**Invited plenary talk on April 13, 2022**
**2022 annual meeting of**
**the Council on Ionizing Radiation Measurements and Standards (CIRMS)**

# Radiotherapy Plan QA using Deep-CNN based Multi-OAR Autosegmentation and GPU-accelerated Monte Carlo Dose Check

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中国科学技术大学
University of Science and Technology of China

# Disclosures:

Developer of commercial software tools:

VirtualDose™ CT
A product of Virtual Phantoms, Inc.

VIRTUAL PHANTOMS, INC.

https://www.virtual-dose.com

**DeepViewer**

ARCHER

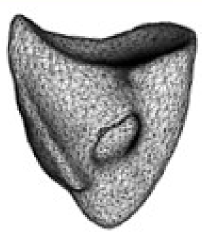
DeePPLAN

Wisdom Tech

http://www.wisdom-tech.online/

# Outline of the presentation

**Anatomical Modeling Tool**



**Dose Reporting Tool**

VirtualDose

**Organ Segmentation Tool**

**Deep Viewer**

**Dose Computing Tool**

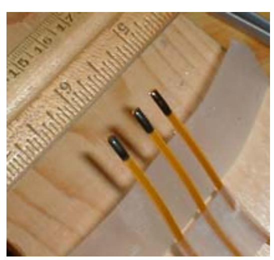
ARCHER

Over the years, we have developed a number of major software tools

# Two Ways to Determine Organ Doses

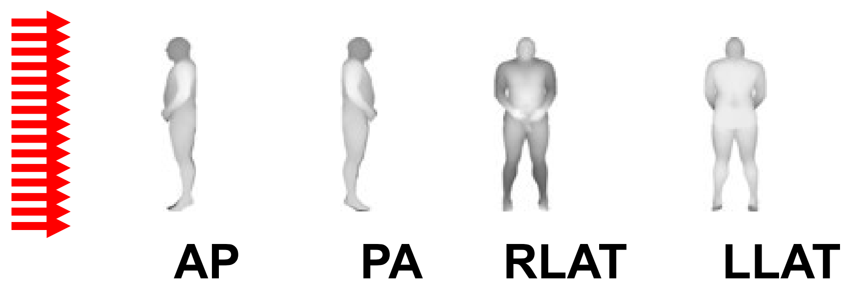
## Measurements

- Dosimeters
- Physical phantom



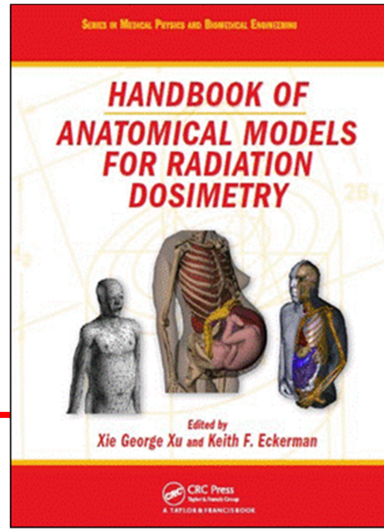
## Monte Carlo Simulations

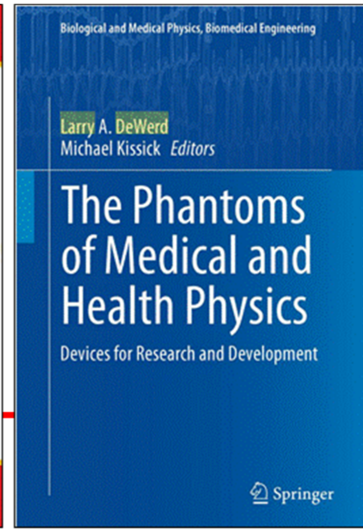
- Computational phantoms
- Monte Carlo codes

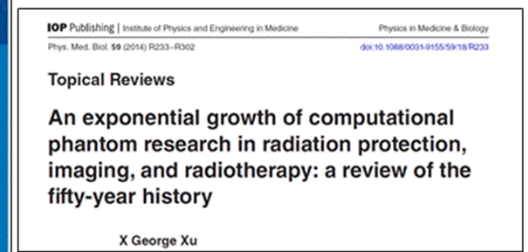


# 60-Year History of Computational Phantoms

- **Radiation Protection**
- **Medical Imaging**
- **Radiotherapy**





IOP Publishing | Institute of Physics and Engineering in Medicine    Physics in Medicine & Biology

Phys. Med. Biol. 59 (2014) R233–R302    doi:10.1088/0031-9155/59/18/R233

Topical Reviews

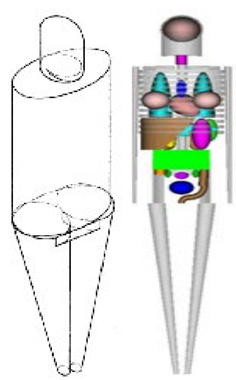
**An exponential growth of computational phantom research in radiation protection, imaging, and radiotherapy: a review of the fifty-year history**

X George Xu

**1st Generation**
STYLIZED

**2nd Generation**
VOXEL

**3rd Generation**
BREP



ORNL family models
1960-1980s

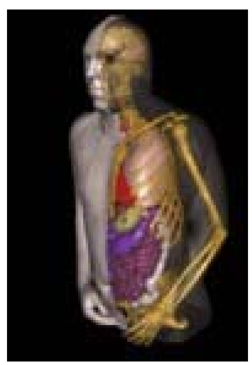
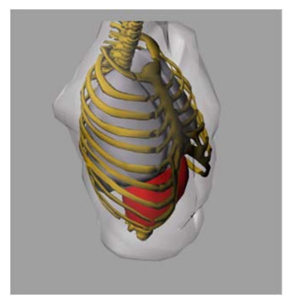


Image-based
1980s-present



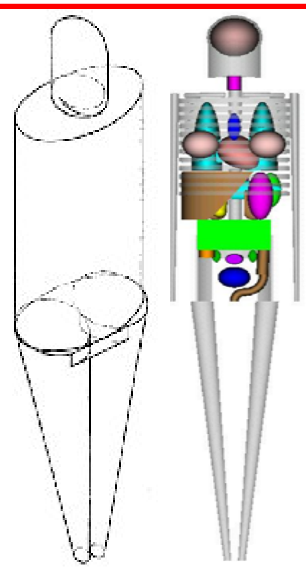
Deformable 4D models
2000s-present

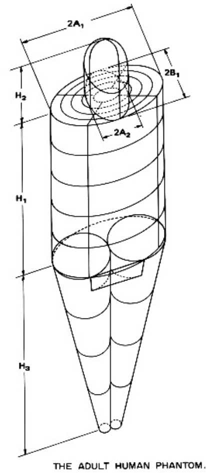
- Personalization
- Multi-scale (voxel – DNA)

# 1st-Generation "Stylized" Phantoms

**(Society of Nuclear Medicine's MIRD Committee)**

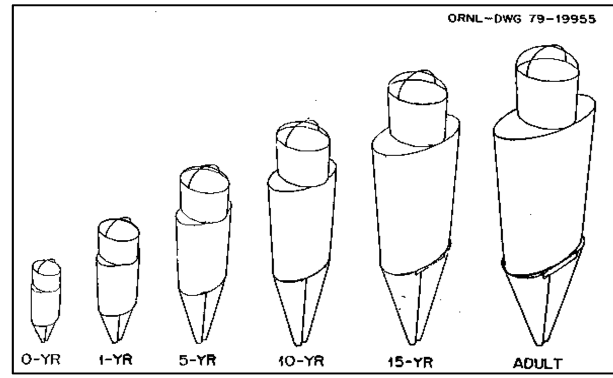
***Anatomically simple and friendly for computers prior to 1980s***



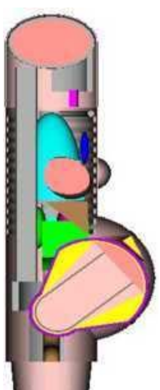



**PHANTOM DIMENSIONS AND DOSE REGIONS**

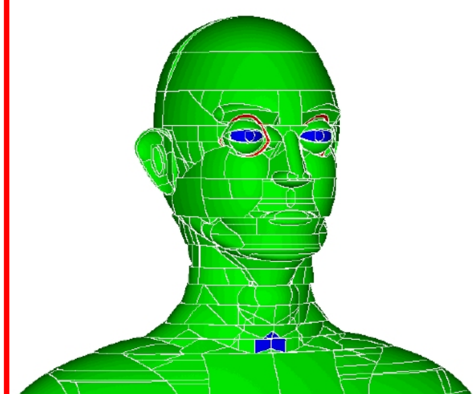
| Age (yr) | Weight (kg) | $H_1$ (cm) | $H_2$ (cm) | $H_3$ (cm) | $A_1$ (cm) | $B_1$ (cm) | $A_2$ (cm) |
|---|---|---|---|---|---|---|---|
| 0 | 3.148 | 23 | 13 | 16 | 5.5 | 5 | 4.5 |
| 1 | 9.112 | 33 | 16 | 28.8 | 8 | 7 | 6.5 |
| 5 | 18.12 | 45 | 20 | 46 | 11 | 7.5 | 6.5 |
| 10 | 30.57 | 54 | 22 | 64 | 14 | 8 | 6.5 |
| 15 | 53.95 | 65 | 23 | 78 | 18 | 9 | 7 |
| Adult | 69.88 | 70 | 24 | 80 | 20 | 10 | 7 |



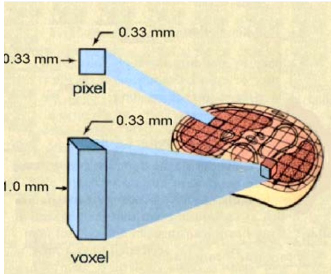

**Snyder *et al* (1978), Cristy (1980), and Cristy and Eckerman (1987), plus ADAM/Eva phantoms by Kramer et al (1982) from Germany**



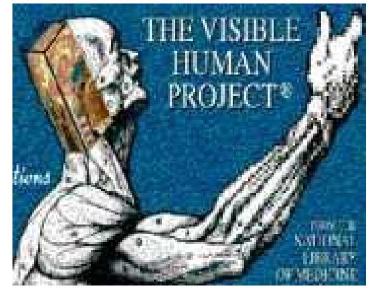
At the end of each trimester of pregnancy (**Stabin *et al* 1995**)



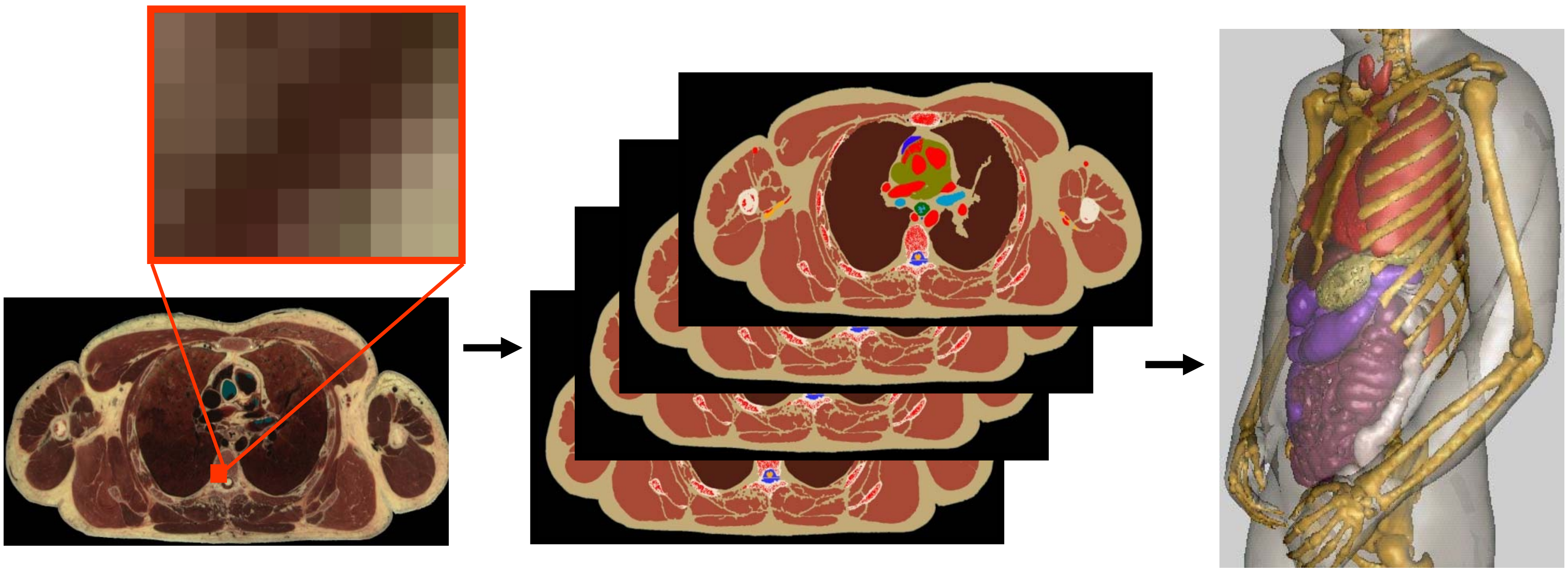
- The Computational Anatomical Man (CAM) and
- CAF (Computerized Anatomical Female)
- by **Billings and Yucker (1973)**
- Used exclusively by NASA




# $2^{nd}$-Generation "Voxel" Phantoms - Example of the VIP-Man (1997-2000)




**Xu XG, Chao TC, Bozkurt A. VIP-Man: An image-based whole-body adult male model constructed from color photographs of the Visible Human Project for multi-particle Monte Carlo calculations. <u>Health Phys</u>., 78(5):476-486, 2000.** ***One of the most cited (450+)***



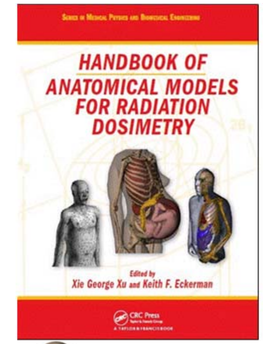
**Identification of organs in each slice of a 2D pixel map**

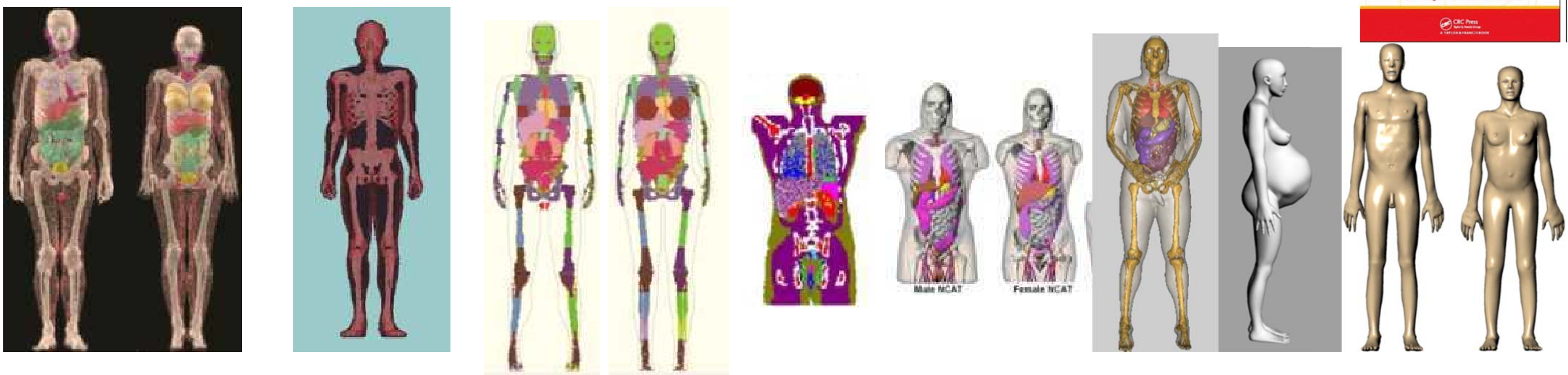
**Registration of all slices**

**Finished 3D voxel VIP-Man**

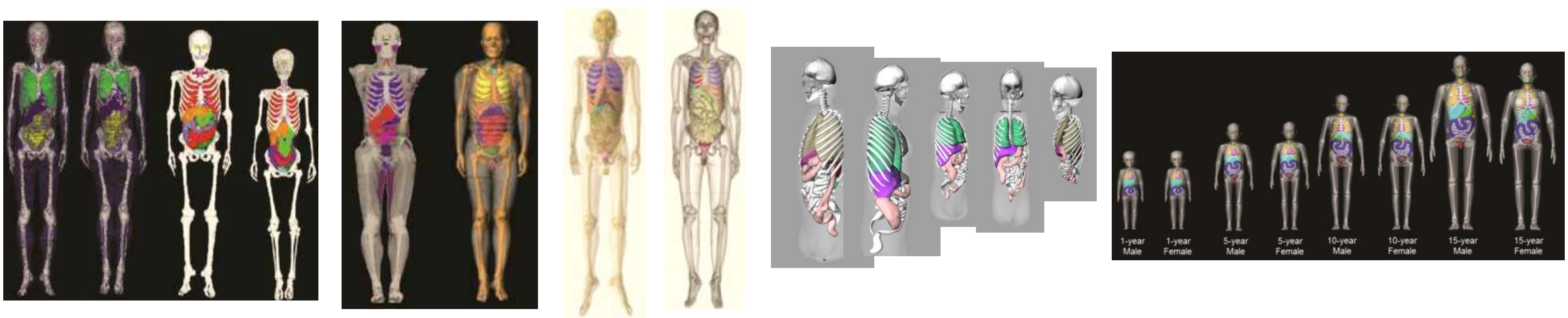
***At the time, organ segmentation was done manually***

# <<Handbook of Anatomical Models for Radiation Dosimetry>> by Xu and Eckerman 2009 *– curtsey images*




REX & REGINA (ICRP) NORMAN MAX06 FAX06 Zubal NCAT VIP-Man, Pregnant, Adult M/F




Otoko Onago JM KF KTMAN 1, 2 CNMAN VCH Vanderbilt Family UF Family

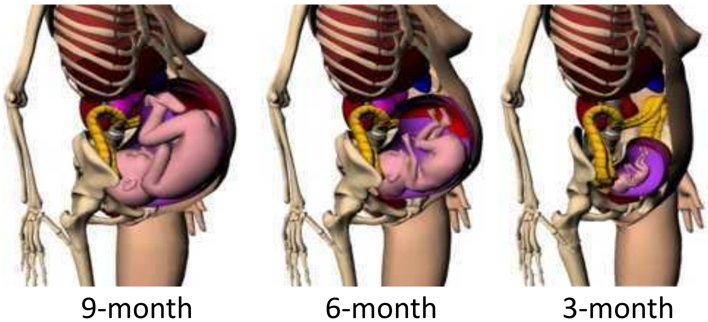
***At the time, organ segmentation was done manually***

# 3rd-Generation "BREP" Phantoms (NURBS or Meshes)

## Pregnant Phantoms

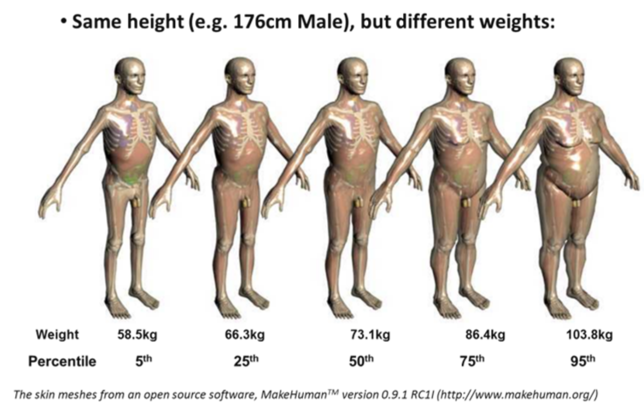
**Xu X G, Taranenko V, Zhang J, Shi C. A boundary-representation method for designing whole-body radiation dosimetry models: pregnant females representing three gestational periods, RPI-P3, -P6 and –P9. Phys. Med. Biol. (2007)**

***The Best 10 papers by PBM in 2007***




## Size and Weight Adjustable Phantoms

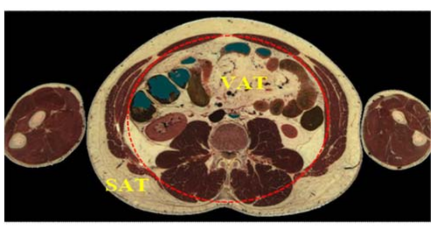
**Na YH, Zhang* B, Zhang* J, Caracappa PF, Xu XG. Deformable Adult Human Phantoms for Radiation Protection Dosimetry: Anatomical Data for Covering 5th- 95th Percentiles of the Population and Software Algorithms. Phys. Med. Biol. 55: 3789-3811 (2010).**



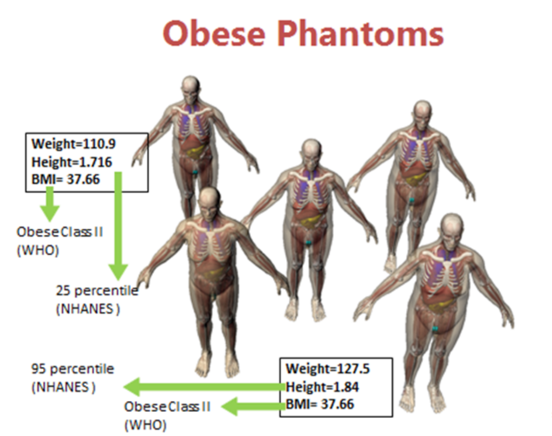

## Obese Individuals

**Ding A, Mille MM, Liu T, Caracappa PF and Xu XG. Phys. Med. Biol. 57:2441–2459 (2012).**

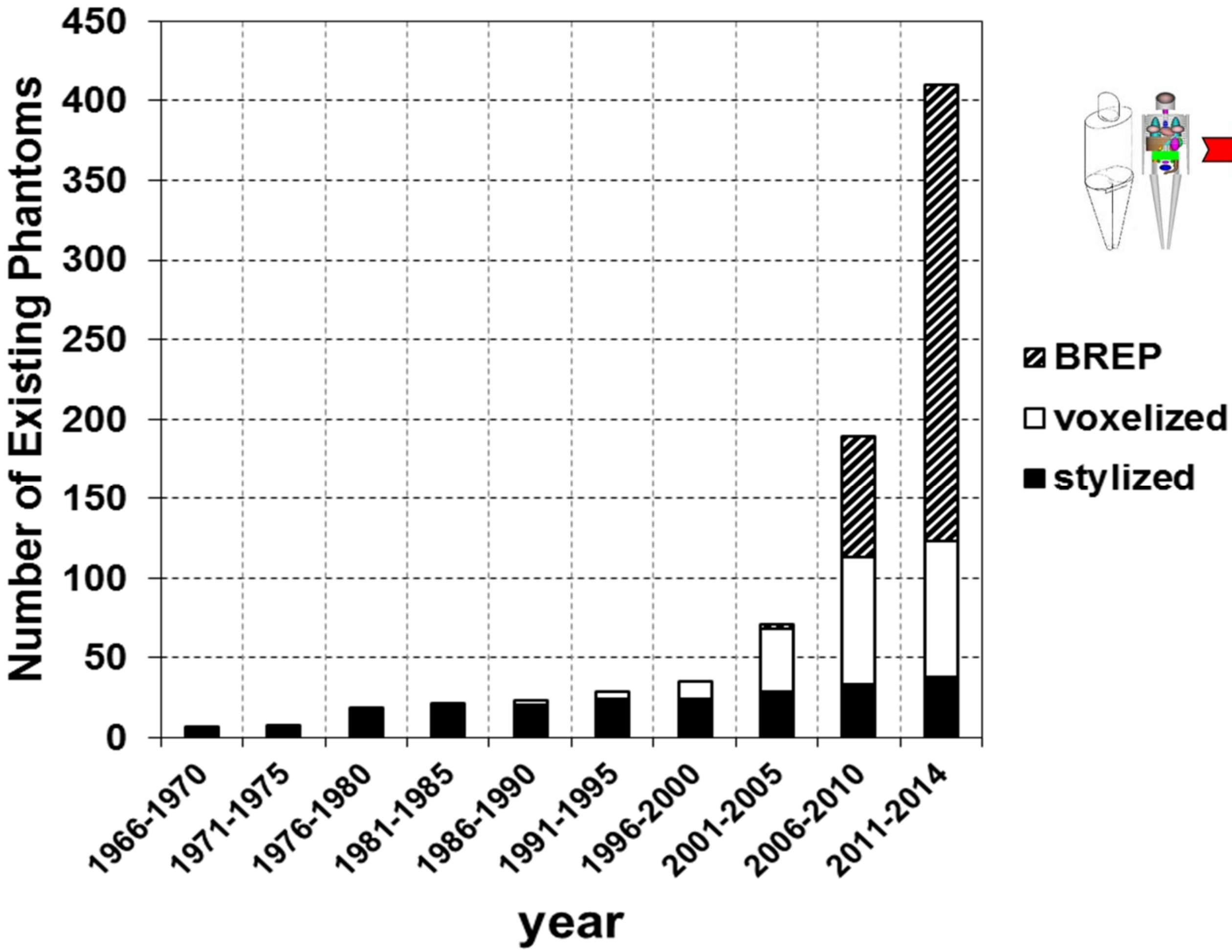
***One of the most downloaded in 2012***




| Weight Category | BMI |
|---|---|
| Underweight | < 18.5 |
| Normal Weight | 18.5-24.9 |
| Overweight | 25-29.9 |
| Obese (I, II) | 30-34.9, 34.9-39.9 |
| Morbidly Obese | >40 |

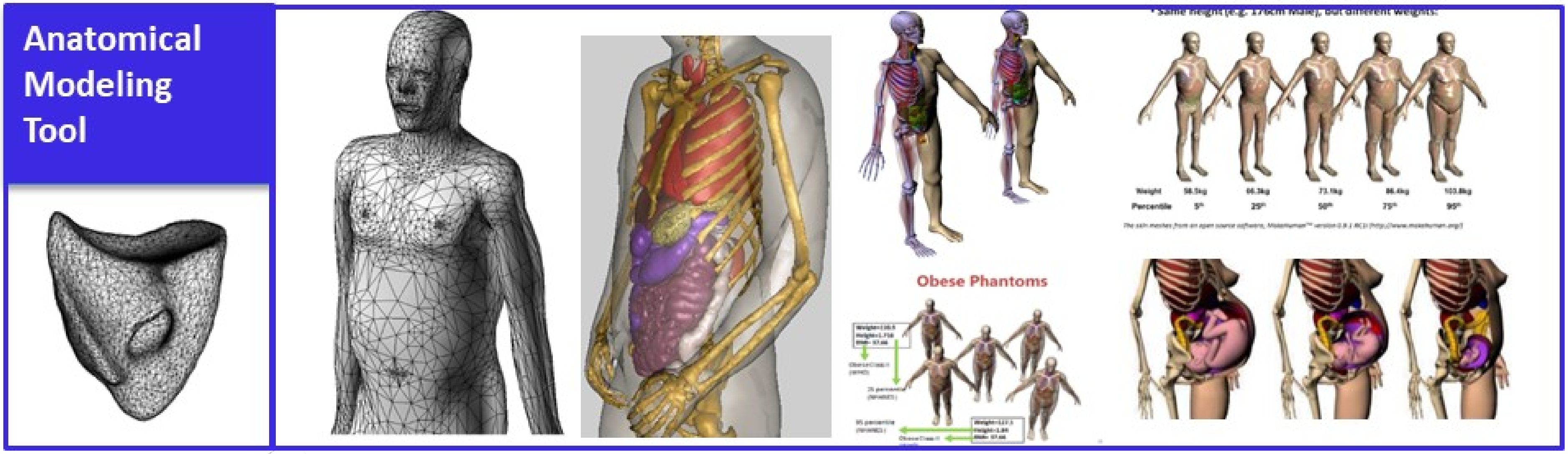


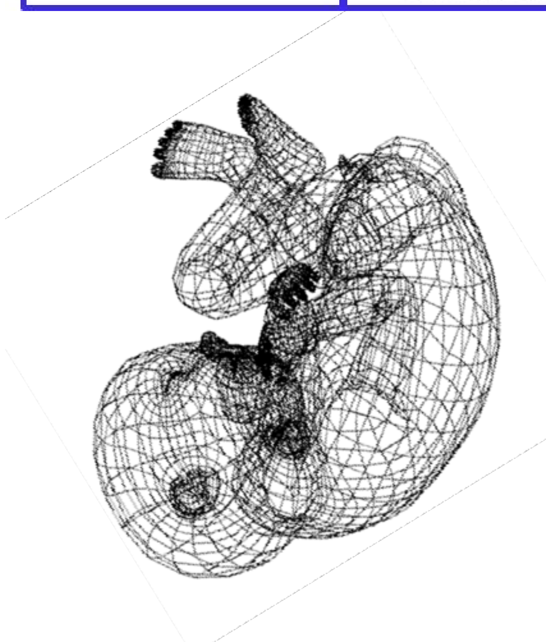
# The number of phantoms in existence since 1966 shows a surprising exponential growth

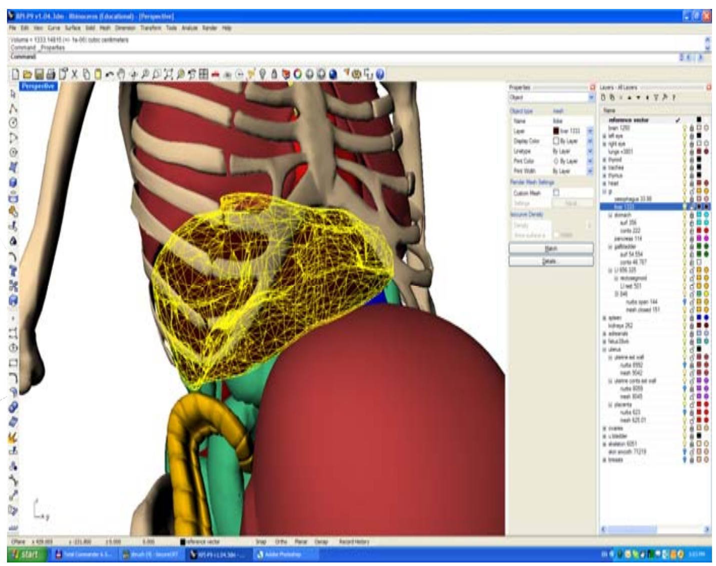


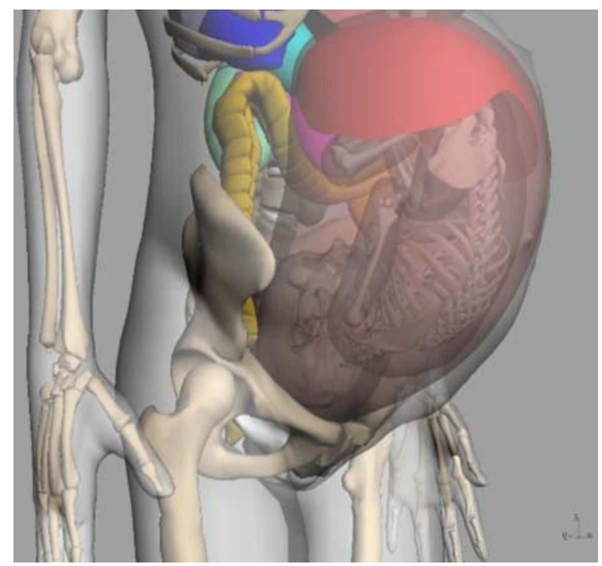

**X. George Xu, "An exponential growth of computational phantom research in radiation protection, imaging, and radiotherapy: a review of the fifty-year history," Physics in Medicine & Biology, 59(R233-R302) 2014.**

# Patient geometric modeling tools

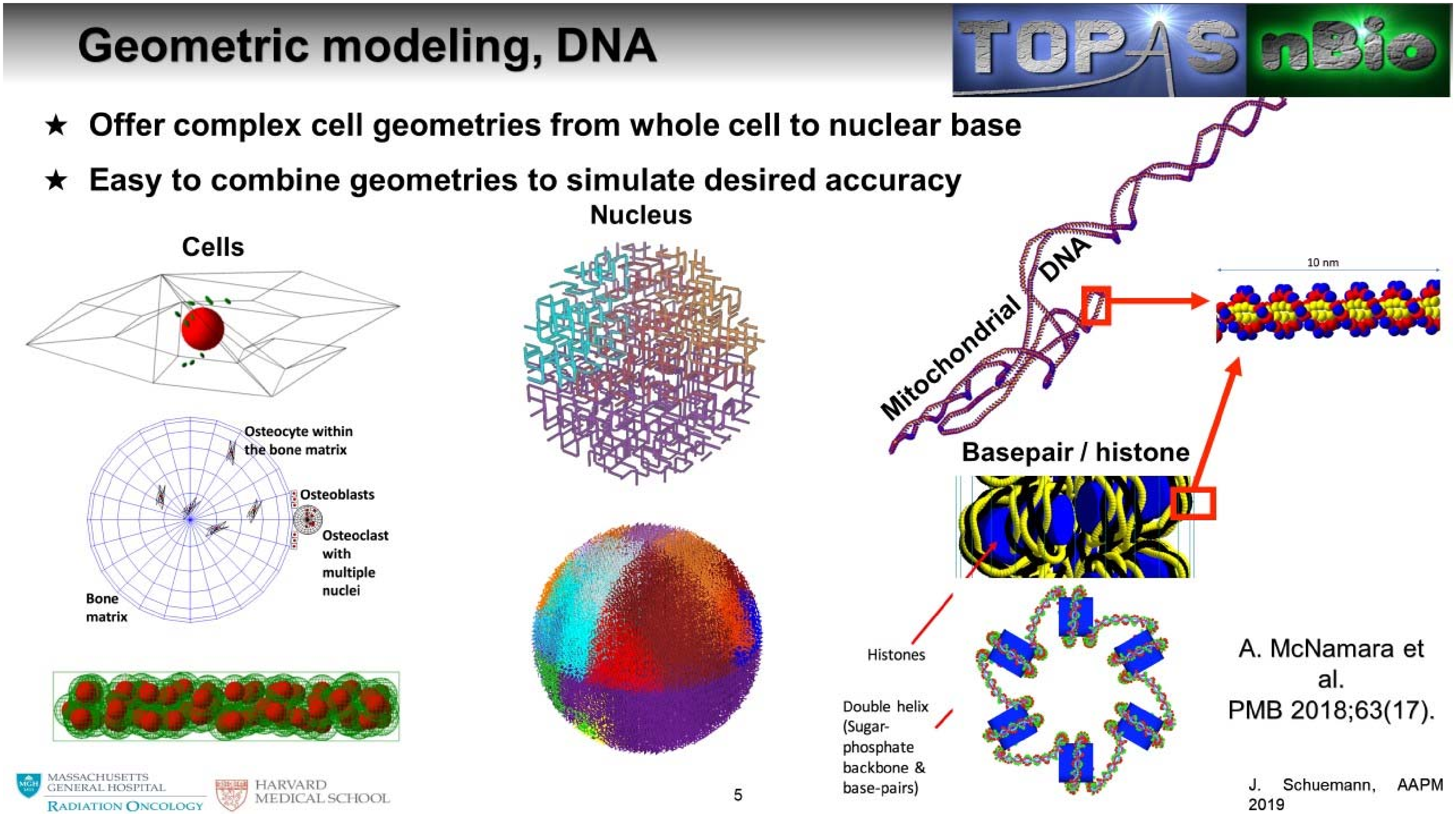






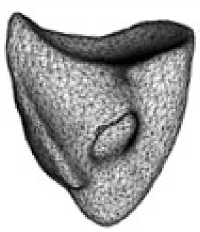
# Future Radiobiological Predictive Modeling at Multi-Scale
# - To Bridge the Gap Between Voxel and DNA




Courtesy slide from Jan Schuemann

# Outline of the presentation

**Anatomical Modeling Tool**



**Dose Reporting Tool**

VirtualDose

**Organ Segmentation Tool**

**Deep Viewer**

**Dose Computing Tool**

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# Cancer risks of pediatrics from CT
# *by Pearce, et al. Lancet 2012*

- 178,604 young patients
- CT scans from 1985 -2002
- 81 hospitals in Great Britain
- Cancer data from 1985 - 2008

| | Male patients | | Female patients | |
|---|---|---|---|---|
| | Brain dose (mGy) | Red bone marrow dose (mGy) | Brain dose (mGy) | Red bone marrow dose (mGy) |
| **Age at brain CT** | | | | |
| 0 years | 28 | 8 | 28 | 8 |
| 5 years | 28 | 9 | 28 | 9 |
| 10 years | 35 | 6 | 35 | 6 |
| 15 years | 43 | 4 | 44 | 6 |
| 20 years | 35 | 2 | 42 | 2 |
| **Age at chest CT** | | | | |
| 0 years | 0·4 | 4 | 0·4 | 4 |
| 5 years | 0·3 | 3 | 0·3 | 3 |
| 10 years | 0·3 | 3 | 0·3 | 3 |
| 15 years | 0·2 | 4 | 0·3 | 4 |
| 20 years | 0·2 | 4 | 0·3 | 4 |
| **Age at abdominal CT** | | | | |
| 0 years | 0·2 | 3 | 0·2 | 3 |
| 5 years | 0·1 | 2 | 0·1 | 2 |
| 10 years | 0·1 | 3 | 0·1 | 3 |
| 15 years | 0·0 | 3 | 0·0 | 3 |
| 20 years | 0·0 | 3 | 0·0 | 4 |
| **Age at extremity CT** | | | | |
| 0 years | 0·0 | 1 | 0·0 | 1 |
| 5 years | 0·0 | 0·2 | 0·0 | 0·2 |
| 10 years | 0·0 | 0·1 | 0·0 | 0·1 |
| 15 years | 0·0 | 0·0 | 0·0 | 0·0 |
| 20 years | 0·0 | 0·0 | 0·0 | 0·0 |

*Table 1:* Estimated radiation doses to the brain and red bone marrow from one CT scan, by scan type, sex, and age at scan, as used in this study for scans after 2001

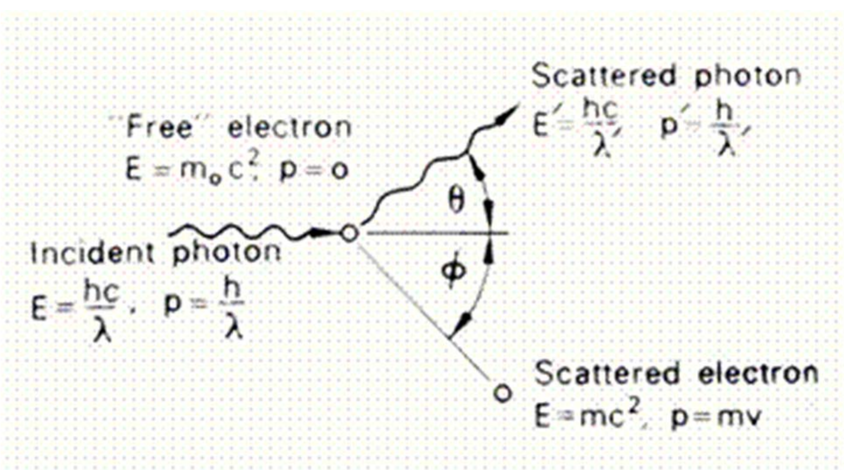
# Radiation Physics for CT Scans

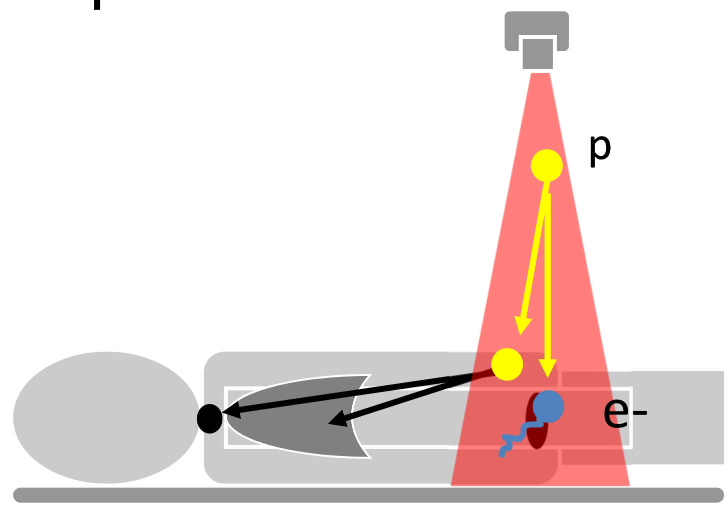
## X-ray photon interactions (< 160 keV)

✓ **Photoelectric effect**

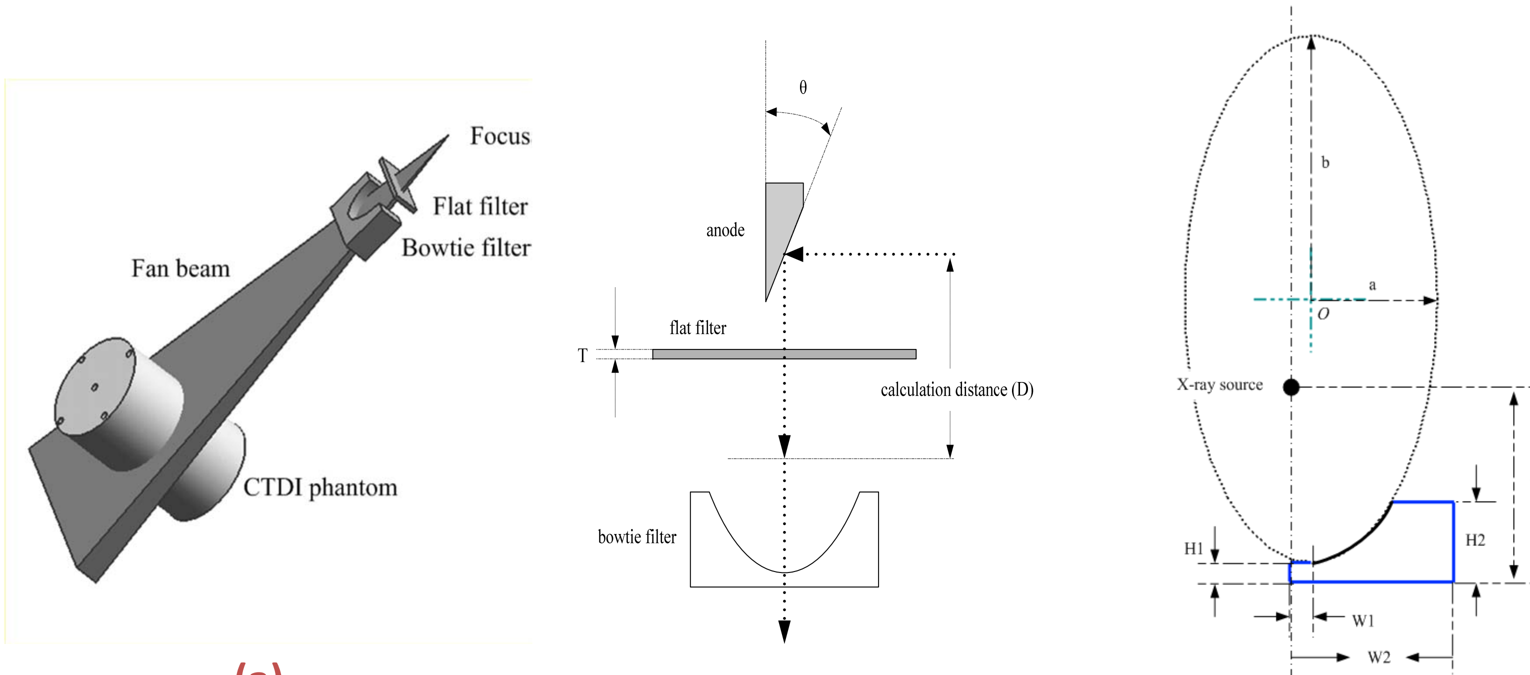
✓ **Compton scattering**

$$E_{pe} = hf - \phi$$



# Method: CT Scanner modeling methodology




(a) (b) (c)

Ding A, Gao Y, Liu H , Caracappa PF, Long DJ, Bolch WE, Liu Bob, Xu XG. VirtualDose: A New CT Dose Reporting Software for Adult and Pediatric Patients. Phys. Med. Biol. 60(14):5601-5625 (2015).

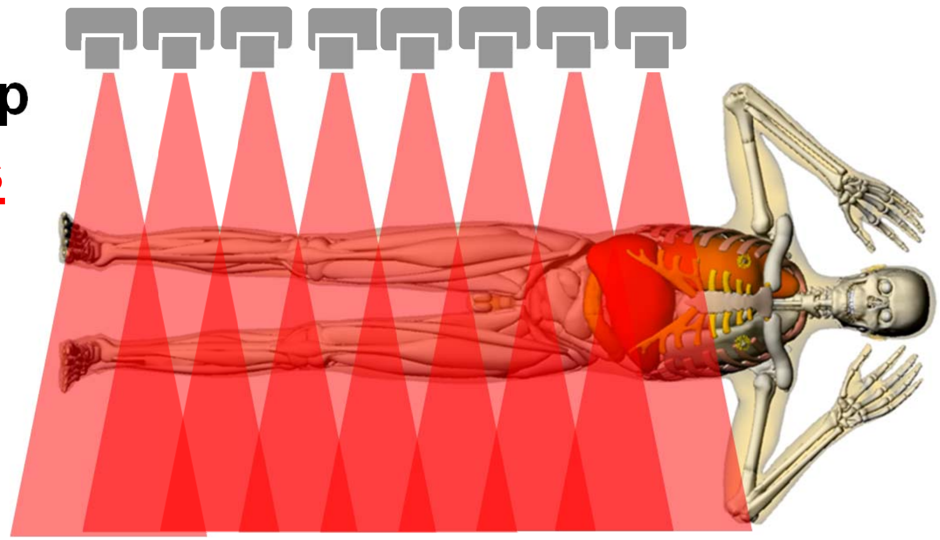
# A Comprehensive Slice-by-slice Organ Dose Database

VirtualDose™ CT
A product of Virtual Phantoms, Inc.

http://www.virtual-dose.com

- **Axial scan simulations in MCNPX**
- **Contiguous scans from the top to the bottom of 27 phantoms**
- CT technical parameters

  -4 different tube voltages: 80, 100, 120, and 140 kVp
  -4 different beam collimations: 1.25, 5, 10 and 20 mm
  -Using both the head and body bowtie filters



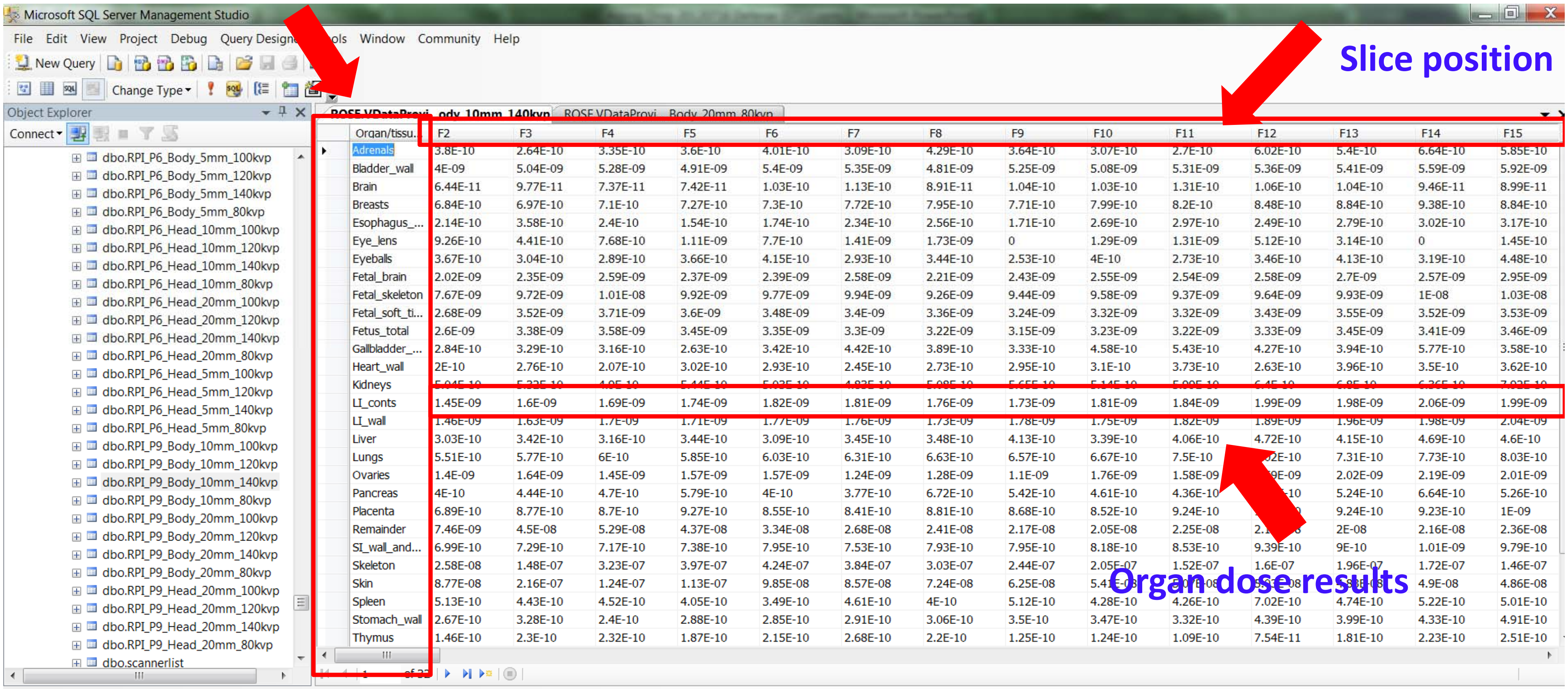
**Ding A, Gao Y, Liu H , Caracappa PF, Long DJ, Bolch WE, Liu Bob, Xu XG. VirtualDose: A New CT Dose Reporting Software for Adult and Pediatric Patients. Phys. Med. Biol. 60(14):5601-5625 (2015).**

# Database Hosted in SQL Data Server

VirtualDose™ CT
A product of Virtual Phantoms, Inc.

http://www.virtual-dose.com

Organ name



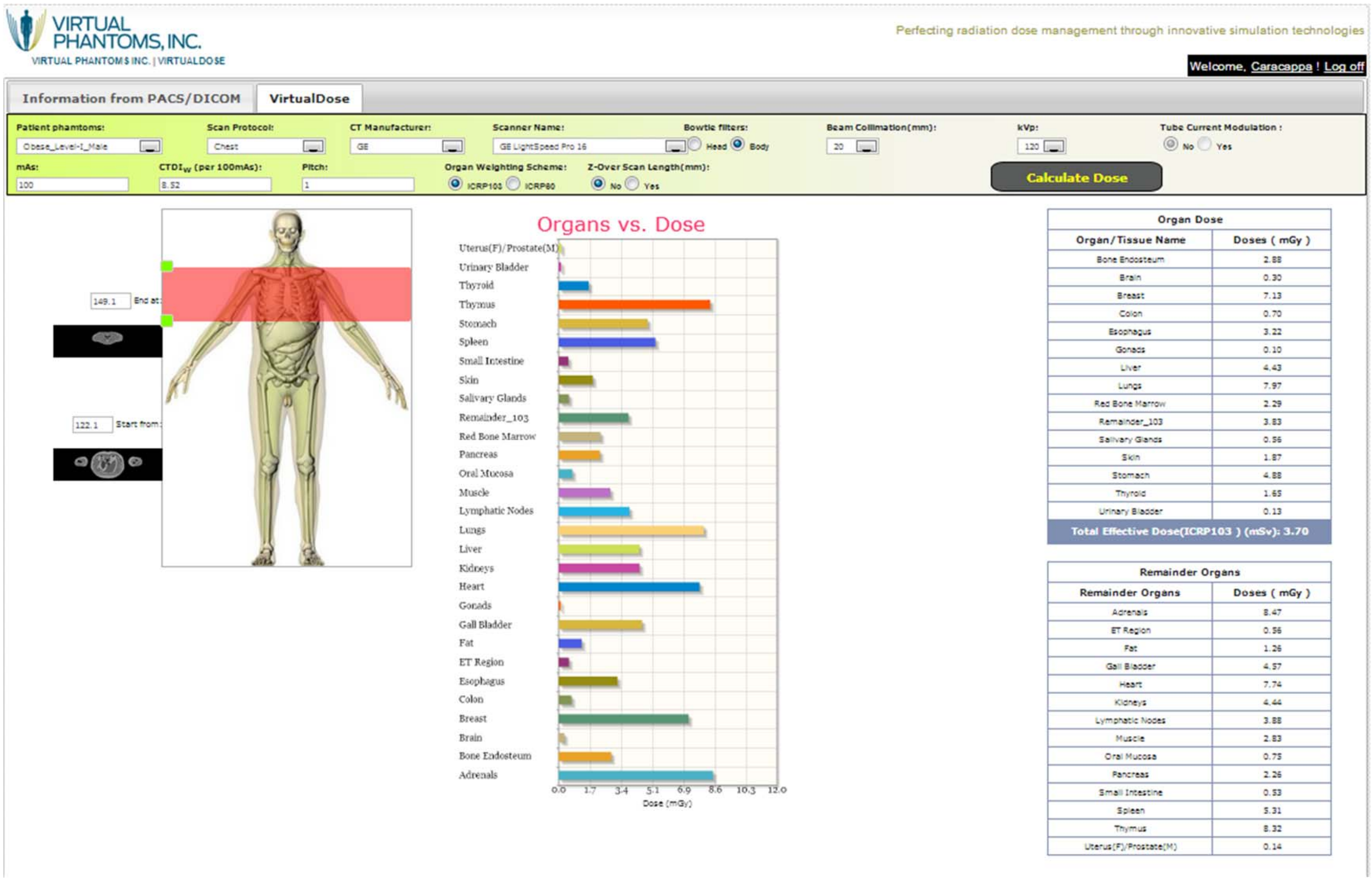

| Organ/tissu... | F2 | F3 | F4 | F5 | F6 | F7 | F8 | F9 | F10 | F11 | F12 | F13 | F14 | F15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Adrenals | 3.8E-10 | 2.64E-10 | 3.35E-10 | 3.6E-10 | 4.01E-10 | 3.09E-10 | 4.29E-10 | 3.64E-10 | 3.07E-10 | 2.7E-10 | 6.02E-10 | 5.4E-10 | 6.64E-10 | 5.85E-10 |
| Bladder_wall | 4E-09 | 5.04E-09 | 5.28E-09 | 4.91E-09 | 5.4E-09 | 5.35E-09 | 4.81E-09 | 5.25E-09 | 5.08E-09 | 5.31E-09 | 5.36E-09 | 5.41E-09 | 5.59E-09 | 5.92E-09 |
| Brain | 6.44E-11 | 9.77E-11 | 7.37E-11 | 7.42E-11 | 1.03E-10 | 1.13E-10 | 8.91E-11 | 1.04E-10 | 1.03E-10 | 1.31E-10 | 1.06E-10 | 1.04E-10 | 9.46E-11 | 8.99E-11 |
| Breasts | 6.84E-10 | 6.97E-10 | 7.1E-10 | 7.27E-10 | 7.3E-10 | 7.72E-10 | 7.95E-10 | 7.71E-10 | 7.99E-10 | 8.2E-10 | 8.48E-10 | 8.84E-10 | 9.38E-10 | 8.84E-10 |
| Esophagus_... | 2.14E-10 | 3.58E-10 | 2.4E-10 | 1.54E-10 | 1.74E-10 | 2.34E-10 | 2.56E-10 | 1.71E-10 | 2.69E-10 | 2.97E-10 | 2.49E-10 | 2.79E-10 | 3.02E-10 | 3.17E-10 |
| Eye_lens | 9.26E-10 | 4.41E-10 | 7.68E-10 | 1.11E-09 | 7.7E-10 | 1.41E-09 | 1.73E-09 | 0 | 1.29E-09 | 1.31E-09 | 5.12E-10 | 3.14E-10 | 0 | 1.45E-10 |
| Eyeballs | 3.67E-10 | 3.04E-10 | 2.89E-10 | 3.66E-10 | 4.15E-10 | 2.93E-10 | 3.44E-10 | 2.53E-10 | 4E-10 | 2.73E-10 | 3.46E-10 | 4.13E-10 | 3.19E-10 | 4.48E-10 |
| Fetal_brain | 2.02E-09 | 2.35E-09 | 2.59E-09 | 2.37E-09 | 2.39E-09 | 2.58E-09 | 2.21E-09 | 2.43E-09 | 2.55E-09 | 2.54E-09 | 2.58E-09 | 2.7E-09 | 2.57E-09 | 2.95E-09 |
| Fetal_skeleton | 7.67E-09 | 9.72E-09 | 1.01E-08 | 9.92E-09 | 9.77E-09 | 9.94E-09 | 9.26E-09 | 9.44E-09 | 9.58E-09 | 9.37E-09 | 9.64E-09 | 9.93E-09 | 1E-08 | 1.03E-08 |
| Fetal_soft_ti... | 2.68E-09 | 3.52E-09 | 3.71E-09 | 3.6E-09 | 3.48E-09 | 3.4E-09 | 3.36E-09 | 3.24E-09 | 3.32E-09 | 3.32E-09 | 3.43E-09 | 3.55E-09 | 3.52E-09 | 3.53E-09 |
| Fetus_total | 2.6E-09 | 3.38E-09 | 3.58E-09 | 3.45E-09 | 3.35E-09 | 3.3E-09 | 3.22E-09 | 3.15E-09 | 3.23E-09 | 3.22E-09 | 3.33E-09 | 3.45E-09 | 3.41E-09 | 3.46E-09 |
| Gallbladder_... | 2.84E-10 | 3.29E-10 | 3.16E-10 | 2.63E-10 | 3.42E-10 | 4.42E-10 | 3.89E-10 | 3.33E-10 | 4.58E-10 | 5.43E-10 | 4.27E-10 | 3.94E-10 | 5.77E-10 | 3.58E-10 |
| Heart_wall | 2E-10 | 2.76E-10 | 2.07E-10 | 3.02E-10 | 2.93E-10 | 2.45E-10 | 2.73E-10 | 2.95E-10 | 3.1E-10 | 3.73E-10 | 2.63E-10 | 3.96E-10 | 3.5E-10 | 3.62E-10 |
| Kidneys | 5.04E-10 | 5.32E-10 | 4.9E-10 | 5.44E-10 | 5.03E-10 | 4.83E-10 | 5.08E-10 | 5.65E-10 | 5.14E-10 | 5.09E-10 | 6.4E-10 | 6.8E-10 | 6.36E-10 | 7.02E-10 |
| LI_conts | 1.45E-09 | 1.6E-09 | 1.69E-09 | 1.74E-09 | 1.82E-09 | 1.81E-09 | 1.76E-09 | 1.73E-09 | 1.81E-09 | 1.84E-09 | 1.99E-09 | 1.98E-09 | 2.06E-09 | 1.99E-09 |
| LI_wall | 1.46E-09 | 1.63E-09 | 1.7E-09 | 1.71E-09 | 1.77E-09 | 1.76E-09 | 1.73E-09 | 1.78E-09 | 1.75E-09 | 1.82E-09 | 1.89E-09 | 1.96E-09 | 1.98E-09 | 2.04E-09 |
| Liver | 3.03E-10 | 3.42E-10 | 3.16E-10 | 3.44E-10 | 3.09E-10 | 3.45E-10 | 3.48E-10 | 4.13E-10 | 3.39E-10 | 4.06E-10 | 4.72E-10 | 4.15E-10 | 4.69E-10 | 4.6E-10 |
| Lungs | 5.51E-10 | 5.77E-10 | 6E-10 | 5.85E-10 | 6.03E-10 | 6.31E-10 | 6.63E-10 | 6.57E-10 | 6.67E-10 | 7.5E-10 | [illegible] | 7.31E-10 | 7.73E-10 | 8.03E-10 |
| Ovaries | 1.4E-09 | 1.64E-09 | 1.45E-09 | 1.57E-09 | 1.57E-09 | 1.24E-09 | 1.28E-09 | 1.1E-09 | 1.76E-09 | 1.58E-09 | [illegible] | 2.02E-09 | 2.19E-09 | 2.01E-09 |
| Pancreas | 4E-10 | 4.44E-10 | 4.7E-10 | 5.79E-10 | 4E-10 | 3.77E-10 | 6.72E-10 | 5.42E-10 | 4.61E-10 | 4.36E-10 | [illegible] | 5.24E-10 | 6.64E-10 | 5.26E-10 |
| Placenta | 6.89E-10 | 8.77E-10 | 8.7E-10 | 9.27E-10 | 8.55E-10 | 8.41E-10 | 8.81E-10 | 8.68E-10 | 8.52E-10 | 9.24E-10 | [illegible] | 9.24E-10 | 9.23E-10 | 1E-09 |
| Remainder | 7.46E-09 | 4.5E-08 | 5.29E-08 | 4.37E-08 | 3.34E-08 | 2.68E-08 | 2.41E-08 | 2.17E-08 | 2.05E-08 | 2.25E-08 | [illegible] | 2E-08 | 2.16E-08 | 2.36E-08 |
| SI_wall_and... | 6.99E-10 | 7.29E-10 | 7.17E-10 | 7.38E-10 | 7.95E-10 | 7.53E-10 | 7.93E-10 | 7.95E-10 | 8.18E-10 | 8.53E-10 | 9.39E-10 | 9E-10 | 1.01E-09 | 9.79E-10 |
| Skeleton | 2.58E-08 | 1.48E-07 | 3.23E-07 | 3.97E-07 | 4.24E-07 | 3.84E-07 | 3.03E-07 | 2.44E-07 | 2.05E-07 | 1.52E-07 | 1.6E-07 | 1.96E-07 | 1.72E-07 | 1.46E-07 |
| Skin | 8.77E-08 | 2.16E-07 | 1.24E-07 | 1.13E-07 | 9.85E-08 | 8.57E-08 | 7.24E-08 | 6.25E-08 | 5.41E-08 | [illegible] | [illegible] | [illegible] | 4.9E-08 | 4.86E-08 |
| Spleen | 5.13E-10 | 4.43E-10 | 4.52E-10 | 4.05E-10 | 3.49E-10 | 4.61E-10 | 4E-10 | 5.12E-10 | 4.28E-10 | 4.26E-10 | 7.02E-10 | 4.74E-10 | 5.22E-10 | 5.01E-10 |
| Stomach_wall | 2.67E-10 | 3.28E-10 | 2.4E-10 | 2.88E-10 | 2.85E-10 | 2.91E-10 | 3.06E-10 | 3.5E-10 | 3.47E-10 | 3.32E-10 | 4.39E-10 | 3.99E-10 | 4.33E-10 | 4.91E-10 |
| Thymus | 1.46E-10 | 2.3E-10 | 2.32E-10 | 1.87E-10 | 2.15E-10 | 2.68E-10 | 2.2E-10 | 1.25E-10 | 1.24E-10 | 1.09E-10 | 7.54E-11 | 1.81E-10 | 2.23E-10 | 2.51E-10 |

Ding A, Gao Y, Liu H , Caracappa PF, Long DJ, Bolch WE, Liu Bob, Xu XG. VirtualDose: A New CT Dose Reporting Software for Adult and Pediatric Patients. Phys. Med. Biol. 60(14):5601-5625 (2015).

# CT Dose Reporting Software

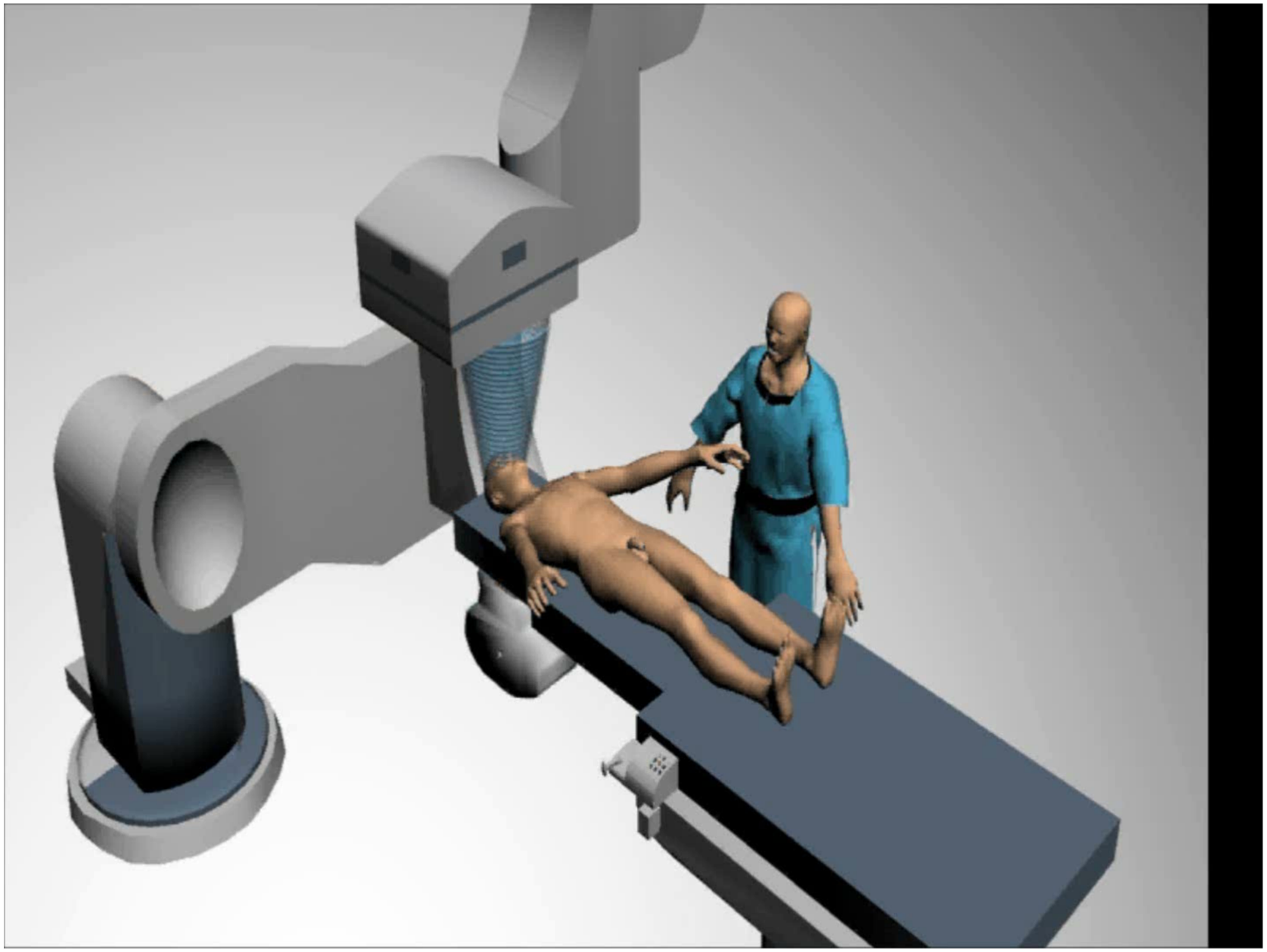
VirtualDose™ CT
A product of Virtual Phantoms, Inc.

http://www.virtual-dose.com



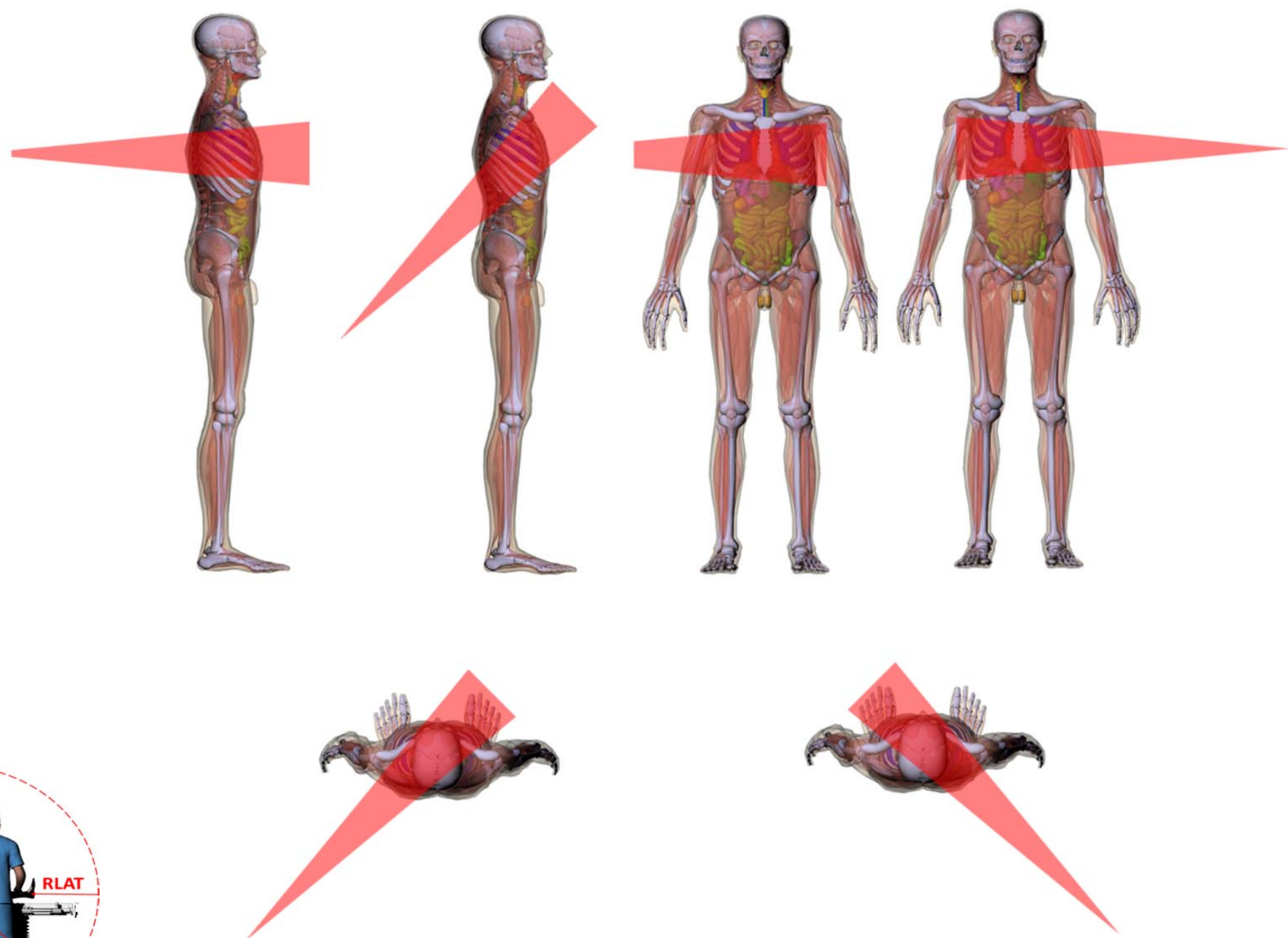

**In 2021, over 32-million dose calculation requests from more than 325 sites worldwide were processed**

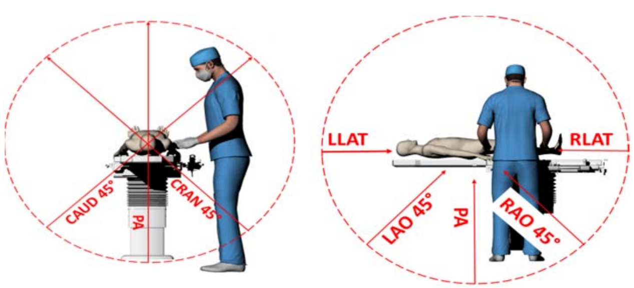
# VirtualDose for Interventional Radiology



# VirtualDose-IR
# Dose from fluoroscopically guided intervention (FGI) - Patients

- **Simulated beam directions:**
  - **Posterior-Anterior, Crani 45 $^{o}$**
  - **Lateral: left & right**
  - **Oblique: $45^{o}$ left & right**



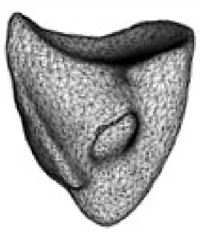


# Comments

- For decades, in imaging procedures, all "organ doses" were assessed using ICRP "Reference Man" approach involving "phantom libraries"
- "Patient-specific organ doses" would require two newly available tools:
    1. automatic organ segmentation
    2. "near real-time" Monte Carlo simulations

# Outline of the presentation

Anatomical Modeling Tool



Dose Reporting Tool

VirtualDose

Organ Segmentation Tool

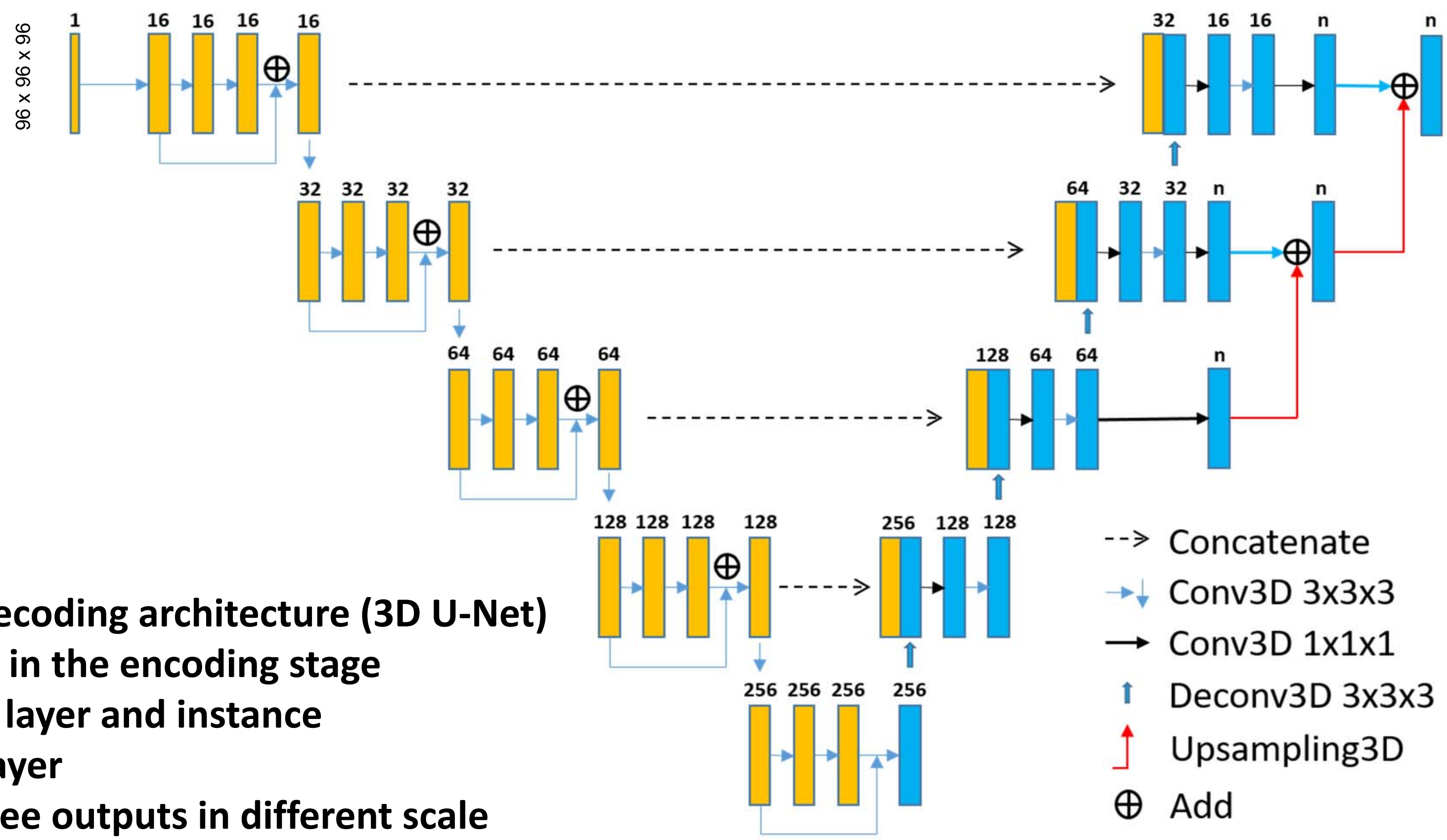
Deep Viewer

Dose Computing Tool

ARCHER

# Auto Multi-organ Segmentation Made Possible Through Deep-Learning based Segmentation Methods

## Network architecture [1] :




**Features:**

- **Encoding and decoding architecture (3D U-Net)**
- **Res-net module in the encoding stage**
- **Spatial dropout layer and instance normalization layer**
- **Merging the three outputs in different scale and getting the final segmentation results**

**[1] O. Ronneberger, P. Fischer, and T. Brox, "U-net: Convolutional networks for biomedical image segmentation," in *International Conference on Medical image computing and computer-assisted intervention*, 2015: Springer, pp. 234-241.**

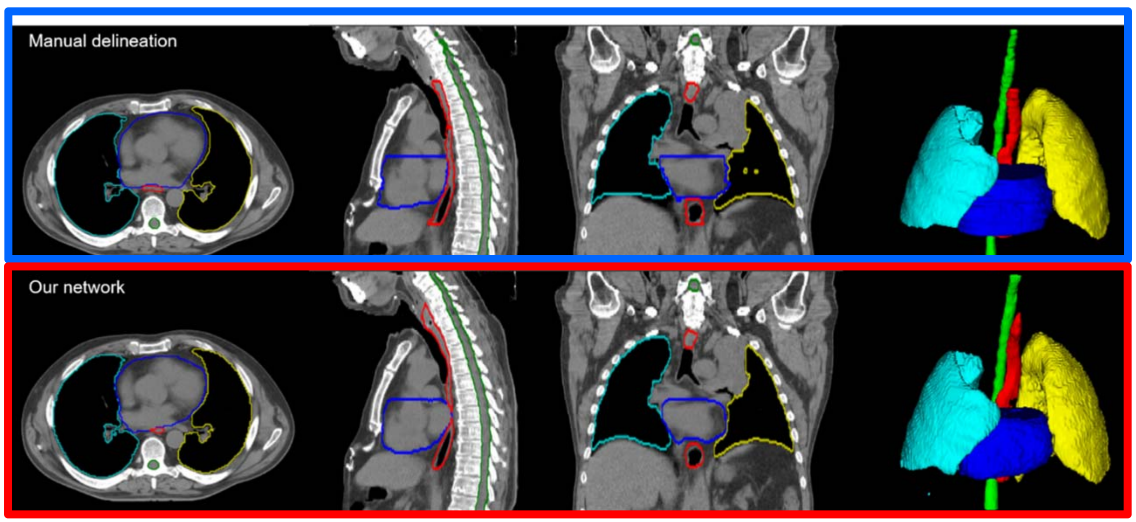
# Dataset 1: Lung CT Segmentation Challenge 2017 (LCTSC) [2]

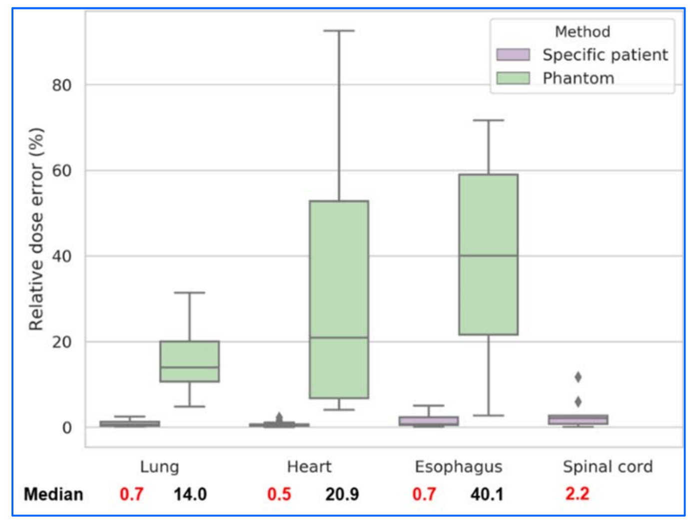
[2] Yang Jinzhong, et al. Data from Lung CT Segmentation Challenge (2017). The Cancer Imaging Archive.

- **Training and validation set:** 48 patients
- **Testing set:** 12 patients
- **Loss function:** weighted dice similarity
- **5 segmented organs:** left lung (yellow), right lung (cyan), heart (blue), spinal cord (green), and esophagus (red)

Dice similarity coefficient (mean ± standard deviation)

| Methods | Left lung | Right lung | Heart | Esophagus | Spinal cord |
|---|---|---|---|---|---|
| Interrater variability | 0.96±0.02 | 0.96±0.02 | 0.93±0.02 | 0.82±0.04 | 0.86±0.04 |
| 1 | 0.97±0.02 | 0.97±0.02 | 0.93±0.02 | 0.72±0.10 | 0.88±0.04 |
| 2 | 0.98±0.01 | 0.97±0.02 | 0.92±0.02 | 0.64±0.20 | 0.89±0.04 |
| 3 | 0.98±0.02 | 0.97±0.02 | 0.91±0.02 | 0.71±0.12 | 0.87±0.11 |
| 4 | 0.97±0.01 | 0.97±0.02 | 0.90±0.03 | 0.64±0.11 | 0.88±0.05 |
| 5 | 0.96±0.03 | 0.95±0.05 | 0.92±0.02 | 0.61±0.11 | 0.85±0.04 |
| 6 | 0.96±0.01 | 0.96±0.02 | 0.90±0.02 | 0.58±0.11 | 0.87±0.02 |
| 7 | 0.95±0.03 | 0.96±0.02 | 0.85±0.04 | 0.55±0.20 | 0.83±0.08 |
| Ours | **0.96±0.01** | **0.96±0.02** | **0.93±0.02** | **0.73±0.10** | **0.88±0.04** |



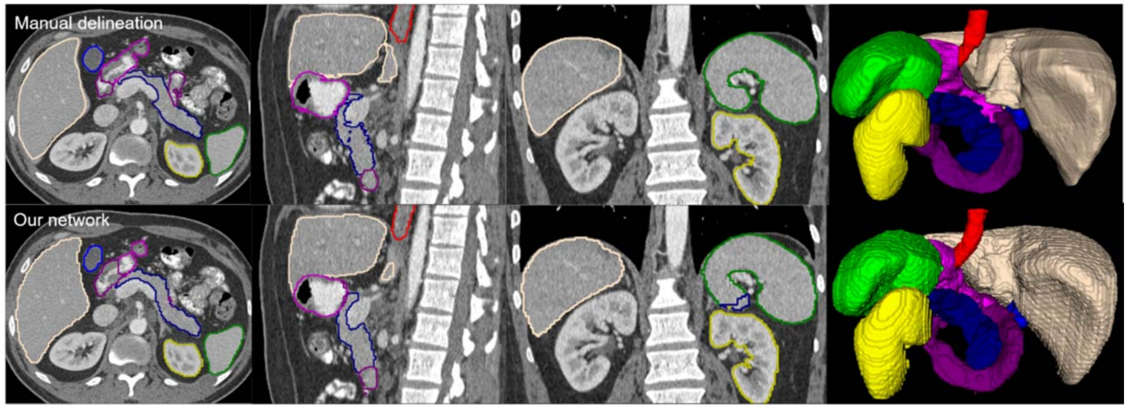



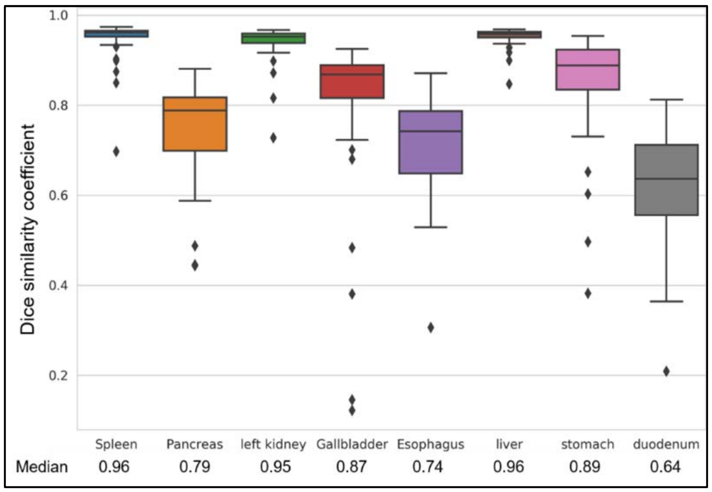

**Peng Z, Fang X, Yan P, Shan H, Liu T, Pei X, Wang G, Liu B, Kalra MK, Xu XG. A Method of Rapid Quantification of Patient-specific Organ Doses for CT Using Deep-learning-based Multi-organ Segmentation and GPU-accelerated Monte Carlo Dose Computing. Med Phys, (47)6: 2526–2536 (2020)**

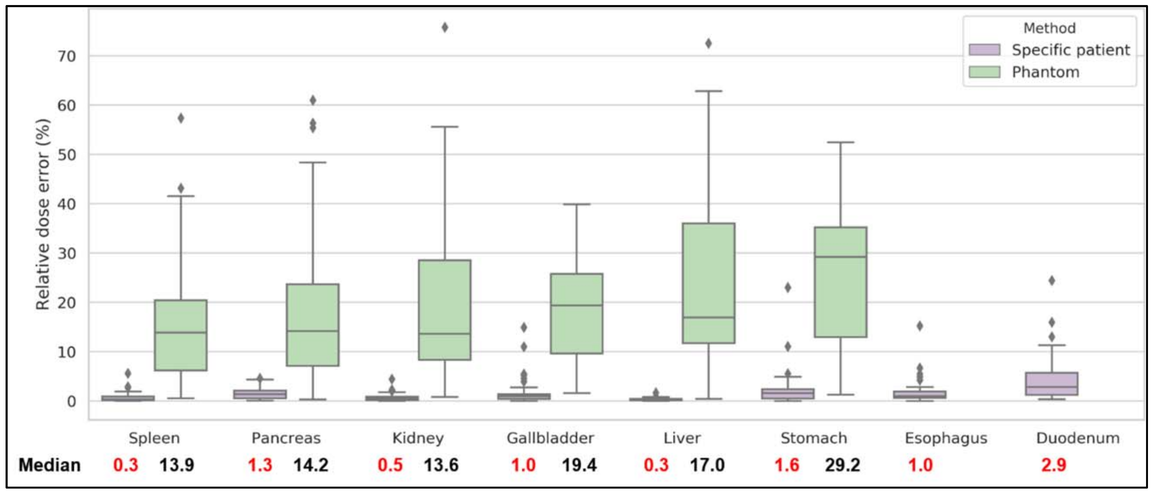
# Dataset 2：The Cancer Image Archive (TCIA) Pancreas-CT [3]

[3] Gibson E, et al. Automatic multi-organ segmentation on abdominal CT with dense v-networks. IEEE Transactions on Medical Imaging, 2018.

**Total patients:** 43
**5 cross-validation:** 8, 8, 9, 9, 9
**Loss function:** weighted dice similarity coefficient
**8 segmented organs:** spleen (green), pancreas (navy), left kidney (yellow), gallbladder (blue), esophagus (red), liver (bisque), stomach (magenta), and duodenum (purple)

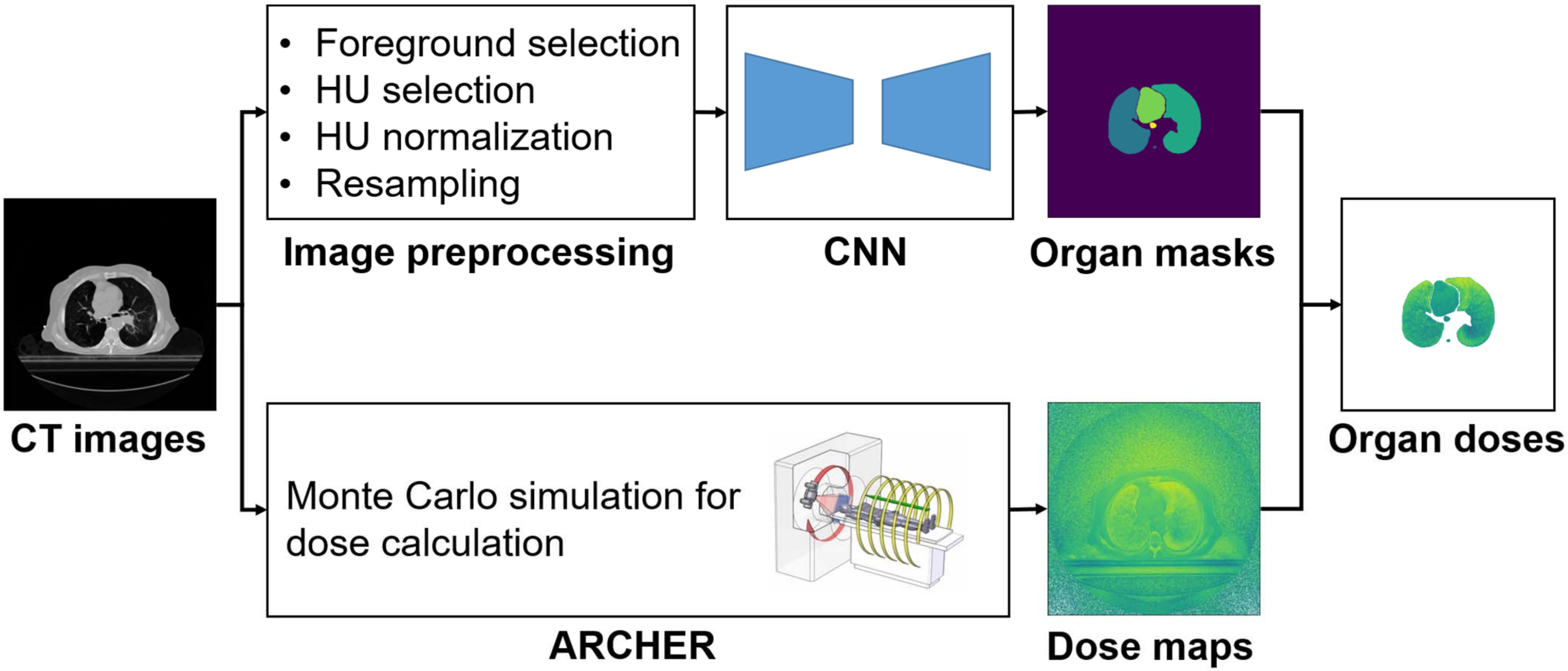



Peng Z, Fang X, Yan P, Shan H, Liu T, Pei X, Wang G, Liu B, Kalra MK, Xu XG. A Method of Rapid Quantification of Patient-specific Organ Doses for CT Using Deep-learning-based Multi-organ Segmentation and GPU-accelerated Monte Carlo Dose Computing. Med Phys, (47)6: 2526–2536 (2020)

# Method: Organ doses for patients undergoing CT exams




Peng Z, Fang X, Yan P, Shan H, Liu T, Pei X, Wang G, Liu B, Kalra MK, Xu XG. A Method of Rapid Quantification of Patient-specific Organ Doses for CT Using Deep-learning-based Multi-organ Segmentation and GPU-accelerated Monte Carlo Dose Computing. Med Phys, (47)6: 2526–2536 (2020)

# Segmentation Testing for the DeepViewer Tool

- **Can perform more than 40 organs and tissues**
- **Whole body in 3-5 minutes**

| Organs | Dice |
|---|---|
| Skin | 0.99 |
| Brain | 0.98 |
| Lung | 0.98 |
| Liver | 0.97 |
| Spleen | 0.95 |
| Bladder | 0.95 |
| Cerebellum | 0.95 |
| Kidney | 0.95 |

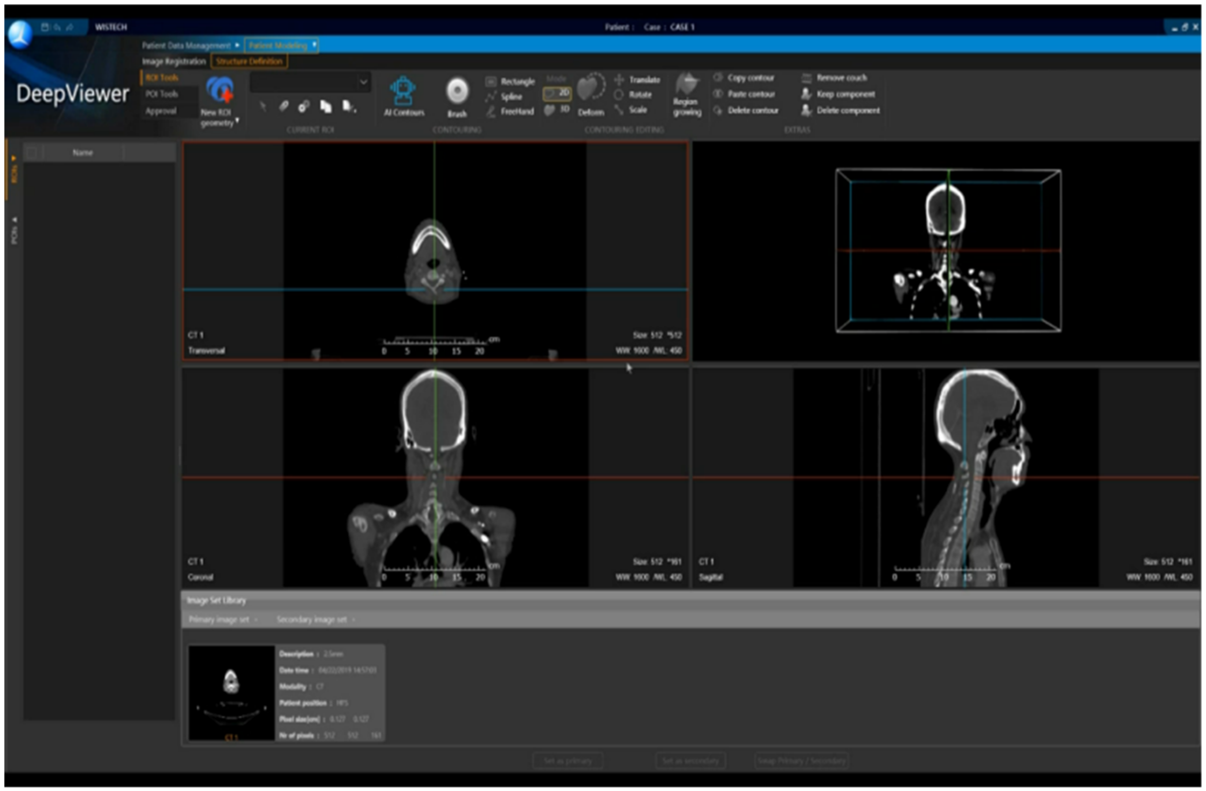
| Organs | Dice |
|---|---|
| Brainstem | 0.94 |
| Femoral Head | 0.93 |
| Pelvis | 0.93 |
| Heart | 0.93 |
| Mandible | 0.93 |
| Trachea | 0.92 |
| Spinal Cord | 0.92 |
| Eye Ball | 0.9 |

| Organs | Dice |
|---|---|
| Stomach | 0.88 |
| Temporal Lobe | 0.88 |
| Parotid | 0.86 |
| Esophagus | 0.86 |
| Pancreas | 0.86 |
| Lens | 0.85 |
| Thyroid | 0.85 |
| Bowel | 0.85 |

| Organs | Dice |
|---|---|
| Larynx | 0.85 |
| Rectum | 0.84 |
| Oral Cavity | 0.83 |
| Breast | 0.81 |
| Optic Nerve | 0.78 |
| Pituitary | 0.76 |
| Optic Chiasm | 0.75 |
| Cochlea | 0.75 |

# *DeepViewer*, for Automatic Target and OAR Contouring in Radiotherapy

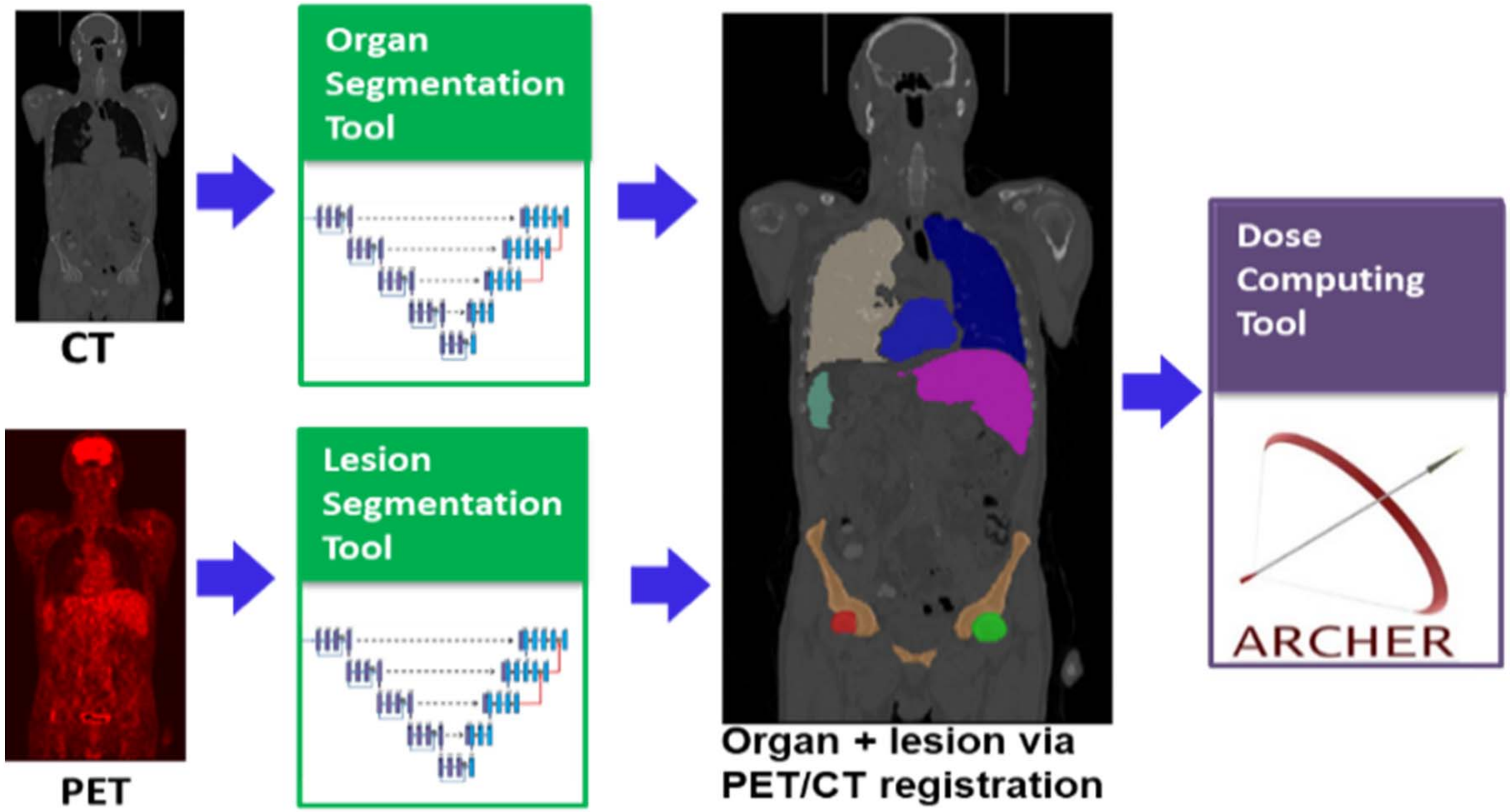
http://www.wisdom-tech.online/




3D visualization

- Head/neck, chest, abdominal treatment plans
- 40+ OARs
- 3-5 minutes to complete
- Acceptance rate 95% or better

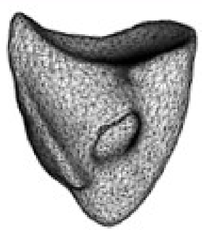
# Archer-NM, Organ doses for patients undergoing PET/CT exams (Nuclear Medicine)




Peng Z, Li Y, Xu Y, Lu Y, Li M, Pei X, Xu XG. Development of a GPU-accelerated Monte Carlo dose calculation module for nuclear medicine, ARCHER-NM: Application for PET/CT imaging procedure. Phys Med  Biol,  67, 06NT02 (2022)

# Outline of the presentation

**Anatomical Modeling Tool**



**Dose Reporting Tool**

VirtualDose

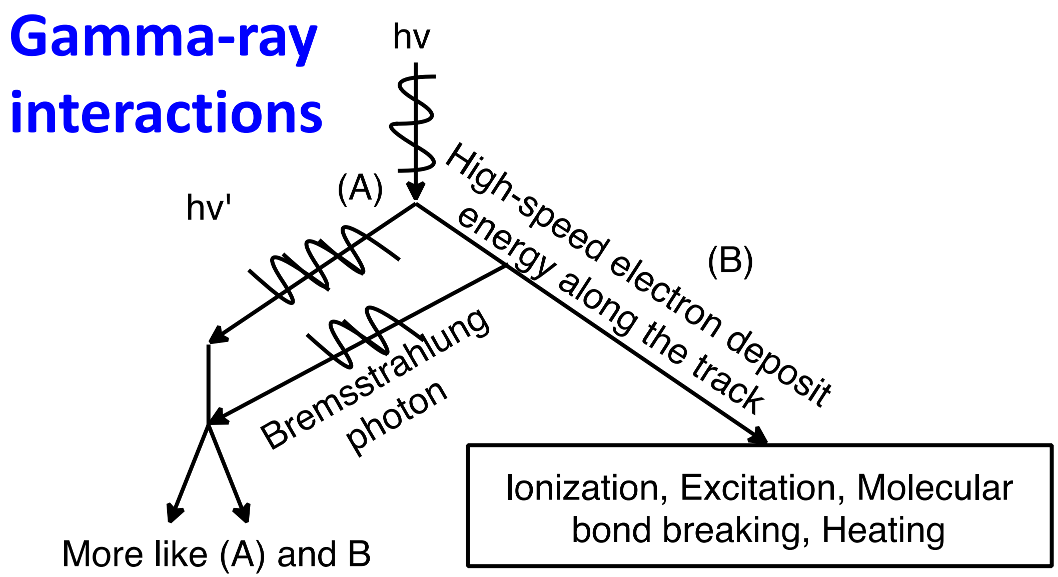
**Organ Segmentation Tool**

Deep Viewer

**Dose Computing Tool**

ARCHER

# Introduction: Dose Calculation and Monte Carlo Methods




- Dose: energy imparted to matter via ionization and excitation per unit mass
- Deterministic methods subject to non-trivial errors by approximating electron transport in water
- Monte Carlo particle transport is the ***gold standard***
- But lengthy computation time is the main bottleneck of MC applications for clinical settings

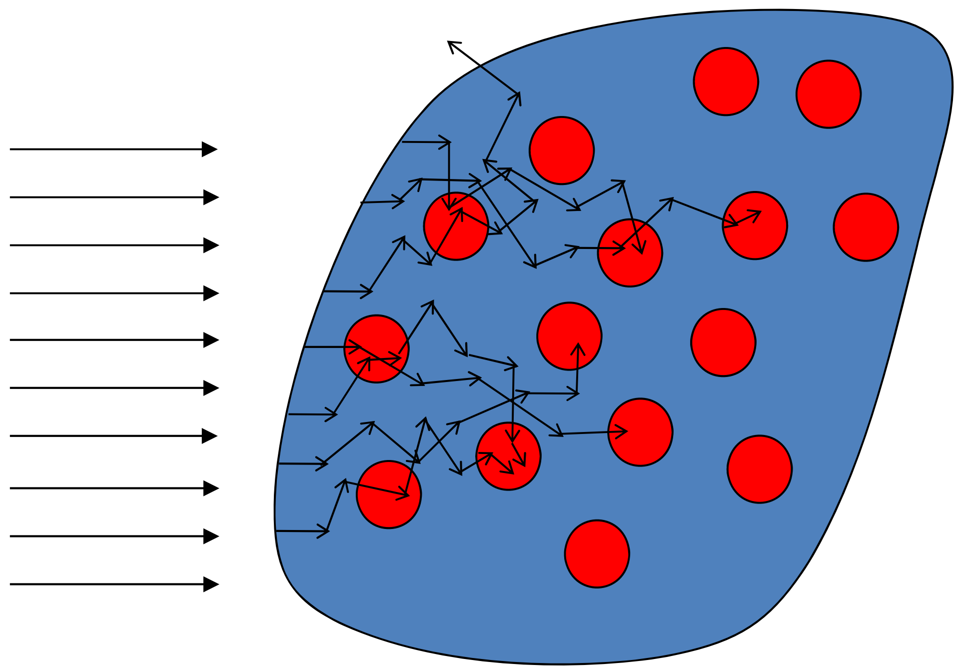
# Monte Carlo Methods Ideal for Radiation Transport Simulations, but *Used to be Extremely Slow*

**Boltzmann Transport Equation can be solved by MC methods**

$$\frac{1}{\mathrm{v}}\frac{\partial}{\partial t}\psi(\vec{r},\hat{\Omega},E,t)+\hat{\Omega}\cdot\vec{\nabla}\psi(\vec{r},\hat{\Omega},E,t)+\Sigma_t(\vec{r},E)\psi(\vec{r},\hat{\Omega},E,t)$$

$$=\int dE'\int d\Omega'\Sigma_s(\vec{r},E'\rightarrow E,\hat{\Omega}'\cdot\hat{\Omega})\psi(\vec{r},\hat{\Omega}',E',t)+S(\vec{r},\hat{\Omega},E,t)$$

**A Statistical Experiment**



# The ARCHER Project

## *-towards "real-time" Monte Carlo*

ARCHER (Accelerated Radiation-transport Computations in Heterogeneous EnviRonments)

- **Initiated in 2009**
- **Goals:**
  1. To understand heterogeneous computing architecture and programming models
  2. To test code performance on GPUs and MICs
  3. To develop functional Monte Carlo codes that take full advantage of CPUs, GPUs and MICs

# Solution: ARCHER – A GPU-based Monte Carlo Code

POINT/COUNTERPOINT

*Suggestions for topics suitable for these Point/Counterpoint debates should be addressed to Colin G. Orton, Professor Emeritus, Wayne State University, Detroit: ortonc@comcast.net. Persons participating in Point/Counterpoint discussions are selected for their knowledge and communicative skill. Their positions for or against a proposition may or may not reflect their personal opinions or the positions of their employers.*

## GPU technology is the hope for near real-time Monte Carlo dose calculations


Xun Jia, Ph.D.
*Department of Radiation Oncol*
*(Tel: 214-648-3224; E-mail: xun*

X. George Xu, Ph.D.
*Nuclear Engineering Program,*
*(Tel: 518-276-4014; E-mail: xug*

Colin G. Orton, Ph.D., Moderator



(Received 15 November 2014; accepted for publication 20 November 2014; published 11 March 2015)

[http://dx.doi.org/10.1118/1.4903901]


### OVERVIEW

Monte Carlo (MC) dose calculations are recognized as being the most accurate modality for radiotherapy treatment planning but, because of the excessive computational time required, they cannot presently be used for near real-time dose calculations. Currently, the most common way to accelerate MC dose calculations is to use clusters of central processing units (CPUs), but some believe that the future of near real-time MC dose calculations lies not with clusters of CPUs but with the use of graphics processing unit (GPU) technology. This is the claim debated in this month's Point/Counterpoint.

Arguing for the Proposition is Xun Jia, Ph.D. Dr. Jia received his Masters degree in Applied Mathematics and Ph.D. degree in Physics, both from UCLA. He is currently an Assistant Professor in the Department of Radiation Oncology, University of Texas Southwestern Medical Center. Dr. Jia's research focuses on GPU-based high-performance computing for medical physics and medical imaging. He has developed several Monte Carlo packages to improve efficiency for photon, electron, and proton transport. Dr. Jia's research has been supported by government and industrial grants and he has published 60 peer-reviewed papers. He is currently a section editor of the *Journal of Applied Clinical Medical Physics.*

Arguing against the Proposition is X. George Xu, Ph.D. Dr. Xu obtained his Ph.D. in Nuclear Engineering from Texas A&M University, College Station, TX and, for the past 20 years, he has been on the faculty of Rensselaer Polytechnic Institute, Troy, NY, where he currently holds the Edward E. Hood Endowed Chair of Engineering. Dr. Xu's research has centered around applications of Monte Carlo methods to problems in radiation protection, imaging, and radiation therapy. He has been continuously funded by the NIH over the past ten years, including an R01 grant to develop a new Monte Carlo code, ARCHER, for heterogeneous computing involving GPUs and coprocessors. He is the author of more than 150 journal papers and book chapters, and 270 conference abstracts. Dr. Xu is a Fellow of the American Association of Physicists in Medicine, the Health Physics Society, and the American Nuclear Society. In 2014, he was re-elected to a 6-yr term as a council member of the National Council on Radiation Protection and Measurements.

### FOR THE PROPOSITION: Xun Jia, Ph.D.

#### Opening Statement

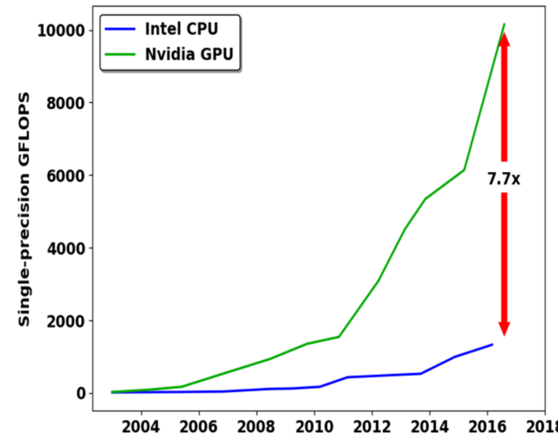
Clinical applications of MC dose calculations have been limited by the long computation time to achieve a sufficient precision level. Over the years, great efforts have been devoted

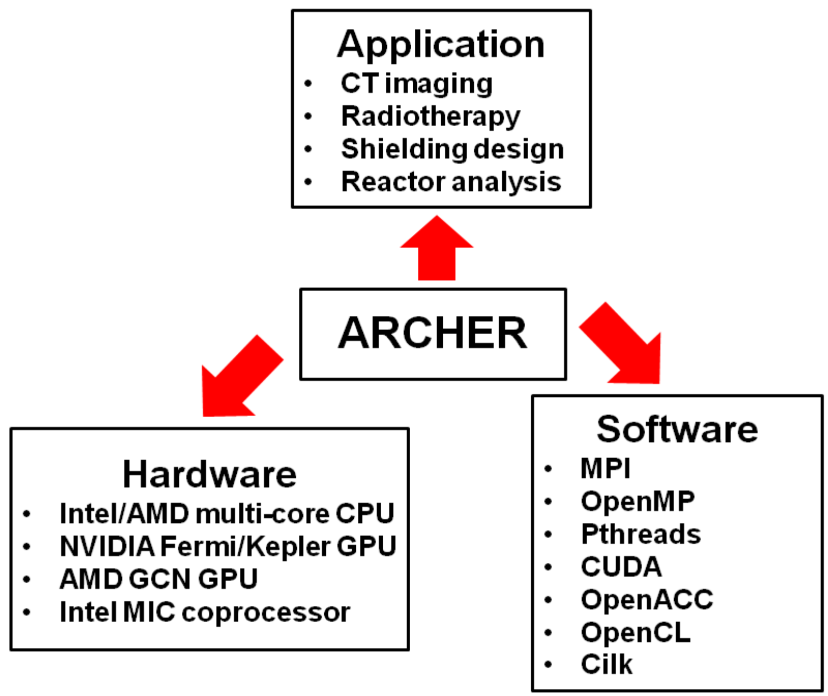


**Real-time MC?**

**Med. Phys. 42 (4), April 2015**

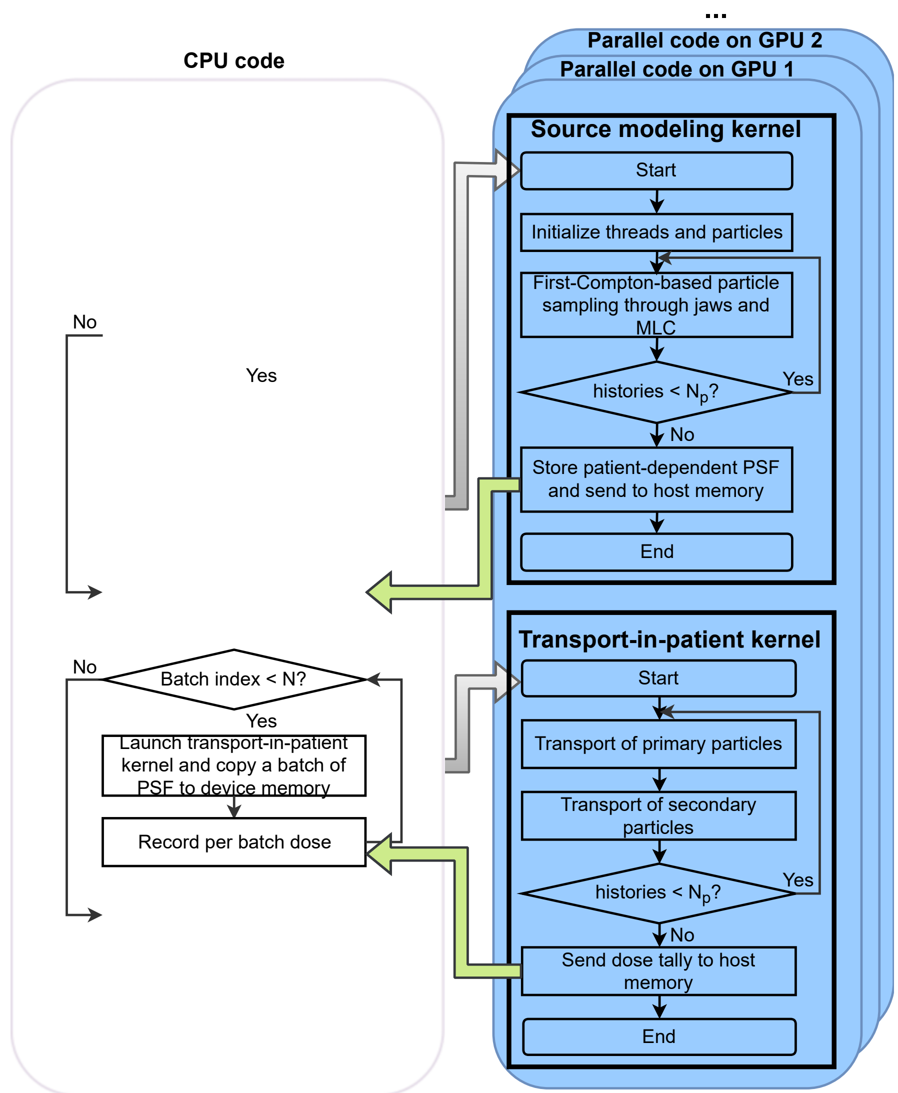
**GPU is more powerful than CPU**



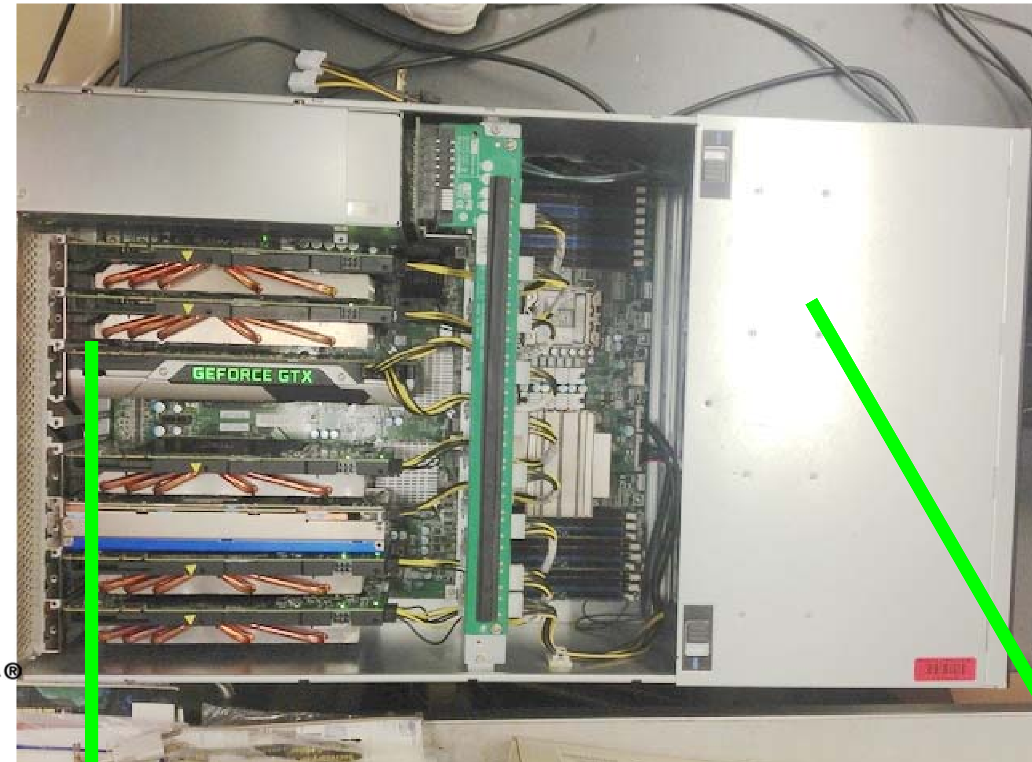



# ARCHER Software Development

- Two code variants
  - ✓ $ARCHER_{CPU}$: multi-threaded parallelization
  - ✓ $ARCHER_{GPU}$: multi-GPUs parallelization
- GPU/CUDA code optimization challenging
- 8 Ph.D. dissertations



# Desk-Top CPU/GPU Hardware @ $10k



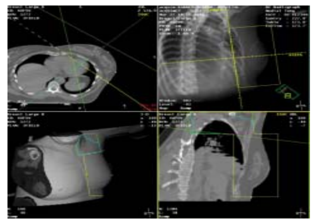

Intel CPU

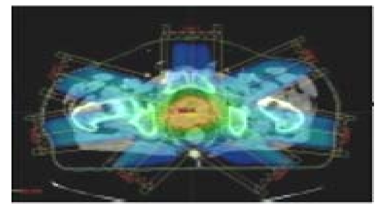
Multiple Nvidia GPU cards


[1]

# Introduction: External-Beam Radiotherapy

Obtain patient CT





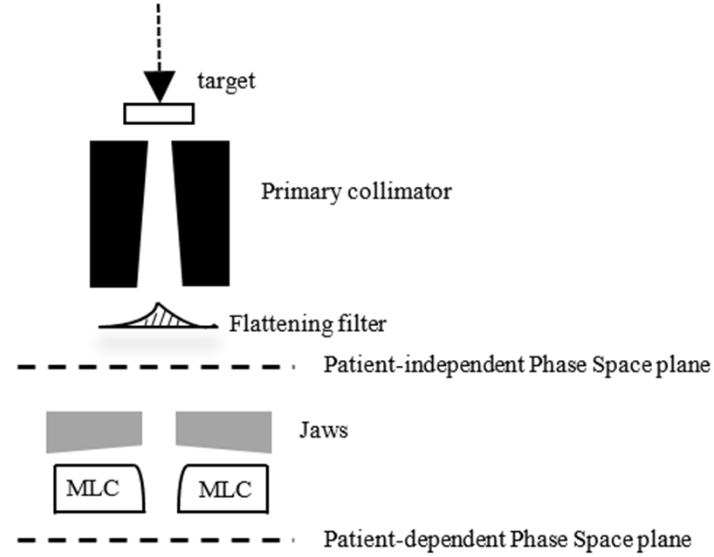
Dose Calculation &

Treatment verification

- ***Dose verification systems provide an opportunity for complementing the measurement-based approach***
- ***Far less time consuming***
- ***3D and patient-specific***

- Report of AAPM Task Group 219 on independent calculation-based dose/MU verification for IMRT（2021）

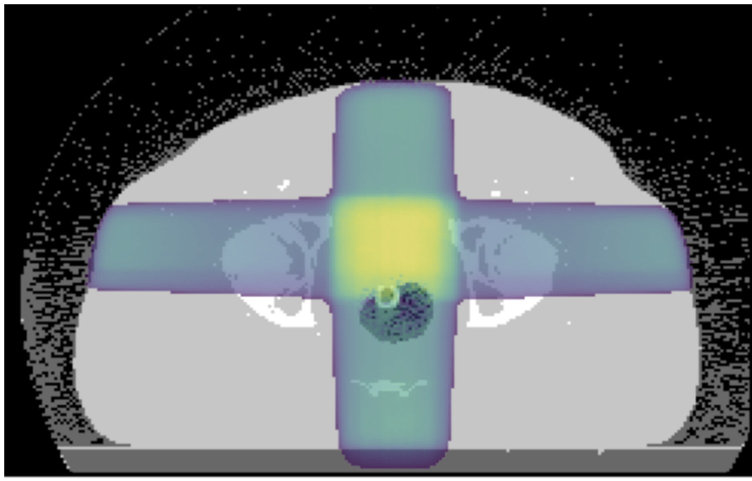
# Virtual Source Modeling



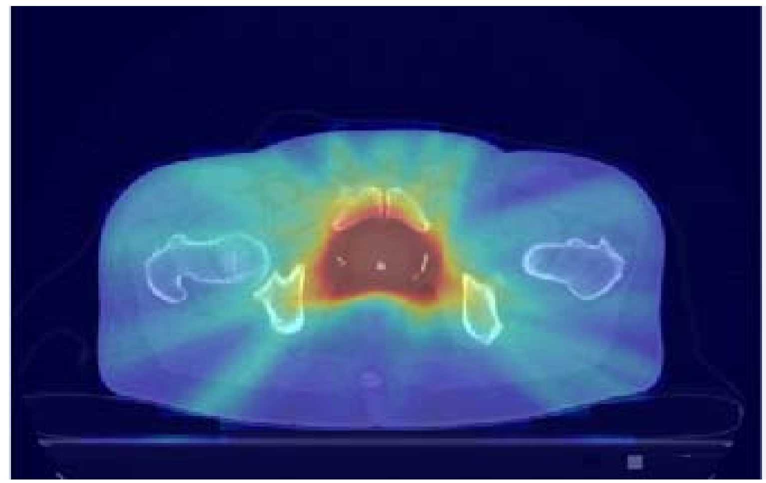

- Phase space source
  - Phase space particles: a collection of representative pseudo-particles emerging from a radiotherapy source along with their properties (x, y, z, u, v, w, E, wt)
  - can be categorized as
    - Patient-independent phase space: could be utilized repeatedly
    - Patient-dependent phase space: specific to each plan and beam

# Results: ARCHER for External-Beam Therapy (Tomotherapy, IMRT and VMAT) [1-5]

**Step and Shoot IMRT**



**VMAT**




(1) Liu T. Development of ARCHER - a parallel Monte Carlo radiation transport code -- for X-ray CT dose calculations using GPU and coprocessor technologies, Ph.D. Dissertation, Rensselaer Polytechnic Institute (2014).

(2) Su L. Development and Application of a GPU-Based Fast Electron-Photon Coupled Monte Carlo Code for Radiation Therapy, Ph.D. Dissertation, Rensselaer Polytechnic Institute (2014).

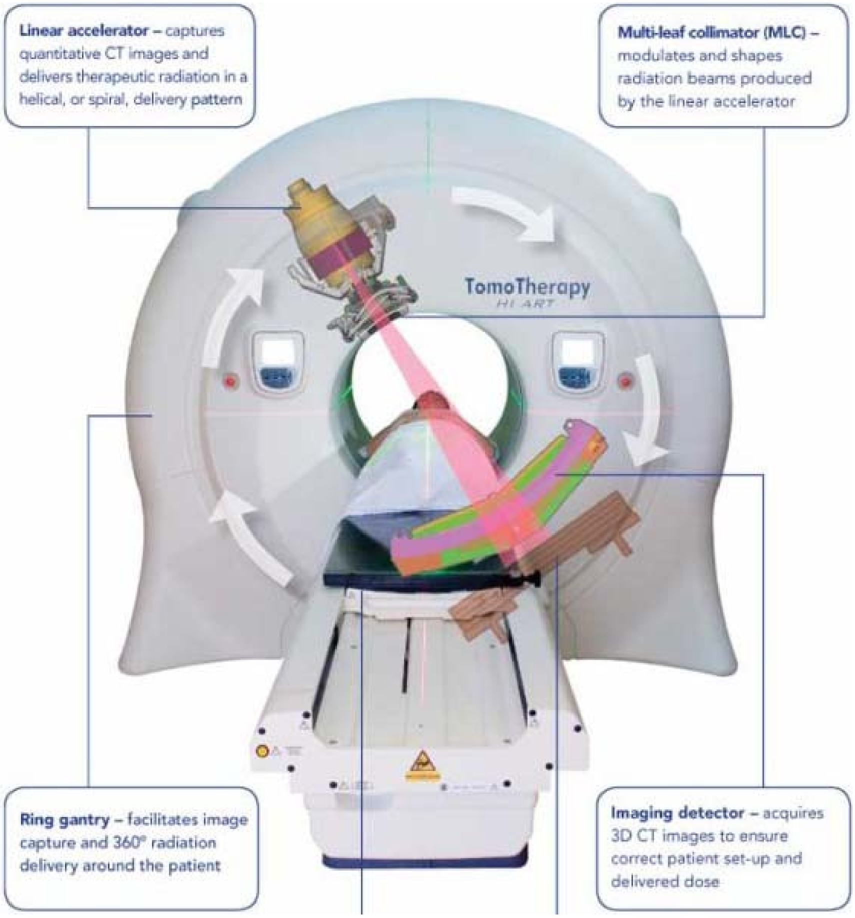
(3) Lin H. GPU-based Monte Carlo Source Modeling and Simulation for Radiation Therapy involving Varian Truebeam Linac. , Ph.D. Dissertation, Rensselaer Polytechnic Institute (2018).

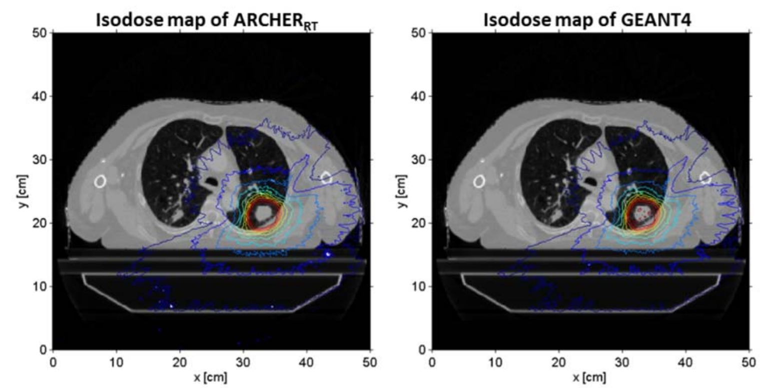
(4) Su L, Yang YM, Bednarz B, Sterpin E, Du X, Liu T, Ji W, Xu XG. $ARCHER_{RT}$ — A Photon-Electron Coupled Monte Carlo Dose Computing Engine for GPU: Software Development of and Application to Helical Tomotherapy. Med Phys. 41:071709 (2014).

(5) Adam DP*, Liu T, Caracappa PF, Bednarz BP, Xu XG. New capabilities of the Monte Carlo dose engine ARCHER-RT: clinical validation of the Varian TrueBeam machine for VMAT external beam radiotherapy. Med Phys 2537-2549 (2020).

# Results: Tomotherapy

**Su L, Yang YM, Bednarz, Edmond Sterpin, Du X, Liu T, Ji W, Xu XG. ARCHER$_{RT}$ — A Photon-Electron Coupled Monte Carlo Dose Computing Engine for GPU: Software Development of and Application to Helical Tomotherapy. Med Phys (2014).**



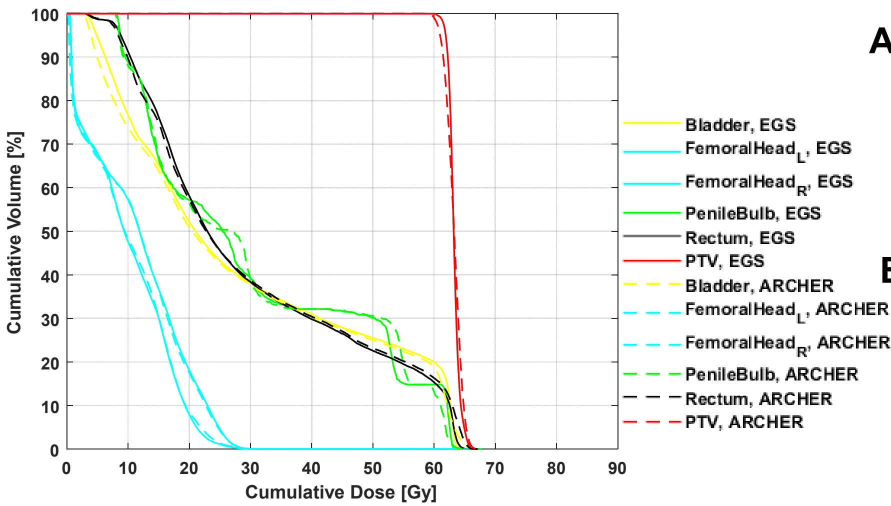

Statistical error in PTV ~1%

2%/2mm Gamma test pass rate: 98.5%

***GPU computing time ~ 1 sec,***

***GEANT4 ~ 500 CPU hours***

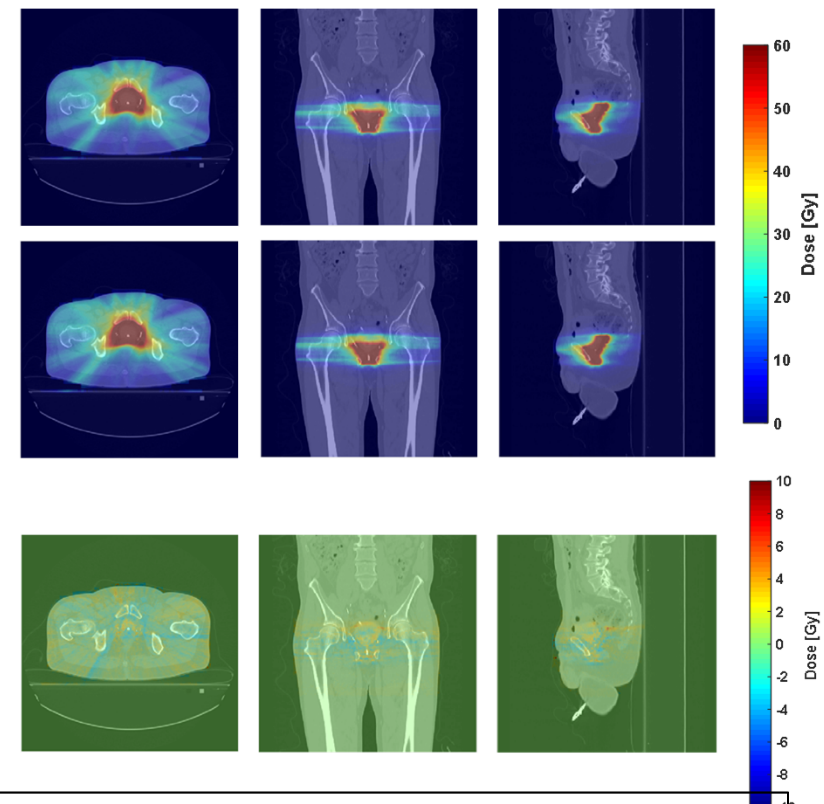
# Results: Clinical VMAT (prostate case)




ARCHER

EGSnrc

EGSnrc - ARCHER




- Gamma pass rates:
  - 3%/3mm: 99.71%

- ❑ **ARCHER (NVIDIA 1080Ti GPU)** ➡ **48 seconds**
  - ❑ Patient transport
  - ❑ Source modeling (linac)
- ❑ **EGSnrc (120-node cluster Intel Xeon E5335 CPUs)** ➡ **24 hours**

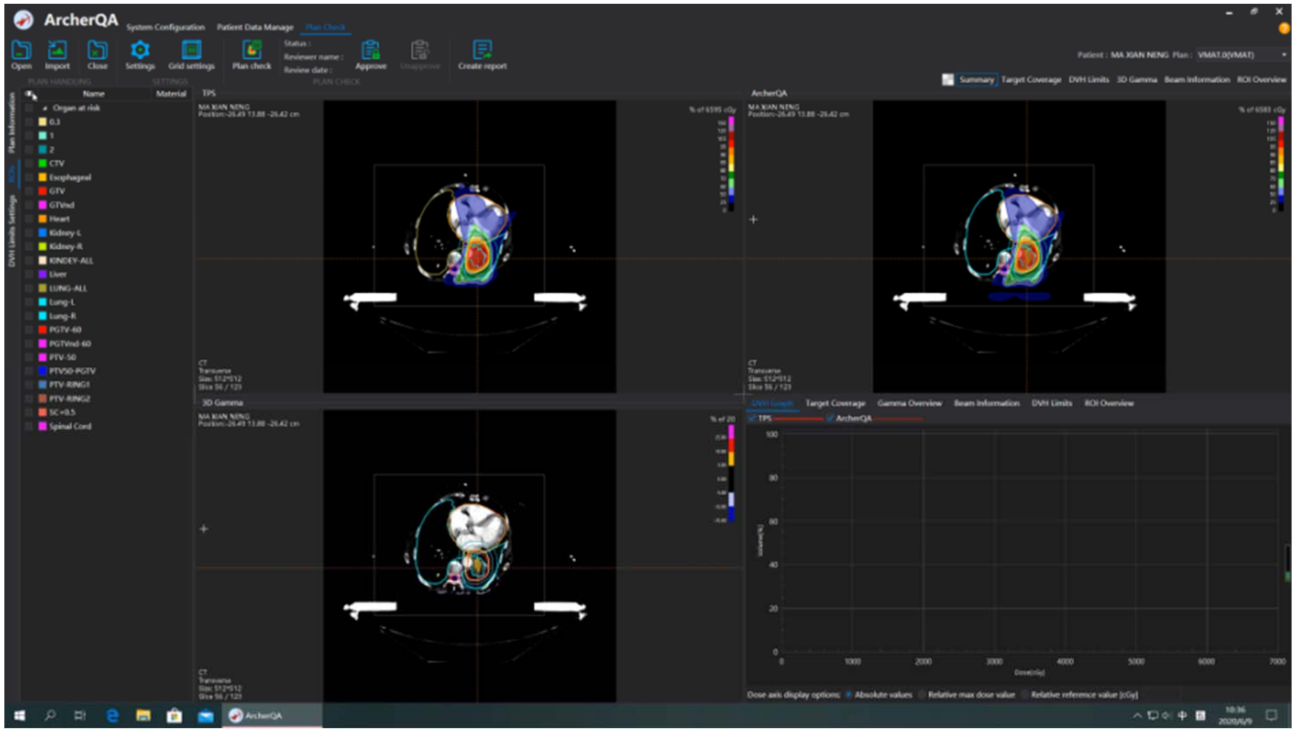
**Adam DP*, Liu T, Caracappa PF, Bednarz BP, Xu XG. New capabilities of the Monte Carlo dose engine ARCHER-RT: clinical validation of the Varian TrueBeam machine for VMAT external beam radiotherapy. Med Phys 2537-2549 (2020).**

# *ArcherQA*, for 3D Independent Dose-check (verification of TPS results)

Wisdom Tech

http://www.wisdom-tech.online/

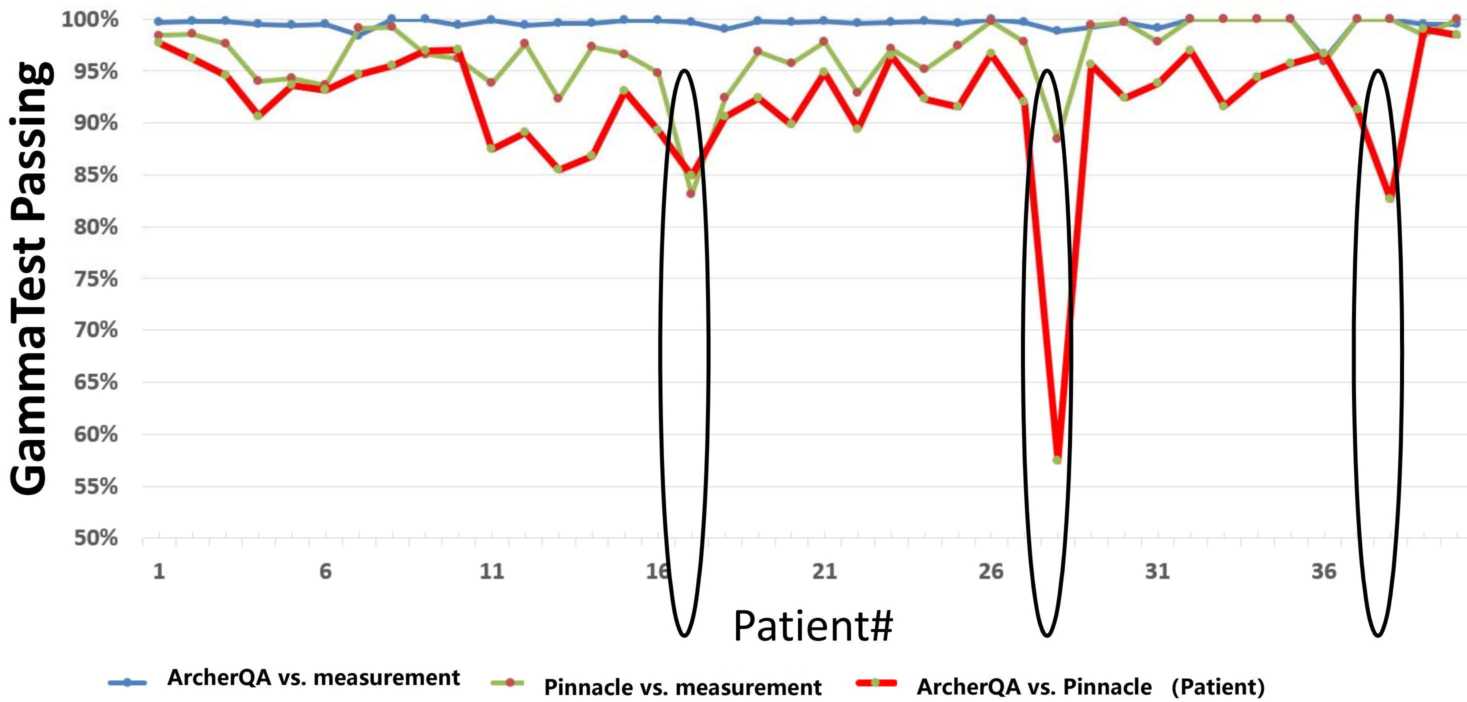
1. GPU-accelerated Monte Carlo dose engine
2. Data analyze tools, such as 2D and 3D Gamma Test and DVHs
3. TPS and Machine Check
4. Friendly user interfaces, easy to commission and setup



# ArcherQA Testing Results

## User report #1 Linac old (~6 years)

Linac : Versa HD (Elekta) TPS: pinnacle




- **Gamma Test: 3%/3mm, >10%**
- **ArcherQA vs. measurement: GammaTest average ~99.56%**
- **Pinnacle vs. measurement: GammaTest average ~ 96.64%**
- **ArcherQA vs. Pinnacle: gammaTest average ~ 91.94%**

# ArcherQA
# Clinical applications

- Installed in more than 30 hospitals in China and U.S.
- Checked more than 6400 patient treatment plans
- Linac types include:

| Vendor | Model |
|---|---|
| Varian | VitalBeam、Truebeam 、Halcyon、EDGE、Trilogy |
| Elekta | Unity、Synergy、Versa HD、Axesse、Infinity、Precise |
| Accuray | Tomotherapy、CyberKnife |

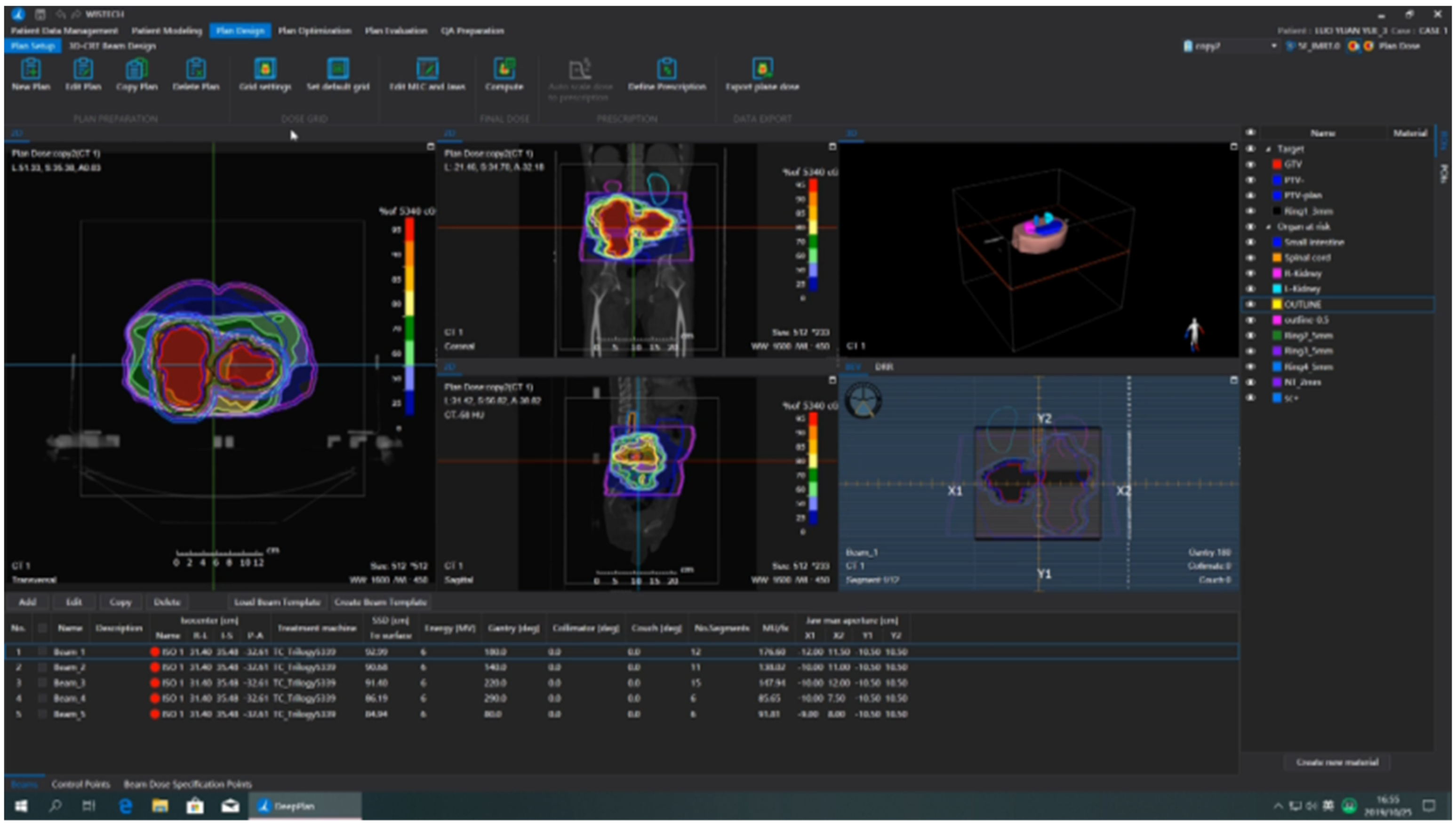
| Chinese vendor | Model |
|---|---|
| United Imaging | 506c |
| ZhongNeng | OMX6i |

On-going Clinical Testing

Wisdom Tech

# DeepPlan, Treatment Planning System (TPS)

- **Photons, electrons, protons**
- **Different dose algorithms including GPU-based Monte Carlo**
- **Integrated with auto contouring and registration**



# Summary

1. **Computational phantoms grew exponentially towards <u>“personalization” and “multi-scale”</u>**

2. **AI facilitates clinical medical physics workflow (segmentation tools are well tested)**

3. **Real-time MC computing provides RT QA solutions**

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**University of Science and Technology of China**

VirtualDose™ CT
A product of Virtual Phantoms, Inc.

DeepViewer

ARCHER

DeepPLAN