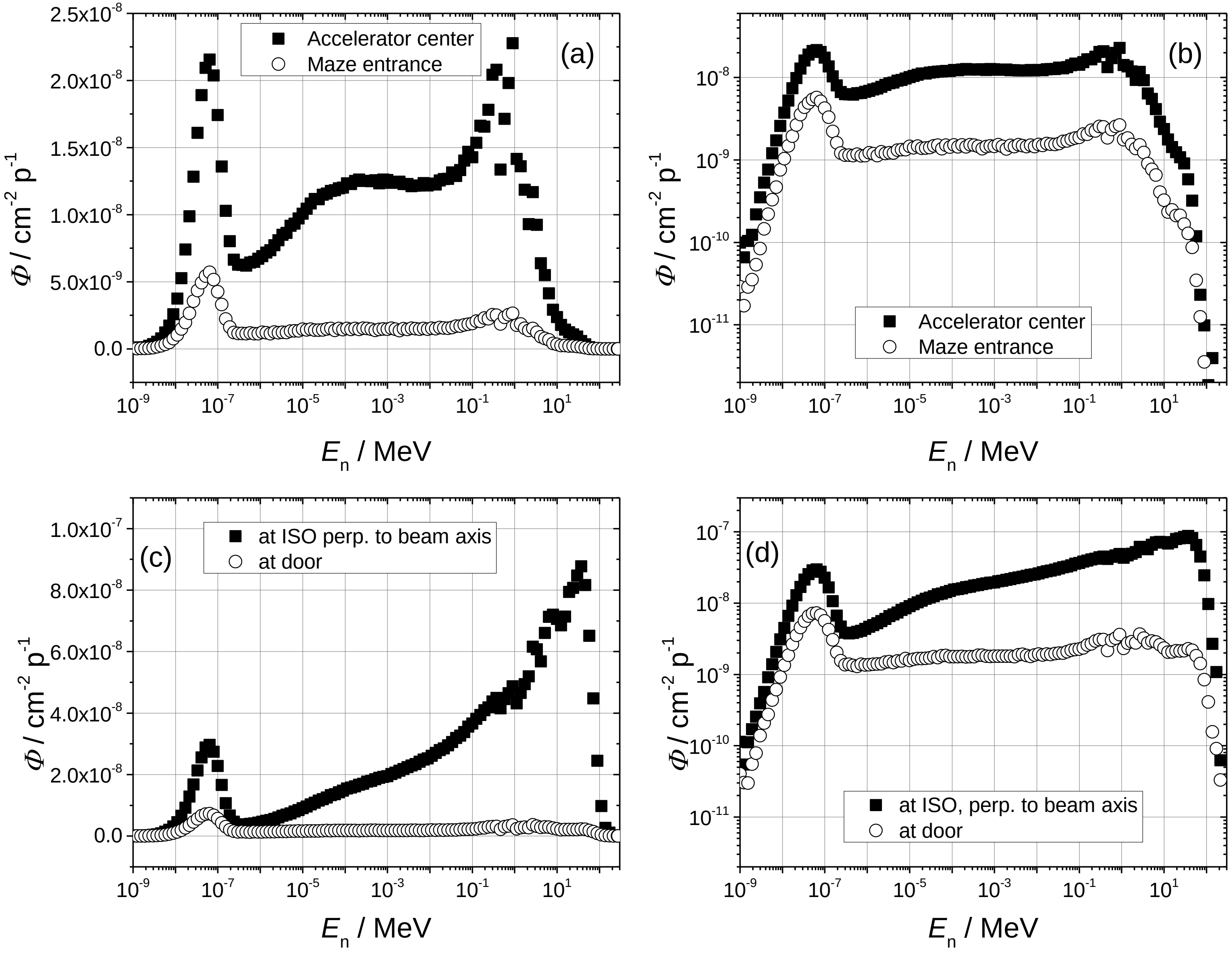
MEE operation

						hourly values	
Sa1	injector	495	uC / 3M	7 MeV	5999	2.8846	uC/h
Sa2		45	uC / 3M	230 MeV		0.2622	uC/h
		90	uC / 3M	200 MeV		0.5245	uC/h
		45	uC / 3M	170 MeV		0.2622	uC/h
		690	uC / 3M	50 MeV		4.021	uC/h
Sa3	Scraper	2217	uC / 3M	50 MeV	5998	12.92	uC/h
Sa4	Extraction	20	uC / 3M	230 MeV	5997	0.1166	uC/h
		41	uC / 3M	200 MeV		0.2389	uC/h
		20	uC / 3M	170 MeV		0.1166	uC/h
Sh1	FCC	10	uC / 3M	230 MeV	5996	0.0583	uC/h
		19	uC / 3M	230 MeV		0.1107	uC/h
		10	uC / 3M	230 MeV		0.0583	uC/h
	damper	17	uC / 3M	230 MeV	5995	0.0991	uC/h
		34	uC / 3M	230 MeV		0.1981	uC/h
		17	uC / 3M	230 MeV		0.0991	uC/h
	ISOs	10	uC / 3M	230 MeV		0.0583	uC/h
		21.25	uC / 3M	200 MeV		0.1238	uC/h
		10	uC / 3M	170 MeV		0.0583	uC/h

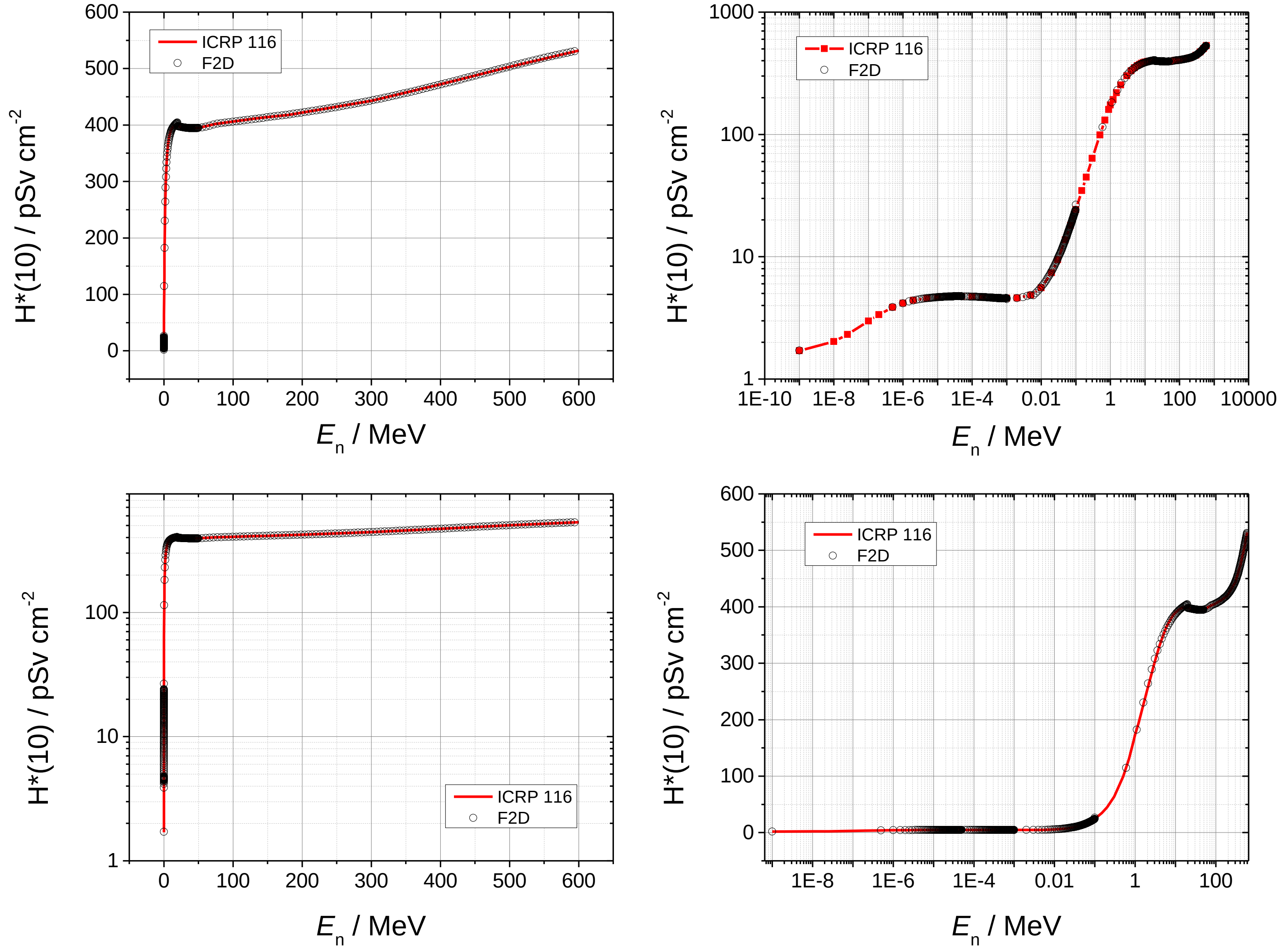
Estimate Fluence



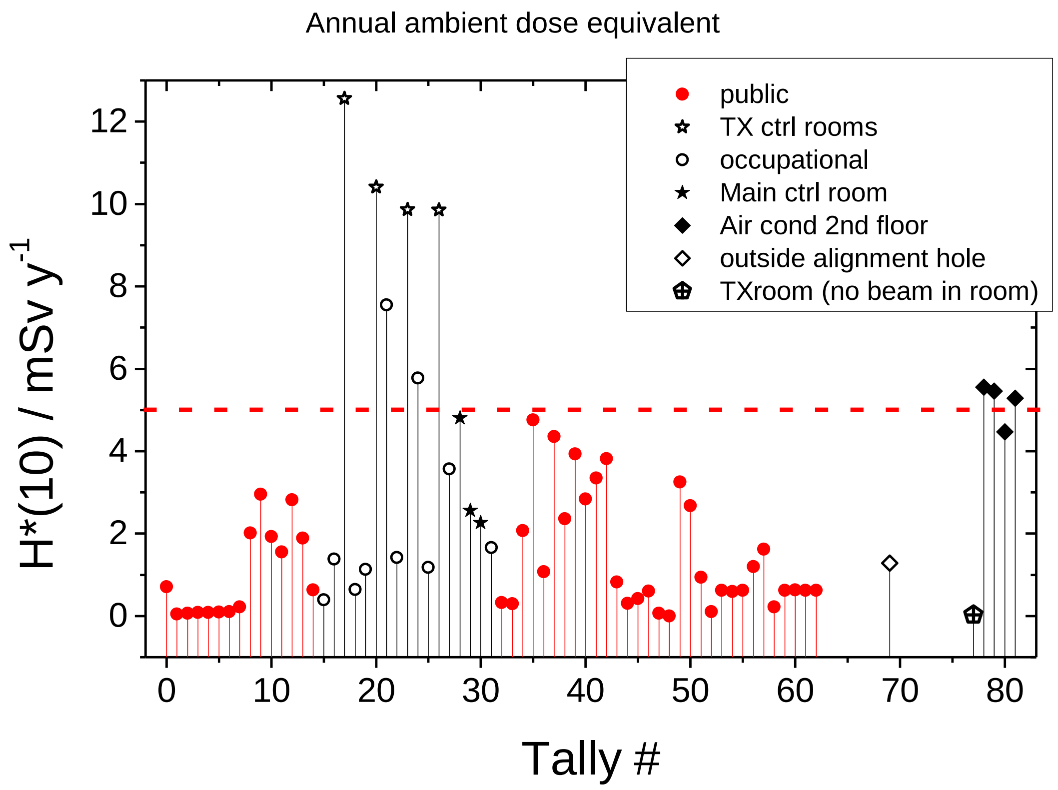
Estimate Fluence

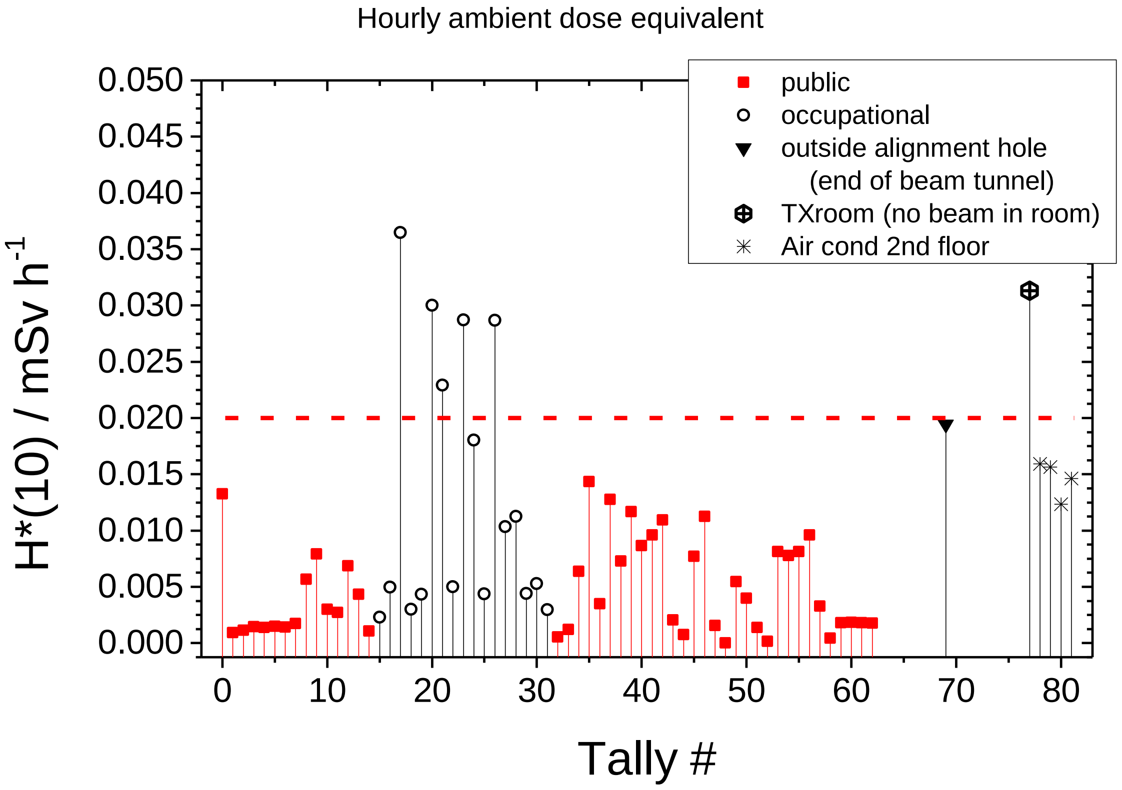


Fluence to Dose conversion (ICRP 116)



Results





Members of the public: **5 mSv / y** and **0.02 mSv** in any one hour

Occupational: **50 mSv / y**

Now the fun stuff…

Ions Heavier Than Protons

- Helium, Lithium, Beryllium, Boron, Carbon
- Exciting new area of research and development
- Long term goal: Establish and heavy ion facility at MDACC

Physical and Biological Aspects

- Heavier ions have superior dose distribution characteristics (less lateral scattering)

- The higher ionization density along their tracks leads to greater biological effectiveness and the ability to overcome radiation resistance of cancer stem cells and hypoxic tumors

Immunogenic and Clinical Aspects

- Heavier ions can induce immunogenic response (e.g., release of tumor antigens, especially at high doses per fraction)
  - Augment radiotherapy's local capabilities with systemic potential to treat regional microscopic and distant metastatic disease (the "abscopal" effect)

- High curative potential, especially in combination with immuno-modulatory drugs

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And many, many more …

1968

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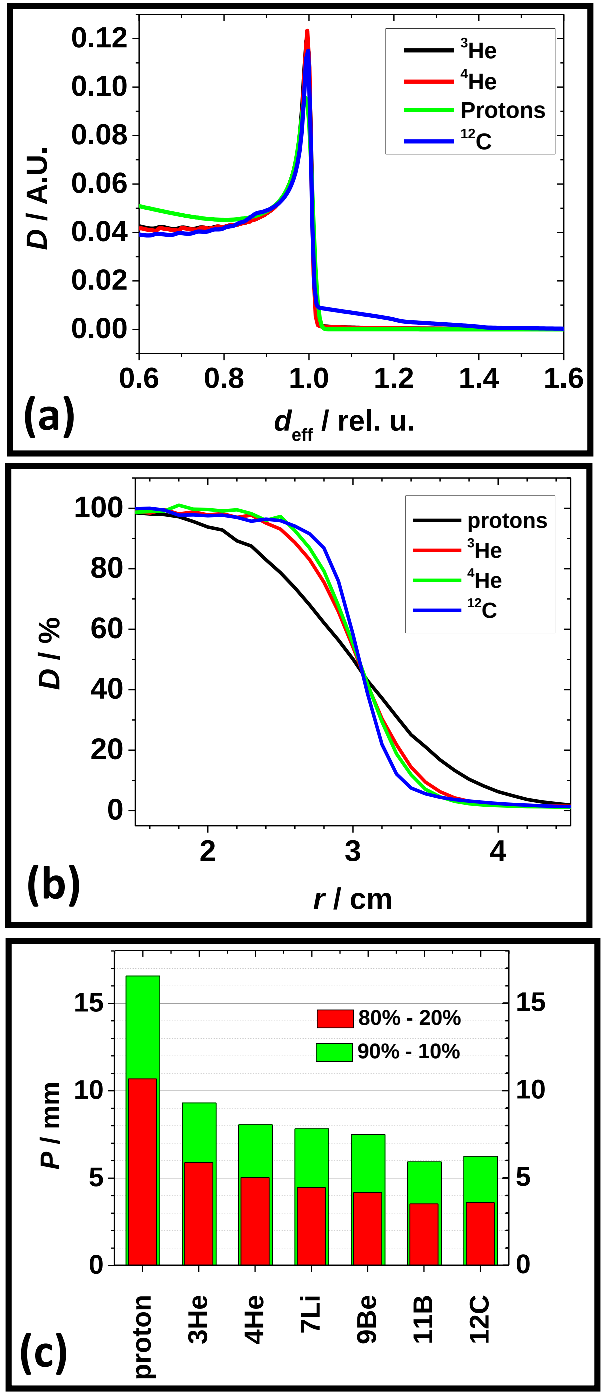
Panel (a) compares beamlet integral DD data for ^+p, ^3He, ^4He and ^{12}C ions. The fragmentation effect for ^{12}C, even for monoenergetic ions, is significant and will be much greater for a spread-out Bragg peak.

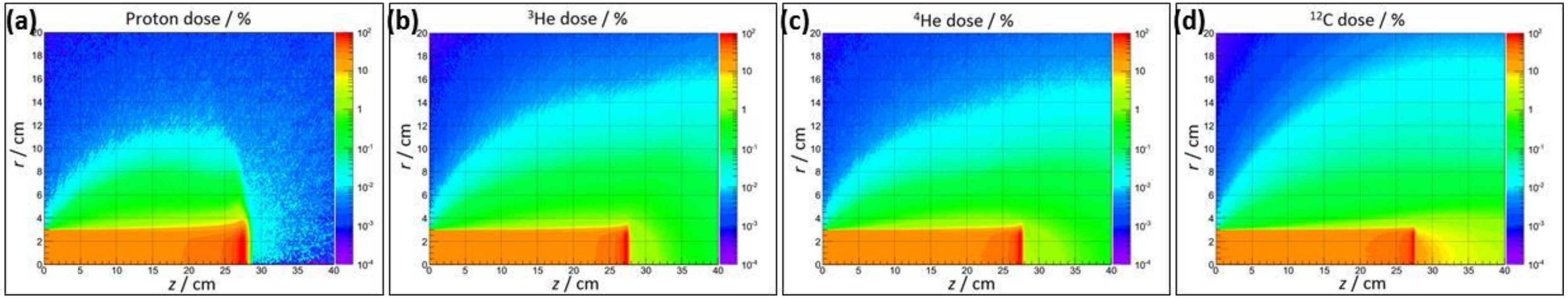
Panel (b) compares profiles at the D_{max} for ion energies with a range of 27 cm for scanned beams (6 cm diameter) for the same set of ions.

Panel (c) compares corresponding penumbra widths (80-20% and 90-10%) for all ions of interest. Heavier ions are significantly superior compared to protons, but the clinical significance of differences among ions from He to C is not *a priori* clear.



Relative dose distributions produced using 6 cm diameter beams of monoenergetic ions (27 cm range in water) for the same dose deposited at the Bragg peak.

Protons | ^{3}He | ^{4}He | ^{12}C



- The out-of-field contributions are produced by secondary particles (mostly neutrons, protons, deuterons, alphas).
- The lateral spread of secondary particles is slightly greater for 3He than for ^{4}He.
- Secondary particle contributions are greatest for carbon, laterally and distally, which may be of concern due to their potential for inducing secondary malignancies. The color wash dose distributions are in log of percent of peak dose.