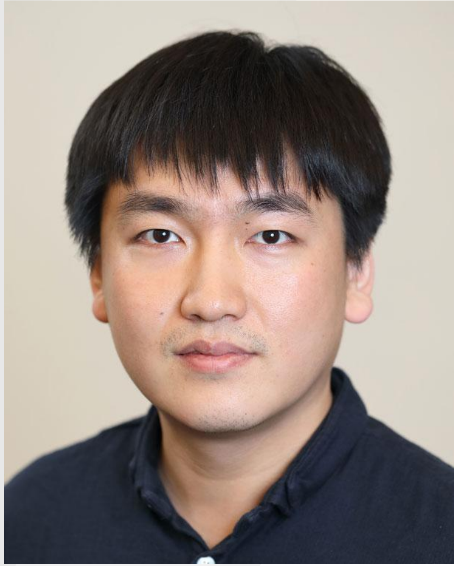
Dosimetry for Epidemiologic Studies of Emerging Radiotherapy

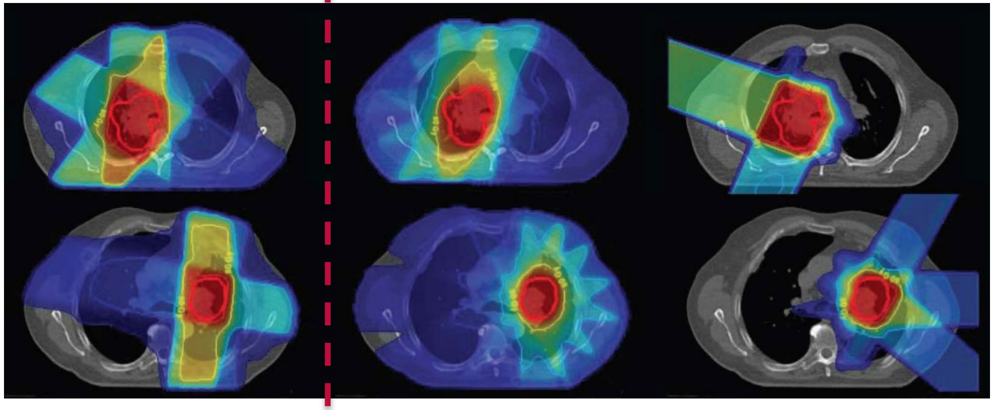
Dr. Yeon Soo Yeom
Radiation Epidemiology Branch
Division of Cancer Epidemiology and Genetics
National Cancer Institute
yeonsoo.yeom@nih.gov



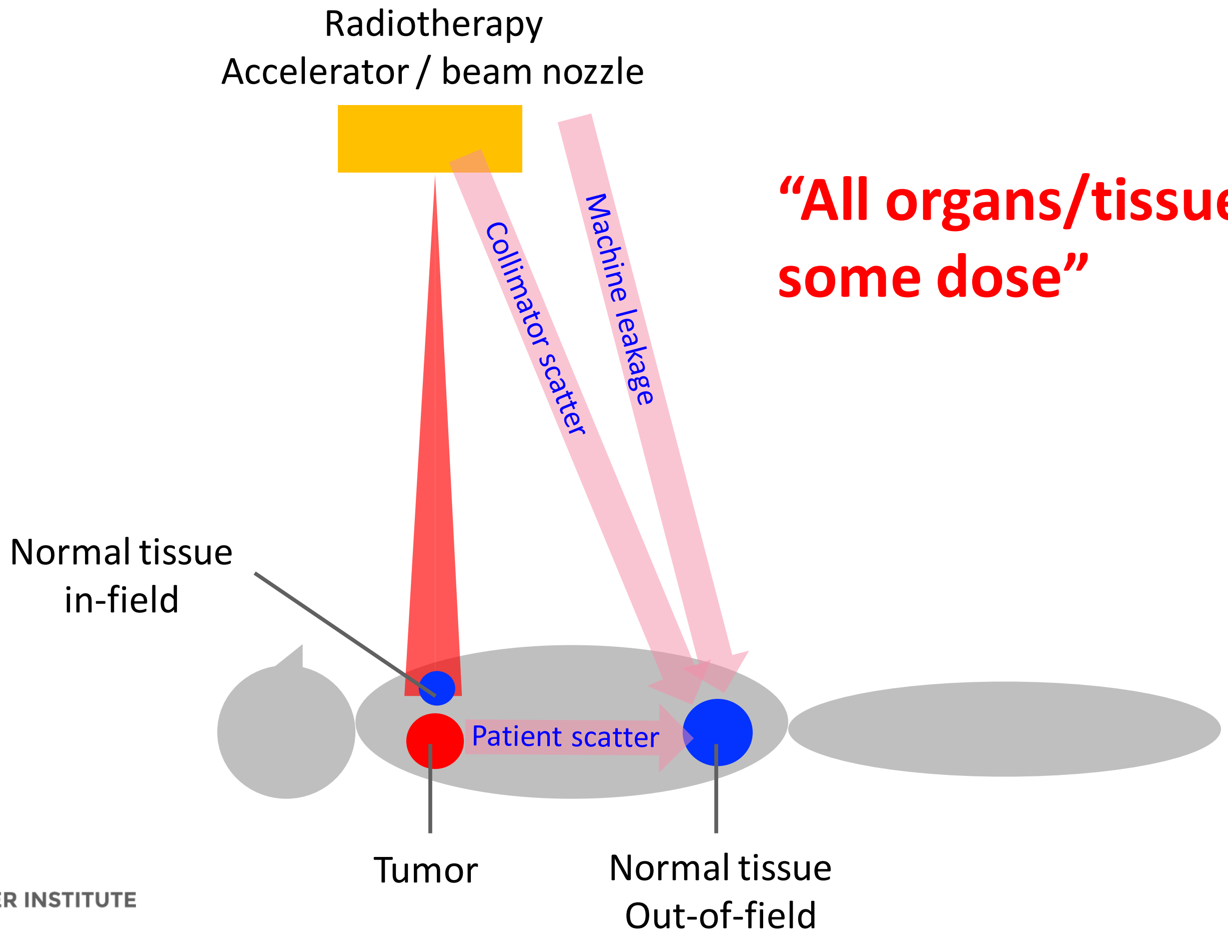
DCEG Radiation Epidemiology and Dosimetry Course 2019

Emerging Radiotherapy Techniques

- Photon Therapy
  - ✓ Intensity modulated radiotherapy (IMRT)
  - ✓ Volumetric modulated arc therapy (VMAT)
- Hadron Therapy (mostly proton)
  - ✓ Passive scattering (PS)
  - ✓ Pencil beam scanning (PBS)

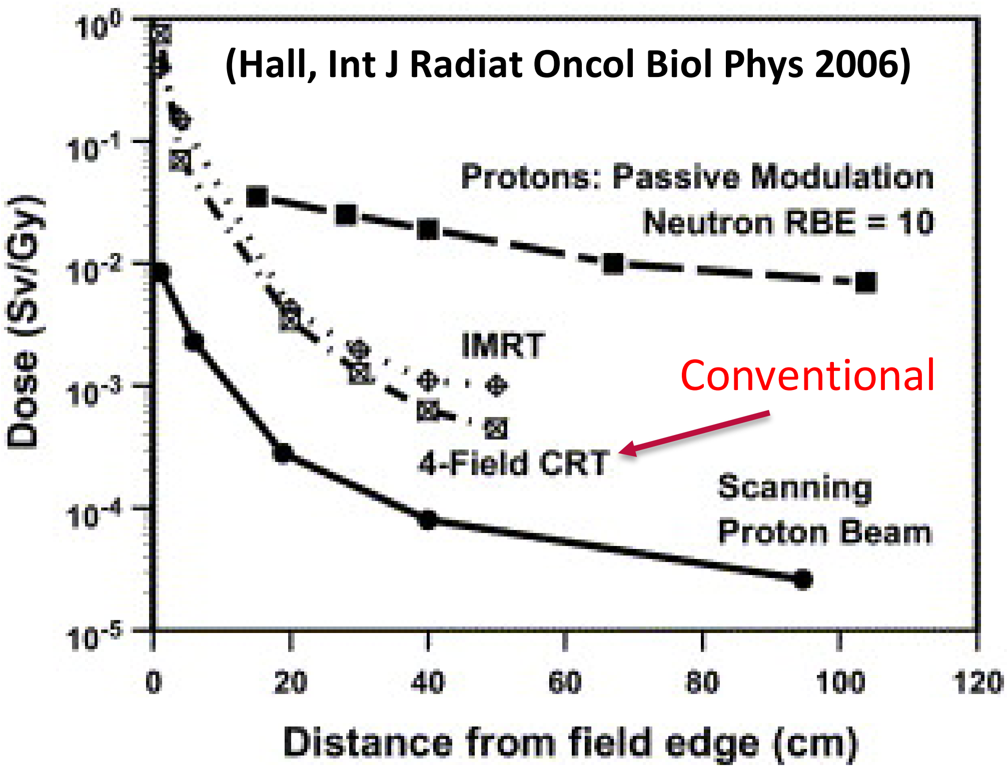


Unintended Radiation Dose to Normal Tissues



"All organs/tissues receive some dose"

Example of Out-of-field Doses (Conventional vs Emerging)



“Low dose RBE for neutron carcinogenesis has <u>a great uncertainty</u>.”

Dosimetry Advantage in Modern Radiotherapy

- Detailed treatment records are managed via an electronic format, **DICOM-RT** (Digital Imaging and Communications in Medicine for radiotherapy).

  ✓ **RT Image**: patient anatomy image (e.g., CT)

  ✓ **RT Structure Set**: a set of areas of significance in radiotherapy (e.g., tumor volume and organs at risk (OARs))

  ✓ **RT Dose**: 2D or 3D radiation dose data (generated from TPS)

  ✓ **RT Plan**: all RT-related information (e.g., beam properties and MLC)

Limitations of DICOM-RT

- **RT Image** may not cover out-of-field region that can include organs of interest in epidemiologic studies.
- **RT Structure Set** may not include organs of interest.
- **RT Dose** may not cover out-of-field dose and has insufficient accuracy in near and out of fields (e.g., no secondary neutron dose in proton therapy).

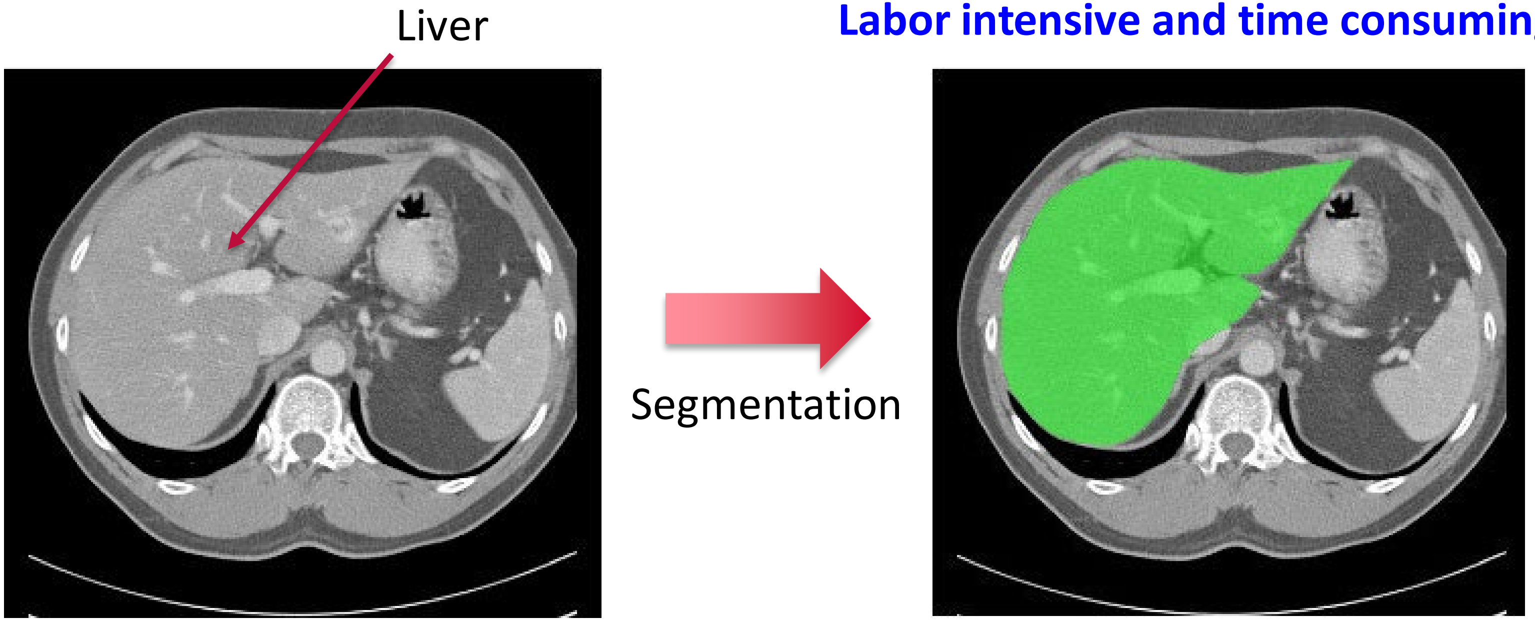
✓ **Realistic patient anatomy models**

✓ **Accurate dose calculation methods**

Patient Anatomy Models

Organ/Tissue Segmentation in Medical Images

Labor intensive and time consuming!!!



- **<u>Need to be automated</u>** for a large-scale cohort of patients required in epidemiologic studies.

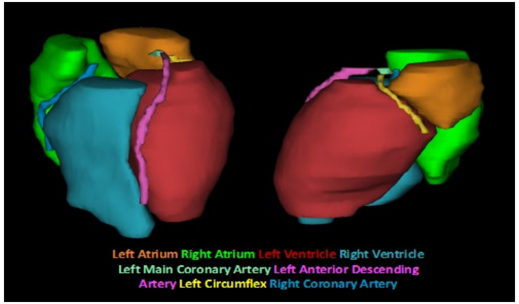
Segmentation Algorithms

- Thresholding
- Region growing
- Classifiers / clustering
- Deformable models
- Atlas-guided approaches
- Artificial neural networks (deep learning)
- Etc.

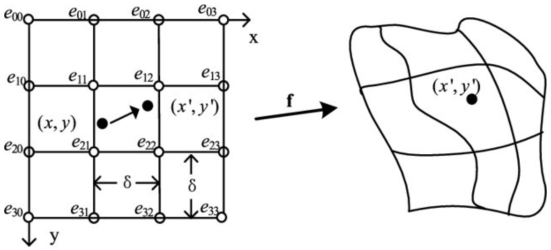
Each has own pros and cons!!!

Automated Heart Segmentation

30 cardiac atlases



B-spline 3D deformation



1. Obtain DICOM-RT structure of the whole heart for a given patient

↓

2. Linearly scale 30 cardiac atlases to match the volume of a given heart

↓

3. Select most similar atlas with the greatest dice similarity coefficient from 30 cardiac atlases

↓

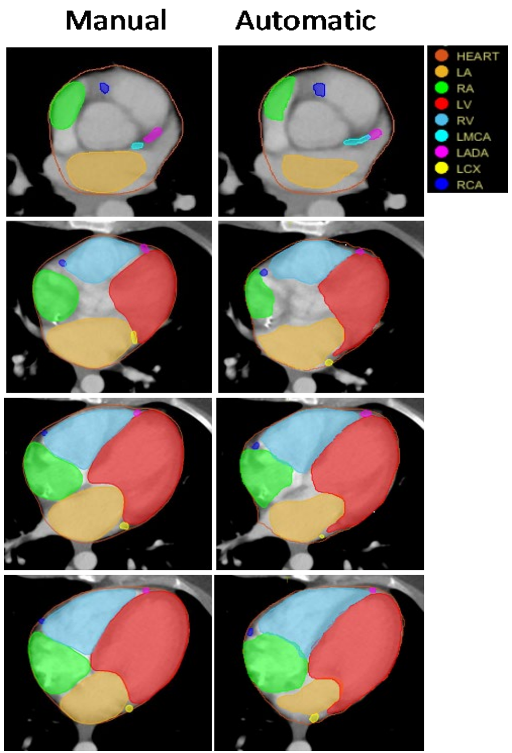
4. Perform B-spline 3D deformation on the selected cardiac structures to match the whole heart contour

↓

5. Write DICOM-RT structure of the resulting cardiac structure

* Jung et al, *PHIRO* (submitted)

Automated Heart Segmentation



✓ Takes less than ten minutes!!!

Cardiac Structures	Manual Dose (Gy)		Automatic Dose (Gy)	
	Mean	Min - Max	Mean	Min - Max
WH	2.4 ± 1.2	1.1 – 6.0	2.5 ± 1.2	1.1 - 6.1
LA	1.3 ± 0.3	0.8 – 2.0	1.2 ± 0.3	0.8 - 1.9
RA	1.1 ± 0.4	0.5 - 1.8	1.0 ± 0.4	0.5 - 1.8
LV	3.3 ± 2.0	1.5 - 9.8	3.1 ± 1.7	1.4 - 8.0
RV	2.1 ± 1.0	0.9 - 5.8	2.2 ± 1.1	0.9 - 5.8
LMCA	1.8 ± 0.5	1.0 - 2.7	1.7 ± 0.5	1.0 - 3.0
LAD	8.8 ± 8.6	2.4 - 33.1	8.2 ± 6.4	2.7 - 25.3
LCX	1.8 ± 0.4	1.2 - 2.8	1.8 ± 0.5	1.2 - 3.2
RCA	1.3 ± 0.5	0.6 - 2.1	1.4 ± 0.6	0.5 - 2.6

*left breast radiotherapy plans

* Jung et al, *PHIRO* (submitted)

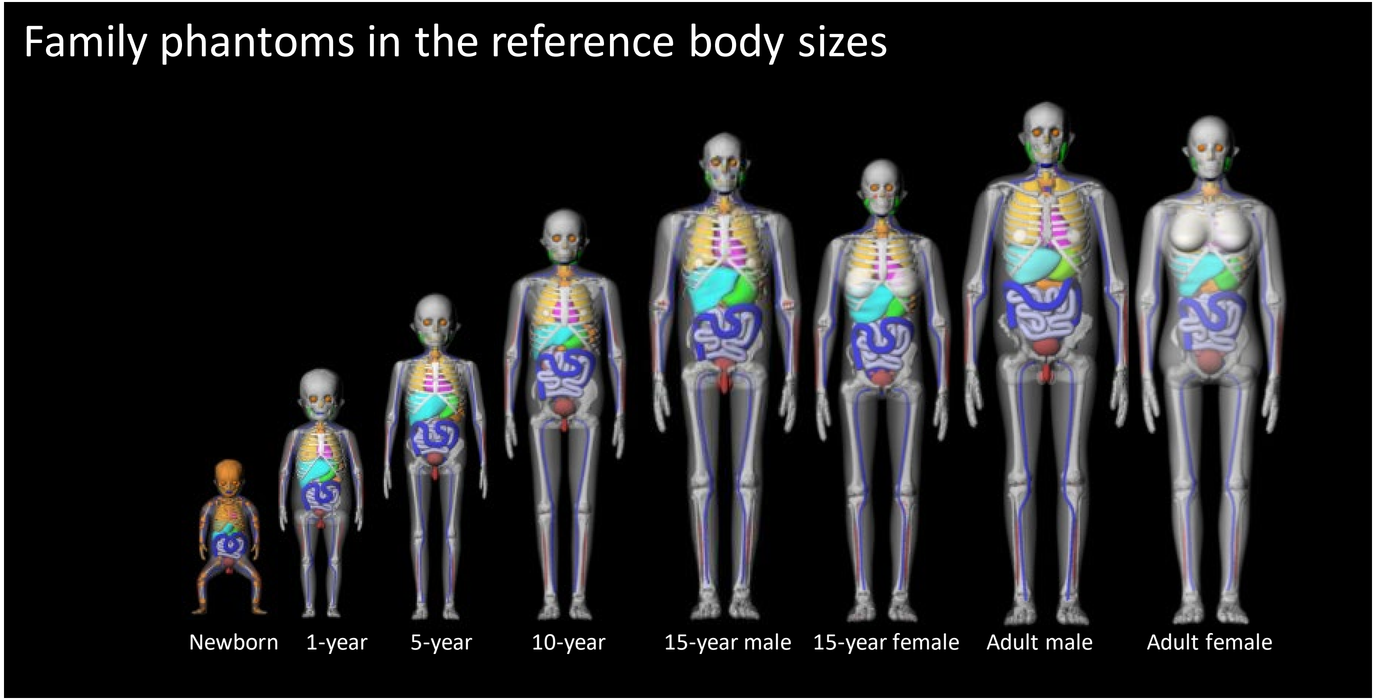
Patient CT May Not Cover Organs of Interest

Brain, thyroid missing

Liver, colon, stomach missing

How can we predict the missing organs?

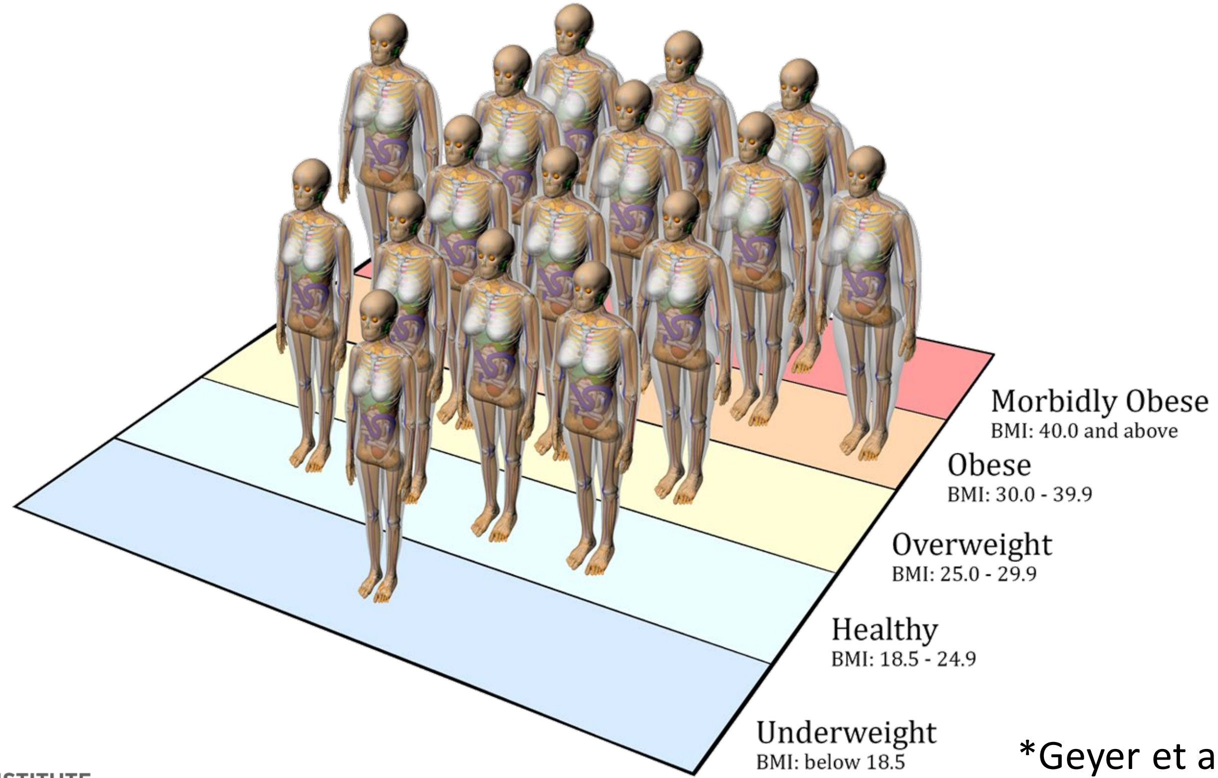
Virtual Human Models (Computational Phantoms)



* Lee et al, *PMB* 2007, *MP* 2008, *PMB* 2010

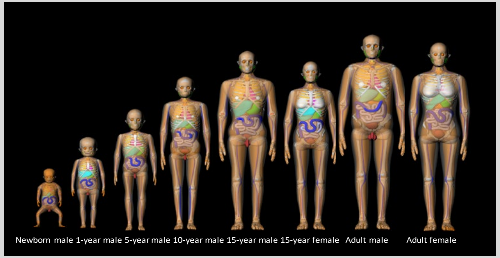
Virtual Human Models (Computational Phantoms)

Phantom library: 351 phantoms in different body sizes

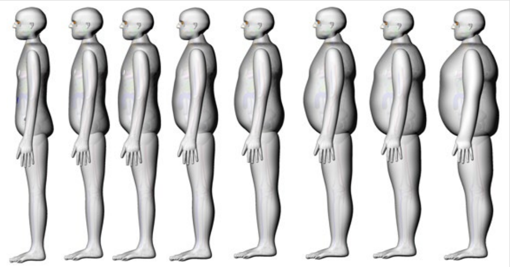


*Geyer et al. *PMB* 2014

Phantom Conversion to DICOM-RT

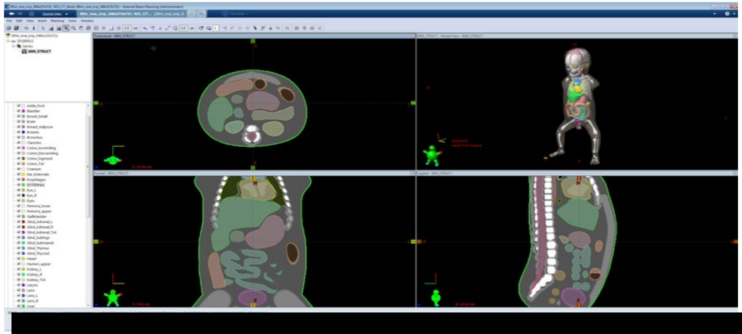


Reference body size



Non-reference body size

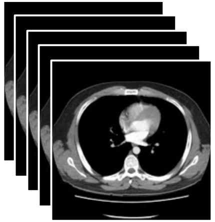
Virtual CT images with pre-contoured organs



*Griffin et al. *PMB* 2019

Extension of Partial Body CT to Whole Body (1)

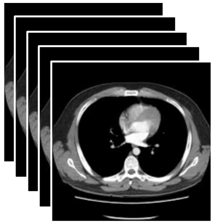
Patient partial body CT



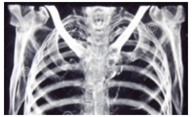
*Kuzmin et al. *RR* 2018

Extension of Partial Body CT to Whole Body (2)

Patient partial body CT

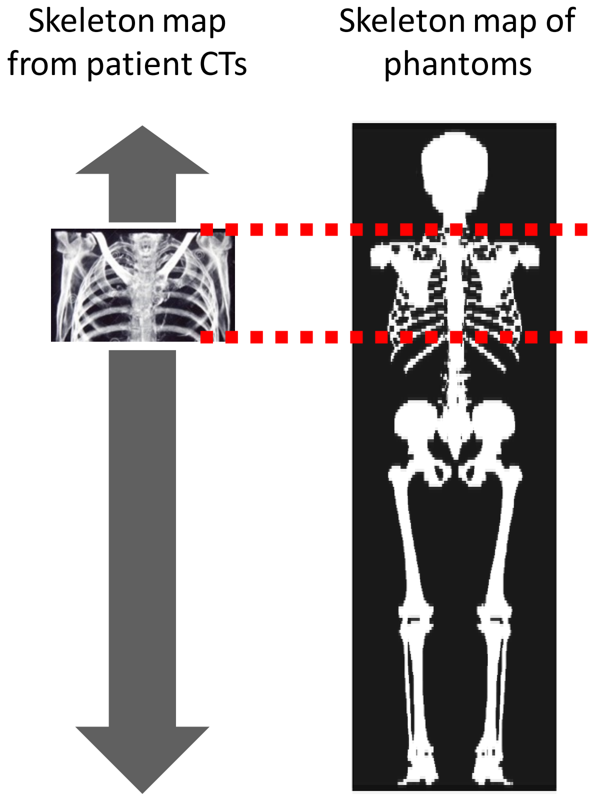


Skeleton map from patient CTs



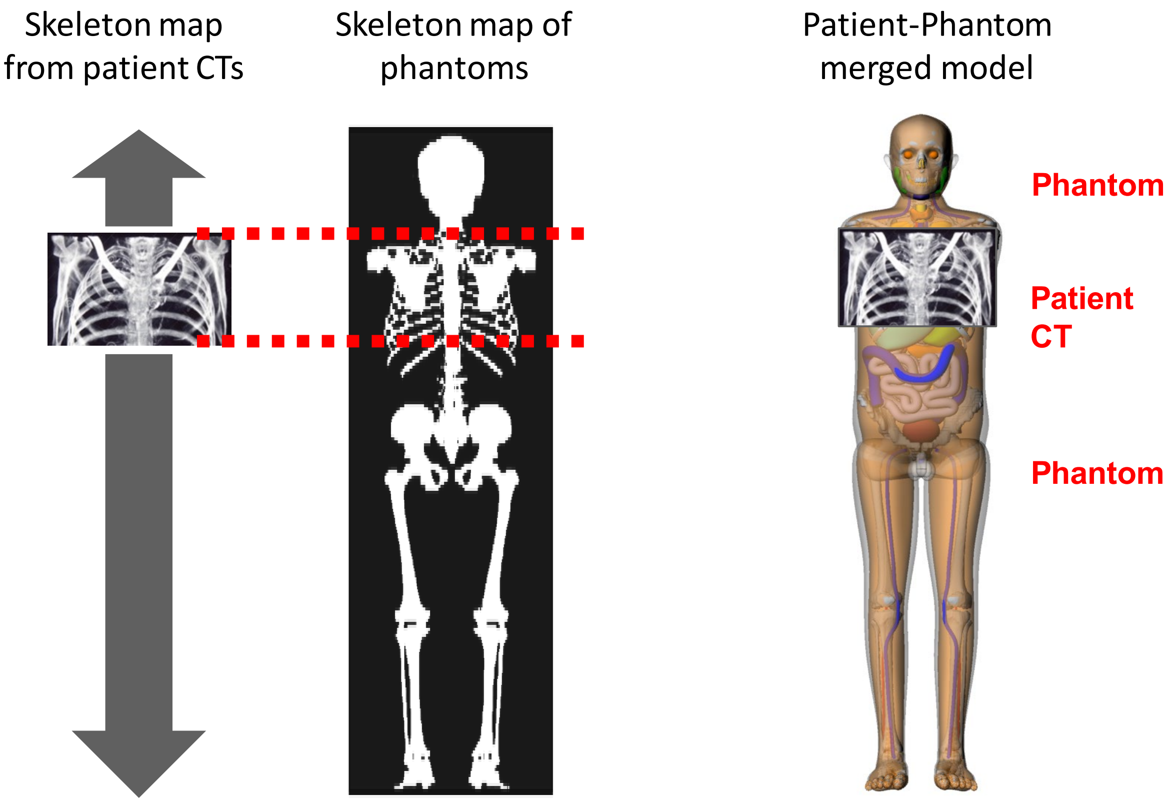
*Kuzmin et al. *RR* 2018

Extension of Partial Body CT to Whole Body (3)



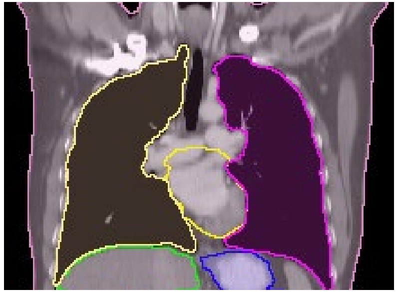
*Kuzmin et al. *RR* 2018

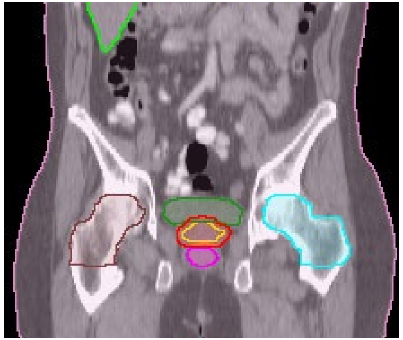
Extension of Partial Body CT to Whole Body (4)



*Kuzmin et al. *RR* 2018

Patient Chest CT

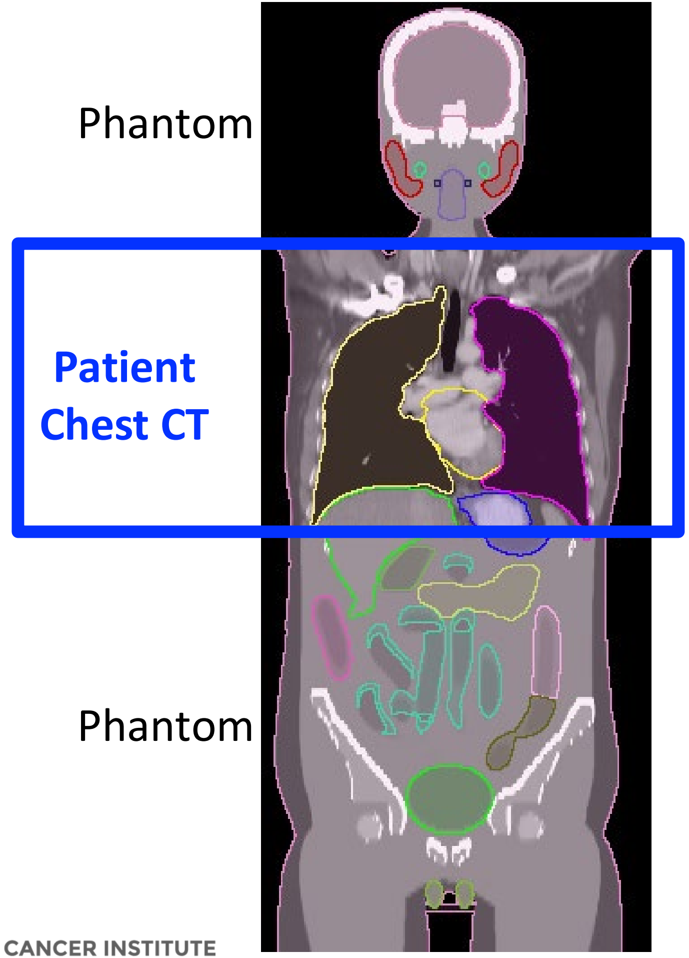


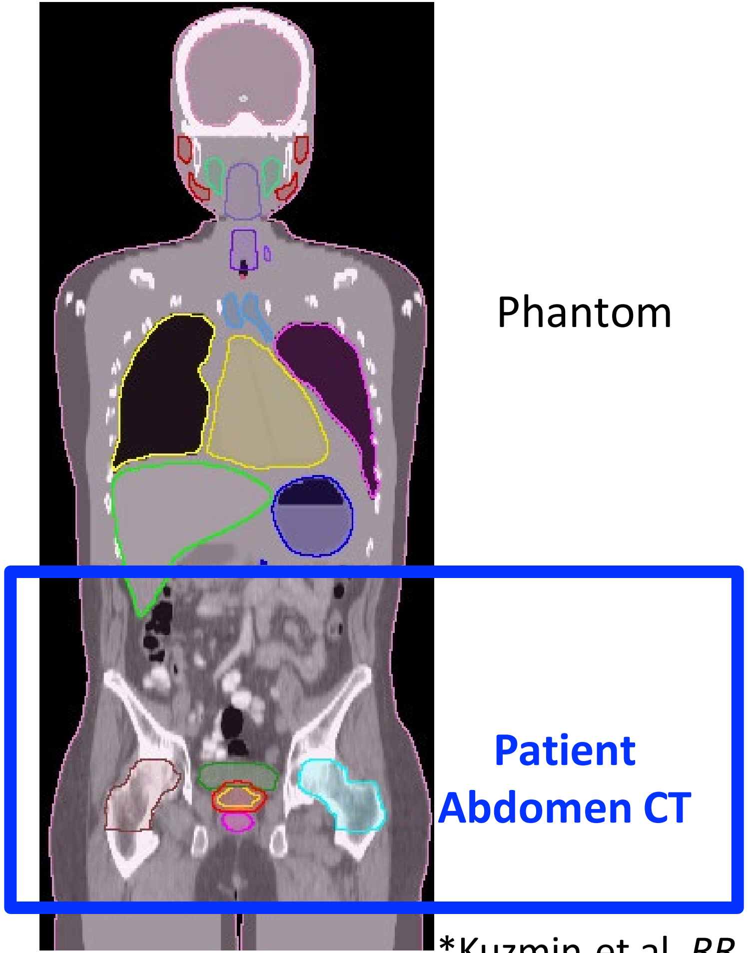


Patient Abdomen CT

*Kuzmin et al. *RR* 2018

Patient-phantom merged models





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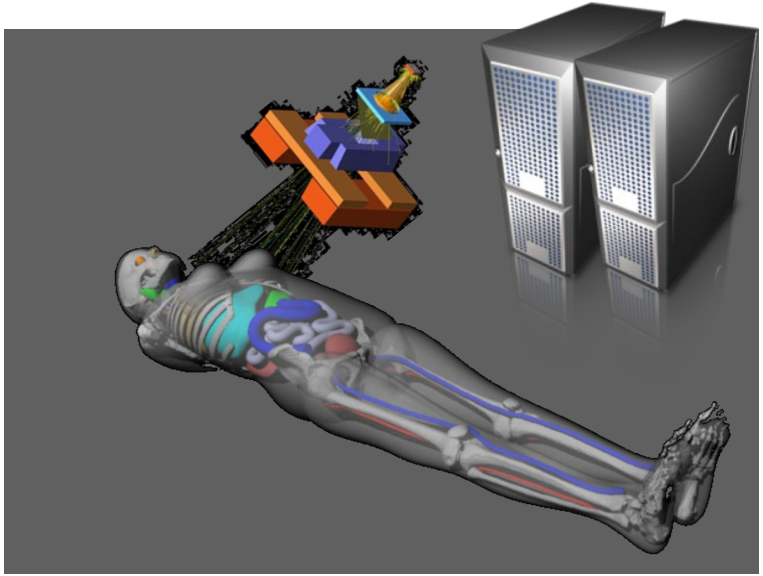
*Kuzmin et al. *RR* 2018

Dose Calculation Methods

MEASUREMENT

- Expensive
- Labor intensive
- Not flexible

COMPUTATION



- Cost-effective
- Automated
- More flexible

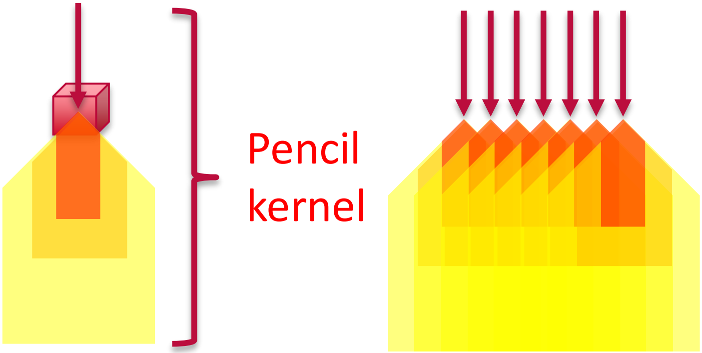
Computational Dosimetry Methods (1)

	Analytical method (Deterministic)	Monte Carlo method (Stochastic)

Computational Dosimetry Methods (2)

	Analytical method (Deterministic)	**Monte Carlo method (Stochastic)**

- ‘Dose kernel’ based algorithms
  - ✓ Pencil beam convolution (Eclipse’s PBC)
  - ✓ Fast-Fourier transform convolution (XiO’s FFT)
- Discrete ordinate methods
  - ✓ Acuros XB (Eclipse’s AXB)
  - ✓ ATTILA code



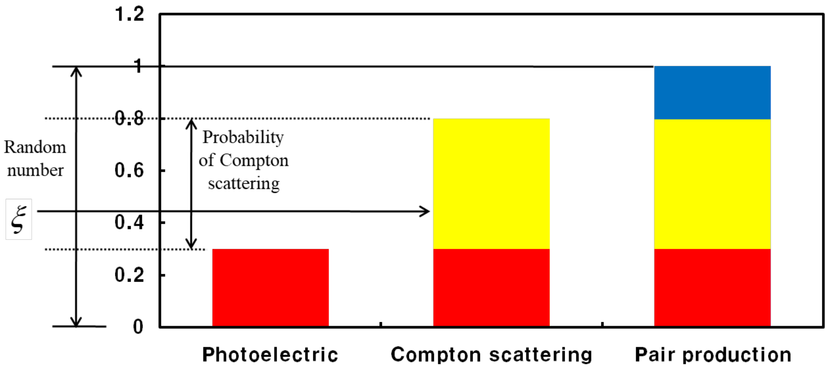
Boltzmann transport equation (BTE)

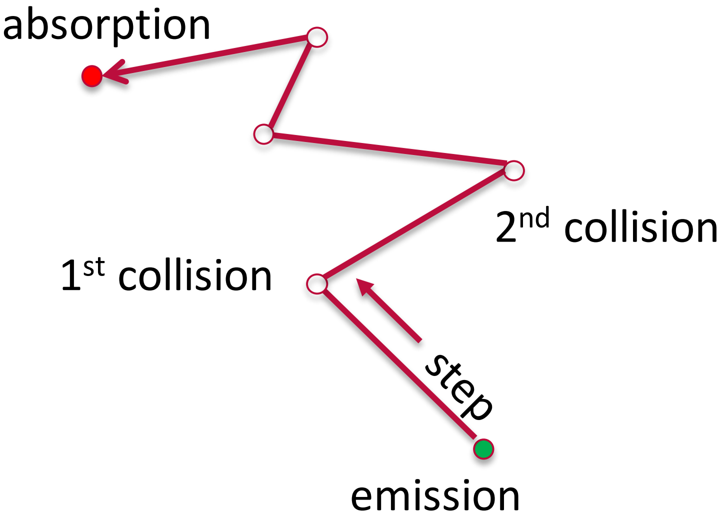
$$\frac{1}{v}\frac{d}{dt}\phi(\vec{r},E,\vec{\Omega},t) = -\Sigma_t(\vec{r},E,t)\phi(\vec{r},E,\vec{\Omega},t) + \int \left(\Sigma_s(\vec{r},E' \to E;\vec{\Omega}' \to \vec{\Omega},t) + v\Sigma_g(\vec{r},E' \to E;\vec{\Omega}' \to \vec{\Omega},t)\right) \times \phi(\vec{r},E',\vec{\Omega}',t)\,dE'\,d\vec{\Omega}' + Q(\vec{r},E,\vec{\Omega},t)$$

Computational Dosimetry Methods (3)

	Analytical method (Deterministic)	Monte Carlo method (Stochastic)

- Duplicate a statistical process (such as interaction with materials) by '**random sampling**' from a probability distribution.





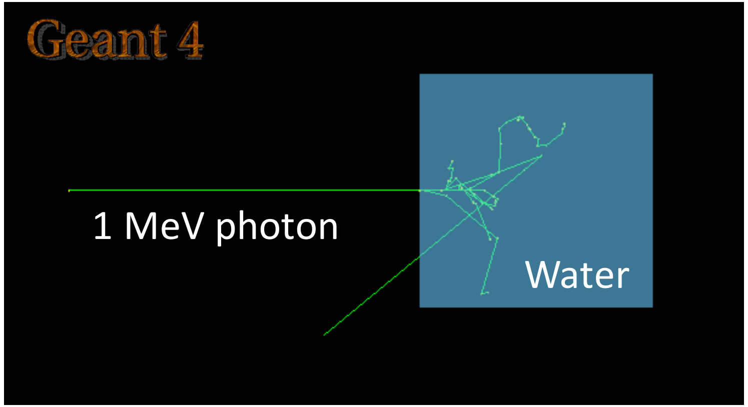
Computational Dosimetry Methods (4)

	Analytical method (Deterministic)	Monte Carlo method (Stochastic)

- Monte Carlo codes
  - MCNP / MCNPX
  - GEANT4
  - PHITS
  - FLUKA
  - EGSnrc / BEAMnrc
  - Penelope

Most particles (MCNP / MCNPX, GEANT4, PHITS, FLUKA)

Photons & electrons (EGSnrc / BEAMnrc, Penelope)



Computational Dosimetry Methods (5)

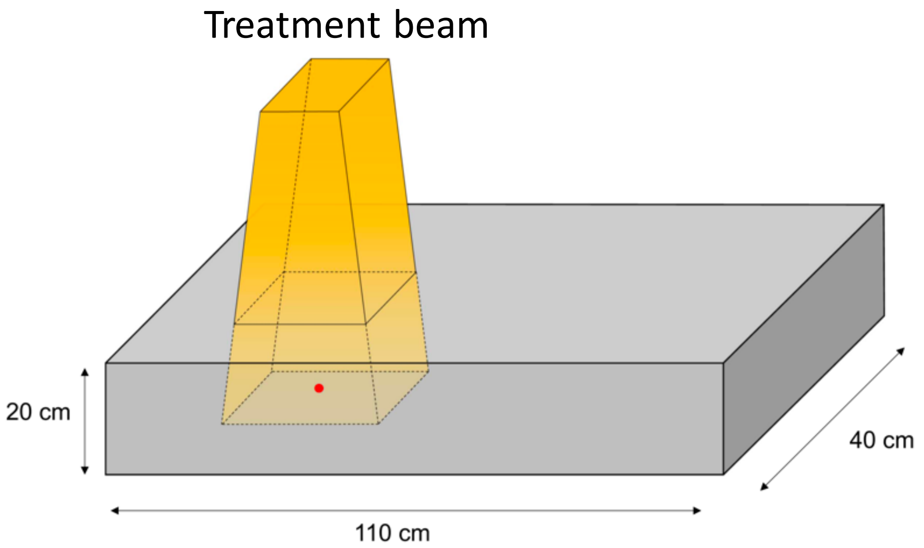
	Analytical method (Deterministic)	Monte Carlo method (Stochastic)
Accuracy		

Computational Dosimetry Methods (6)

	Analytical method (Deterministic)	Monte Carlo method (Stochastic)
Accuracy		
Computation speed		

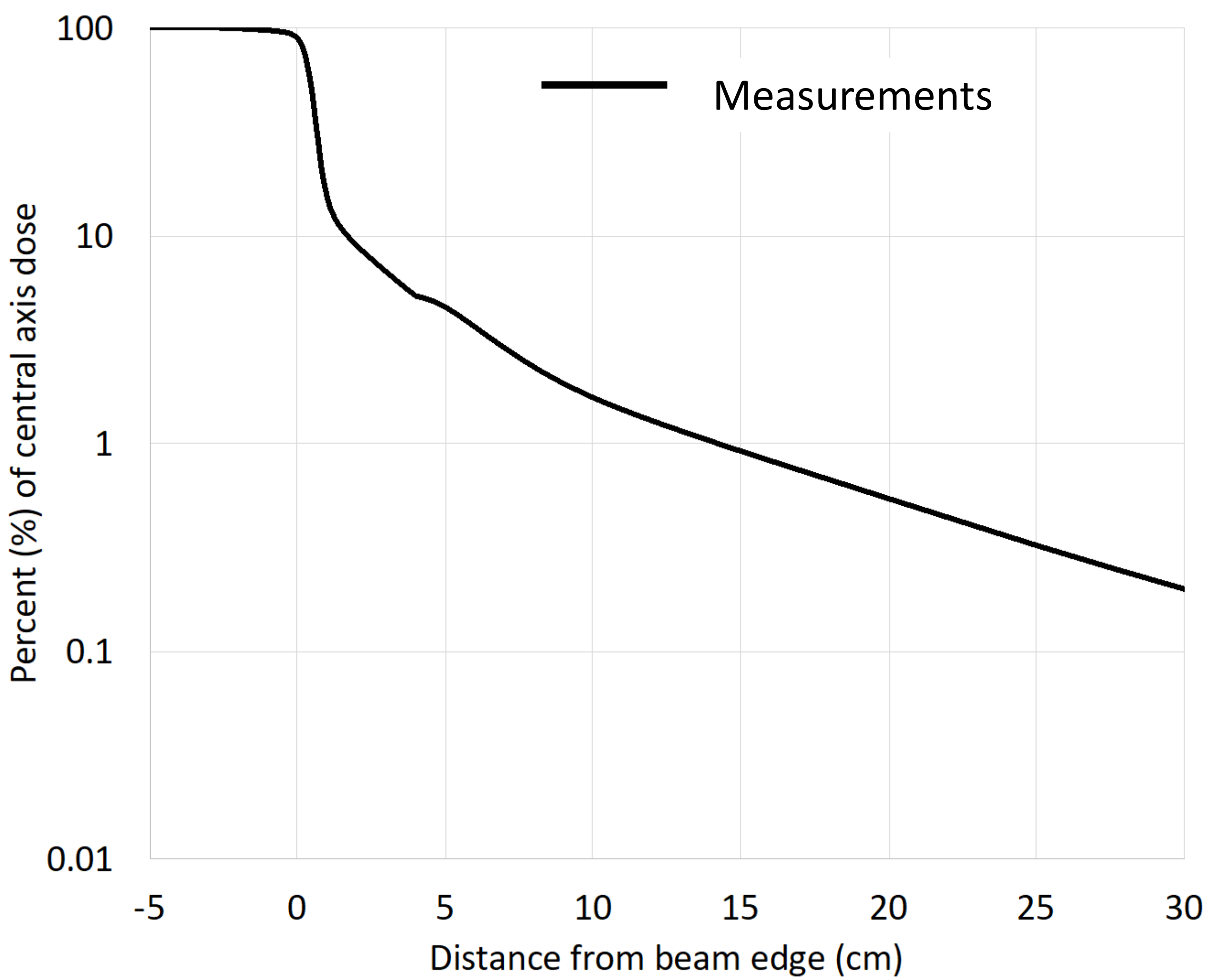
Accelerated Monte Carlo Method for Photon Therapy

- XVMC (Fippel et al. 1999), an accelerated Monte Carlo code, adopted and modified
- Comprehensive benchmarking with measurements conducted

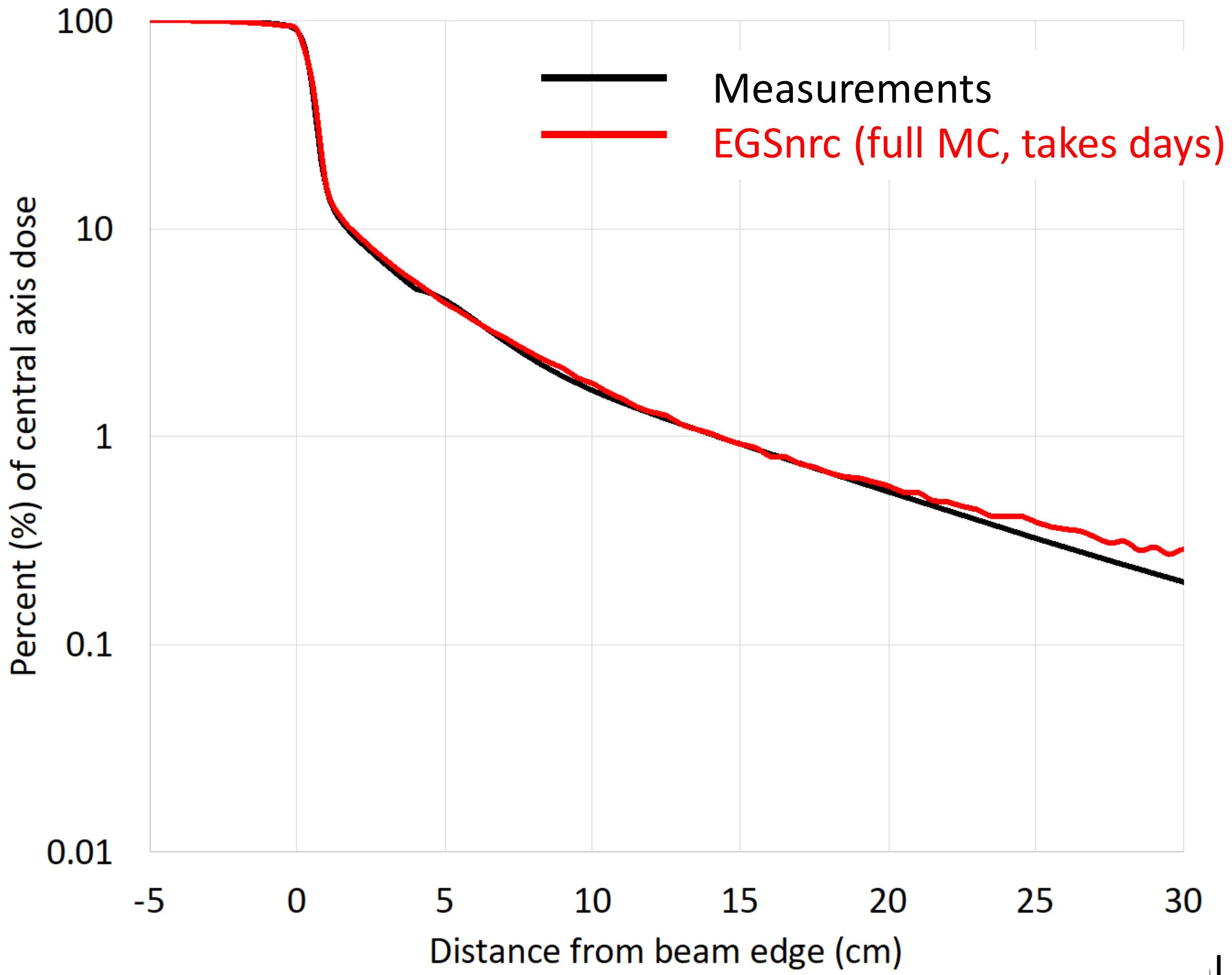


Water phantom for dose measurements

*Mille et al., JRP 2018


Measurements
Percent (%) of central axis dose
100
10
1
0.1
0.01
-5
0
5
10
15
20
25
30
Distance from beam edge (cm)

l., JRP 2018



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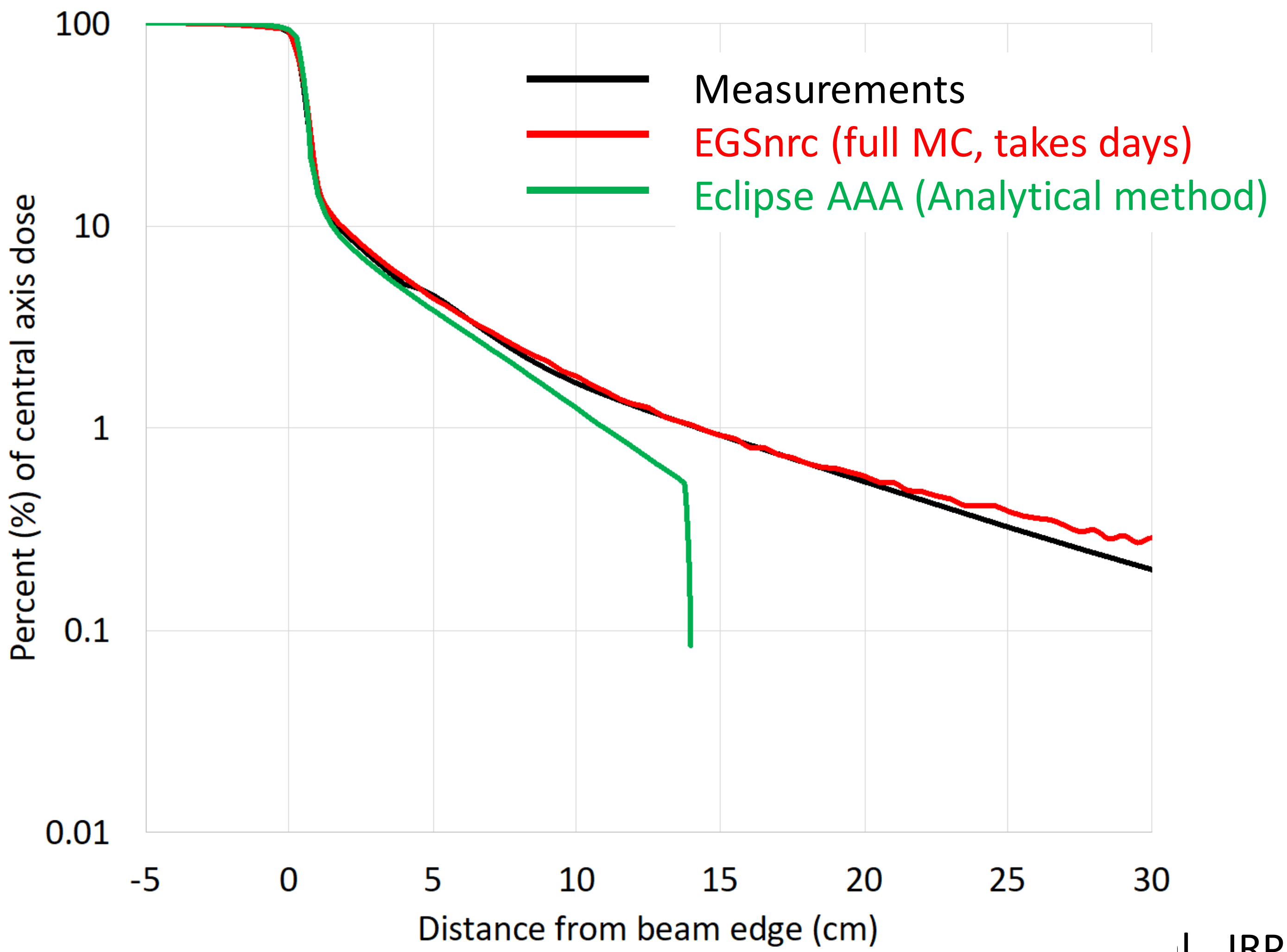
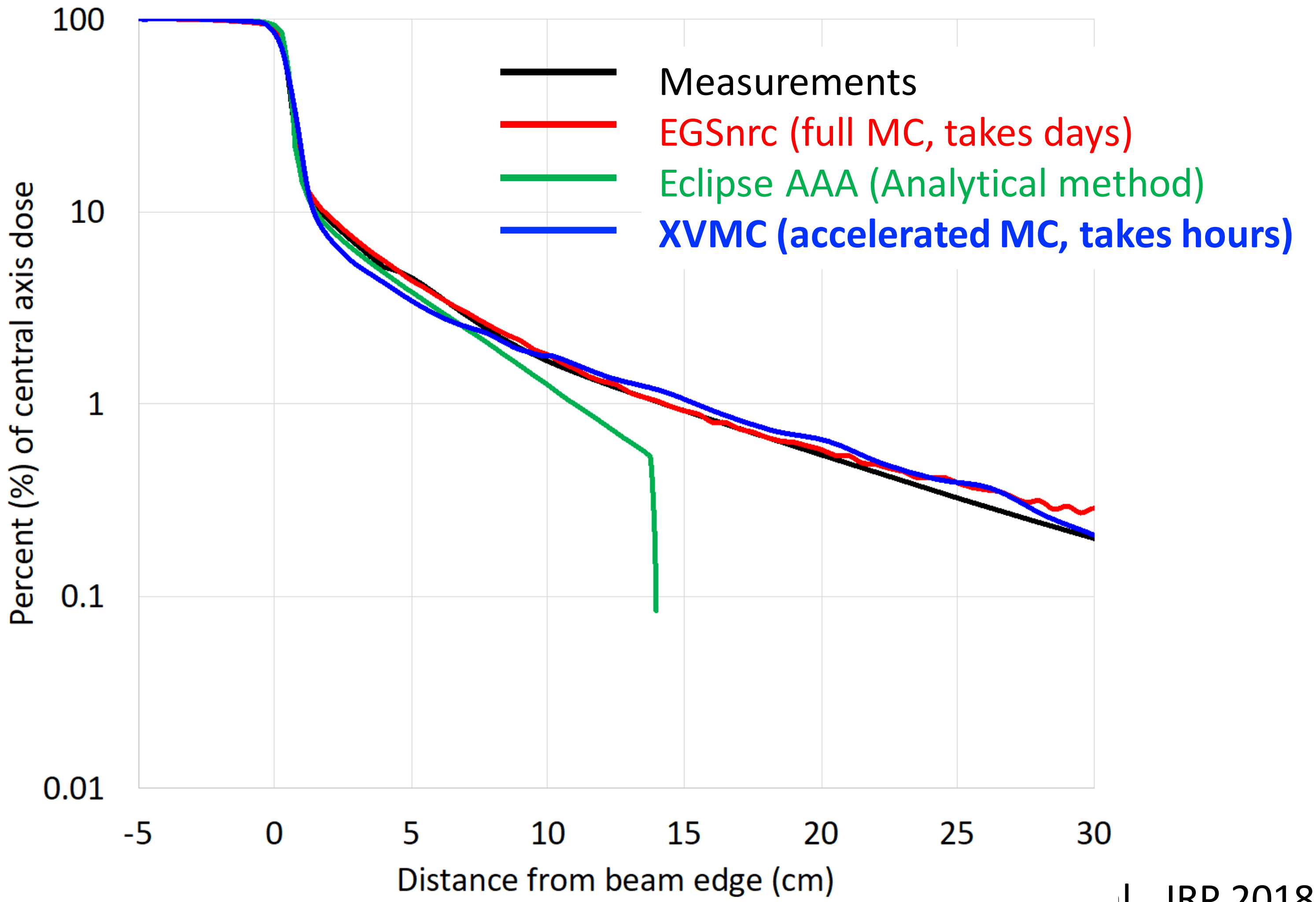
l., JRP 2018



100
10
1
0.1
0.01
Percent (%) of central axis dose
-5
0
5
10
15
20
25
30
Distance from beam edge (cm)
Measurements
EGSnrc (full MC, takes days)
Eclipse AAA (Analytical method)

l., JRP 2018



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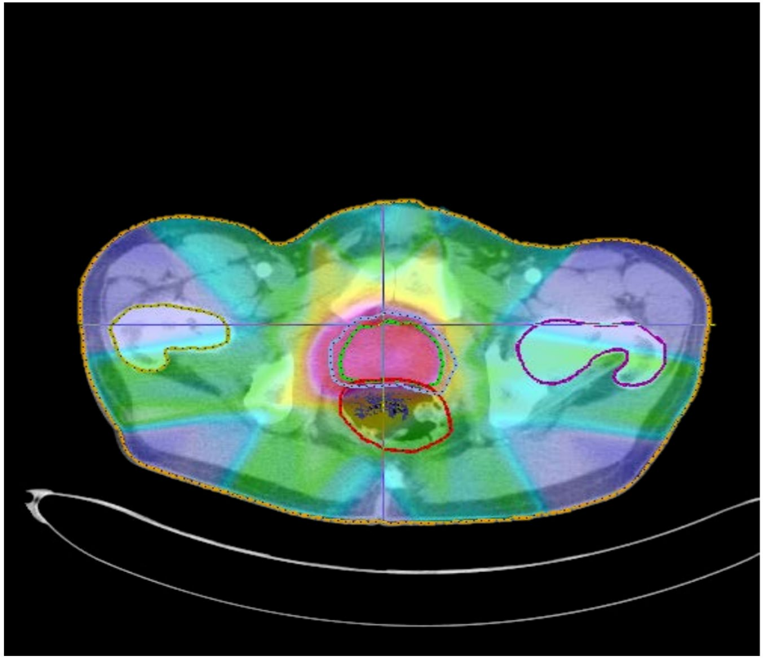
l., JRP 2018

Example of IMRT Dose Calculation



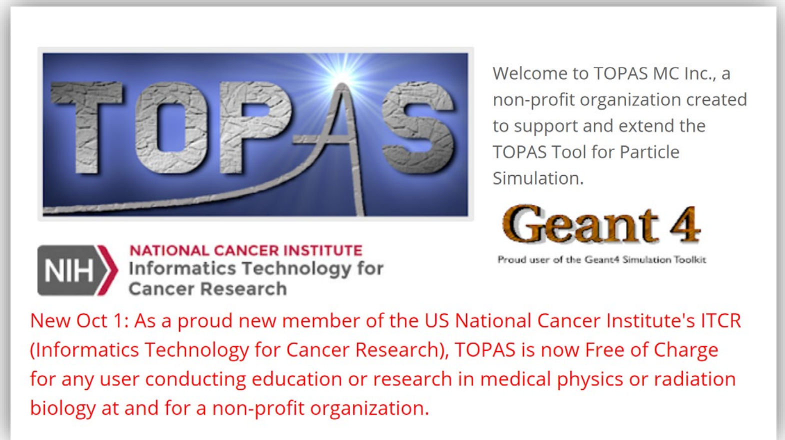
Dose distribution for the 7-field IMRT plan on the patient CT calculated by XVMC

Organ	Metric	Patient Dose (cGy)	Phantom Dose (cGy)	% Difference
Liver	Mean	3.10	1.67	46.1
	Maximum	11.98	6.16	48.6
	Minimum	0.00	0.40	
Right Lung	Mean	0.88	0.41	53.4
	Maximum	3.84	2.13	44.5
	Minimum	0.00	0.03	
Left Lung	Mean	0.92	0.43	53.3
	Maximum	3.68	1.72	53.3
	Minimum	0.00	0.04	

Monte Carlo Method for Proton Therapy

MARYLAND PROTON TREATMENT CENTER
AFFILIATED WITH UNIVERSITY OF MARYLAND MARLENE AND STEWART GREENEBAUM COMPREHENSIVE CANCER CENTER

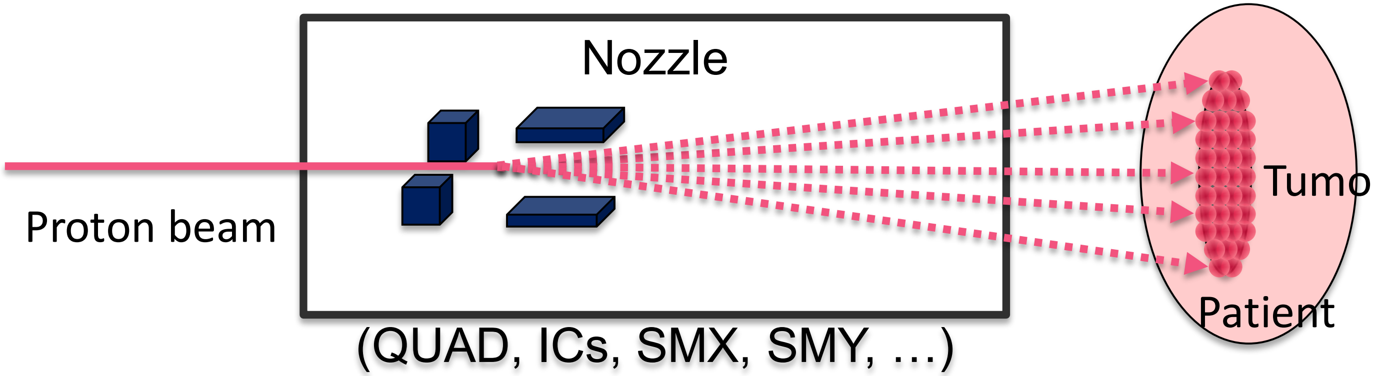
Varian ProBeam (pencil beam scanning)



TOPAS MC code

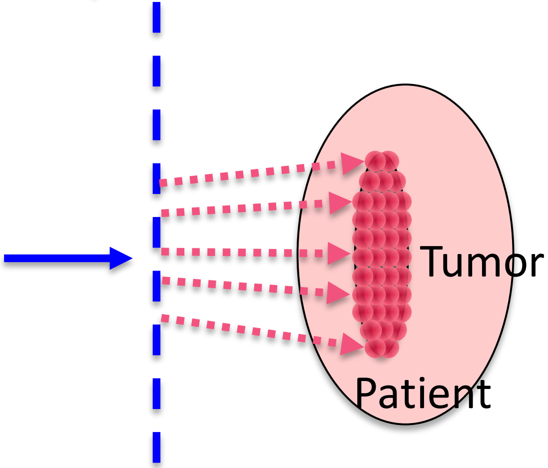
*Yeom et al., *JRP* (submitted)

Pencil Beam Scanning (PBS) MC Modeling



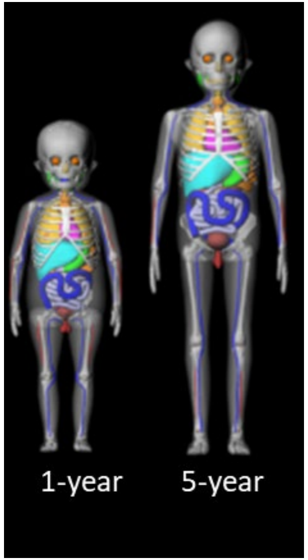
Beam measurement data
- Spot profile
- Integral depth dose

Spot properties
- Mean energy (E_0)
- Energy spread (σ_E)
- Spot size (σ_x, σ_y)
- Divergence (σ_θ, σ_ϕ)

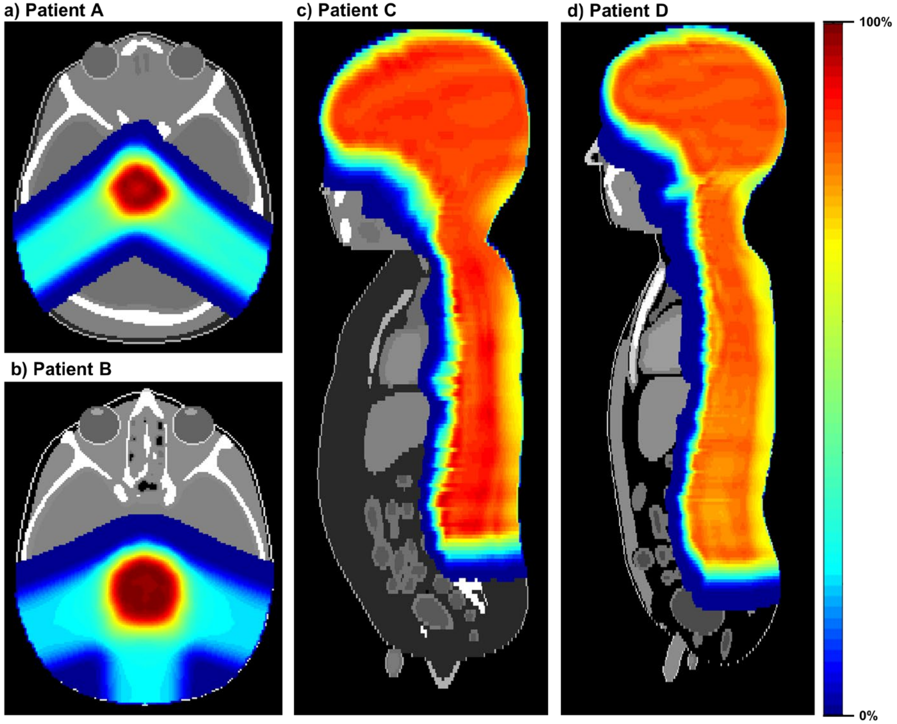


*Yeom et al., *JRP* (submitted)

Example Dose Calculations for PBS Irradiations



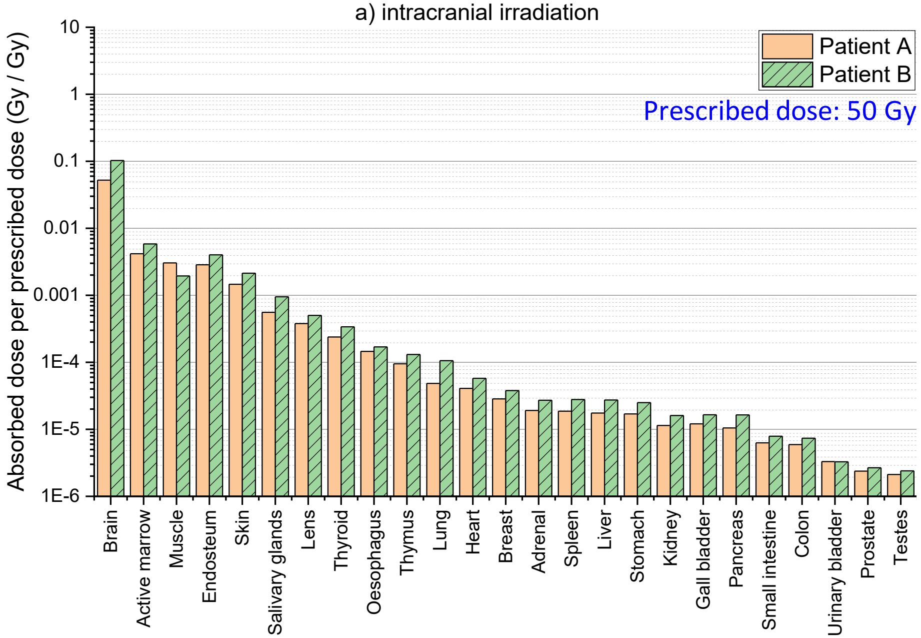
Pediatric phantoms

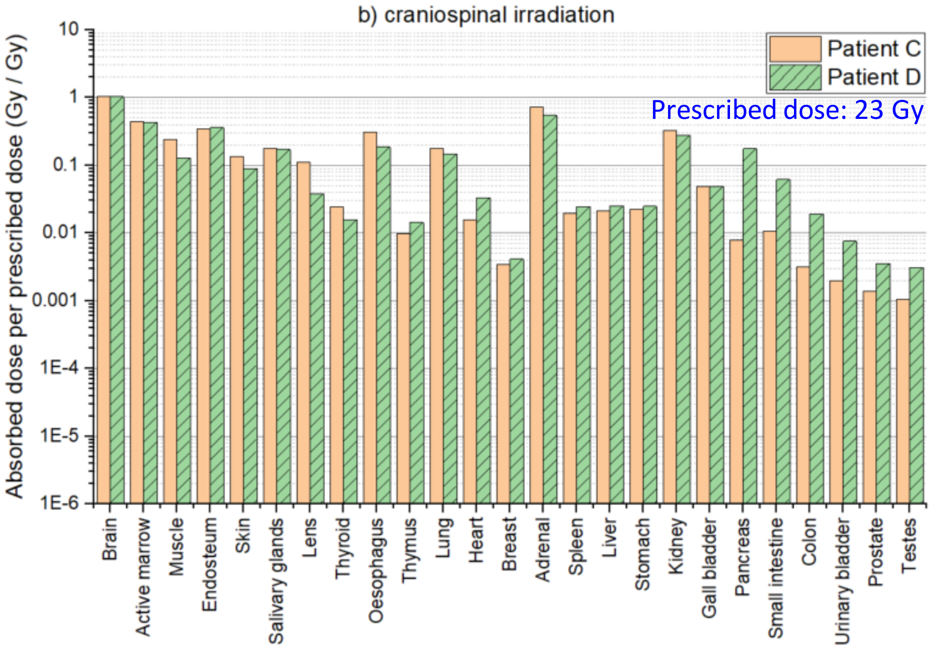


Proton irradiations planned by MPTC TPS

*Yeom et al., *JRP* (submitted)

Example Dose Calculations for PBS Irradiations





*Yeom et al., *JRP* (submitted)

Can we use the MC PBS model for other proton centers (machines) in patient dose reconstruction?

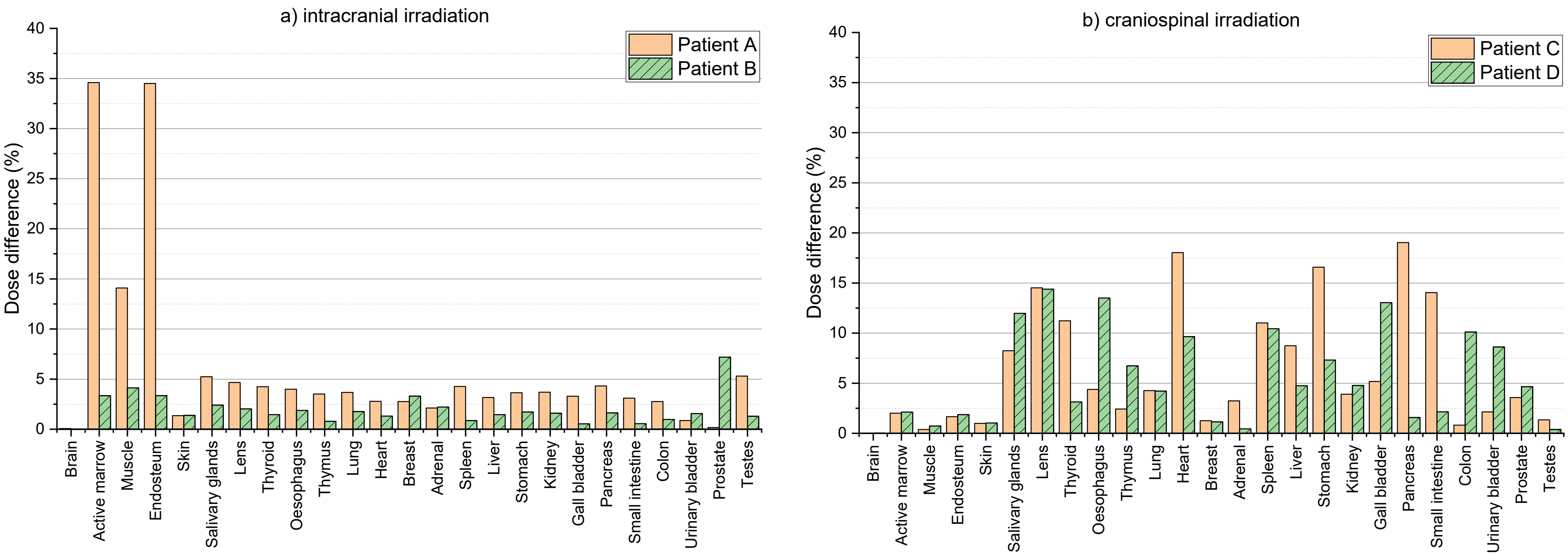
Simplified MC model

- Energy spread = 0
- Spot size = 0
- Divergence = 0

How will organ/tissue doses change?

*Yeom et al., *JRP* (submitted)

Dose Differences (MPTC vs Simplified)



Variation of beam characteristics in different machines **would not significantly affect** patient dose reconstruction.

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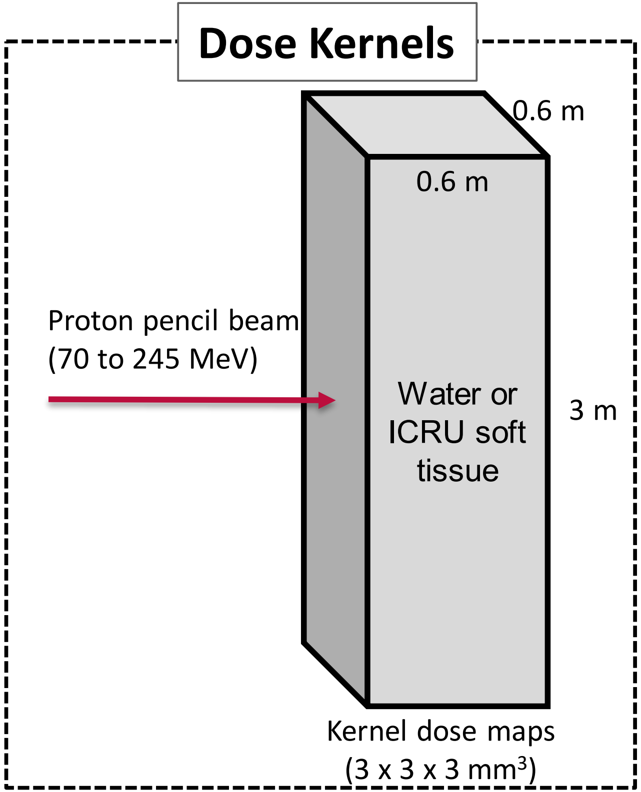
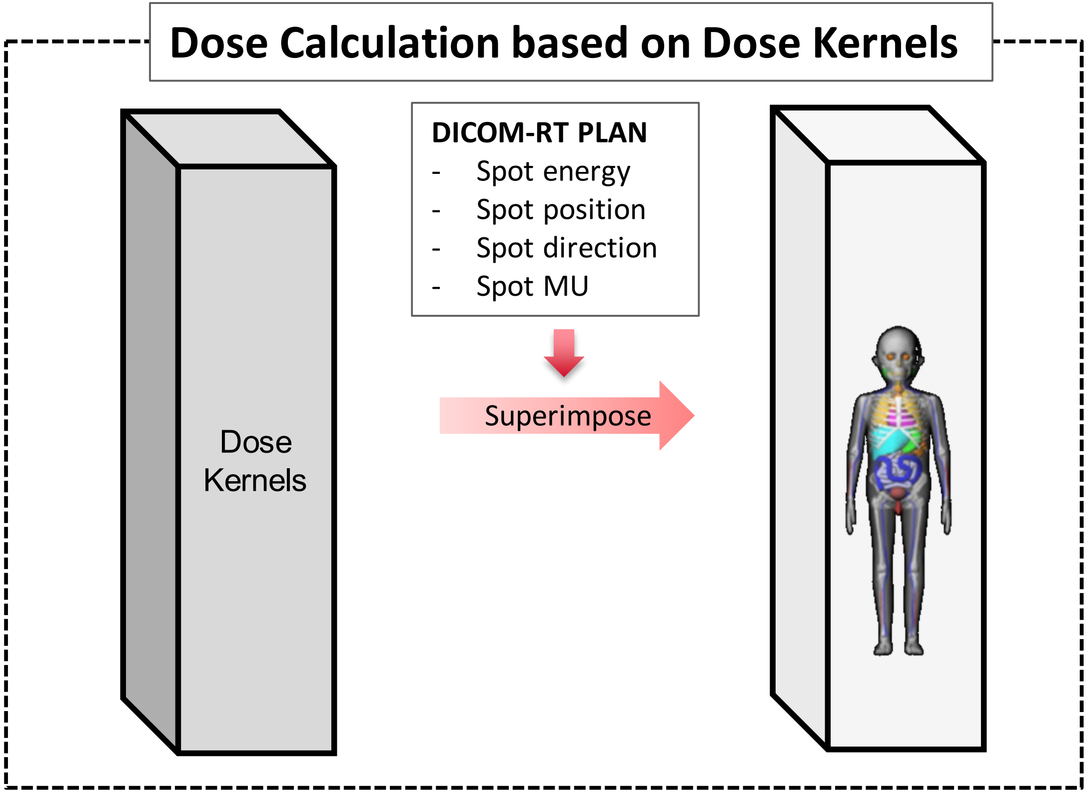
*Yeom et al., *JRP* (submitted)

Issue on Computation Speed

About 2 days for one patient calculation using 1500 CPU cores (3000 threads) on an NIH's Biowulf cluster (i.e., about 10 years using a single CPU core)

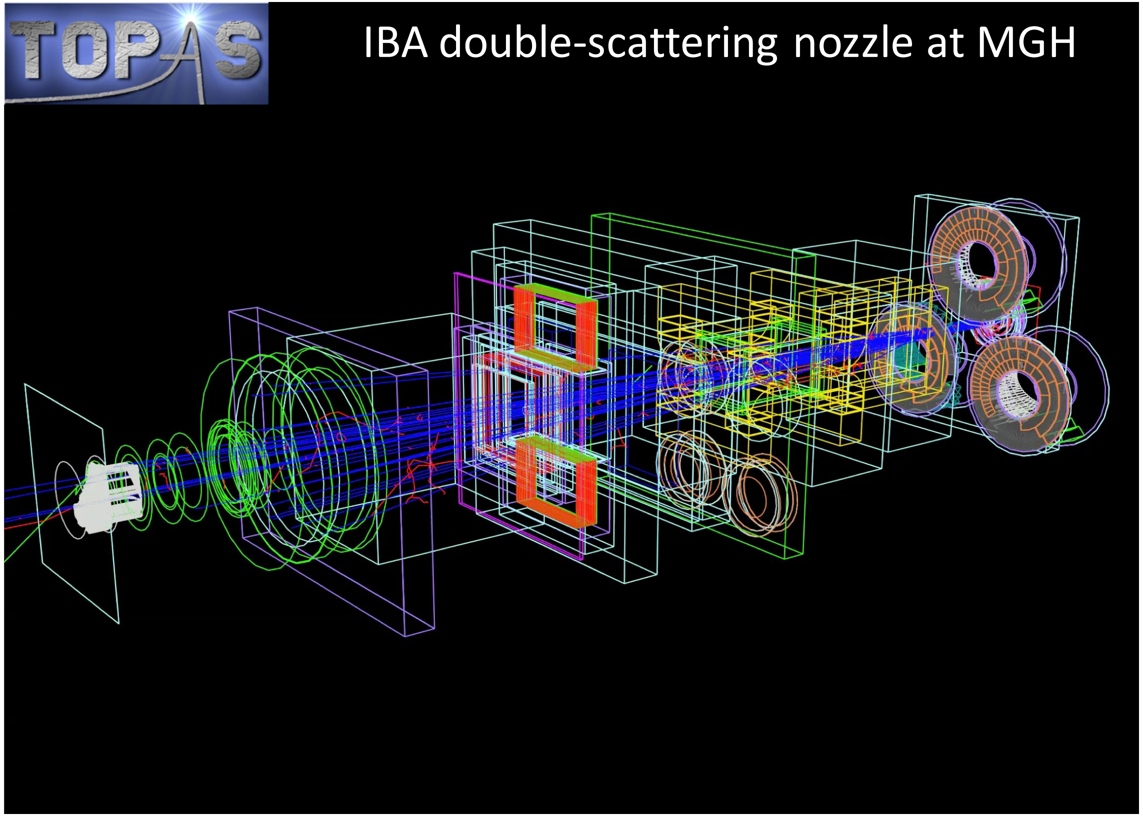
Dose Kernel Based Method for PBS





*Yeom et al. (in preparation)

Passive Scattering (PS) MC Modeling

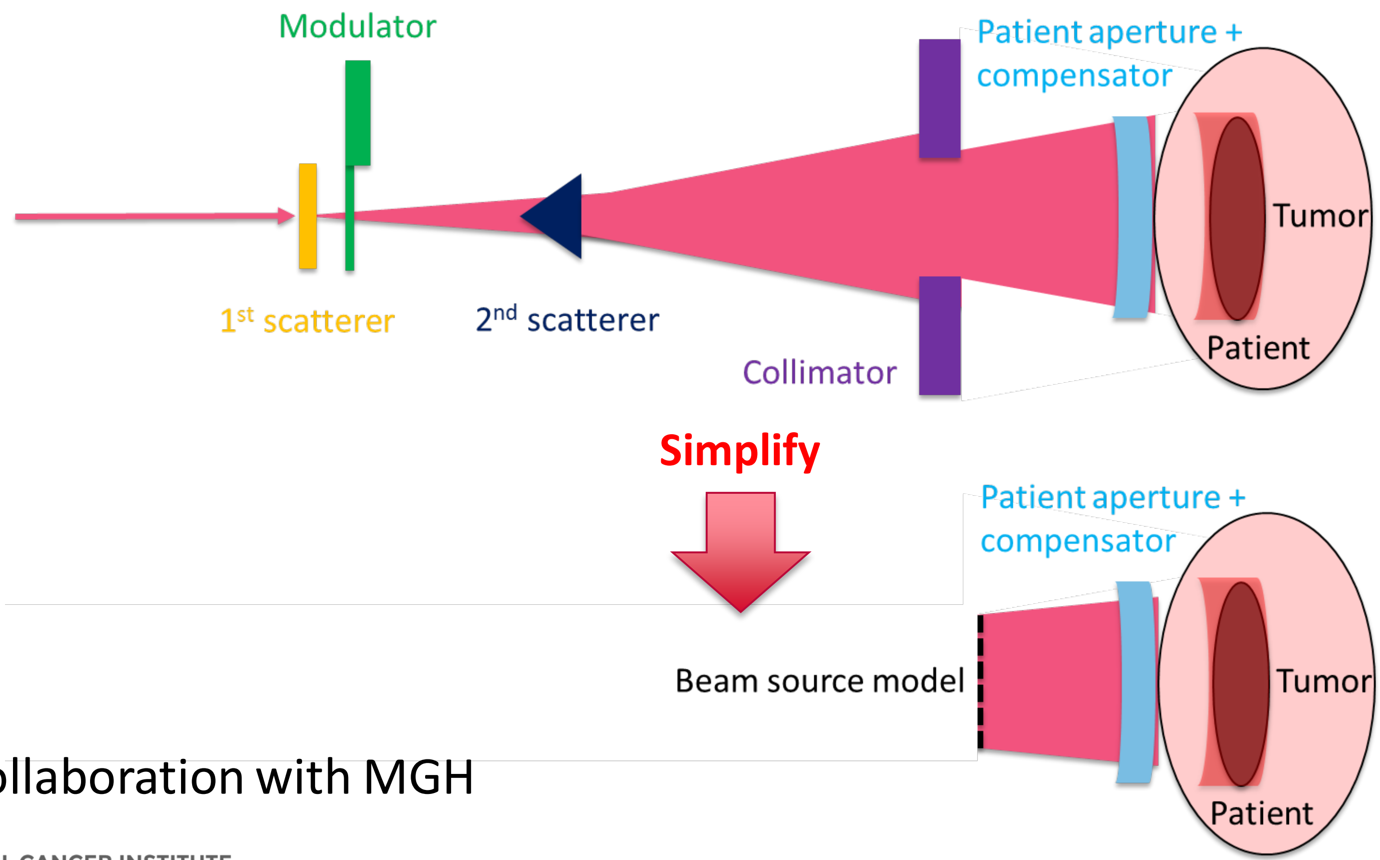


*Jung et al. *PMB* 2012

Challenges on PS Patient Dose Reconstruction

- A PS nozzle has many components (modulator, scatters, collimator, compensator, aperture, etc.).
- A PS nozzle highly depends on proton centers/machines (IBA, HITACHI, Sumitomo).
- Compensators and apertures are patient specific.

Generic PS Nozzle Modeling



In collaboration with MGH

Summary

- A great dosimetry benefit for emerging radiotherapy due to DICOM-RT
- Limitations of DICOM-RT
  - ✓ Cover a partial body of clinical interest
  - ✓ Focus on in-field dose.
- Patient anatomy models
  - ✓ Segmentation of organs/tissues of interest
  - ✓ Patient anatomy prediction
- Dose calculation methods
  - ✓ Analytical method (fast) / Monte Carlo method (accurate)
  - ✓ Generic dose calculation method

Quiz#1: Emerging radiotherapy can result in zero dose to normal tissues.

- A. True
- B. False

Quiz#1: Emerging radiotherapy can result in zero dose to normal tissues.

- A. True
- B. False

Quiz#2: Emerging radiotherapy always results in lower dose to normal tissues compared to conventional radiotherapy.

- A. True
- B. False

Quiz#2: Emerging radiotherapy always results in lower dose to normal tissues compared to conventional radiotherapy.

- A. True
- B. False

Quiz#3: What is the radiation source of normal tissue dose for radiotherapy patient?

- A. Leakage radiation from machine head
- B. Scatter radiation from beam collimation
- C. Scatter radiation from the patient him/herself
- D. All of the above

Quiz#3: What is the radiation source of normal tissue dose for radiotherapy patient?

- A. Leakage radiation from machine head
- B. Scatter radiation from beam collimation
- C. Scatter radiation from the patient him/herself
- D. All of the above

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