The Recipient of 2015 Randall S. Caswell Award for Distinguished Achievements in the Field of Ionizing Radiation Measurements and Standards

Dr. X. George Xu
The Edward E. Hood Endowed Chair of Engineering
Professor of Nuclear Engineering
Rensselaer Polytechnic Institute

Tuesday, April 28, 2015 @CIRMS 2015

Dr. Randall S. Caswell

- Physicist, Radiation Physics Division, 1952-1957
- Chief, Neutron Physics Section, 1957-1969
- Deputy Director, Center for Radiation Research, 1969-1978
- Chief, Nuclear Radiation Division, Center for Radiation Research, 1978-1985.
- Chief, Ionizing Radiation Division, Physics Laboratory, 1985-1994.

Past Randall S. Caswell Awardees

2002	H. Thompson Heaton II	FDA
2004	Anthony J. Berejka	Ionicorp
2006	Kenneth L. Swinth	Swinth Associates
2007	Bert M. Coursey	U.S. DHS
2008	Larry A. DeWerd	University of Wisconsin
2009	Marshall R. Cleland	IBA Industrial, Incorporated
2010	Geoffrey Ibbott	MD Anderson Cancer Center
2011	Dr. Kenneth Inn	NIST
2012	Joseph C. McDonald	PNNL
2013	Stephen M. Seltzer	NIST

Research on Radiation Dosimetry and Monte Carlo Simulation at RPI – A Review

X. George Xu

(xug2@rpi.edu)

Tuesday, April 28, 2015 @CIRMS 2015

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Acknowledgements

Rensselaer Radiation Measurements and Dosimetry Group (RRMDG):

http://RRMDG.rpi.edu

Outline

1. <u>Computational Human Phantoms</u>

2. ARCHER Monte Carlo Code

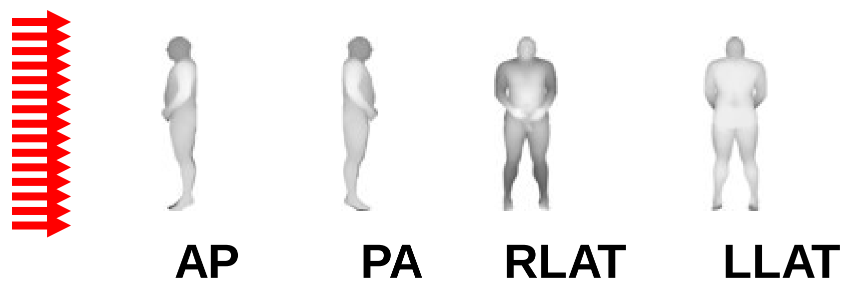
Experimental vs Computational Approaches

Measurements

- Dosimeters
- Physical phantom

Monte Carlo Simulations

- Computational phantoms
- Monte Carlo codes

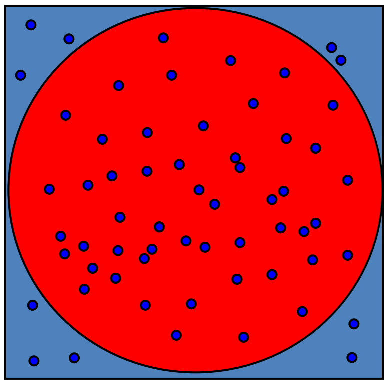


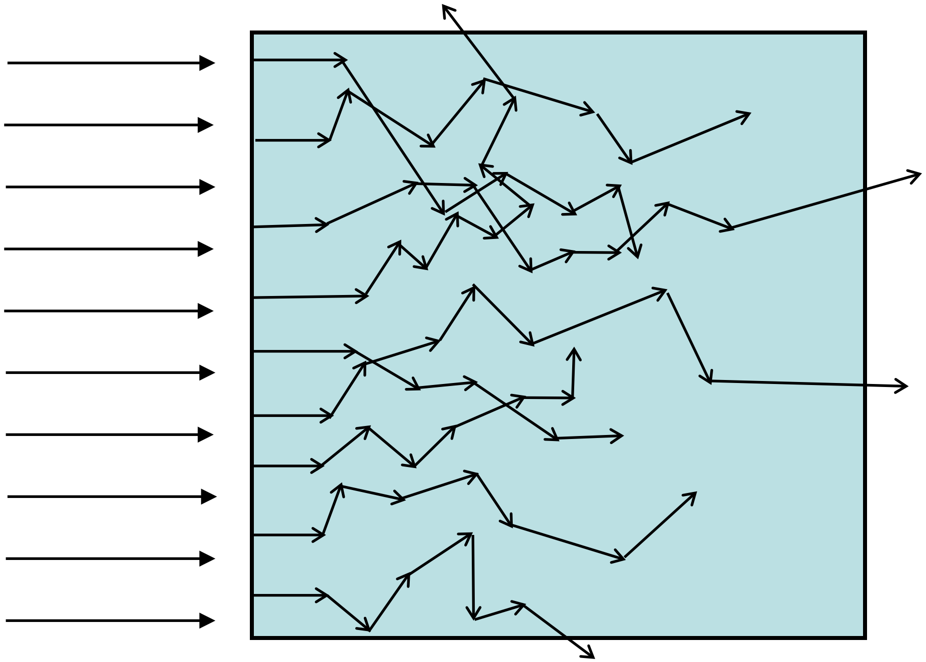
Boltzmann Radiation Transport Calculations

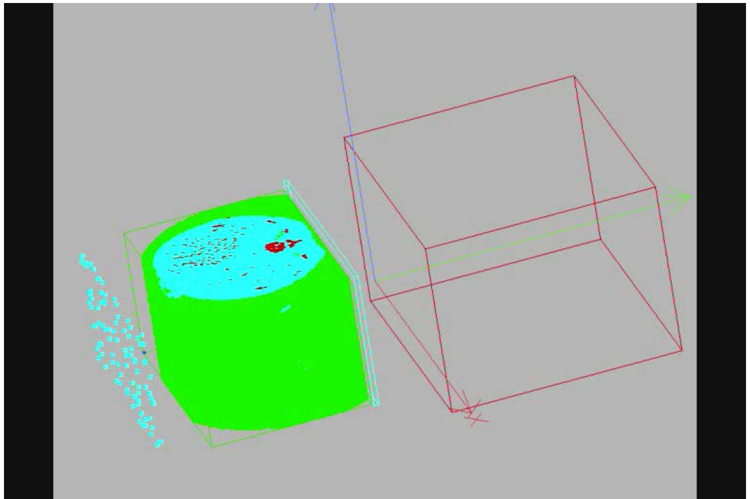
$$\frac{1}{\mathrm{v}}\frac{\partial}{\partial t}\psi(\vec{r},\hat{\Omega},E,t)+\hat{\Omega}\cdot\vec{\nabla}\psi(\vec{r},\hat{\Omega},E,t)+\Sigma_t(\vec{r},E)\psi(\vec{r},\hat{\Omega},E,t)$$

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

Monte Carlo Simulation Methods







Ptrac tracking
Moritz software

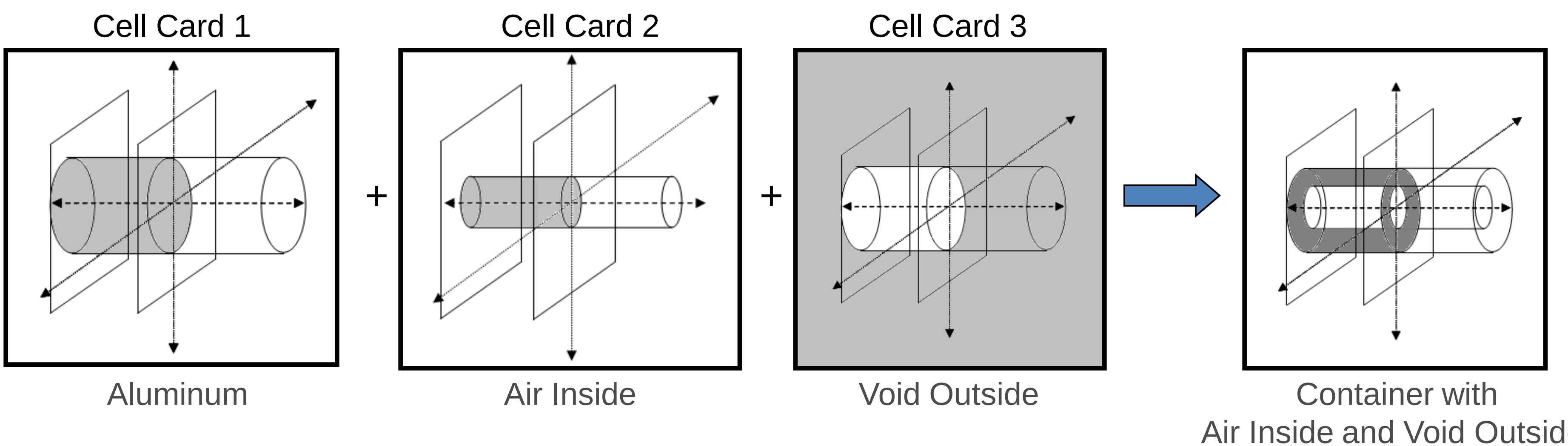
MCNP Geometry Example – HPGe Gamma Detector

```
C CELL CARDS

1     4 -2.698   2 -3 -1     IMP:P=1    #2          $Aluminum Material
2     2 -0.000125 2 -4 -1 imp:p=1                   $Air
3     0 -2:3:1 IMP:P=0                              $Void Outside
```

Not include cell #2

- The Cell Cards define the geometry using the shapes provided in the Surface Cards.



- They also define the material type and its density
  - Cell 1 → Material 4 (Aluminum), ρ = 2.698 g/cm^3
  - Cell 2 → Material 2 (Air), ρ = .000125 g/cm^3
  - Cell 3 → Void
- The negative signs designate which face of the geometry the program is to consider

US Patent Serial #6,518,579 "Non-destructive In-situ Method and Apparatus for Determining Radionuclide Depth in Media" by X.G. Xu and E.P. Naessens. Awarded February 11, 2003.

US006518579B1

(12) **United States Patent**
Xu et al.

(10) **Patent No.: US 6,518,579 B1**
(45) **Date of Patent: Feb. 11, 2003**

(54) **NON-DESTRUCTIVE IN-SITU METHOD AND APPARATUS FOR DETERMINING RADIONUCLIDE DEPTH IN MEDIA**

(75) Inventors: **X. George Xu**, Clifton Park, NY (US); **Edward P. Naessens**, West Point, NY (US)

(73) Assignee: **Rensselaer Polytechnic Institute**, Troy, NY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/330,660**

(22) Filed: **Jun. 11, 1999**

(51) **Int. Cl.**[7] **G01T 1/00**
(52) **U.S. Cl.** **250/393**
(58) **Field of Search** 250/370.01, 363.01, 250/363.1, 358.1, 393

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,680,470 A * 7/1987 Heald 250/358.1
5,412,206 A * 5/1995 Seidel et al. 250/253

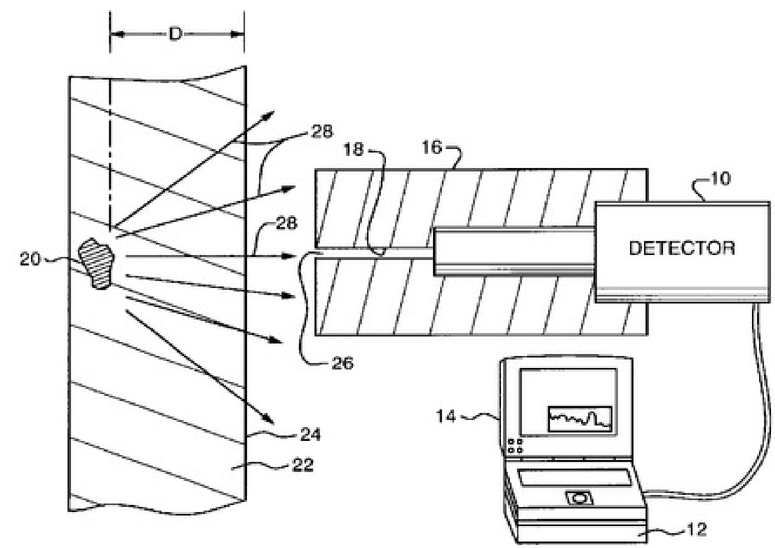
* cited by examiner

Primary Examiner—Constantine Hannaher
Assistant Examiner—Shun Lee
(74) *Attorney, Agent, or Firm*—Notaro & Michalos P.C.

(57) **ABSTRACT**

A non-destructive method and apparatus which is based on in-situ gamma spectroscopy is used to determine the depth of radiological contamination in media such as concrete. An algorithm, Gamma Penetration Depth Unfolding Algorithm (GPDUA), uses point kernel techniques to predict the depth of contamination based on the results of uncollided peak information from the in-situ gamma spectroscopy. The invention is better, faster, safer, and/cheaper than the current practice in decontamination and decommissioning of facilities that are slow, rough and unsafe. The invention uses a priori knowledge of the contaminant source distribution. The applicable radiological contaminants of interest are any isotopes that emit two or more gamma rays per disintegration or isotopes that emit a single gamma ray but have gamma-emitting progeny in secular equilibrium with its parent (e.g., ^{60}Co, ^{235}U, and ^{137}Cs to name a few). The predicted depths from the GPDUA algorithm using Monte Carlo N-Particle Transport Code (MCNP) simulations and laboratory experiments using ^{60}Co have consistently produced predicted depths within 20% of the actual or known depth.

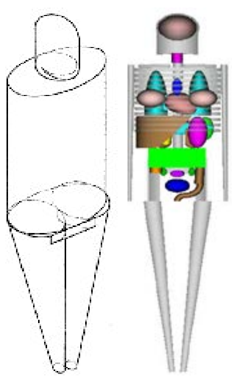
8 Claims, 5 Drawing Sheets



50-Year History of Computational Phantoms

- Radiation Protection
- Medical Imaging
- Radiotherapy

1st Generation



MIRD anthropomorphic models in 1980s

STYLIZED

2nd Generation

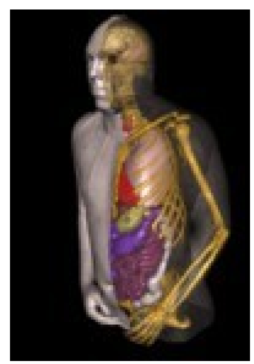
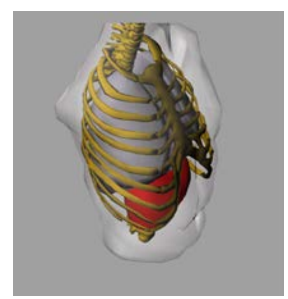


Image-based rigid, 3D model in 1990-2000s

VOXEL

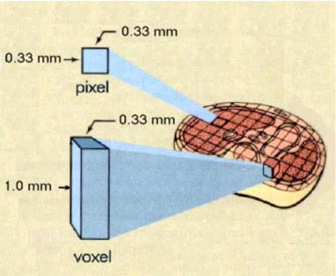
3rd Generation



Deformable and moving 4D models 2008-2010

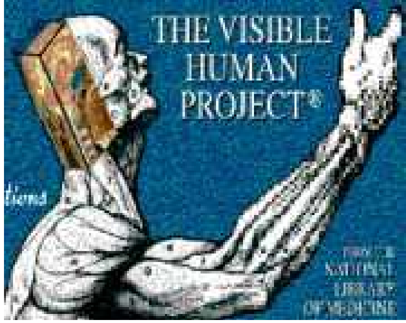
BREP

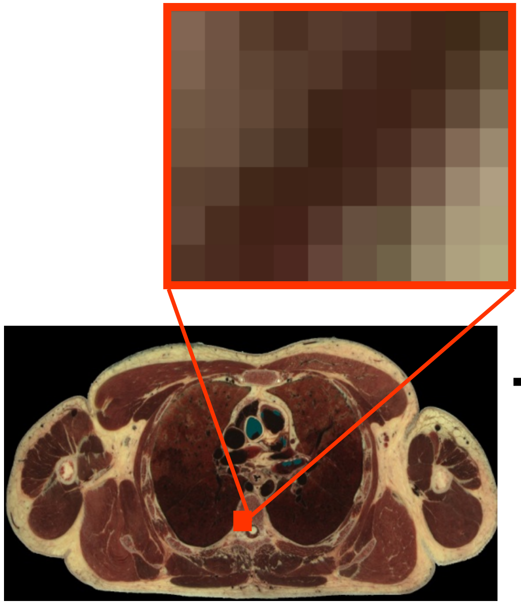
Personalization is Future

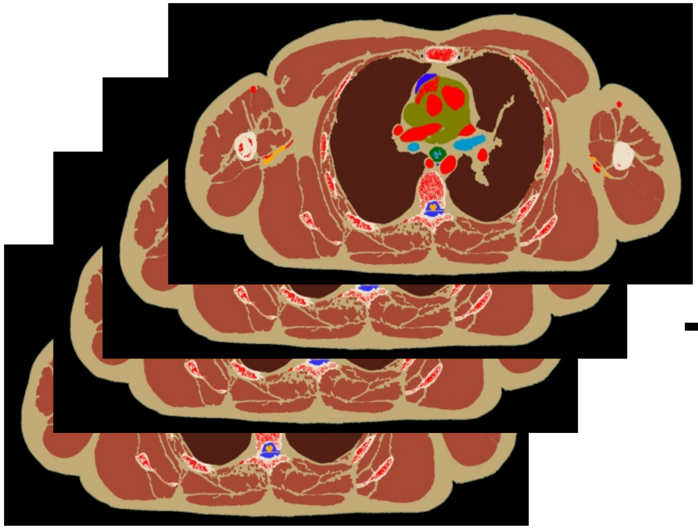


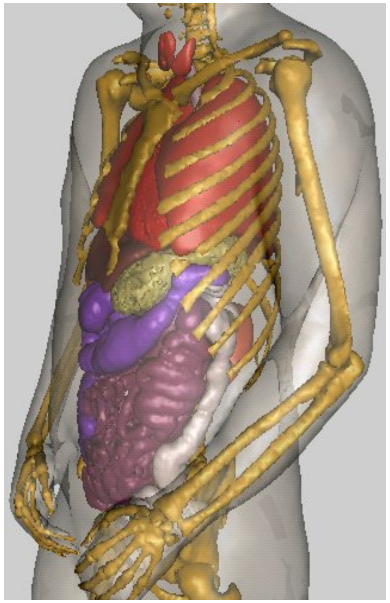
2^{nd}-Generation "Voxel" Phantoms - Example of the VIP-Man (1997-2000)

Xu et al. Health Physics 2000









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

Registration of all slices

Finished 3D voxel phantom

VIP-Man Phantom For Radiation Dosimetry

Xu, X. G. Chao, T.C. and Bozkurt A. Health Physics, 78(5):476-486, 2000. "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".

EGS4 Code

0.33 mm x 0.33 mm x 1 mm Resolution
Photons / Electrons

MCNP5 Code
4 mm x 4mm x 4 mm Resolution
Photons/Electros/ Neutrons

MCNPX Code
And

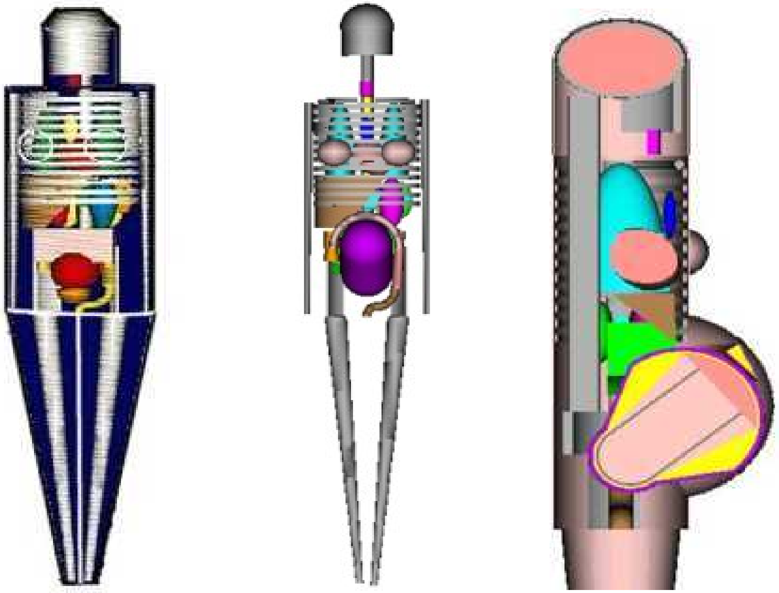
GEANT4 Code
Protons etc

Dr. T.C. (Ephraim) Chao, Class 2001

Dr. Ahmet Bozkurt, Class 2000

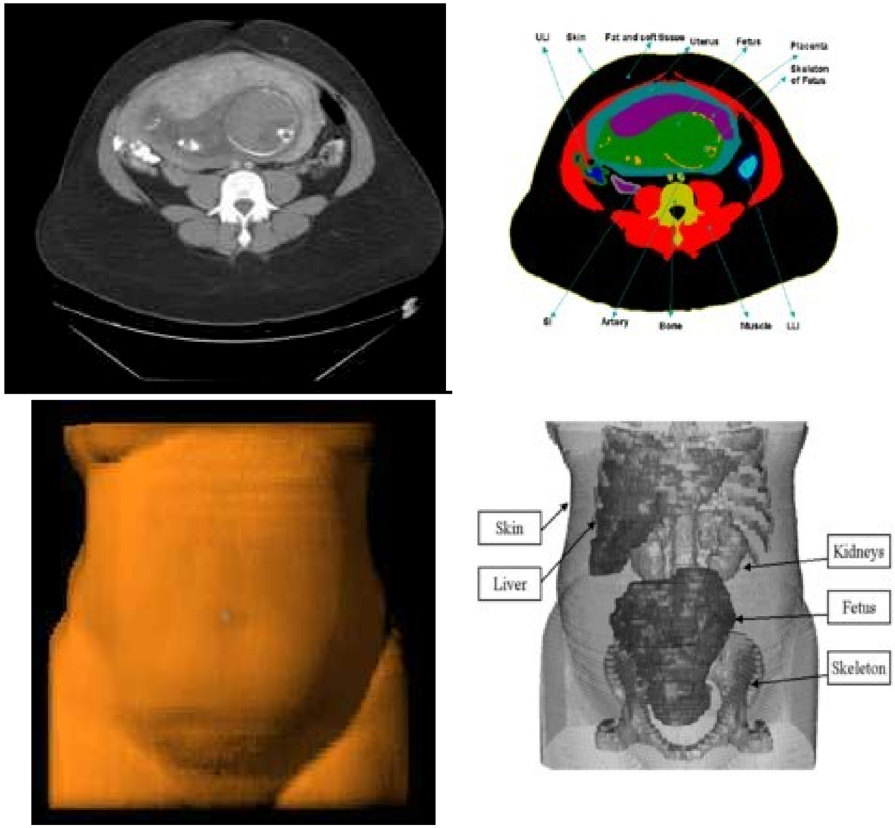
Earlier Pregnant Female Phantoms

Stylized models



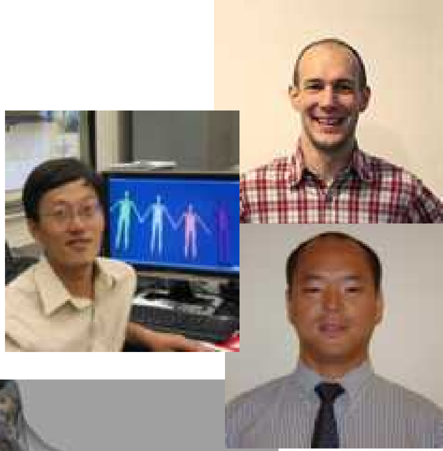
Curtsey of Stabin et al (1995)

Partial-body CT phantom (7-month)

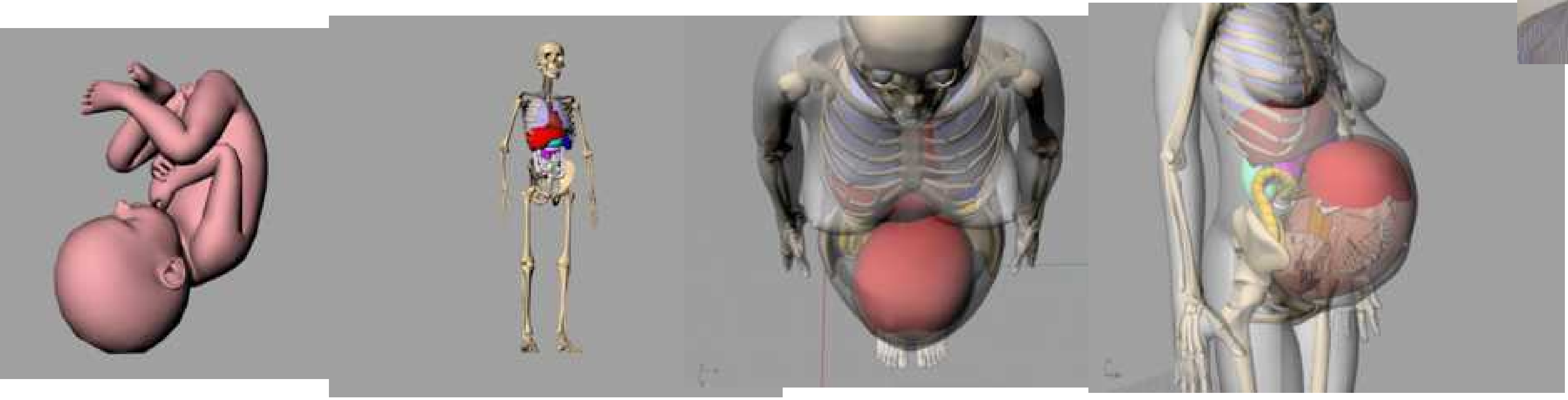


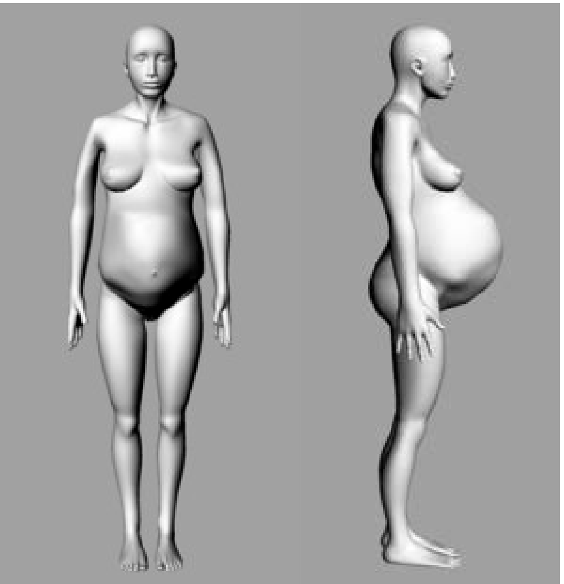
Shi and Xu (2004)

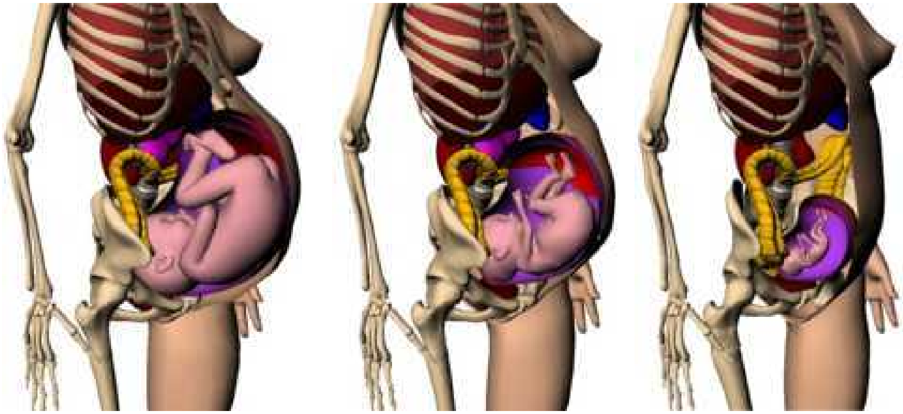
A New Method of Morphing and Deforming



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

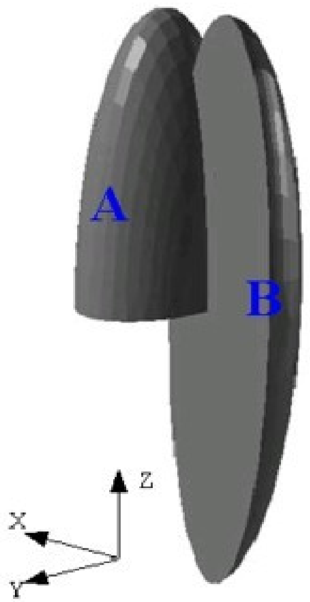


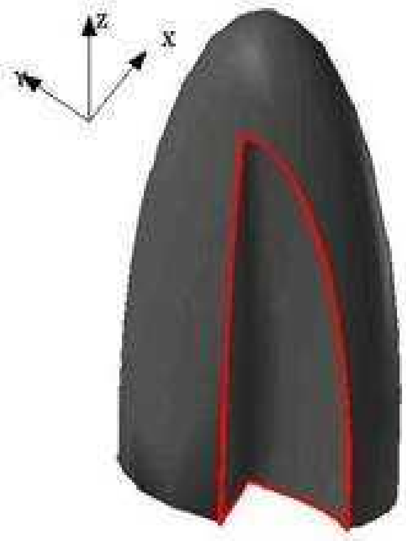




A Major Advancement in Phantom Geometry

from Constructed Solid Geometry (CSG) to Boundary Representation (BREP)

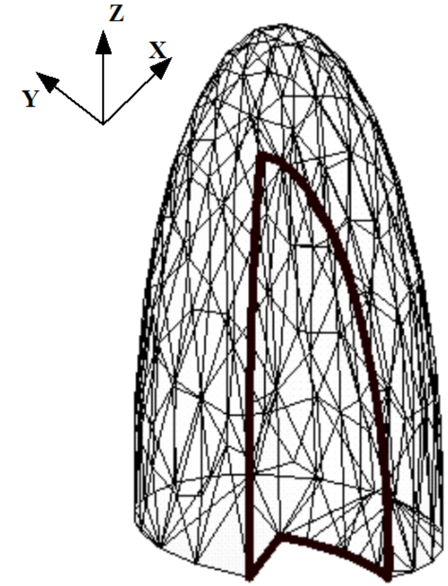




$$A: \left(\frac{X-8.5}{5}\right)^2+\left(\frac{Y}{7.5}\right)^2+\left(\frac{Z-43.5}{24}\right)^2 \le 1 \text{ ,} Z \ge 43.5$$

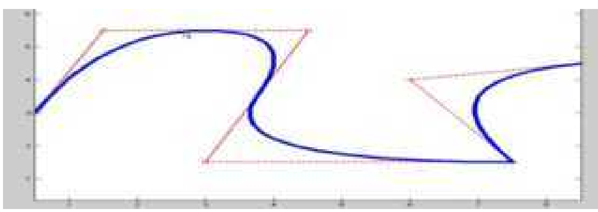
$$B: \left(\frac{X-2.5}{5}\right)^2+\left(\frac{Y}{7.5}\right)^2+\left(\frac{Z-43.5}{24}\right)^2 \ge 1 \text{ ,} if\ y<0$$

Polygon meshes



Non-Uniform Rational B-Splines (NURBS)

$$S^w(u,v) = \sum_{i=0}^{n}\sum_{j=0}^{m} N_{i,p}(u)N_{j,q}(v)P_{i,j}^w$$

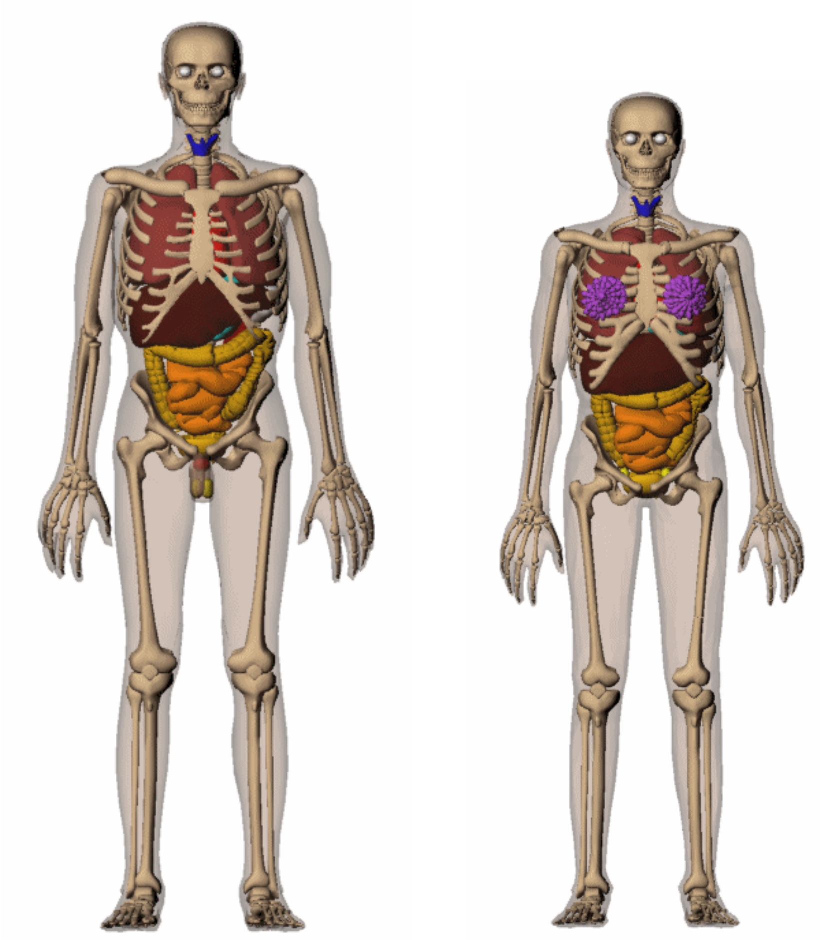


RPI Adult Male and Female Phantoms

Zhang* J, Na* YH, Caracappa PF, Xu XG. RPI-AM and RPI-AF, a pair of mesh-based, size-adjustable adult male and female computational phantoms using ICRP-89 parameters and their calculations for organ doses from monoenergetic photon beams. Phys. Med. Biol. 54:5885-5908. 2009

RPI Adult Male

Height: 176cm
Weight: 73 Kg



RPI Adult female

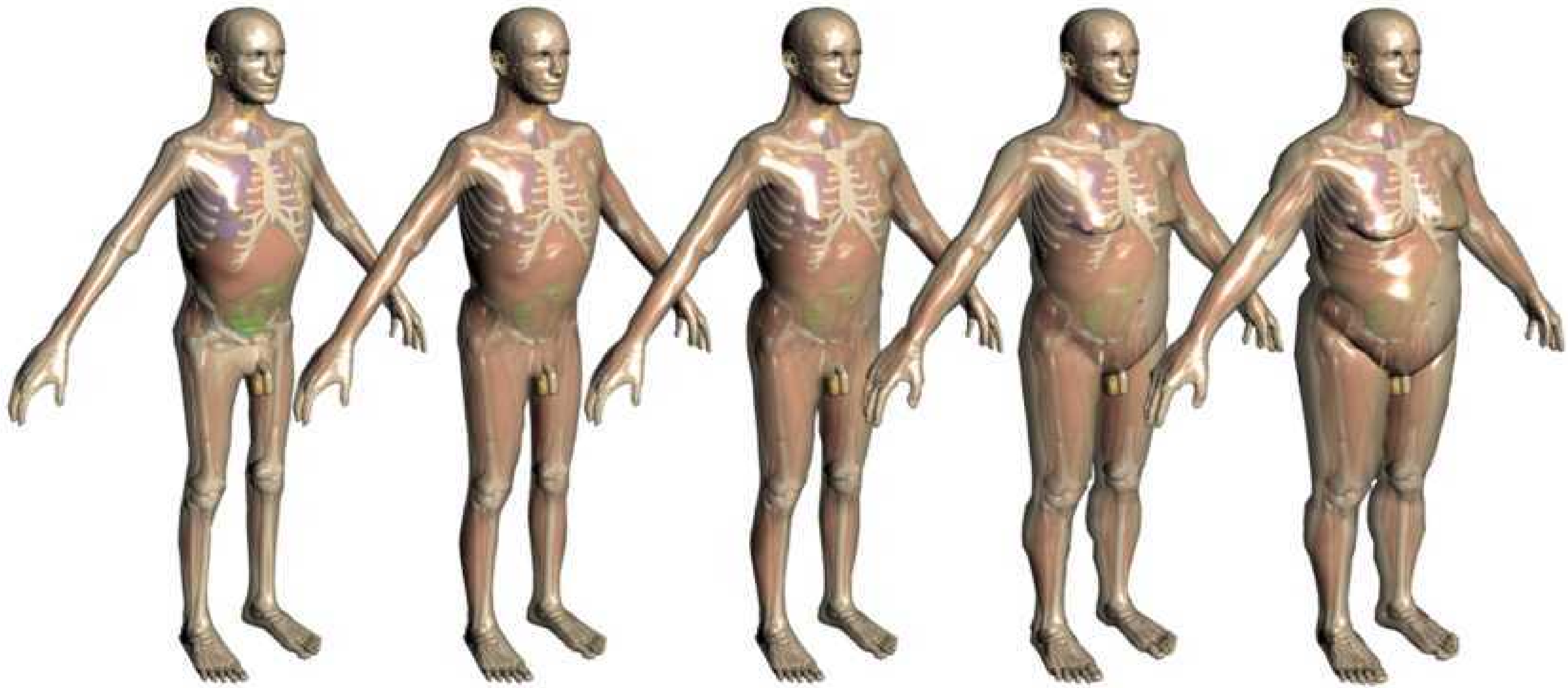
Height: 163 cm
Weight: 60 Kg

70 Organs; 45 Bone Components; 4 Muscle Structures

Size and Weight Adjustable Phantoms

Na* YH, Zhang* B, Zhang* J, 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. (submitted)

- **Same height (e.g. 176cm Male), but different weights:**

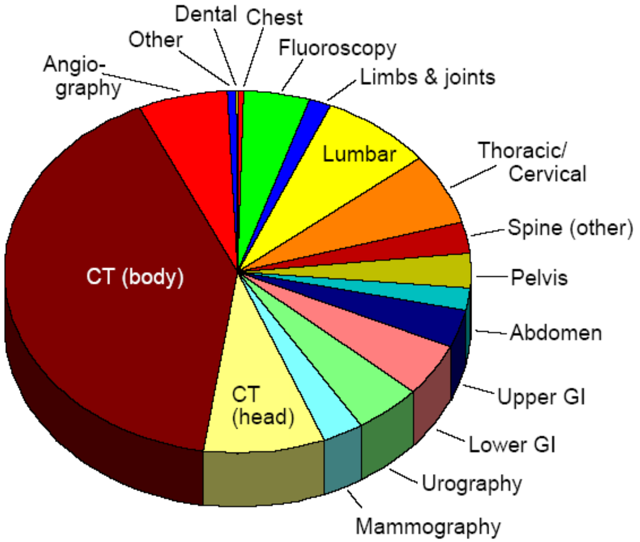


Weight	**58.5kg**	**66.3kg**	**73.1kg**	**86.4kg**	**103.8kg**
Percentile	**5th**	**25th**	**50th**	**75th**	**95th**

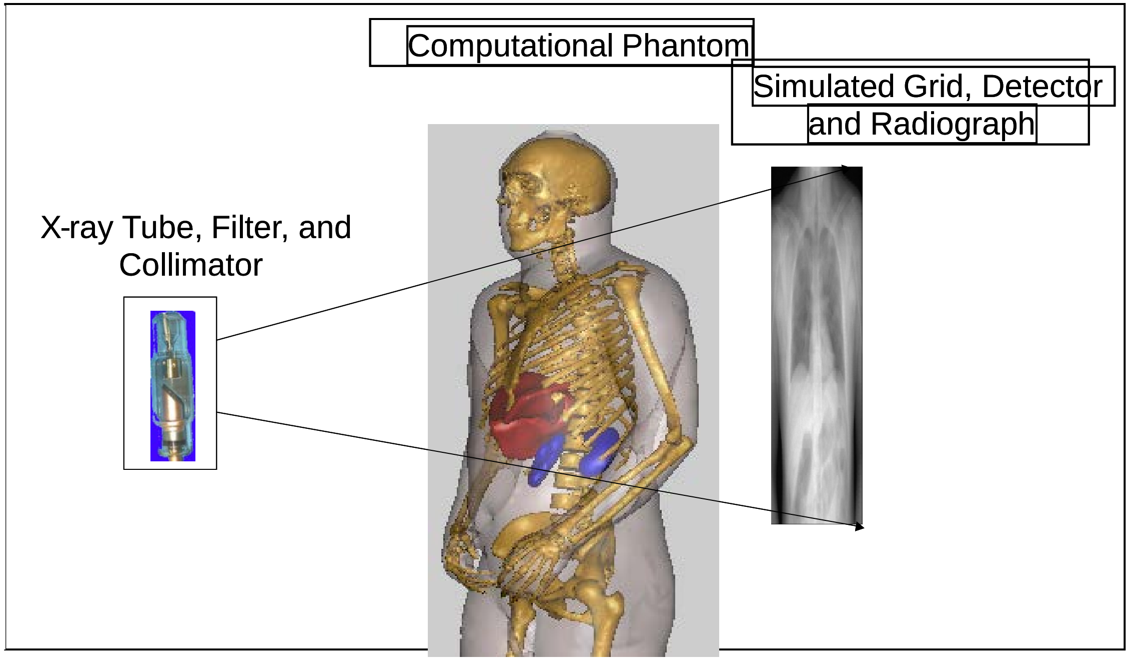
The skin meshes from an open source software, MakeHuman™ version 0.9.1 RC1I (http://www.makehuman.org/)

Radiograph Image Optimization (External Dosimetry)

- Simulator linking image quality with x-ray tube settings (mAs, kVp, filtration, grid etc).
- Optimization involves
  - **Maximizing diagnostic information (resolution, contrast, SNR)**
  - **Minimizing organ doses**



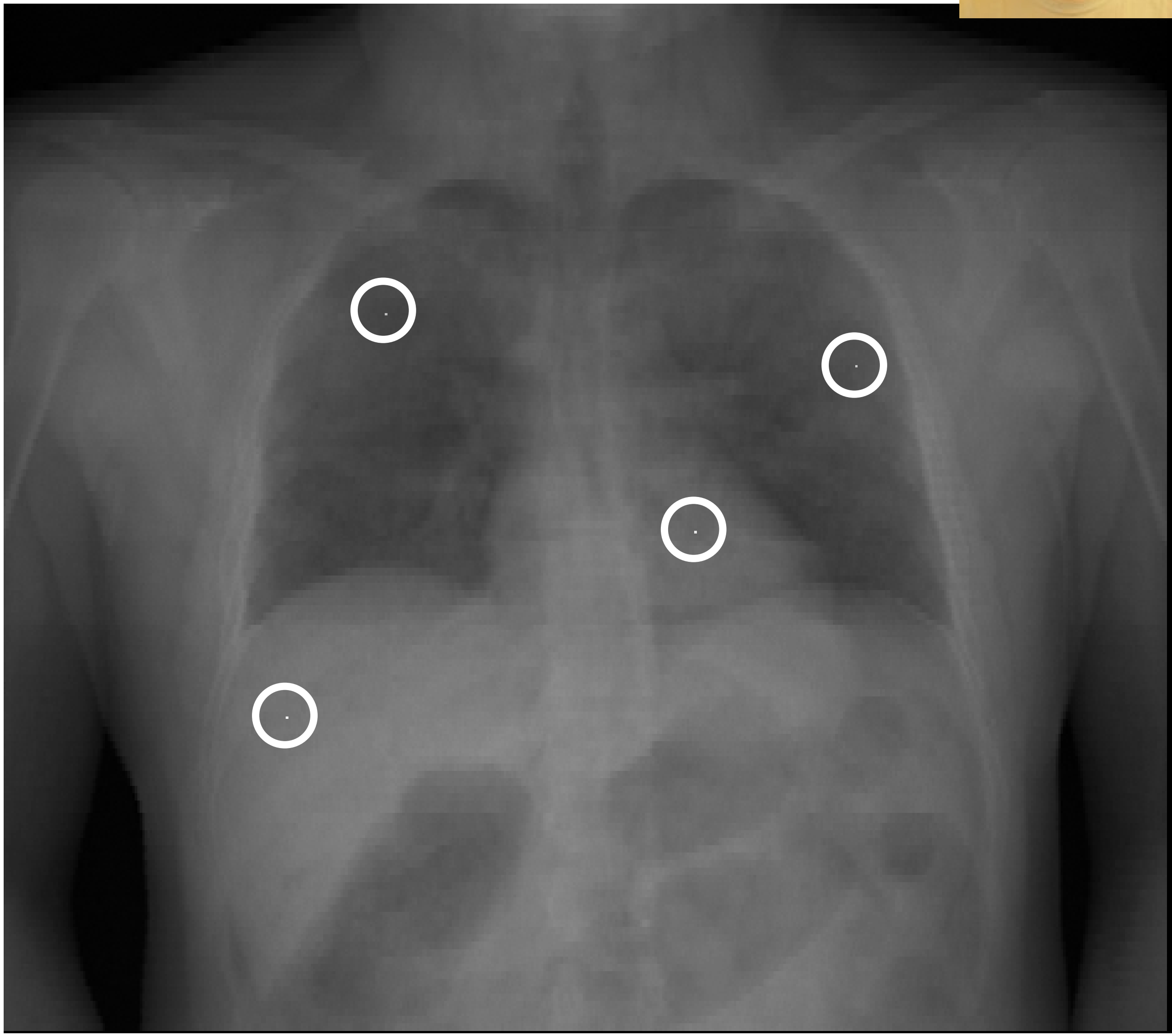
The relative contribution of diagnostic procedures to the collective medical dose estimated for the year 1996.



Simulation of Lesions

Locations

1. Right Lung, Behind Rib
2. Left Lung, Clear
3. Behind Heart
4. In Liver



Low dose and low resolution

Results

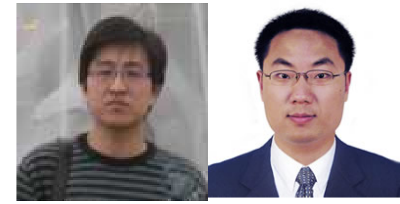
Comparison of chest x-ray from different mAs settings and doses

high dose and high resolution

Optimized dose and resolution

Winslow M. Xu, X.G, Yazici, B. Development of a Simulator for Radiographic Image Optimization. Computer Methods and Programs in Biomedicine. 78 (3):179-190. 2005.

Son I.Y., Winslow M., Xu X.G., Yazici B. X-ray imaging optimization using virtual phantoms and computerized observer modelling. Phys. Med. Biol. 51:4289-4310, 2006.

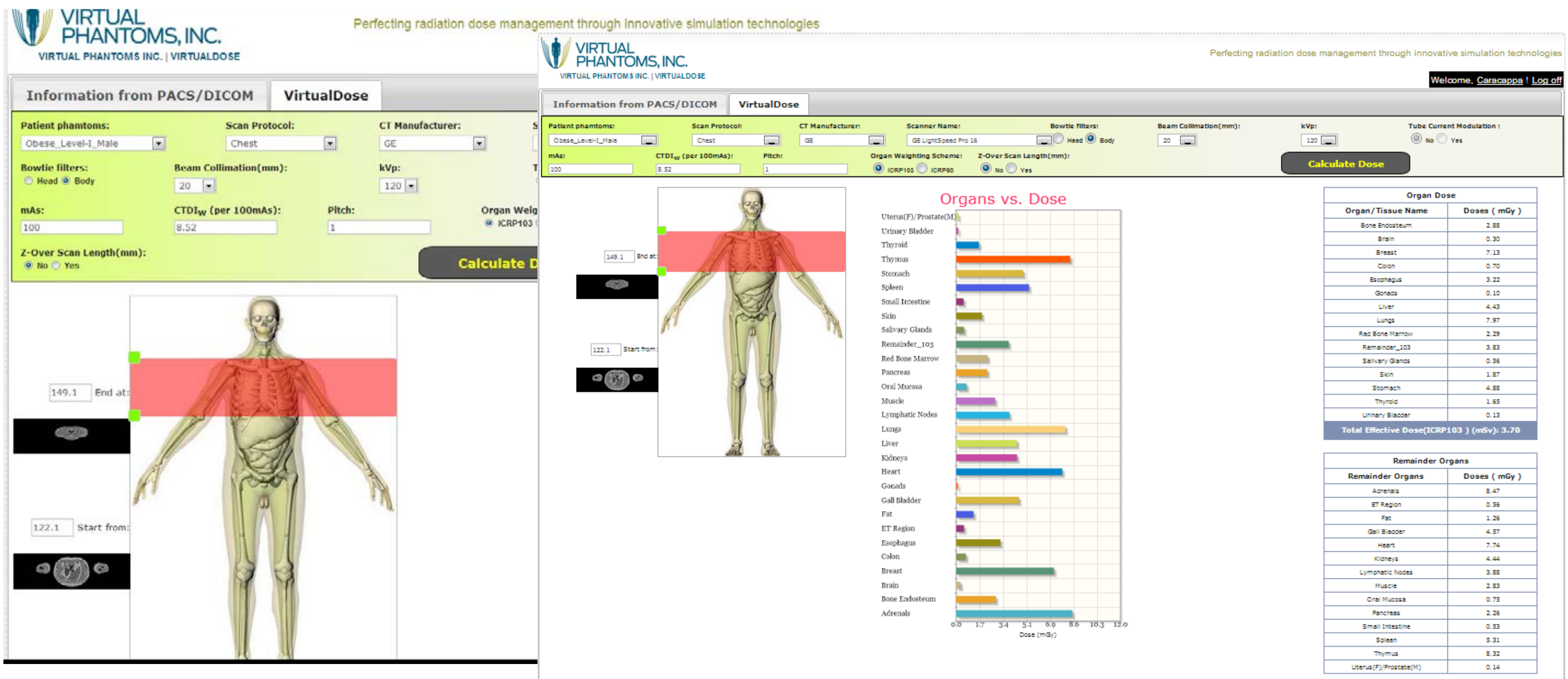


VirtualDose™ CT

A product of Virtual Phantoms, Inc.

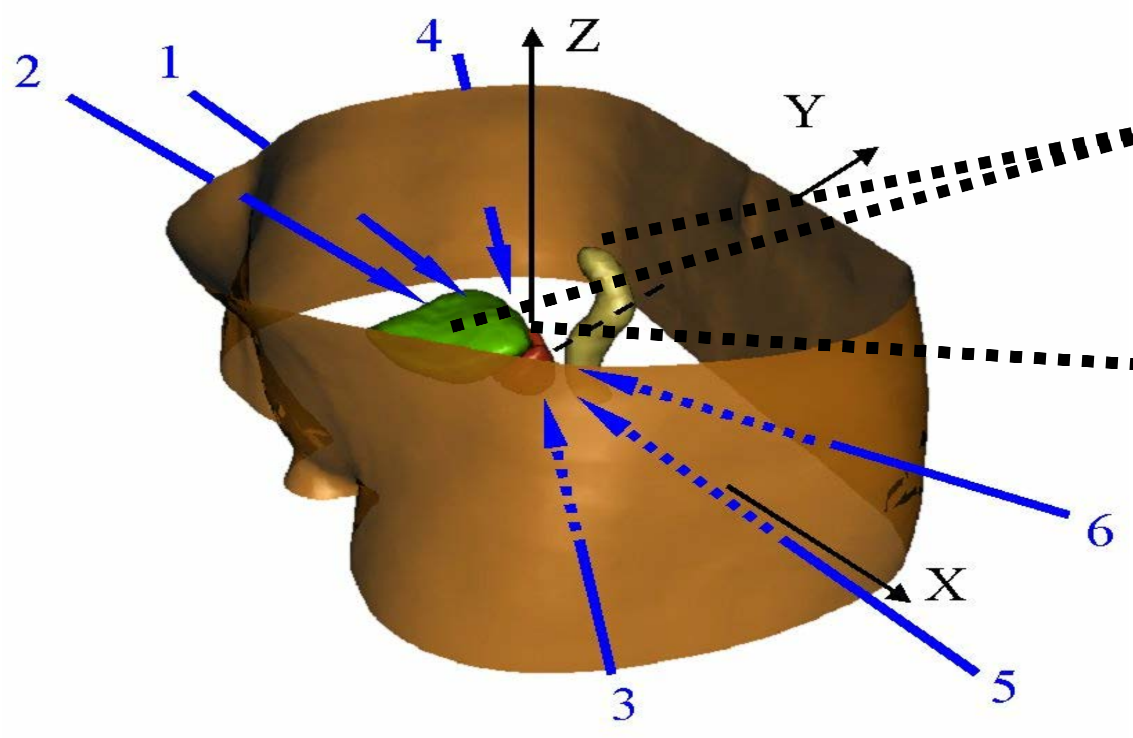
A platform independent, browser-based software

http://www.virtual-dose.com



3D CRT Beam Selection Using Adjoint MC

Wang* B., Xu X.G., Goldstein M., Sahoo N. Adjoint Monte Carlo method for prostate external photon beam treatment planning: An application to 3-D patient anatomy. <u>Phys. Med. Biol</u>. 50: 923-935, 2005.



OARs

- Bladder

- Rectum

PTV

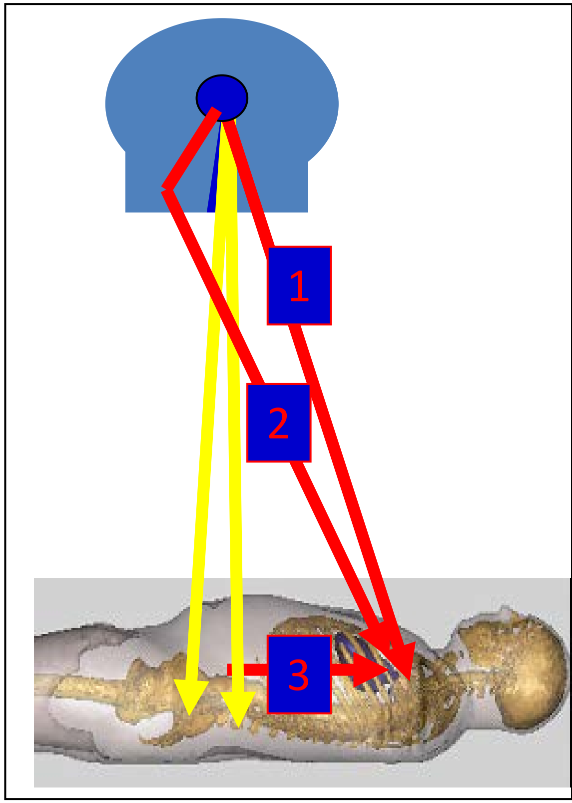
-Prostate

Secondary Cancer from Non-target Doses in Radiation Therapy: A Price to Pay for Successful RT

Hall and Wuu. Radiation-induced second cancers: The impact of 3D-CRT and IMRT. Int. J. Radiation Oncology Biol. Phys. Vol. 56, No. 1 pp 83-88. 2003.

Suit, et al. Secondary Carcinogenesis in Radiation Treated Patients; Part 1. A Review of Data on Radiation Induced Cancers in Human, non Human Primate, Canine and Rodent Subjects. Submitted to Radiation Research.

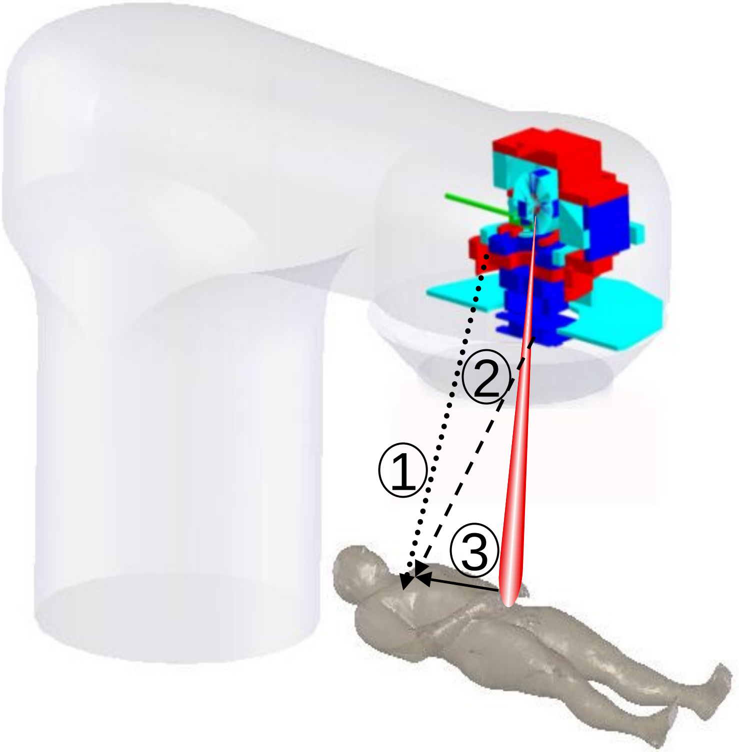
- **Cancer patients survive and live longer**
- **Patient younger**
- **Latent effects expected to increase**
- **IMRT requires greater MU (x3 3DCRT)**



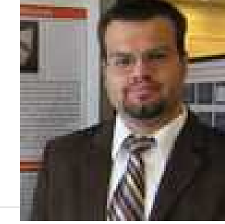
Secondary Cancer from Non-target Doses in Radiation Therapy

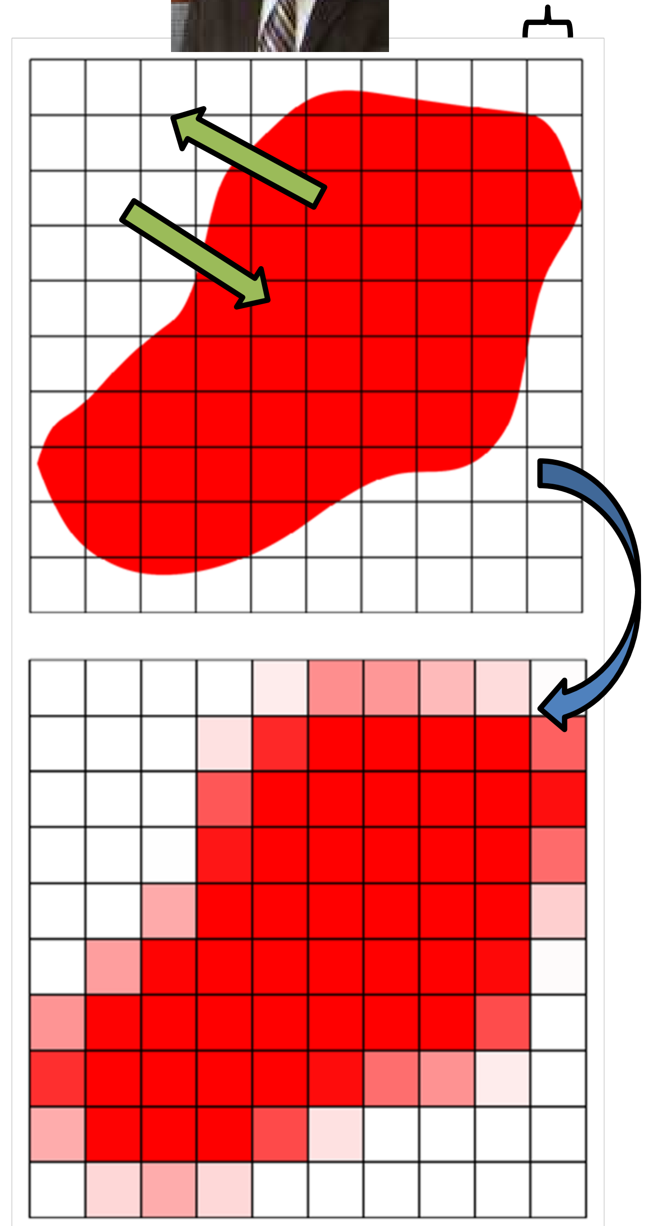
Bednarz* B, Xu XG. Monte Carlo modeling of a 6 and 18 MV Varian Clinac medical accelerator for in-field and out-of-field dose calculations: development and validation. Phys. Med. Biol., 54:N43-N57, 2009.

- Include both accelerator model and computational phantom
- The Accelerator Details:
  - Varian blueprints of 2100C
  - Model by Kase et al. in HPJ
- Patient Details:
  - RANDO Phantom
  - VIP-Man
  - Pregnant patients
  - RPI adult male and female



PET and The Partial Volume Effect

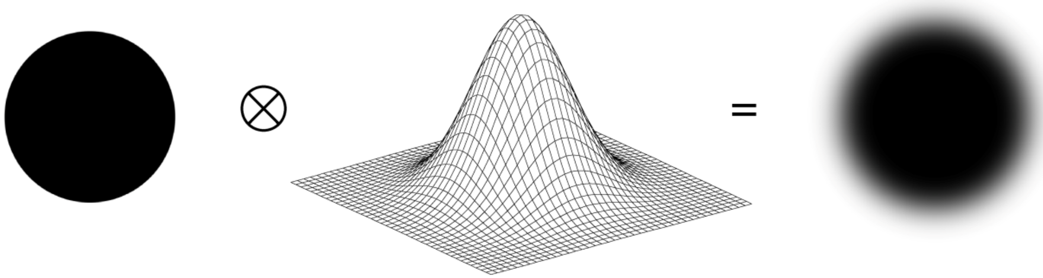




Arises from the poor spatial resolution:

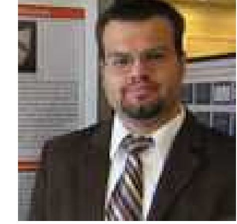
1) Spreading of counts across physical tumor boundaries due to image blurring
2) Tissue fractionation due to coarse voxel grid

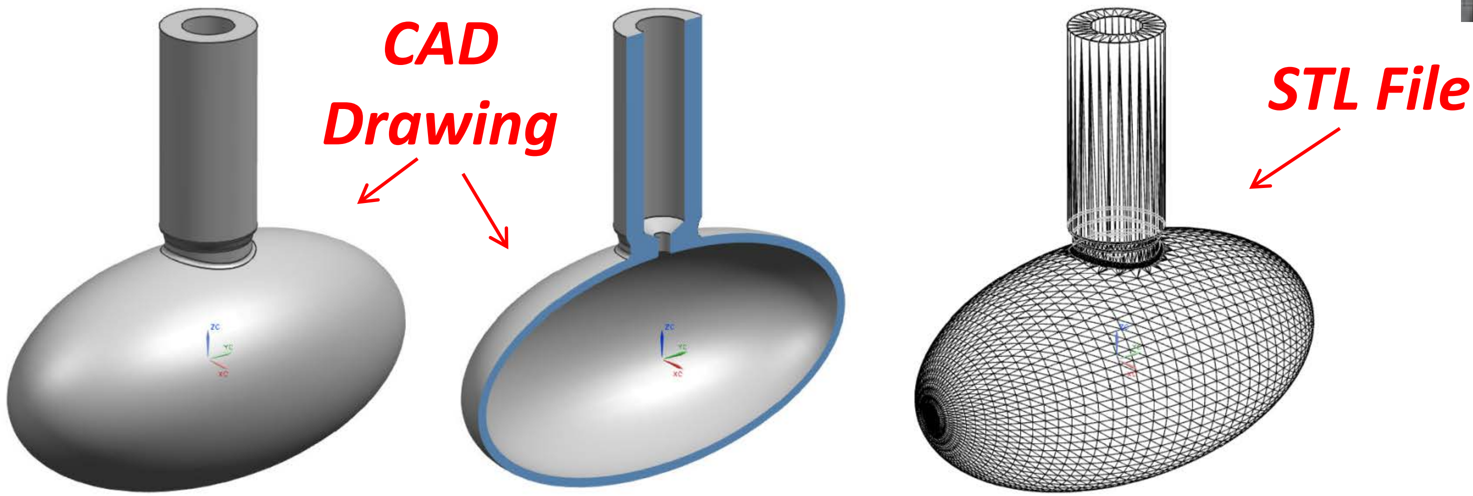
General tendency is to make small lesions look *<u>less metabolically active</u>*



True Image **Gaussian Point-Spread Function** **Measured Image**

Exp. Methods: Ellipsoid Phantom Designs



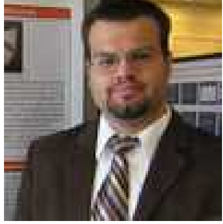


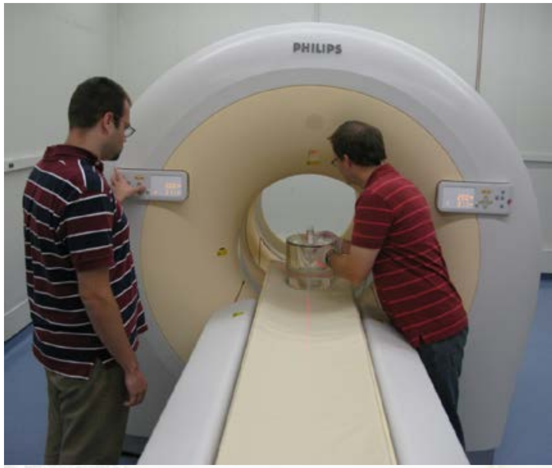
Axis Ratio		Fill Volume (cm^3)					
		A	B	C	D	E	F
		26.52	11.49	5.58	2.57	1.15	0.52
		Inner Diameter (mm)					
		A	B	C	D	E	F
1:1	Major	37.0	28.0	22.0	17.0	13.0	10.0
4:3	Minor	33.6	25.4	20.0	15.4	11.8	9.1
	Major	44.8	33.9	26.7	20.6	15.7	12.1
8:5	Minor	31.6	23.9	18.8	14.5	11.1	8.5
	Major	50.6	38.3	30.1	23.3	17.8	13.7
2:1	Minor	29.4	22.2	17.5	13.5	10.3	7.9
	Major	58.7	44.4	34.9	27.0	20.6	15.9

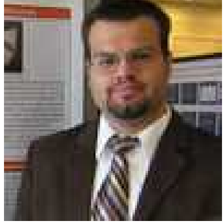
Tumor volumes same as that of NEMA image quality phantom

Experimental Methods:

Preparation of Phantoms with Radioactivity

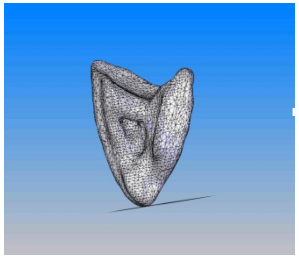






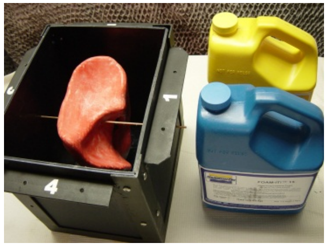
CAD/CAM Phantom Fabrication

1. **Rapid Prototyping the lung in a plaster material (i.e., 3D printing)**
2. **Suspend lung prototype in mold box**
3. **Pour foaming plastic around to form a mold and wait to cure**
4. **Cut mold apart after and seal with epoxy**

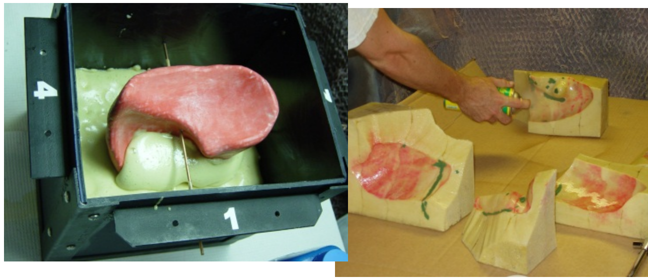


(1) CAD model

(2) Prototype

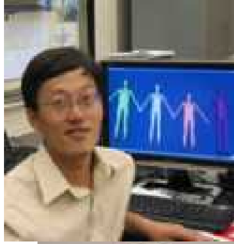


(3) Molding box

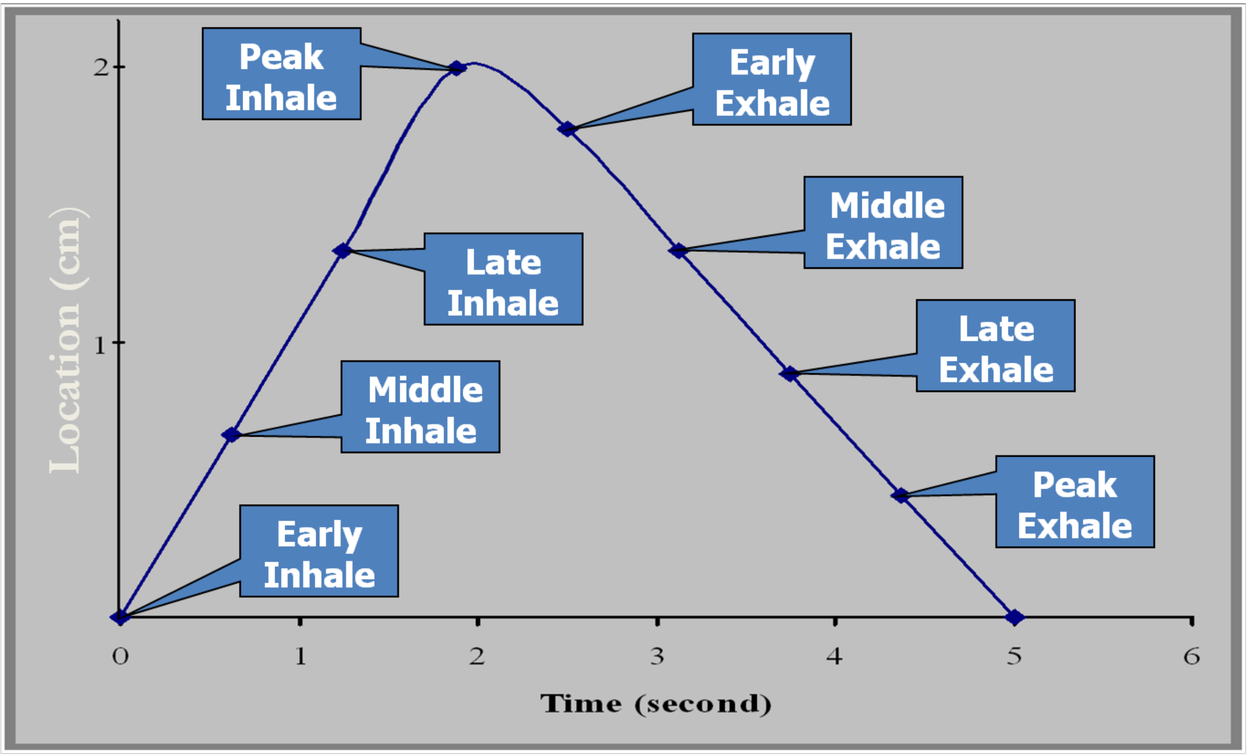


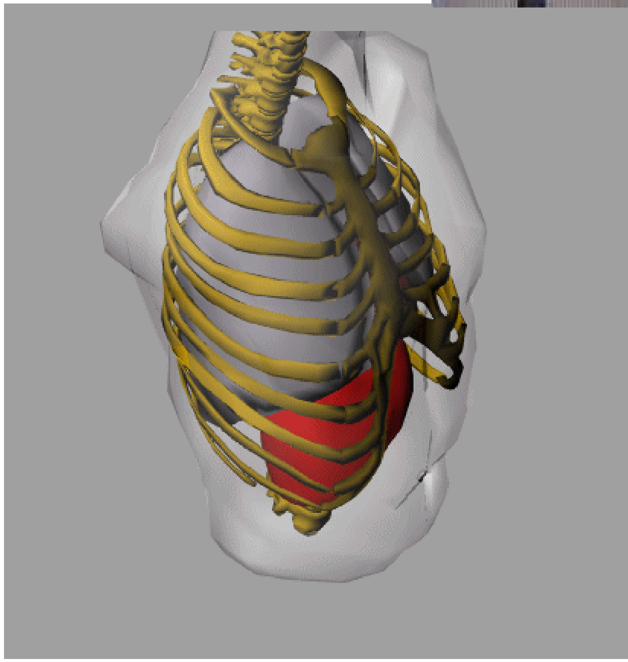
(4) Mold parts

4D Geometry-Based Respiration Modeling



Zhang JY, Xu XG, Shi C.Y, Fuss M. Development of A Geometry-Based Respiratory-Motion-Simulating Patient Model for Radiation Dosimetry. Journal of Applied Clinical Med. Phys., 9(1):16-28, 2008





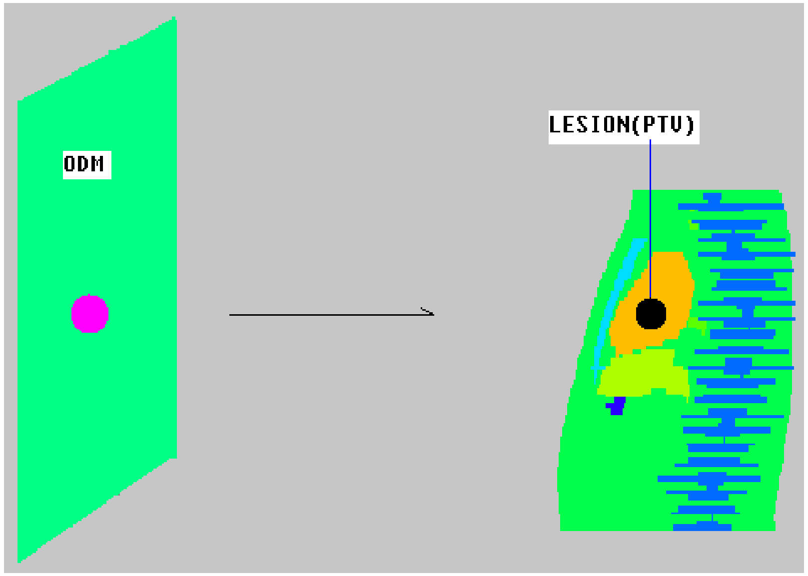
Two Treatment Plans Simulated in Monte Carlo Code

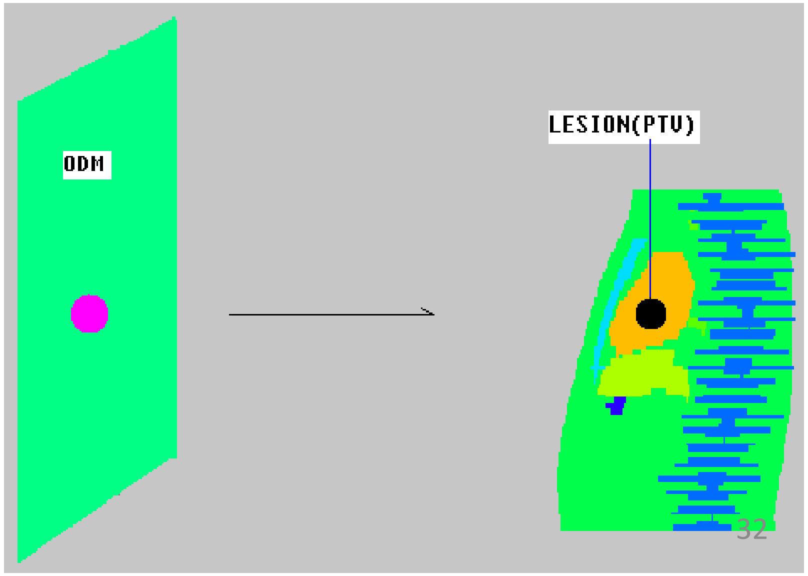
Treatment Planning #1 (gating TP)

- The center of ODM is aligned to the lesion in Phase 1 (early inhalation), i.e., 3D treatment planning

Treatment Planning #2 (4D TP)

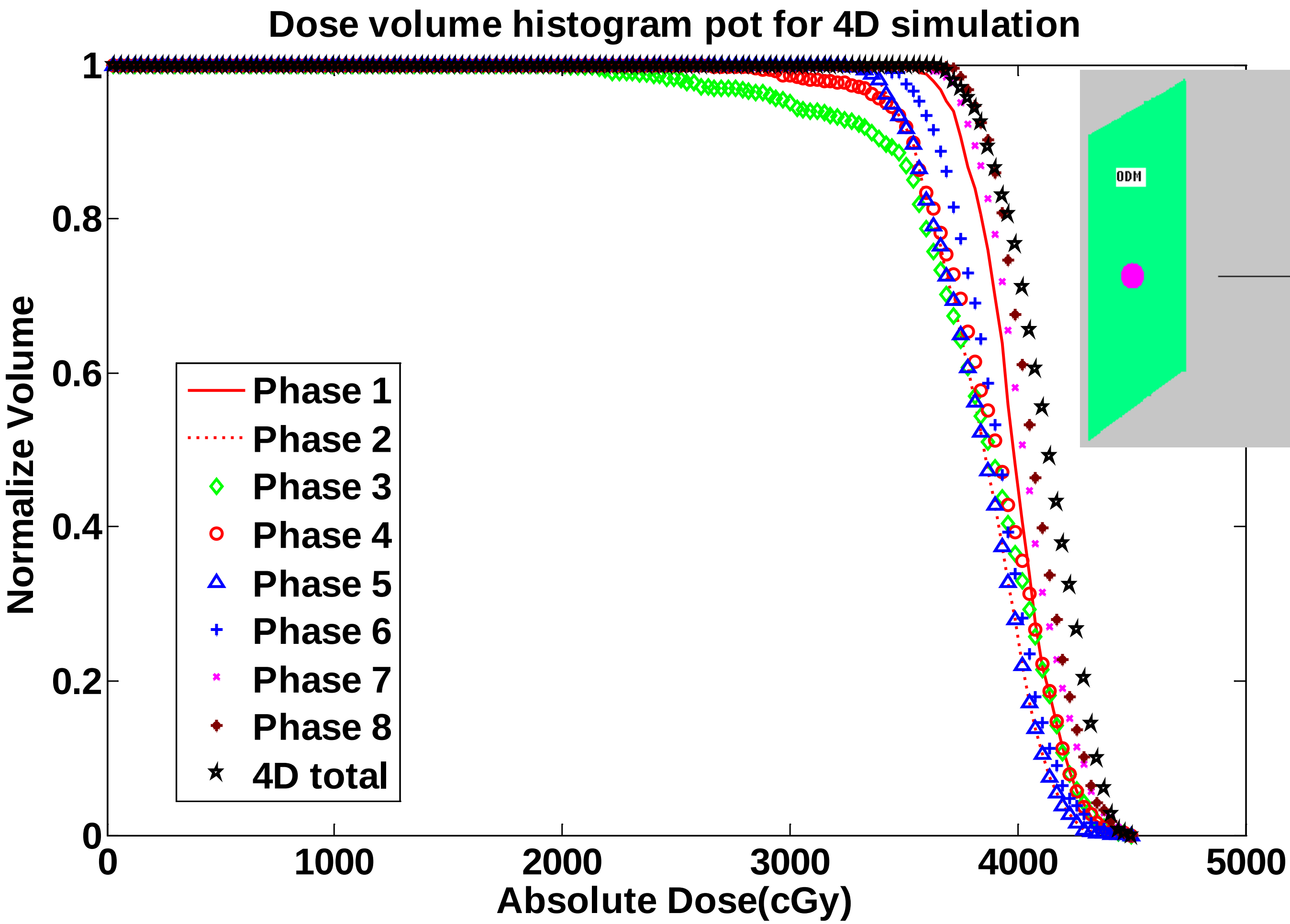
- The "image-guided" 4D TP where PTV moves according to 8 phases

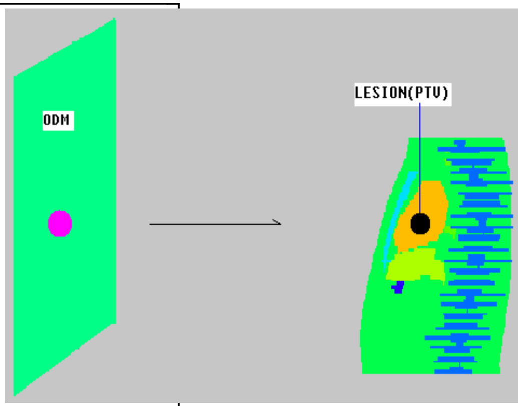




4D Monte Carlo Dose Simulations

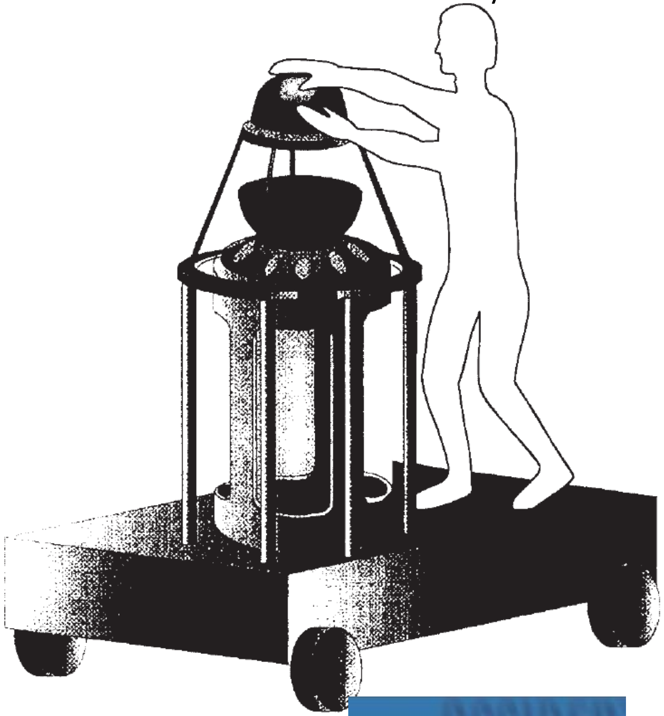
- The center of ODM is always kept conformal to the center of the lesion in Phase1.
- The data show that dose distributions in phase 3 and phase 4 are under-dosed



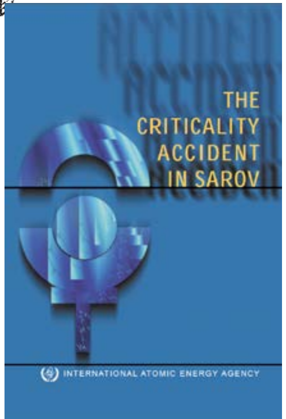


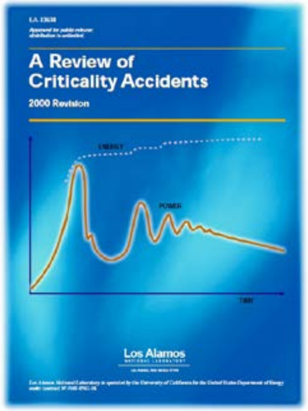
Posture Simulation for Criticality Accident

Vazquez* JA., Ding A, Haley T, Caracappa PF., Xu XG. A dose-reconstruction study of the 1997 Sarov criticality accident using animated dosimetry techniques. Health Phys. 106(5):571-82 (2014). Cover page
Vazquez* JA., Caracappa PF, Xu XG. Development of posture-specific computational phantoms using motion capture technology and application to radiation dose reconstruction for the 1999 Tokai-mura nuclear criticality accident. Phys. Med. Biol. 59: 5277-5286 (2014).

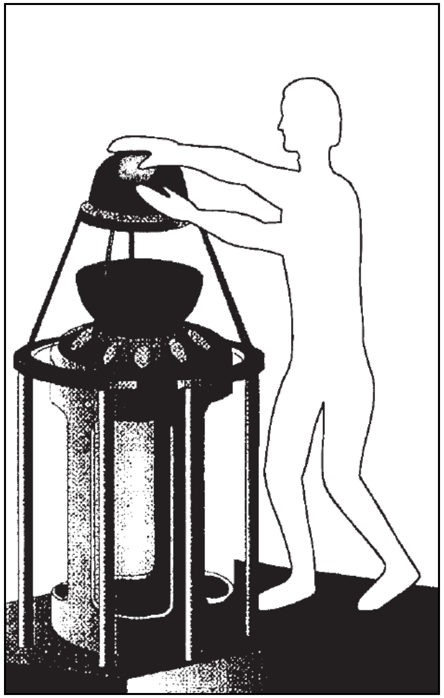


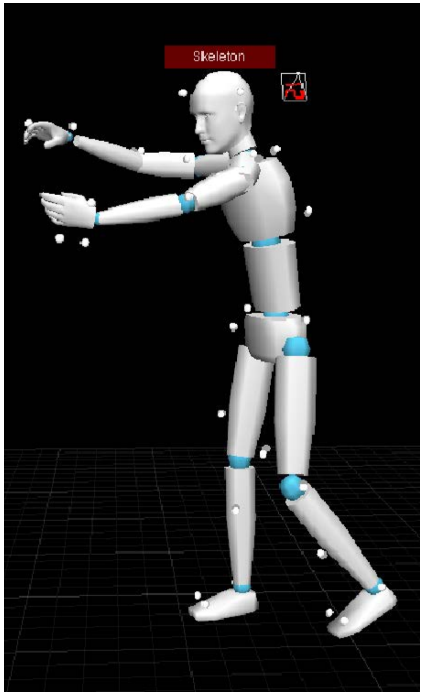
- **1997 accident at a nuclear testing facility in Sarov, Russia**
- **Technician exposed to radiation resulting from a criticality excursion**
- **Death 66 hours later**

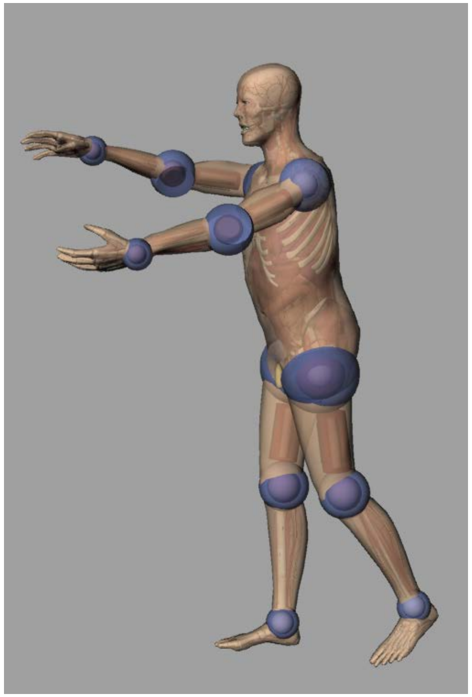




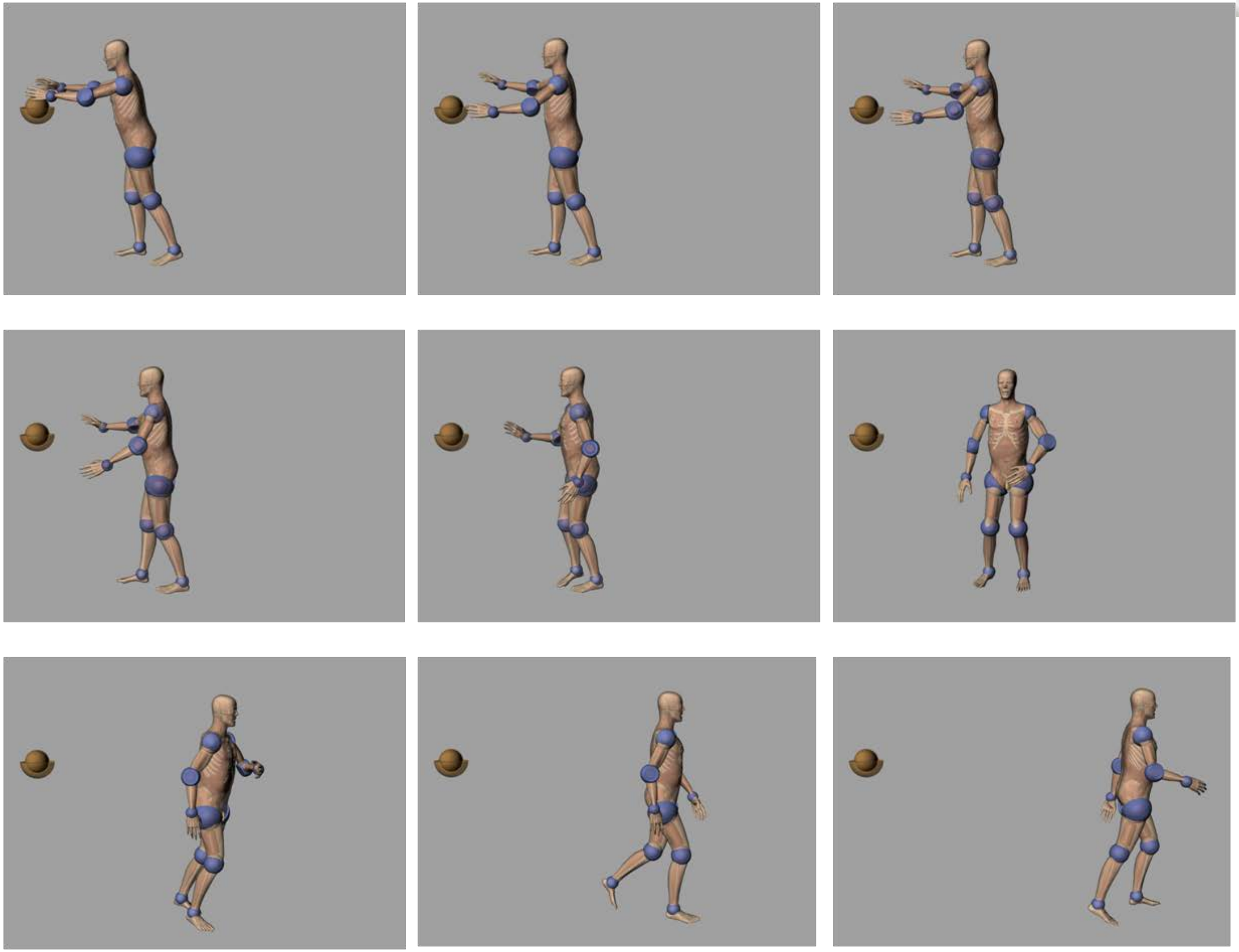
Simulating the Sarov Accident



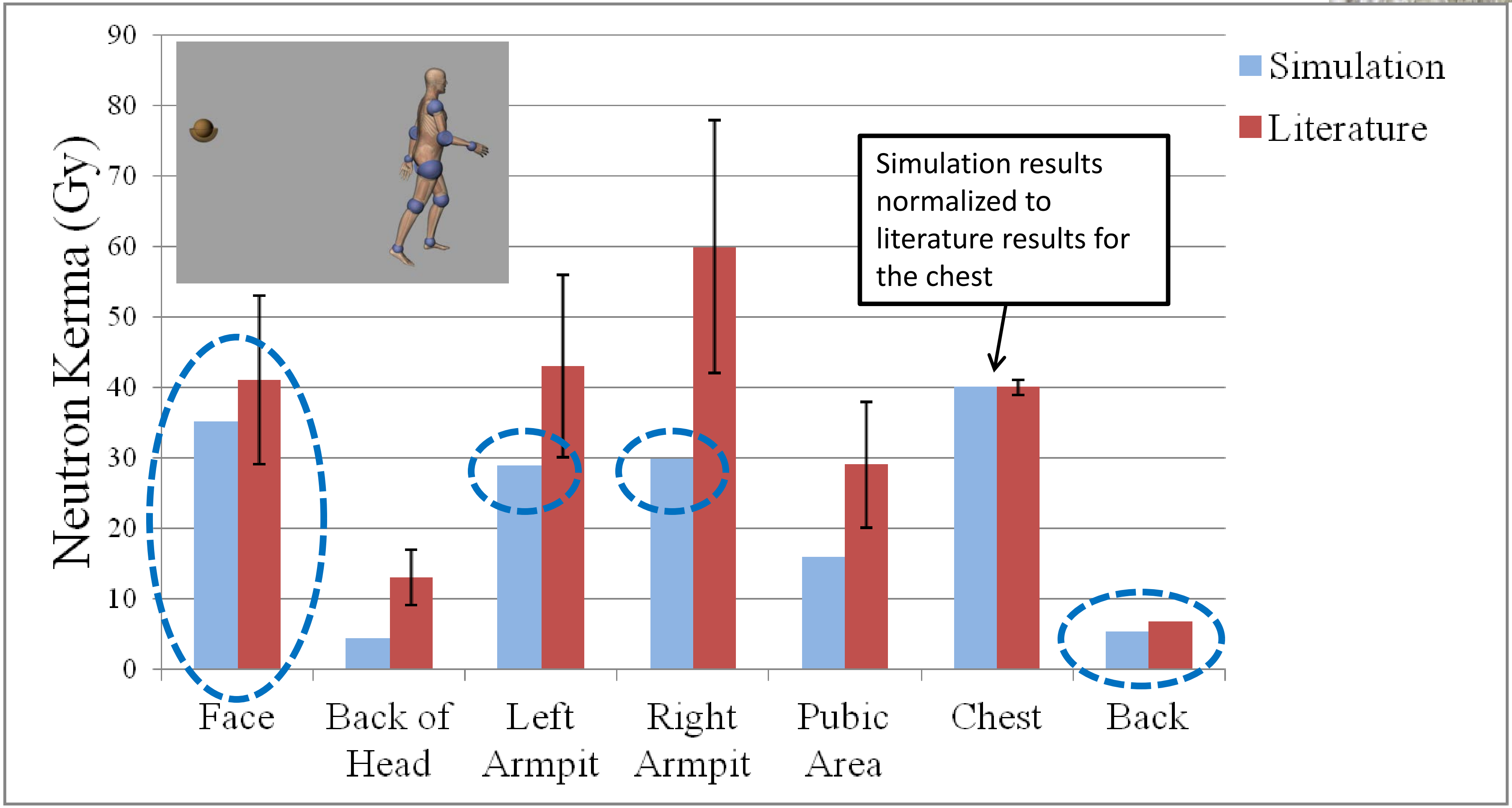




Simulating the Sarov Accident



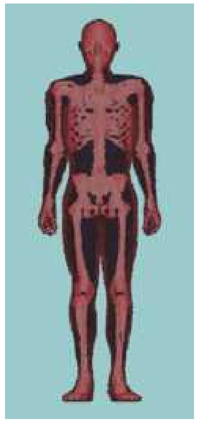
Results: Neutron Kerma



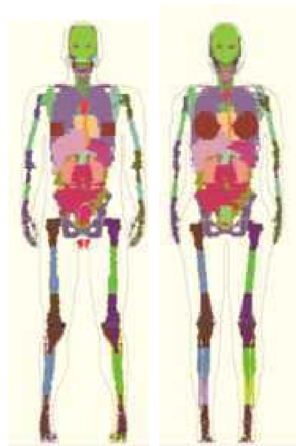
<<Handbook of Anatomical Models for Radiation Dosimetry>>

– *curtsey images from various authors*

REX & REGINA (ICRP)

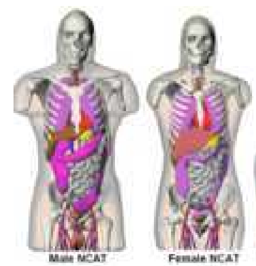


NORMAN

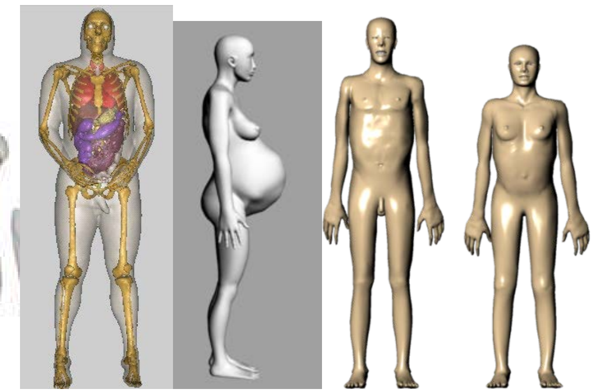


MAX06 FAX06

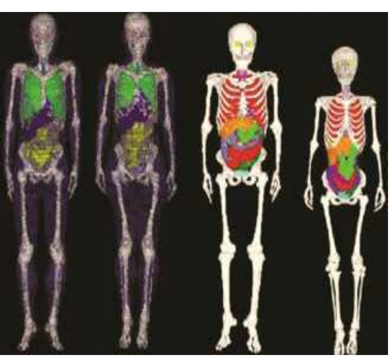
Zubal



NCAT

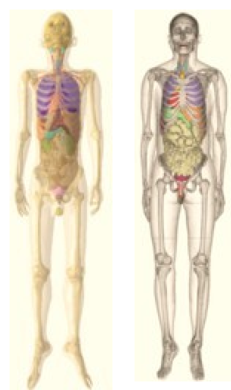


VIP-Man, Pregnant, Adult M/F

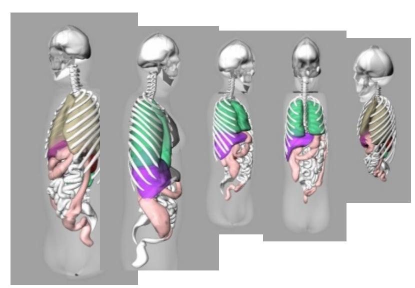


Otoko Onago JM KF

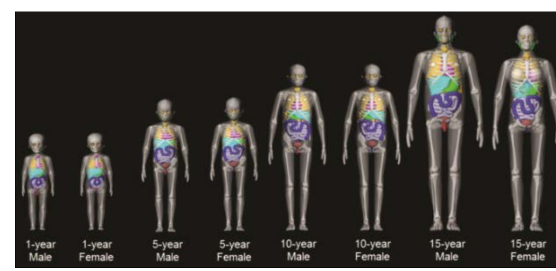
KTMAN 1, 2



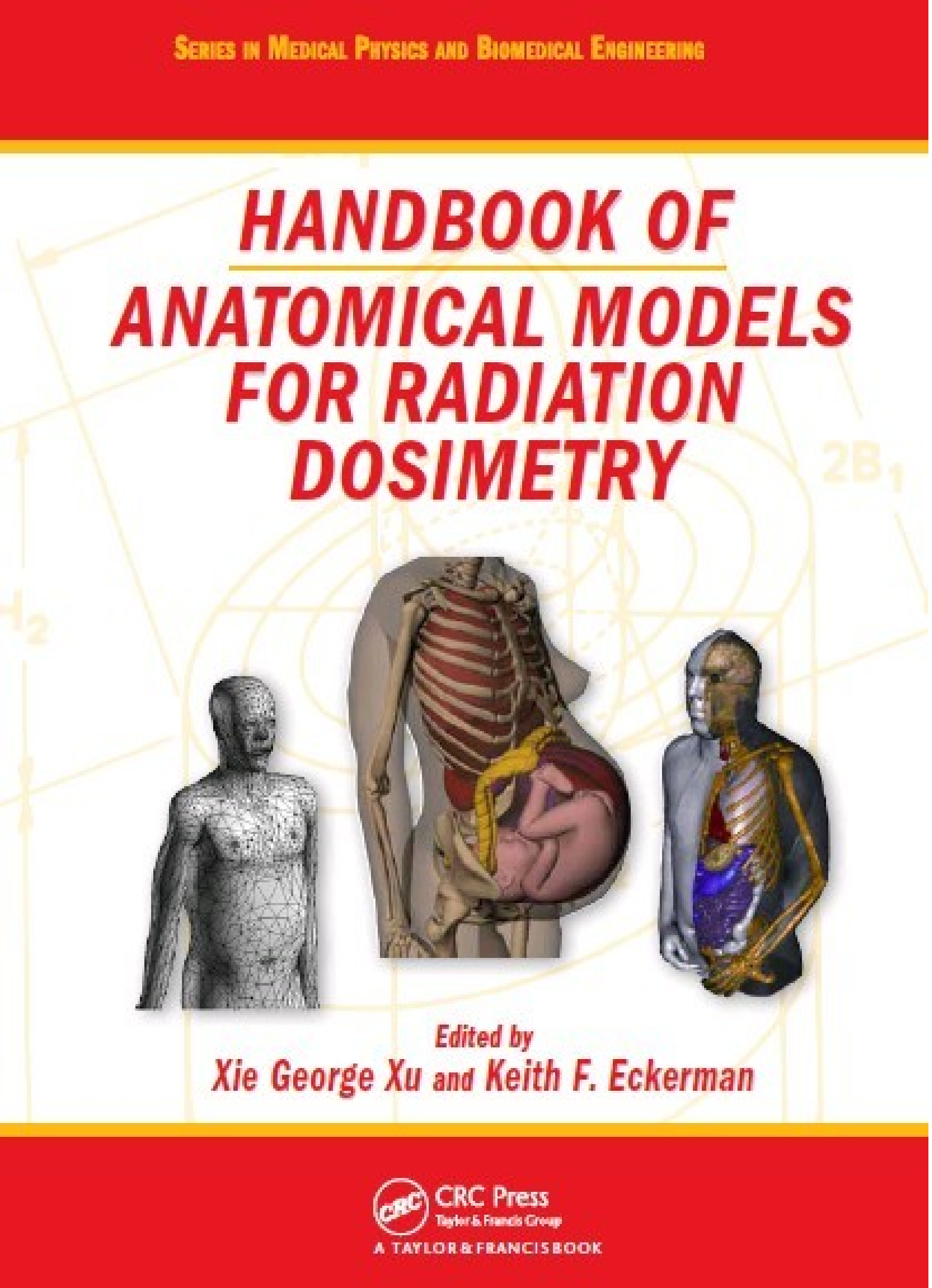
CNMAN VCH



Vanderbilt Family



UF Family



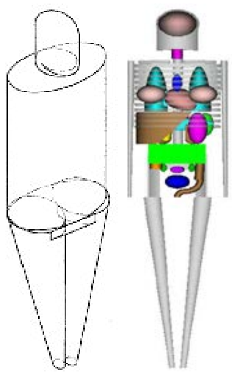
Published in late 2009

- 50-y history
- 30 chapters
- 64 authors
- 13 countries (regions)
- **100+ phantoms**

50-Year History of Computational Phantoms

- Radiation Protection
- Medical Imaging
- Radiotherapy

1st Generation



MIRD anthropomorphic models in 1980s

STYLIZED

2nd Generation

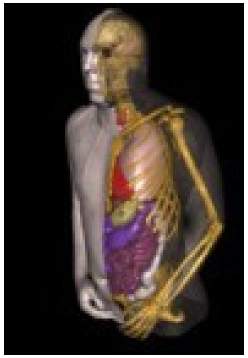
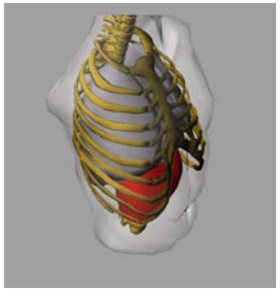


Image-based rigid, 3D model in 1990-2000s

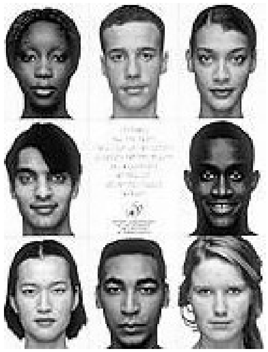
VOXEL

3rd Generation



Deformable and moving 4D models 2008-2010

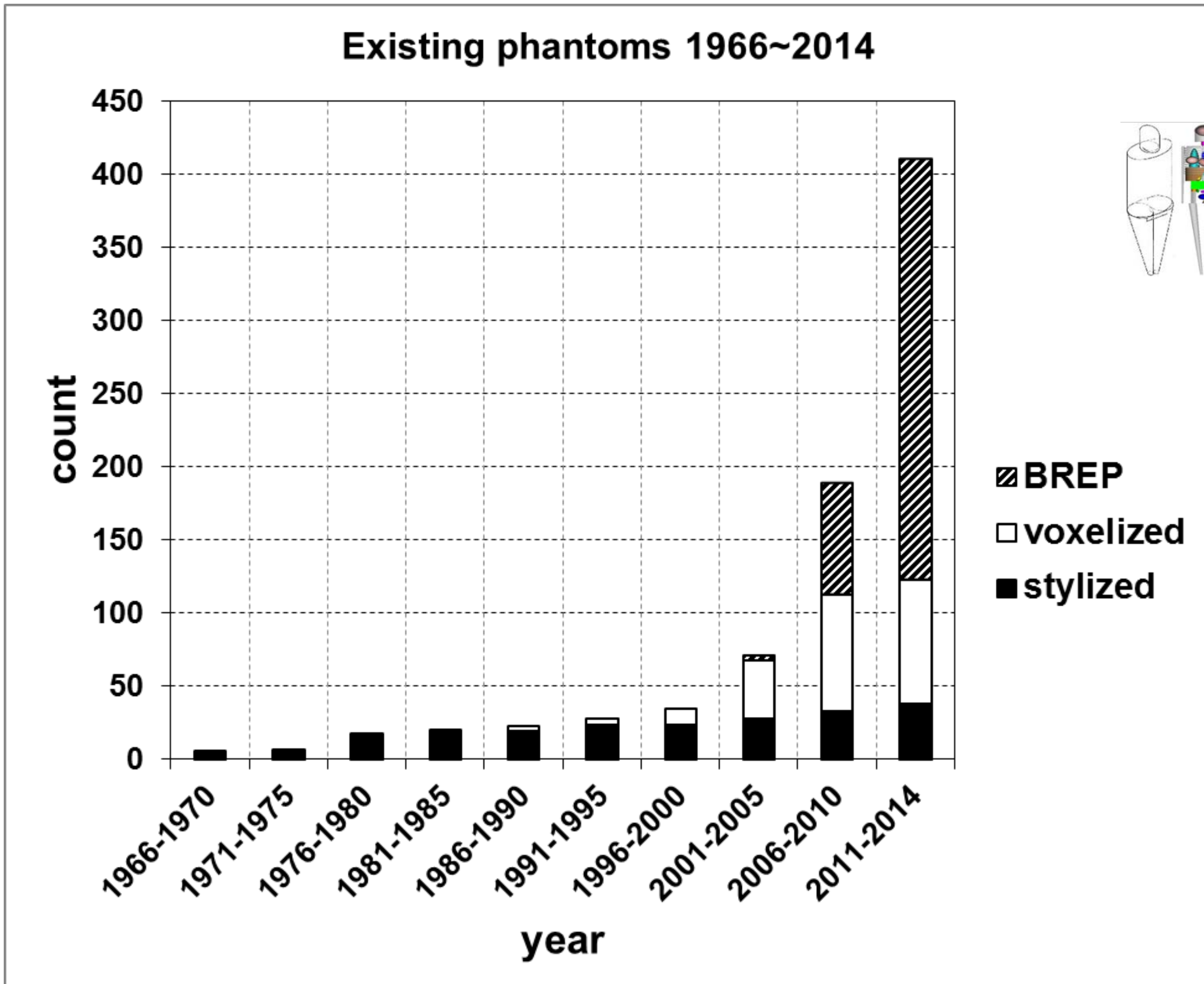
BREP



Personalization is Future

The Number of New Phantoms Increased Exponentially

Xu XG. An exponential growth of computational phantom research in radiation protection, imaging, and radiotherapy: a review of the fifty-year history. **Phys. Med. Biol.** (2014).
<u>Top-10 most-downloaded paper in PMB during 2014</u>



Outline

1. Computational Human Phantoms

2. ARCHER Monte Carlo Code

Recent Work on Fast Monte Carlo Methods

- **Monte Carlo method is the gold standard in radiation transport analysis and dose calculations**

- **Advantages**
  - Accurate physics model
  - Particle tracking in heterogeneous systems
  - 3-D geometry

- **Disadvantage**
  - Long computation time to achieve acceptable statistical uncertainty (a few hours to days)

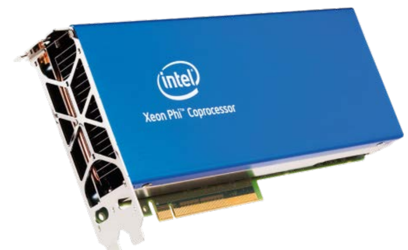
- **Traditional parallel paradigms are CPU-based**
  - Message Passing Interface (MPI): MPICH, OpenMPI
  - Multithreading: OpenMP, Pthreads

High-Performance Computing Depends on Hardware Accelerators

- **Hardware accelerators**
  - ➢High computing efficiency

Nvidia GPU [1]

AMD GPU [2]



Intel coprocessor [3]

IBM PowerXCell 8i processor [4]

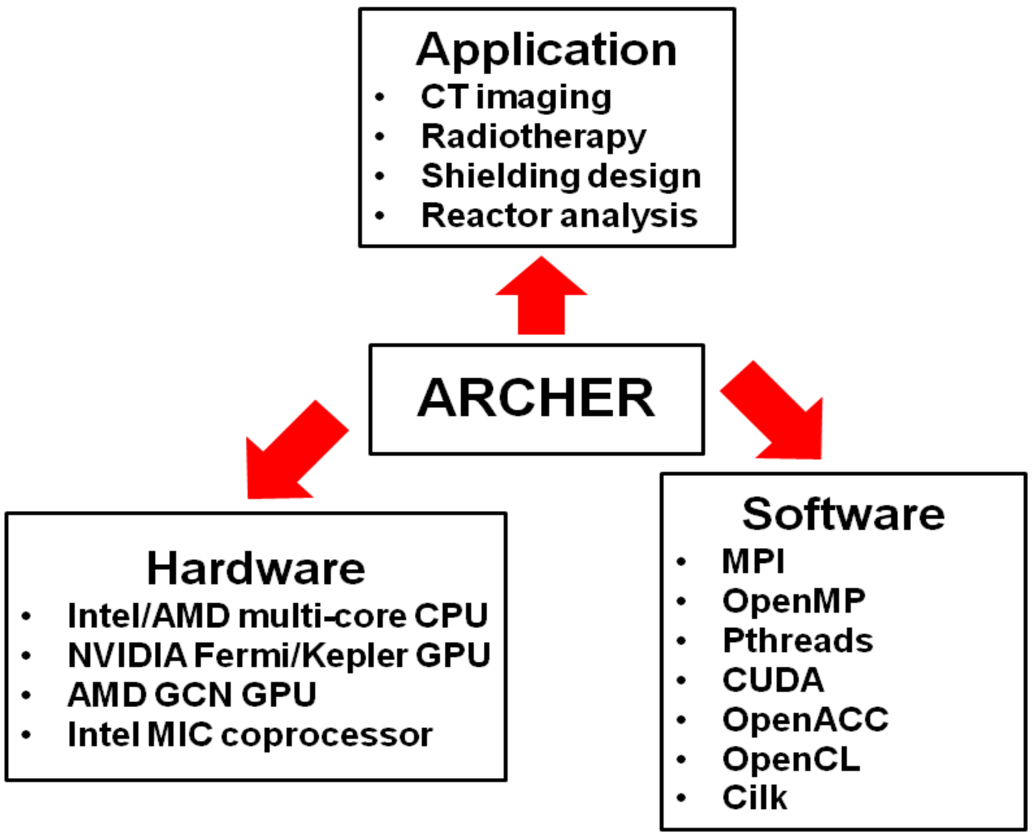
ClearSpeed CSX processor [5]

Figure sources: [1]Nvidia Press Center, [2] AMD Workstation Product, [3] Max Expansion, [4] Fixstars User's Manual, [5] ClearSpeed Whitepaper.

ARCHER – A Monte Carlo Testbed



Accelerated Radiation-transport Computations in Heterogeneous EnviRonments



ARCHER

www.archer-MC.com

Two Recent Examples:

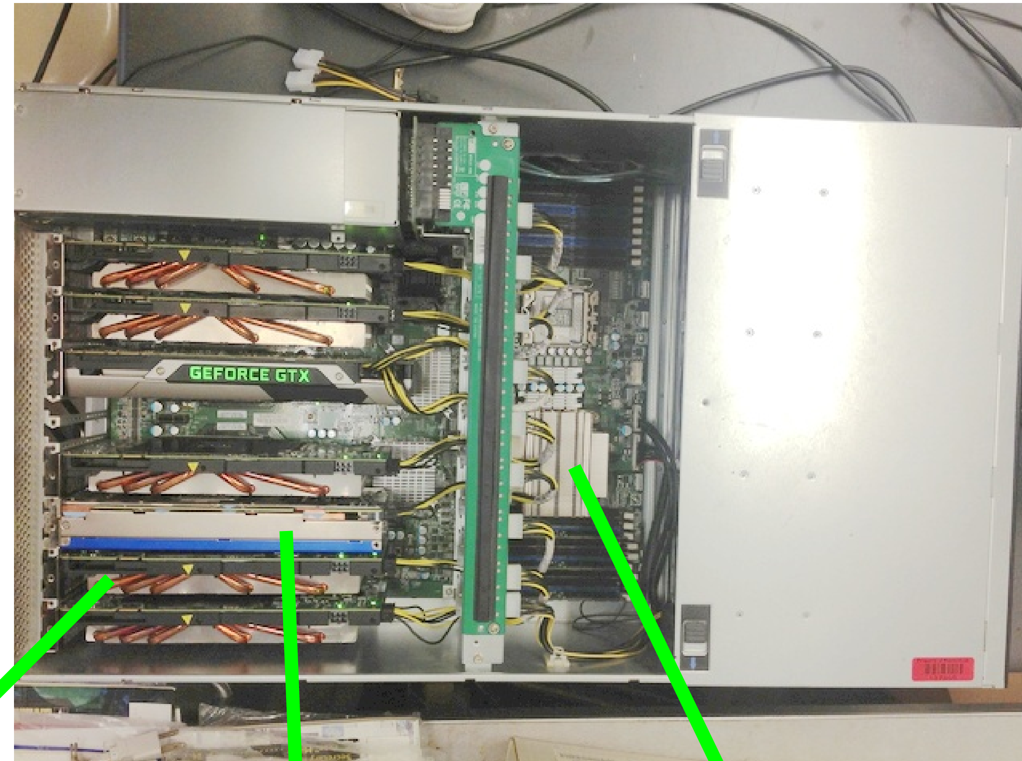
1. CT imaging

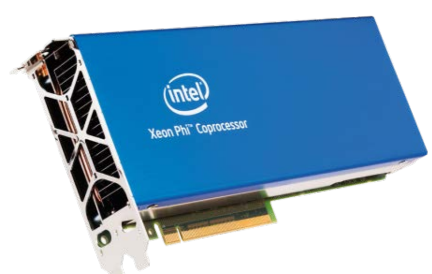
2. Radiotherapy

ARCHER

Materials and Methods: Hardware @ $10k

- **Tyan FT77B7015 server**
- **Intel Xeon X5650 CPU**
  - 6 cores
  - 12 hyperthreads in total
- **Nvidia Tesla M2090 GPU**
- **Intel Xeon Phi 5110p coprocessor**



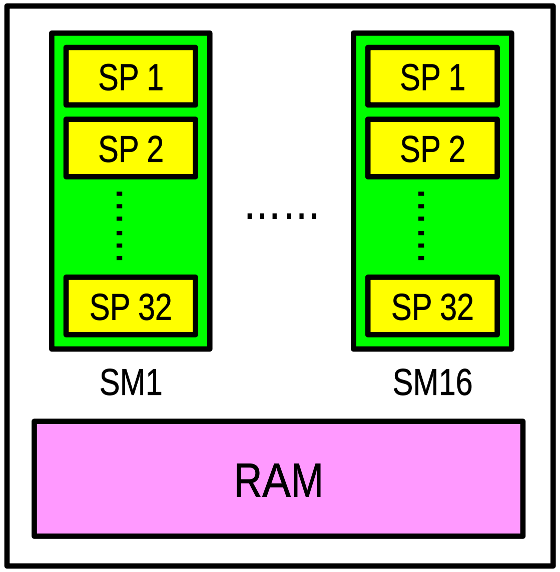


[1]

[1] CPU figure resource: SuperBiiz

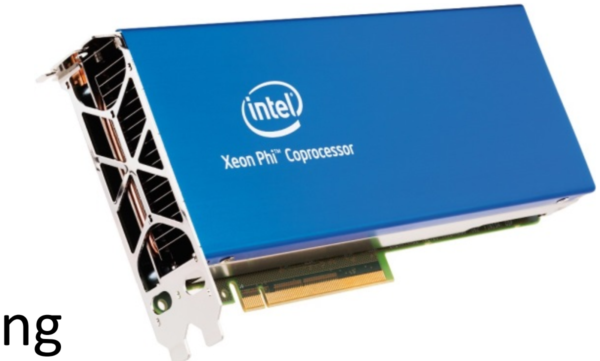
Method: Nvidia Tesla M2090 GPU

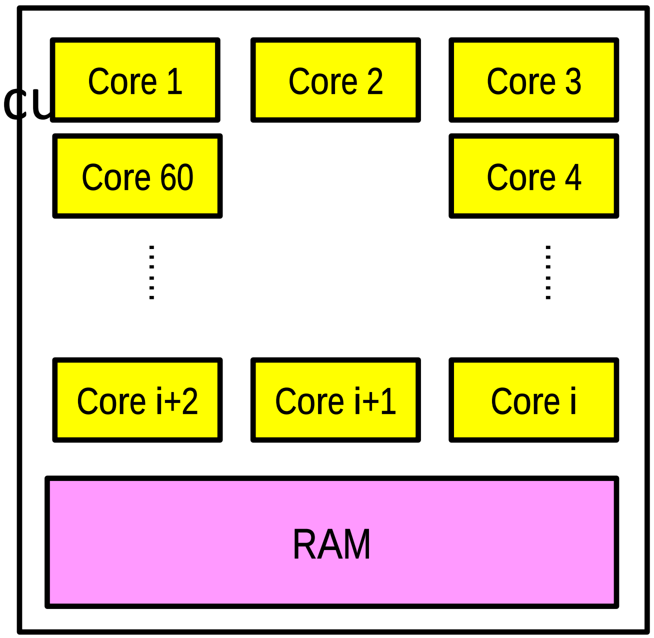
- **Fermi architecture**
  - 16 Streaming Multiprocessors (**SM**)/GPU
  - 32 Streaming Processors (**SP**)/SM→CUDA core
  - 6 GB RAM
- **Parallelism achieved by:**
  - GPU: thread blocks are distributed among the SMs for **simultaneous** execution
  - SM: threads are pushed into the instruction pipelines for **concurrent** execution
- **Number of active resident threads on a GPU**
  - Problem-dependent
  - ~8000 in our case



Introduction: Intel Xeon Phi "coprocessor"

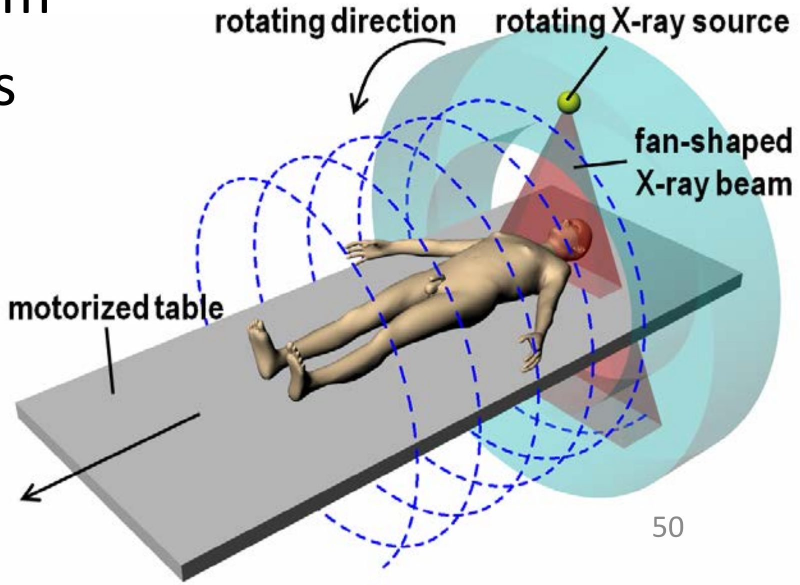
- **Many Integrated Core (MIC) architecture**
  - 60 Pentium cores
  - 8 GB RAM
- **Parallelism achieved by:**
  - coprocessor: threads are distributed among the cores for **simultaneous** execution
  - core: 4 hyper-threads for **concurrent** execu
- **Number of threads on a coprocessor**
  - 240 (fixed)





Materials and Methods: CT scanner model (w Dr. Bob Liu and Mannu Kalra, MGH)

- **GE LightSpeed third-generation 16-multi-detector CT scanner**
  - Validated with experimental CTDI data
- **Scan protocol**
  - Tube voltage: 80, 100, 120, 140 kVp
  - Beam collimation: 1.25, 5, 10, 20 mm
  - Scan type: head, body bowtie filters
  - Scan mode: helical, axial



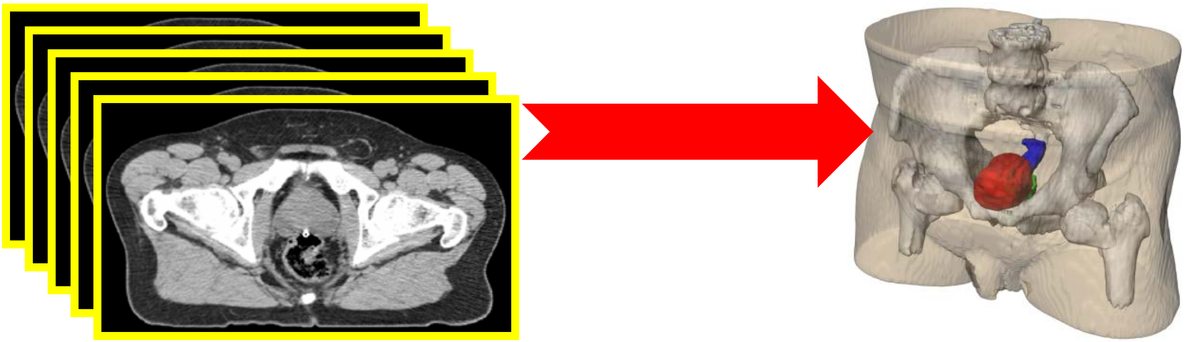
Results and Discussion: Performance benchmark

Code	Runtime configs	Computation time [min]	Speedup to ARCHERCPU
Parallel MCNPX	12 MPI procs	476.35	--
ARCHER-CTCPU	12 HTs	11.40	1.00×
ARCHER-CTGPU	100 photons/thread 256 threads/block	2.38	4.80×
ARCHER-CTCOP	60 MPI procs, 4 HTs/proc Native execution mode	3.48	3.28×

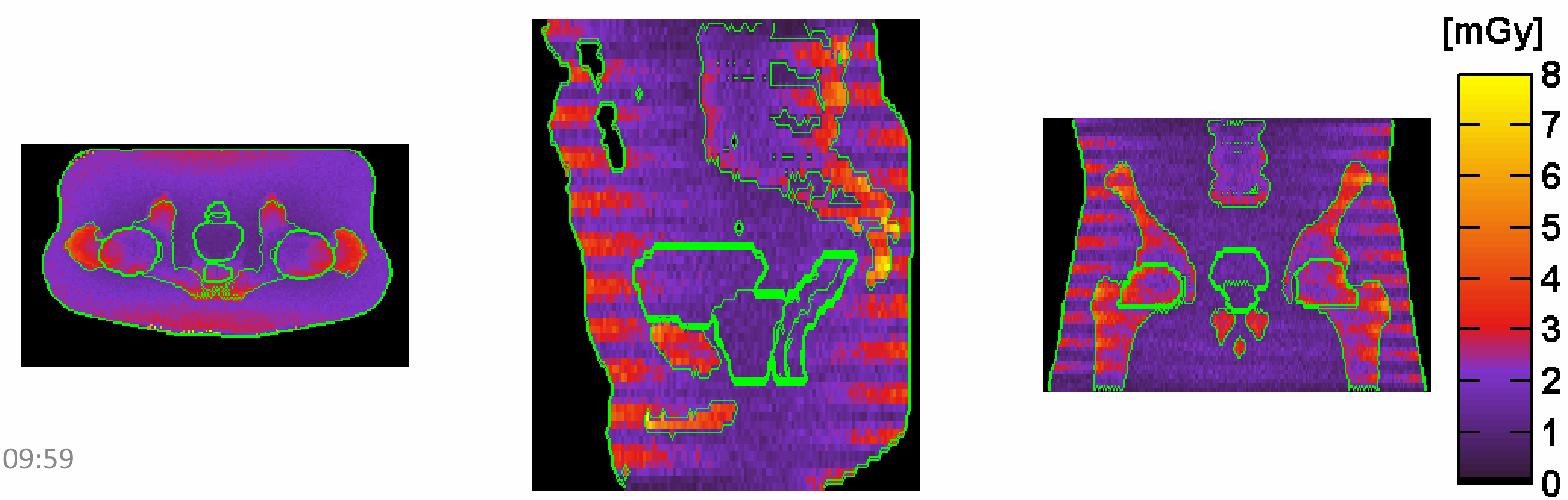
- **Theoretical peak performance**
  - GPU: 1.3 TFLOPS
  - Coprocessor: 2 TFLOPS
- **But ARCHER-CTGPU is 46% faster than ARCHER-CTCOP**

Results and Discussion: Clinical CT case

- **CT images converted to voxelized phantom**



- **3D CT imaging dose distribution by ARCHER-CT$_{GPU}$**
  - 1 GPU: **3.7 seconds**
  - 6 GPUs: **0.6 seconds – *real-time speed***



Simulation of Tomotherapy (w/ Dr Bryan Bednarz of UW-Madison)

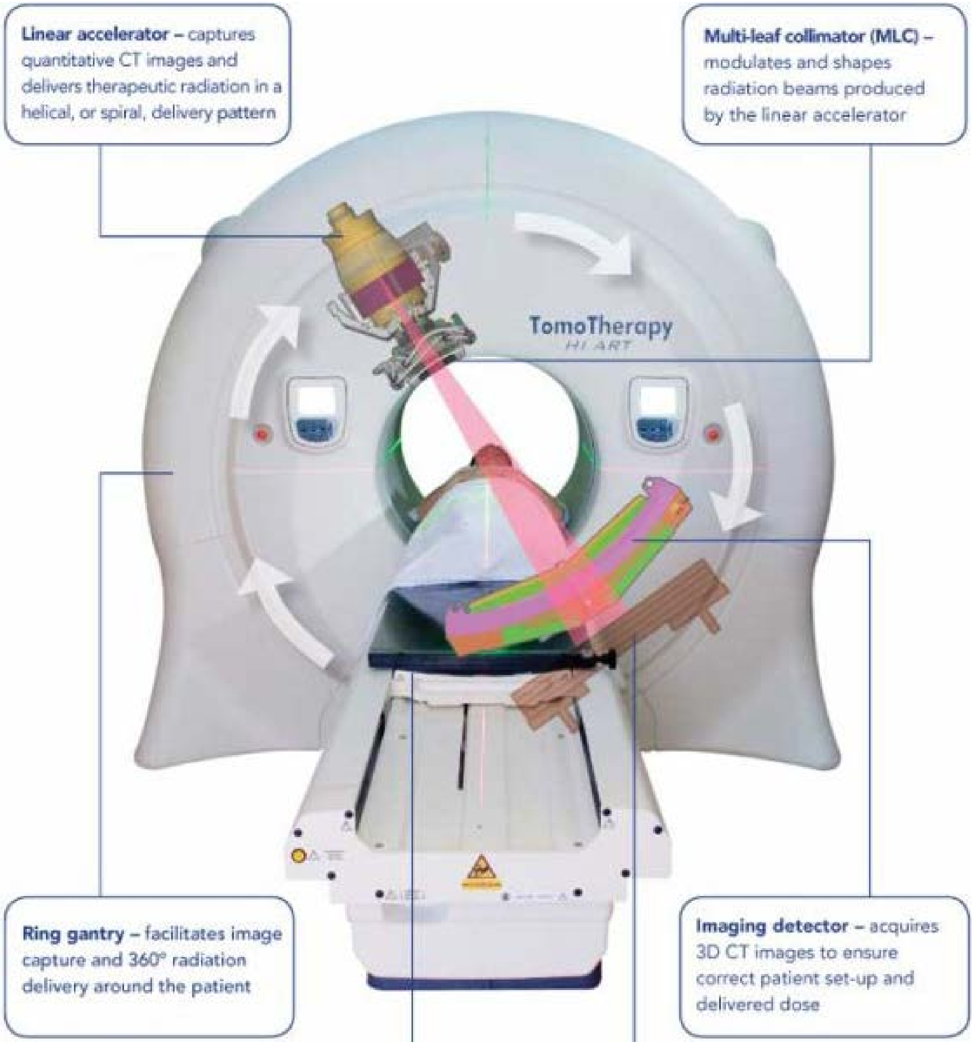
Su* L Yang YM, Bednarz, Edmond Sterpin, Du* X, Liu* T, Ji W, Xu XG. ARCHERRT — A Photon-Electron Coupled Monte Carlo Dose Computing Engine for GPU: Software Development of and Application to Helical Tomotherapy. Med Phys. 41:071709 (2014).

MC for helical tomotherapy dose calculation

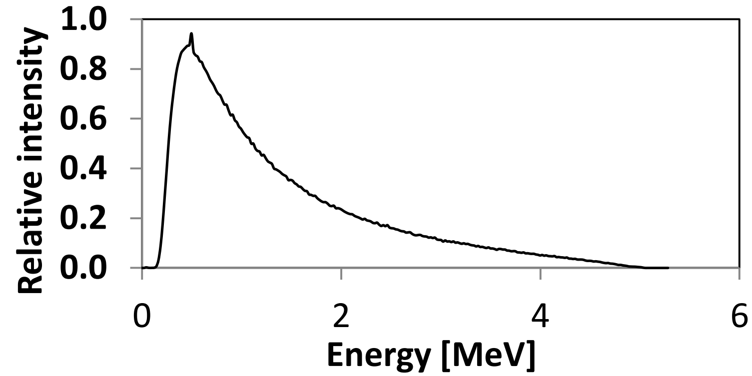
- Megavoltage X-ray source
  - 6MV electron linac
  - secondary electrons transported
- Phase space file (PSF) used for input
  - Patient-specific
- Electron + photon transport in ARCHER

Introduction: TomoTherapy PSF

6 MeV photon hit on target, generate X-ray



Adopted from TomoTherapy website



Mean energy: 1.45 MeV

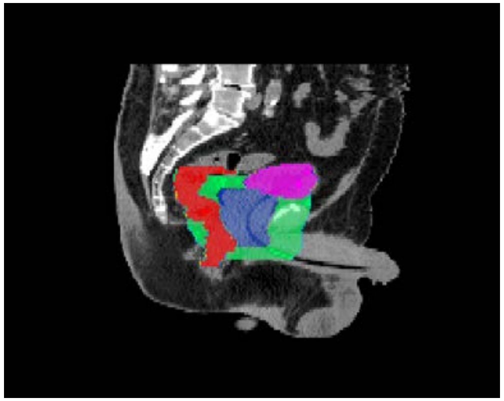
With the rotation of gantry and translation of bench, the PS particles form a cylinder

~10^8 photons PSF size ~GBs
Reading time nontrival ~30 sec

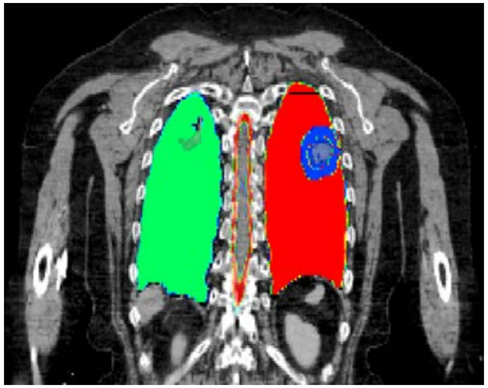
Materials and Methods: cases tested

- 6 MV SIEMENS PRIMS accelerator PSF dose distribution in water
- Three clinical TomoTherapy cases
- Prostate PSF, 200M particles, 2x recycle (600M particles in total)
- Lung PSF, 53M particles, 9x recycle (530M particles in total)
- Head & Neck PSF, 160 M particles, 4x recycle (800M particles in total)
- E_{cutoff}=200 keV ; Ph_{cutoff}=10 keV

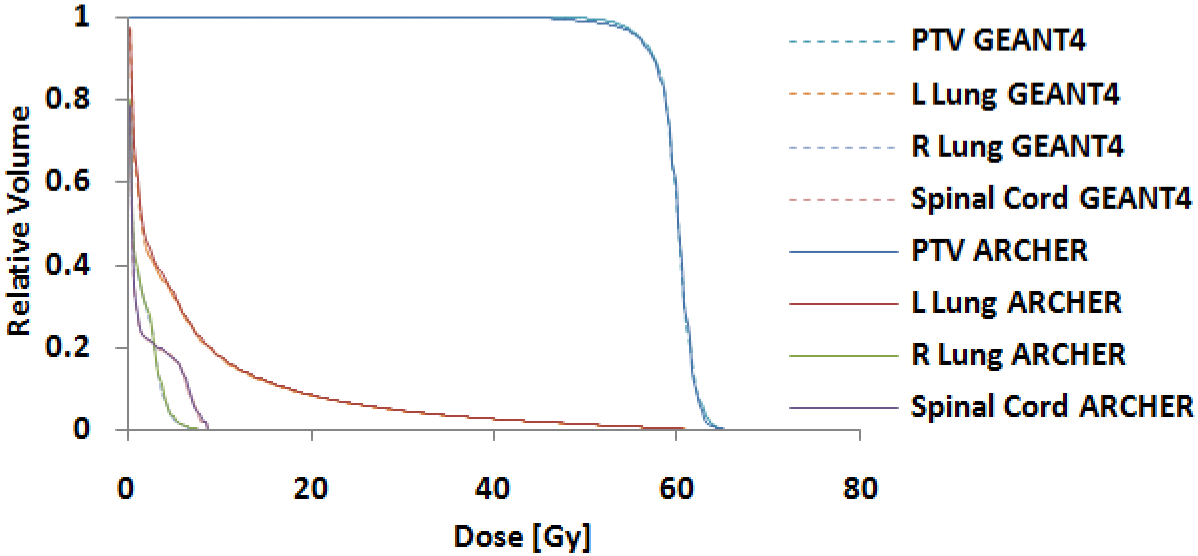
Prostate Case

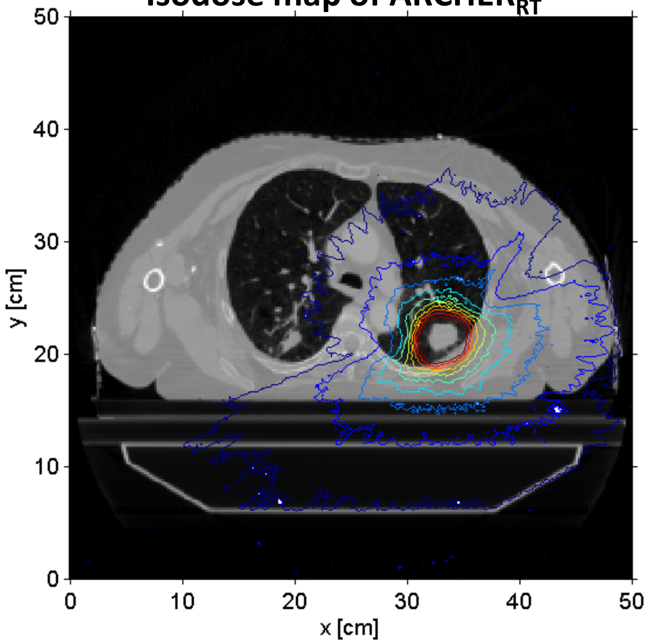


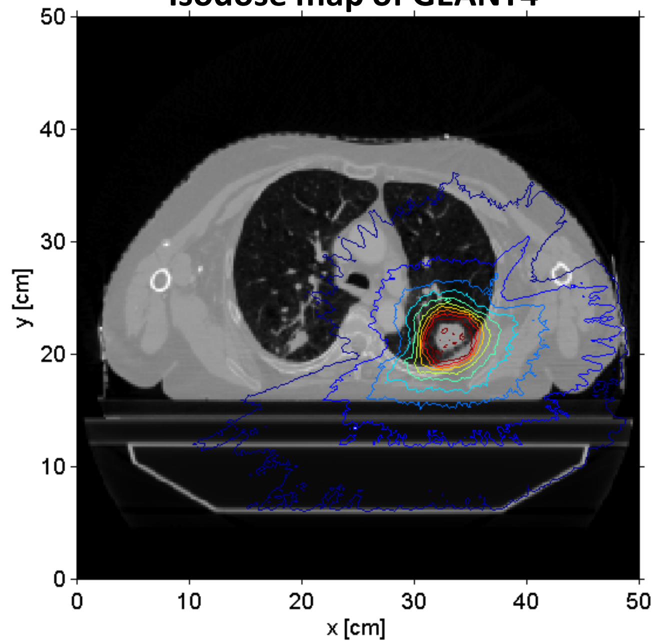
Lung Case



Results: Lung case







Statistical error in PTV ~1%

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

Results: MC Transport Time Comparison

Clinical cases	Intel X5650 (12 threads) time [s]	K40 GPU time [s]
Prostate	729 (1x)	37.9 (19.2x)
Lung	507 (1x)	29.7 (17.1x)
Head & neck	876 (1x)	44.2 (19.8x)

In contrast, GEANT4 <u>needs ~ 500 CPU hours</u> for the similar simulation

Summary

1. **Phantom research advanced exponentially in the past 60 years**

2. **GPU and MIC hardware will drive high-performance computing in this decade, leading to "real-time" Monte Carlo simulations**

More info at http://RRMDG.rpi.edu

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