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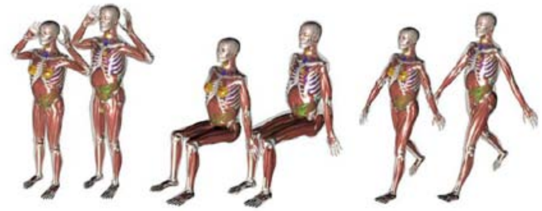

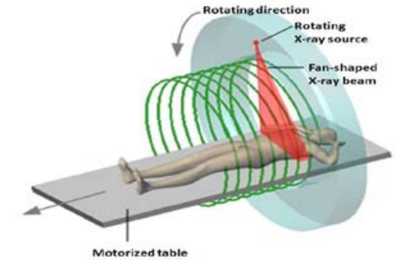

3D/4D HUMAN MODELING AND MONTE CARLO DOSE CALCULATION FOR RADIATION PROTECTION, IMAGING AND RADIOTHERAPY

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Troy, New York
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Plenary presentation for SNA + MC2010

Hitotsubashi Memorial Hall, Tokyo, Japan

October 20, 2010

SNA + MC 2010
Joint International Conference on Supercomputing in Nuclear Applications + Monte Carlo 2010 Tokyo

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Acknowledgements

Collaborators and Resources

- I am indebted to fruitful collaboration with many colleagues who shared wisdom and resources

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- NIH, NLM (R03 LM007964), 2003 – 2006
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- DOE, (DE-FG07-07ID14770), 2007 – 2010
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- NIH NIM (R01LM009362-03S1), 2009-2011
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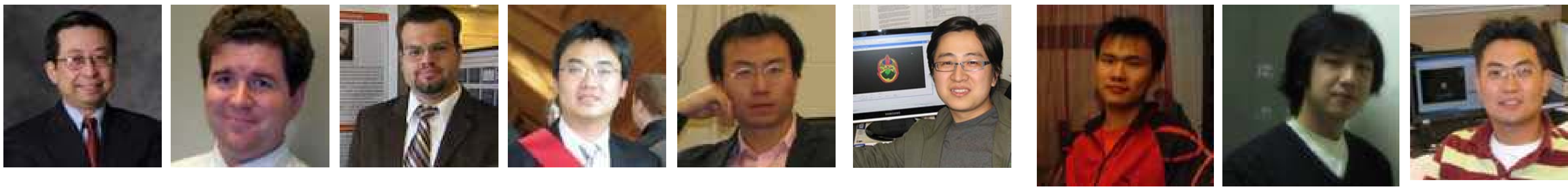
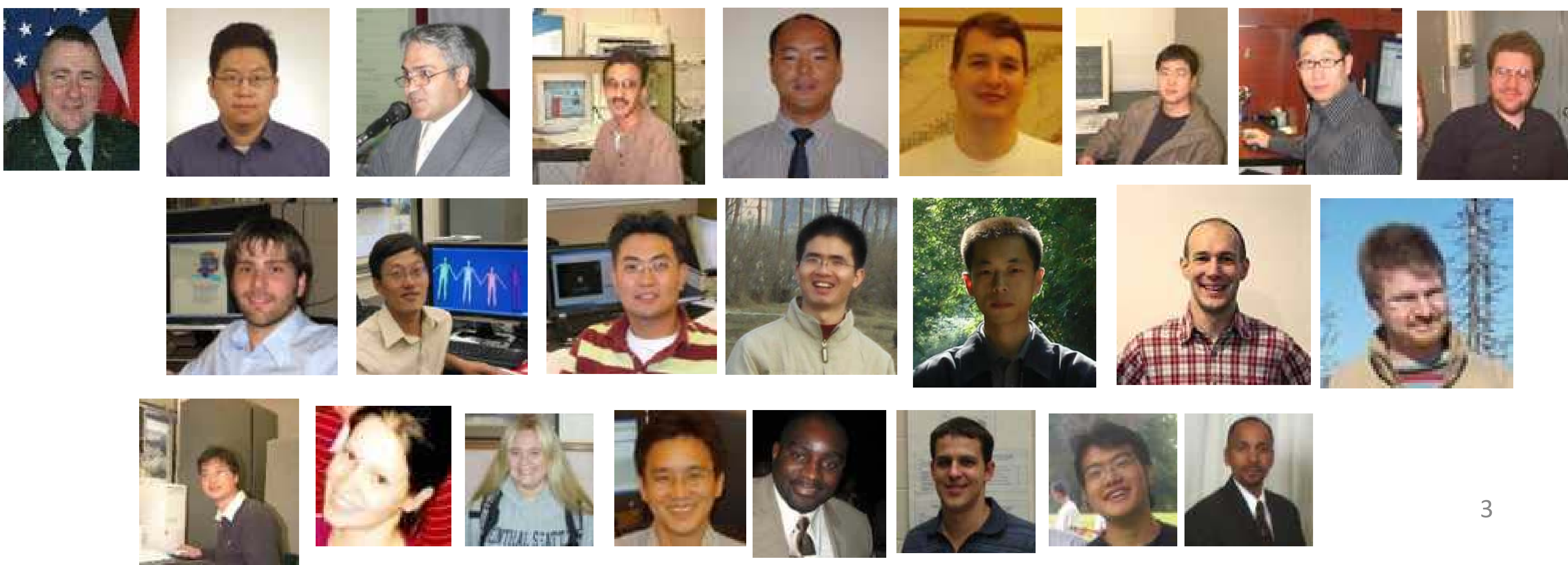
http://RRMDG.rpi.edu

Current Students/Research Staff



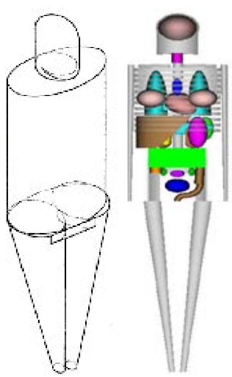
Alumni (Not including undergraduate)



50-Year History of Computational Phantoms

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

1st Generation



MIRD anthropomorphic models in 1980s

STYLIZED

2nd Generation

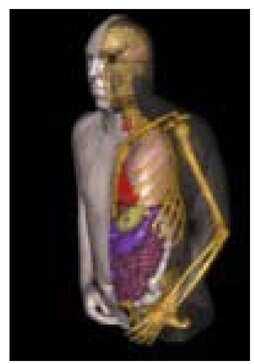
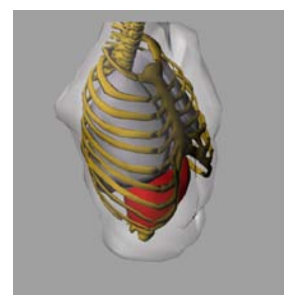


Image-based rigid, 3D model in 1990-2000s

VOXEL

3rd Generation



Deformable and moving 4D models 2008-2010

BREP

Personalization is Future

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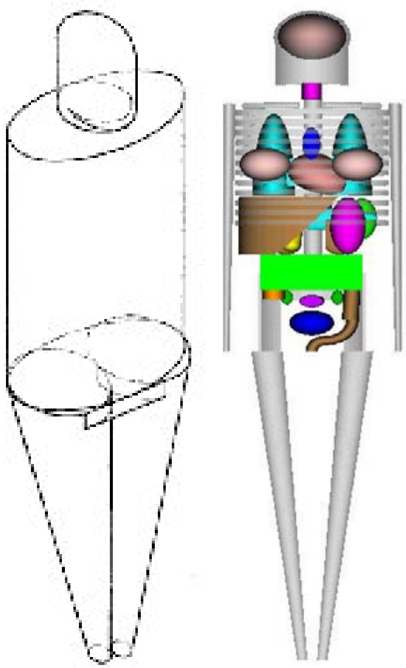
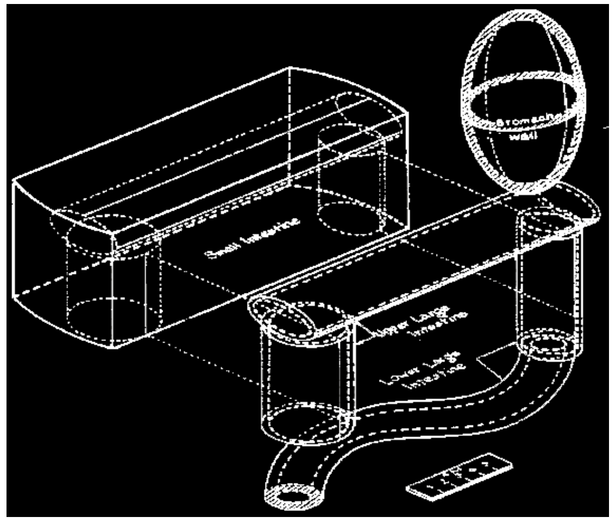
1st-Generation "Stylized" Phantoms Depicting ICRP "Reference Man" for 50 Years

(Society of Nuclear Medicine's MIRD Committee)

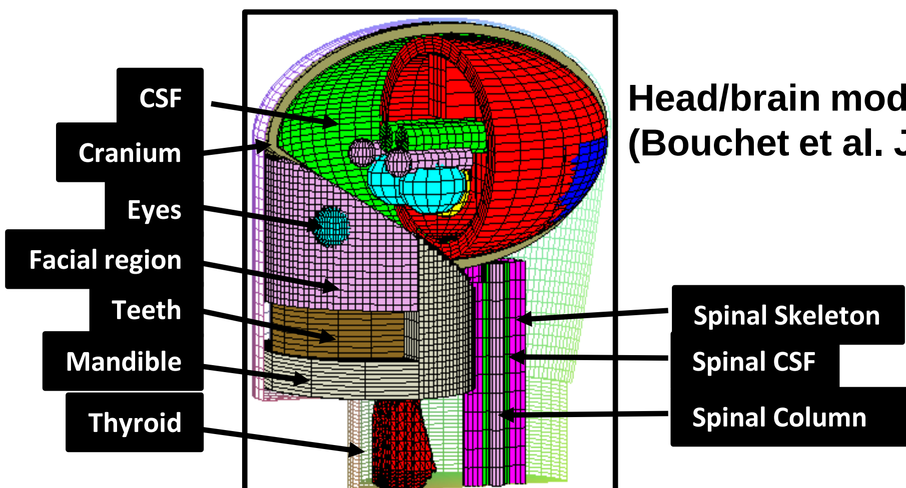


Stylized adult male
(Cristry and Eckerman 1987)

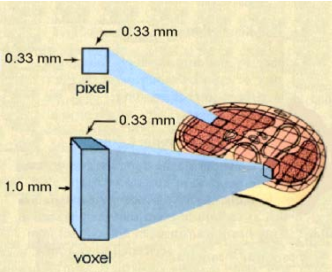


Stomach defined as concentric ellipsoids:

$$\left(\frac{x-x_0}{a}\right)^2+\left(\frac{y-y_0}{b}\right)^2+\left(\frac{z-z_0}{c}\right)^2\leq 1$$

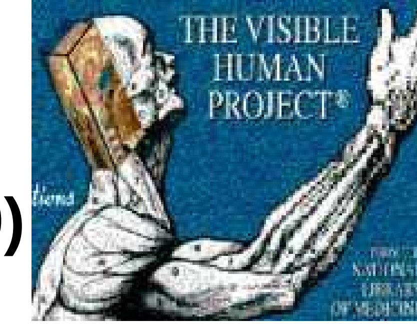


Head/brain model
(Bouchet et al. JNM 1996)

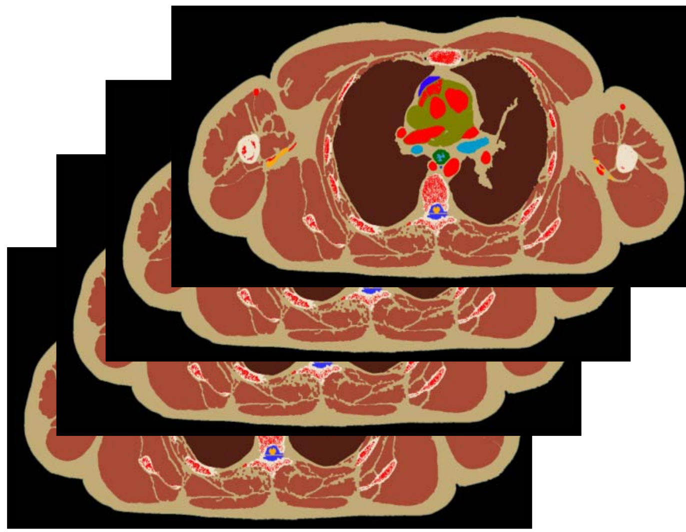


2nd-Generation “Voxel” Phantoms - Example of the VIP-Man (1997-2000)

Xu et al. Health Physics 2000



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

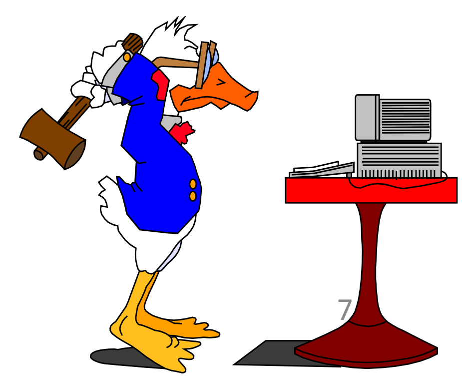


Registration of all slices

Finished 3D voxel phantom

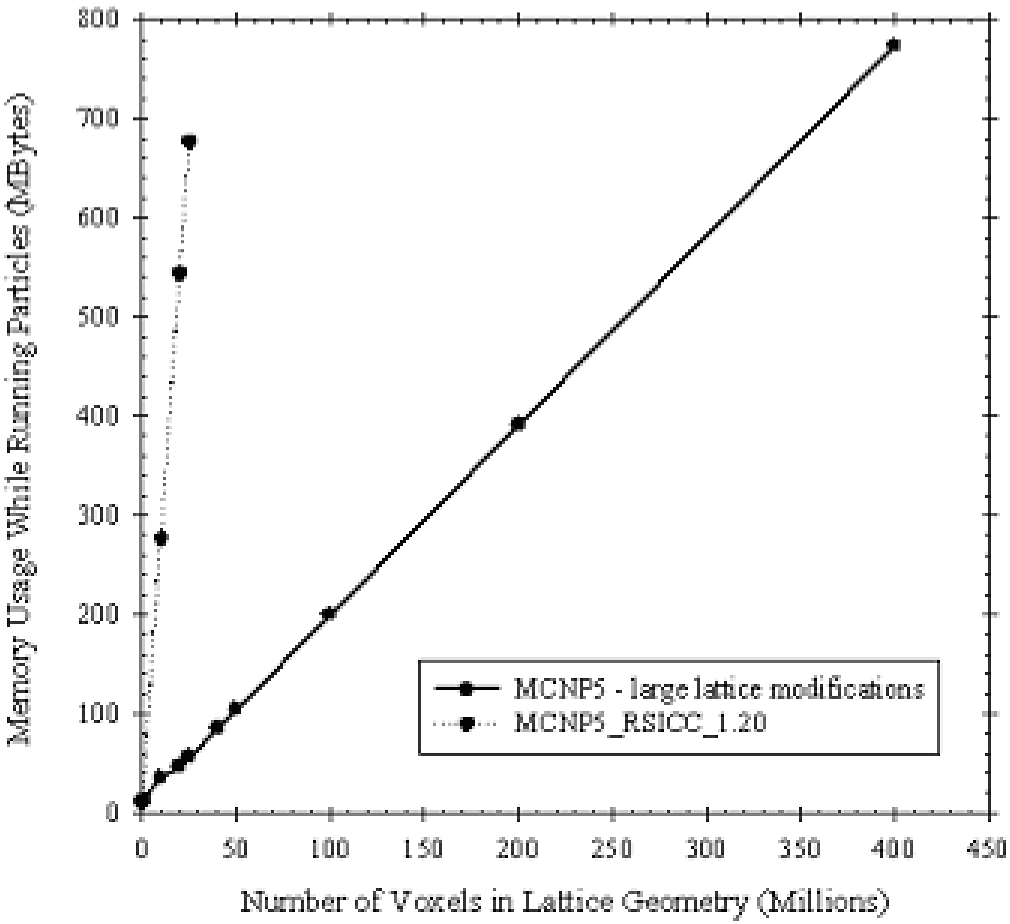
Challenges (Several years ago…)

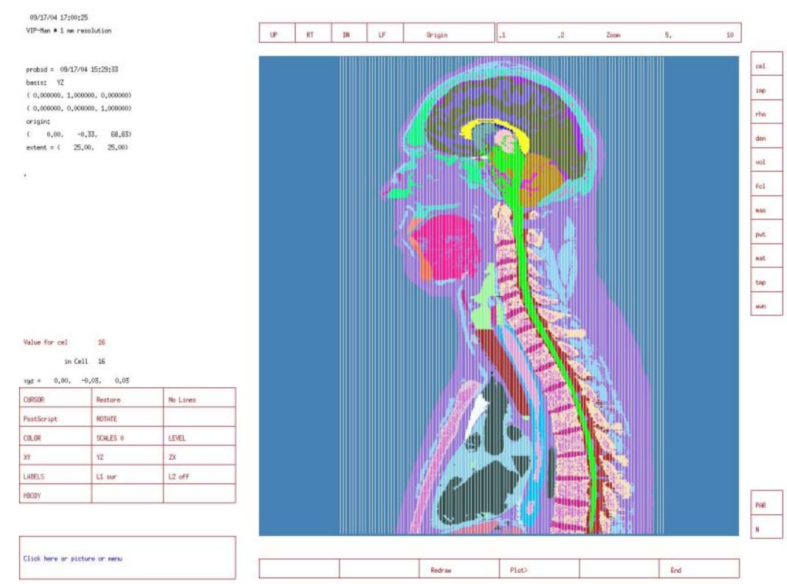
- Computer Memory
  - Visible Man (0.33mm x 0.33mm x 1mm) is 3.7 GB data set
  - The max. allowable RAM is < 2 GB
- Monte Carlo Codes
  - EGS4 and MCNP4b/MCNPX had to be enhanced for handling such huge voxel data
- Computer Timing
  - The smaller the voxel size, the longer to run (~several hours)



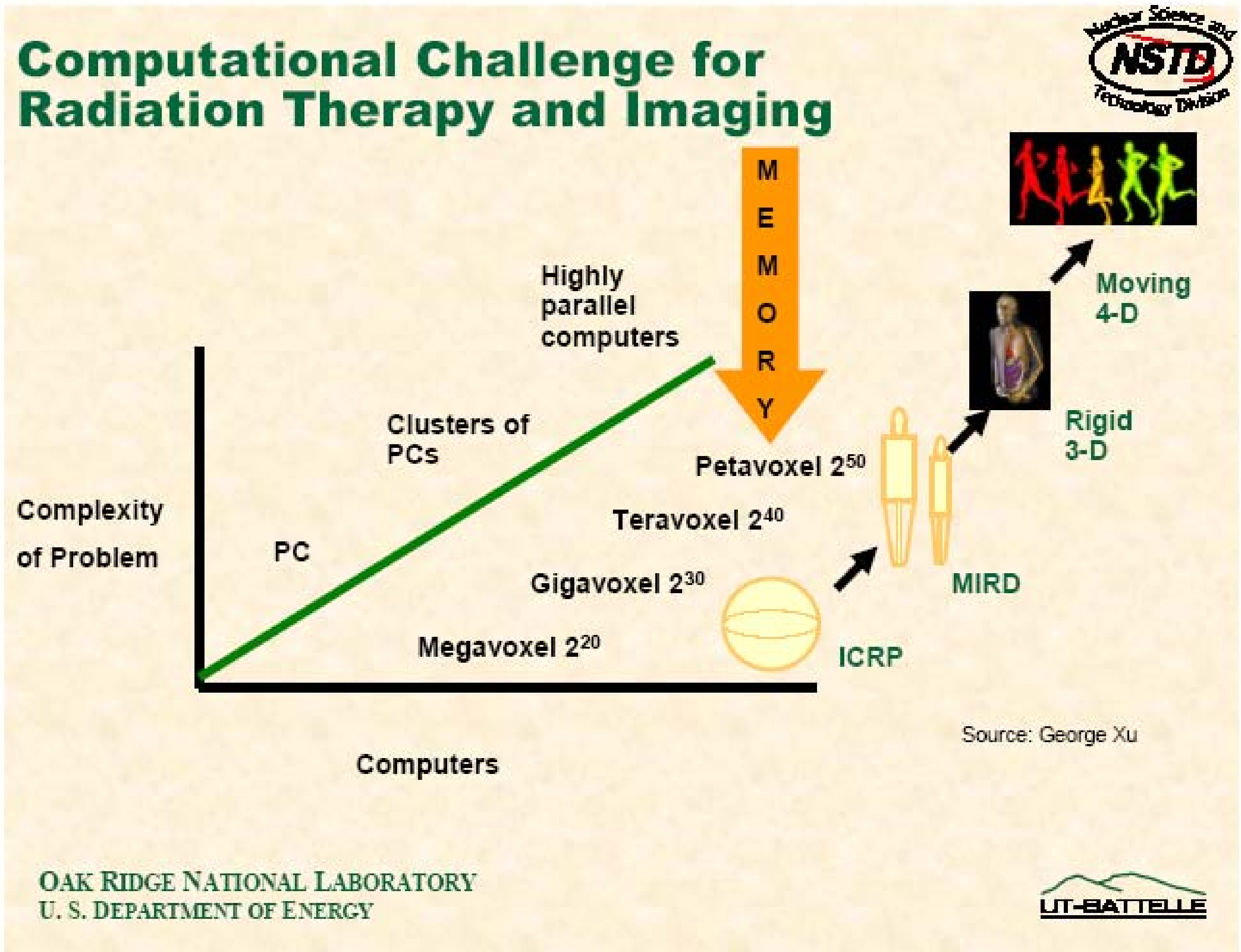
Memory Usage and Voxel Limitation of MCNP

Wang, Xu, and Goorley. Issues Related To The Use Of MCNP Code For An Extremely Large Voxel Model VIP-Man. Monte Carlo 2005 in Chattanooga, TN





For the VIP-Man phantom (See Tim Goorley's tutorial on Med Phy applications)

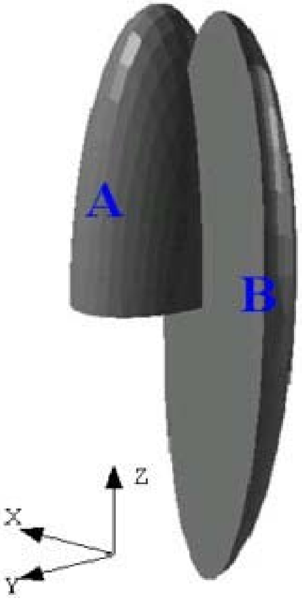


Slide from Bernie Kirk, ORNL

Computational Medical Physics Working Group (CMPWG) Workshop, October 26, 2005

A Major Advancement in Phantom Geometry

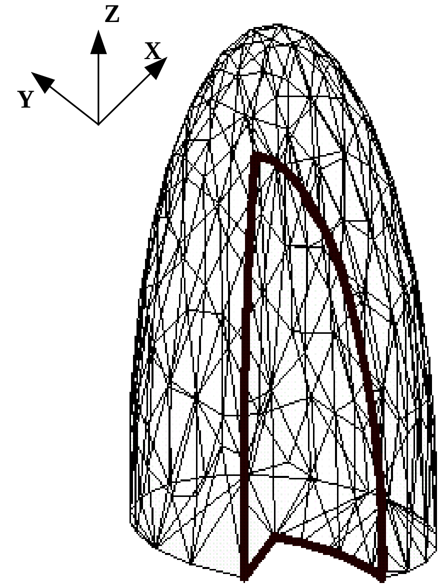
from Constructed Solid Geometry (CSG) to Boundary Representation (BREP)



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

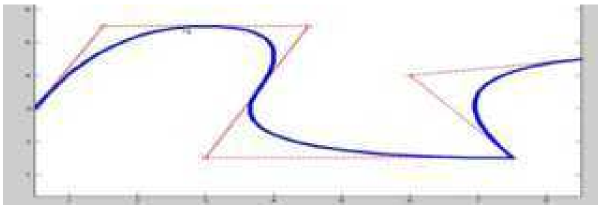
$$B:\ \left(\frac{X-2.5}{5}\right)^2+\left(\frac{Y}{7.5}\right)^2+\left(\frac{Z-43.5}{24}\right)^2 \ge 1\ , if\ y<0$$

Polygon meshes



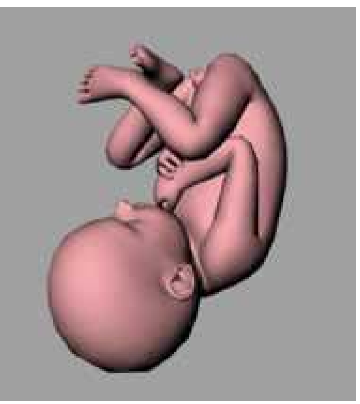
Non-Uniform Rational B-Splines (NURBS)

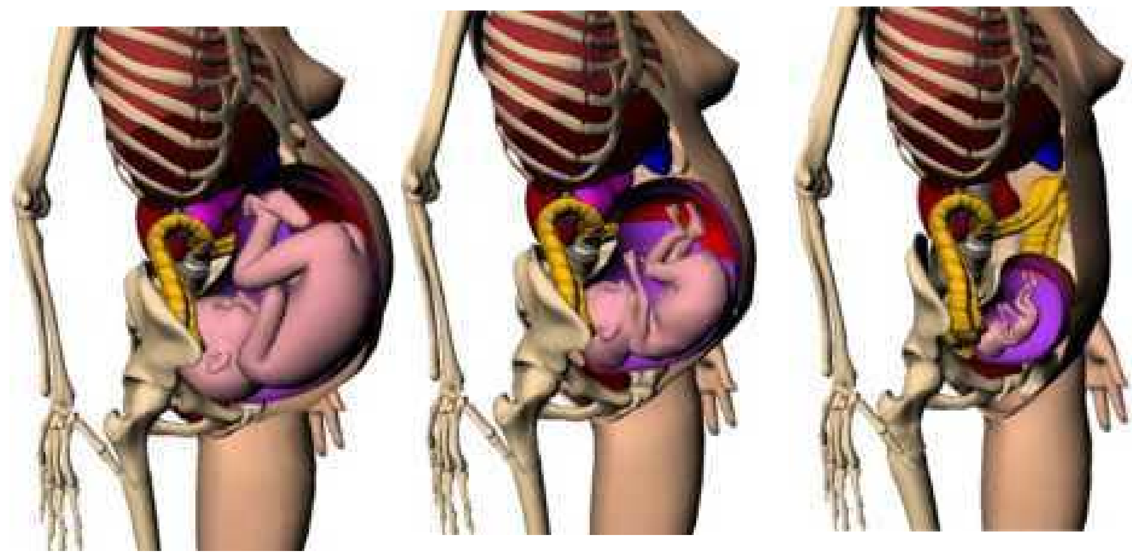
$$S^w(u,v)=\sum_{i=0}^{n}\sum_{j=0}^{m} N_{i,p}(u)N_{j,q}(v)P_{i,j}^w$$



3rd-Generatioin “BREP” Phantoms (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**





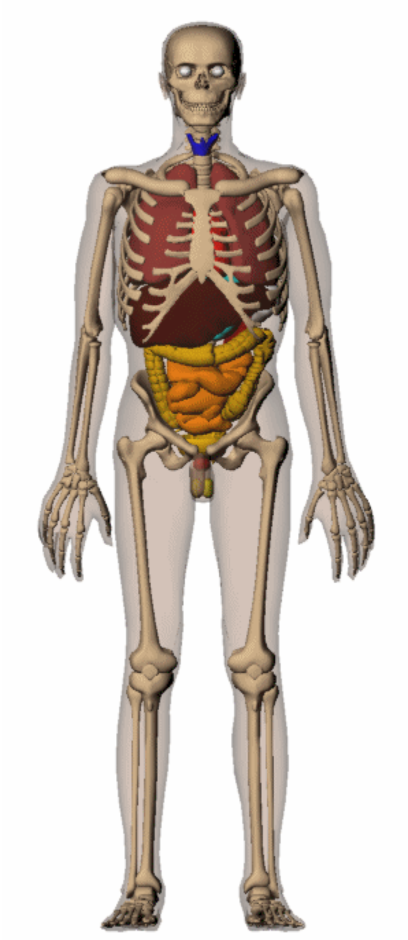
9-month 6-month 3-month

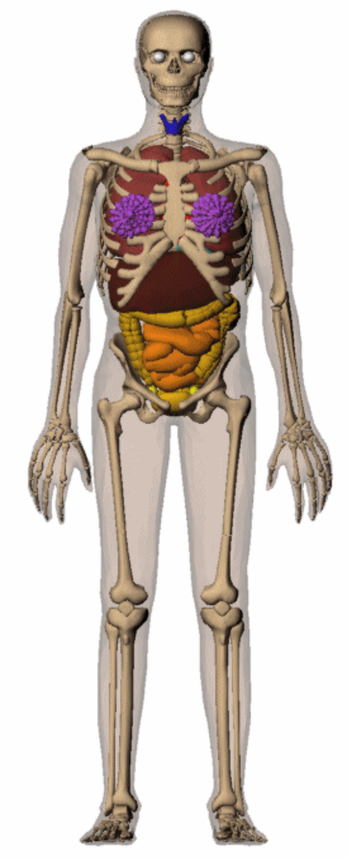
Polygon Mesh-based Phantoms: RPI Adult Male and Female

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





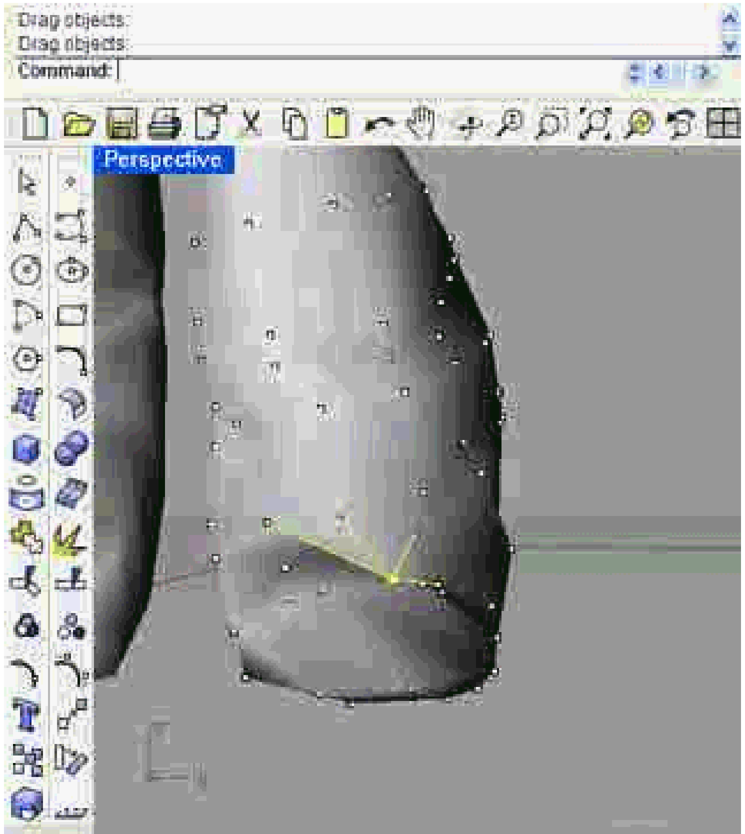
RPI Adult female

Height: 163 cm
Weight: 60 Kg

70 Organs; 45 Bone Components; 4 Muscle Structures

Mesh is Easy To Deform

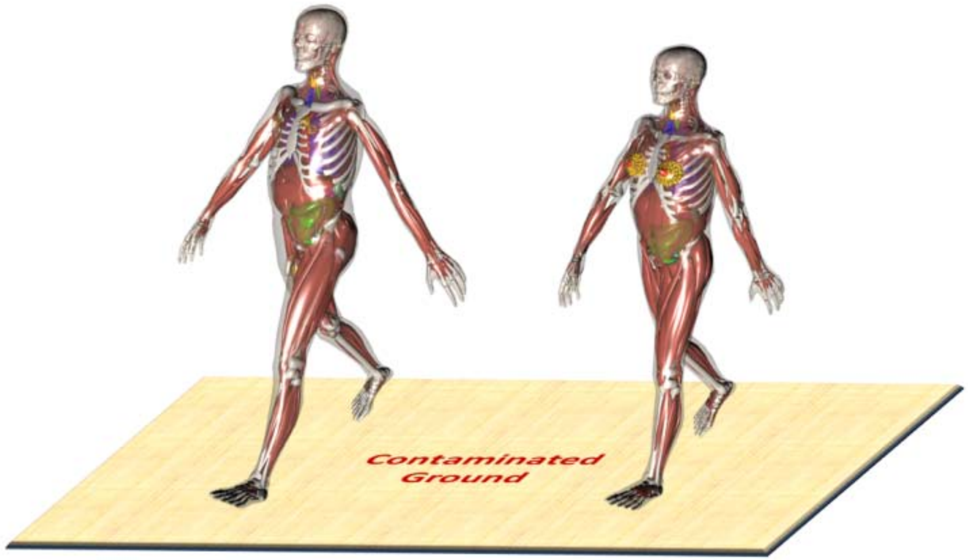
- **Deform the various internal organ geometries to agree within 0.5% with the ICRP reference male and female organ volume and mass data.**



Applications to Environmental Radiation Protection

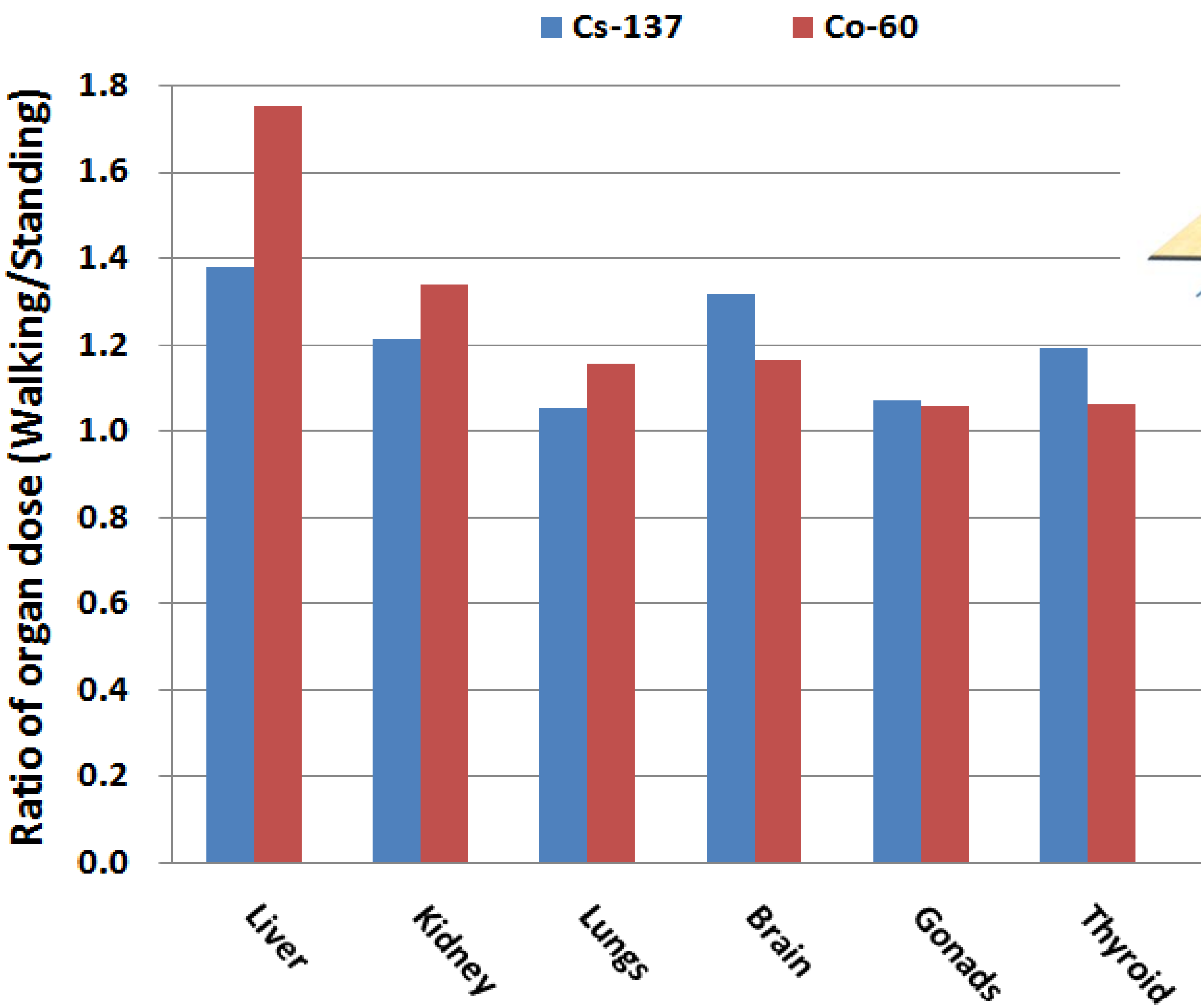
Walking Phantoms (on Contaminated Ground)

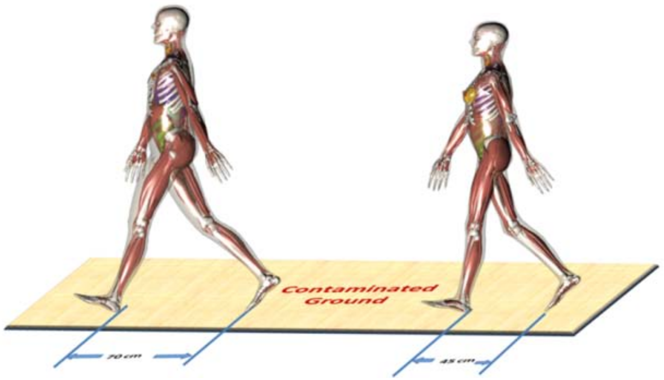
- Cs-137 and Co-60 with concentrations of 30 kBq m^{-2}
- Parallel and isotropic planar sources

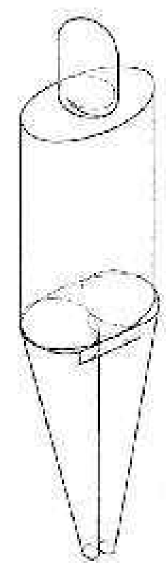


70 cm and 45 cm of step lengths for male and female, respectively

Results: Organ Doses

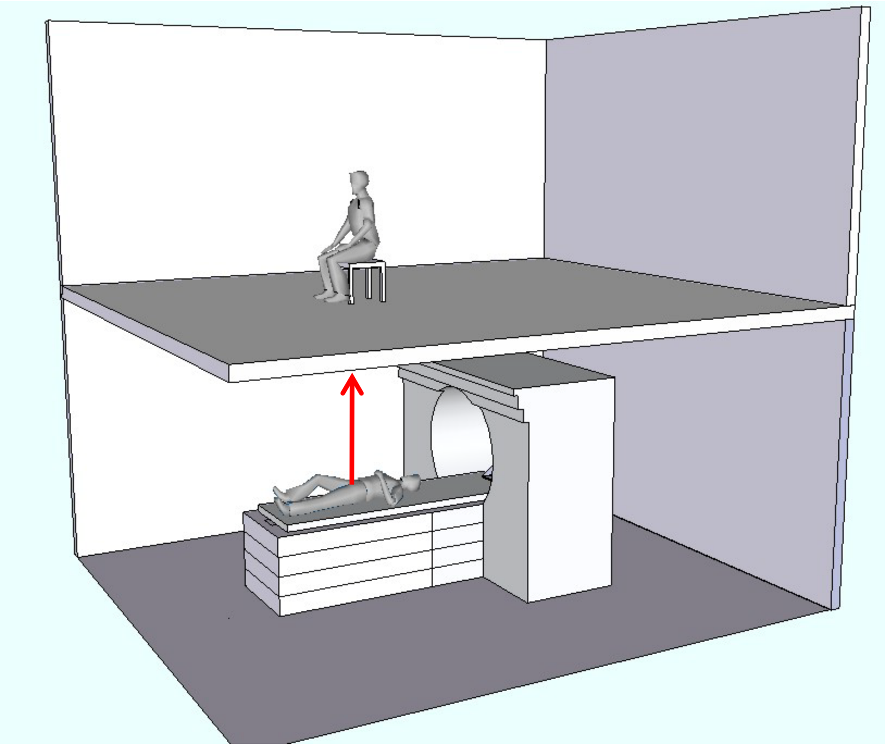




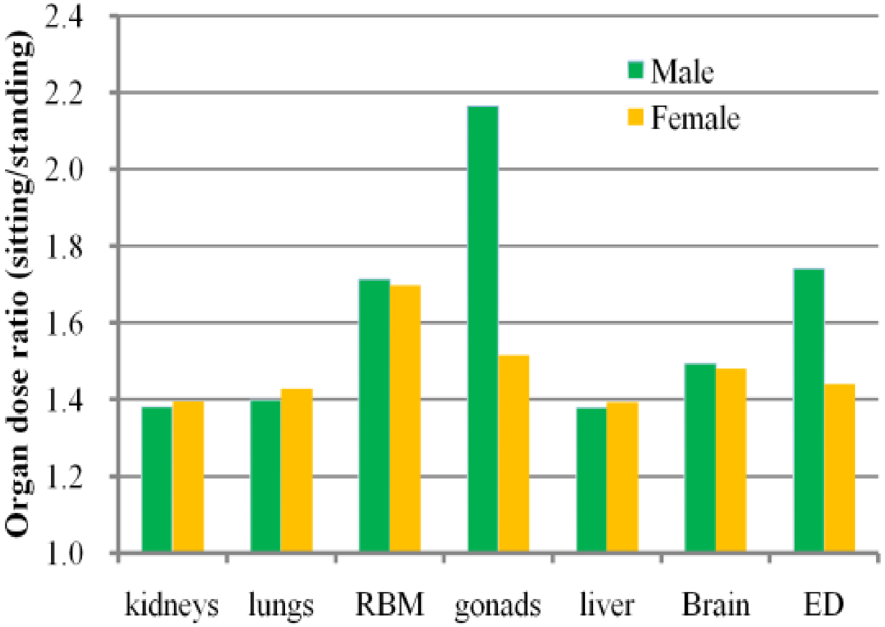


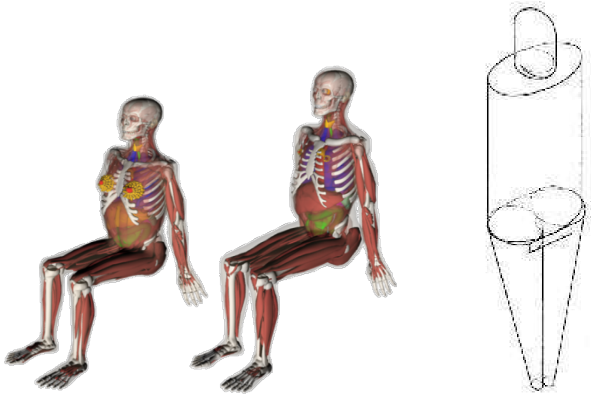
Old phantom with closed legs

Sitting Phantoms (Above a PET Imaging Clinic)



Patient emits 0.511 MeV photons





Applications to Imaging: CT Dose Reporting

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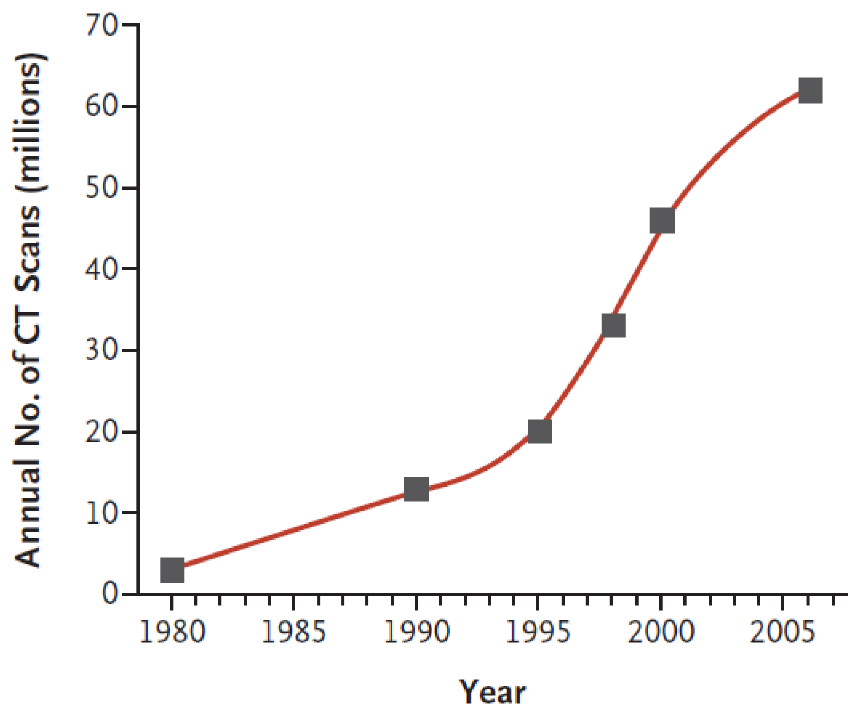
Alarming Trend of CT Exposures

- **Usage grown 20 times in 26 years**
  - **3 million in 1980**
  - **62 million in 2006**

- **1000 times higher dose in one scan than conventional x-rays**

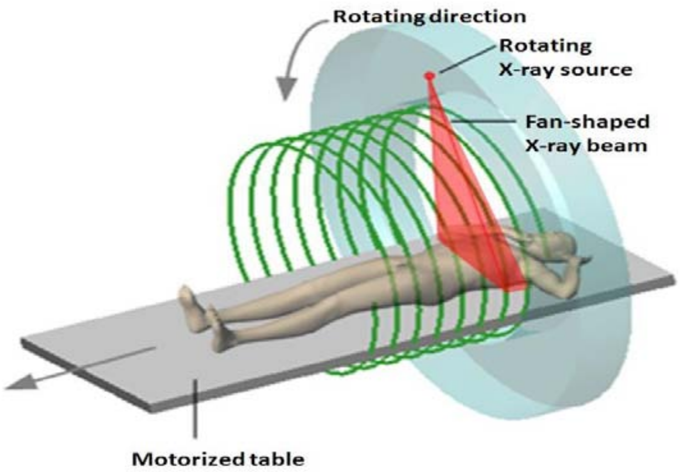
- **MDCT is being adopted for multiple applications**
  - **nuclear medicine**
  - **emergency room**
  - **Image-guided radiation therapy**
  - **public screening**

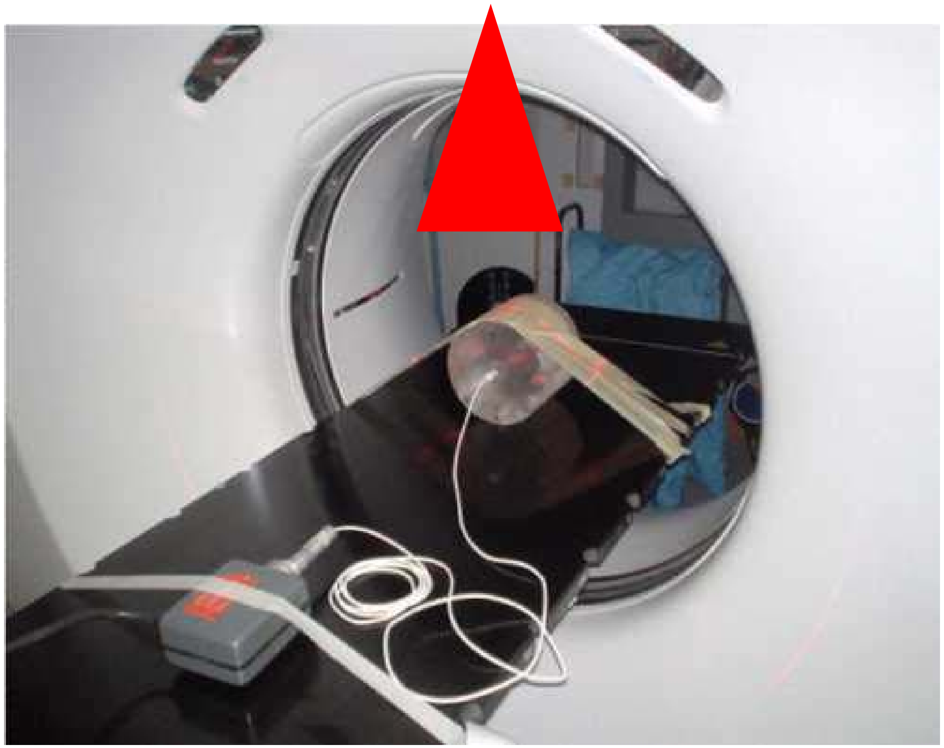


- NCRP. Report No. 160, Ionizing Radiation Exposure of the Population of the United States. 2008.

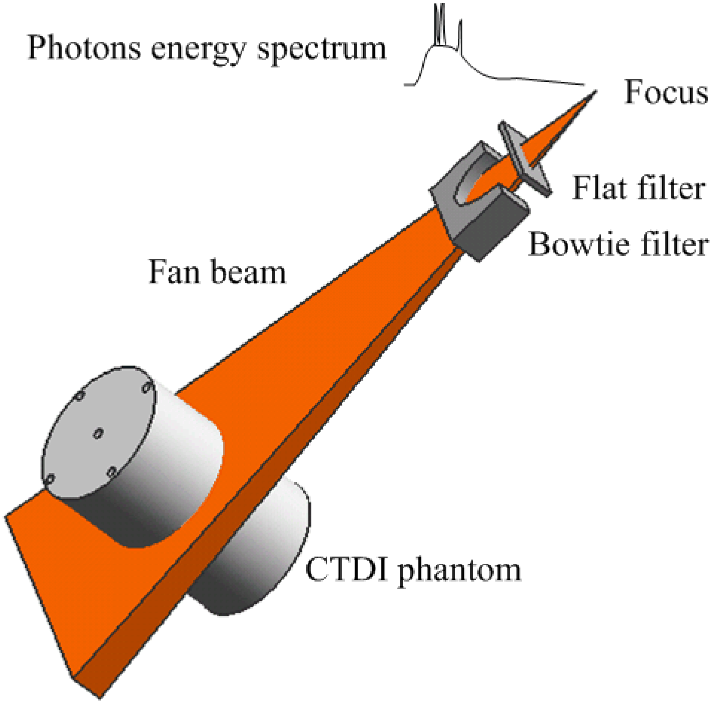
CT Scanner Modeling

GE LightSpeed 16 scanner model





CT experiment using CTDI phantom



Gu et al, PMB 2009

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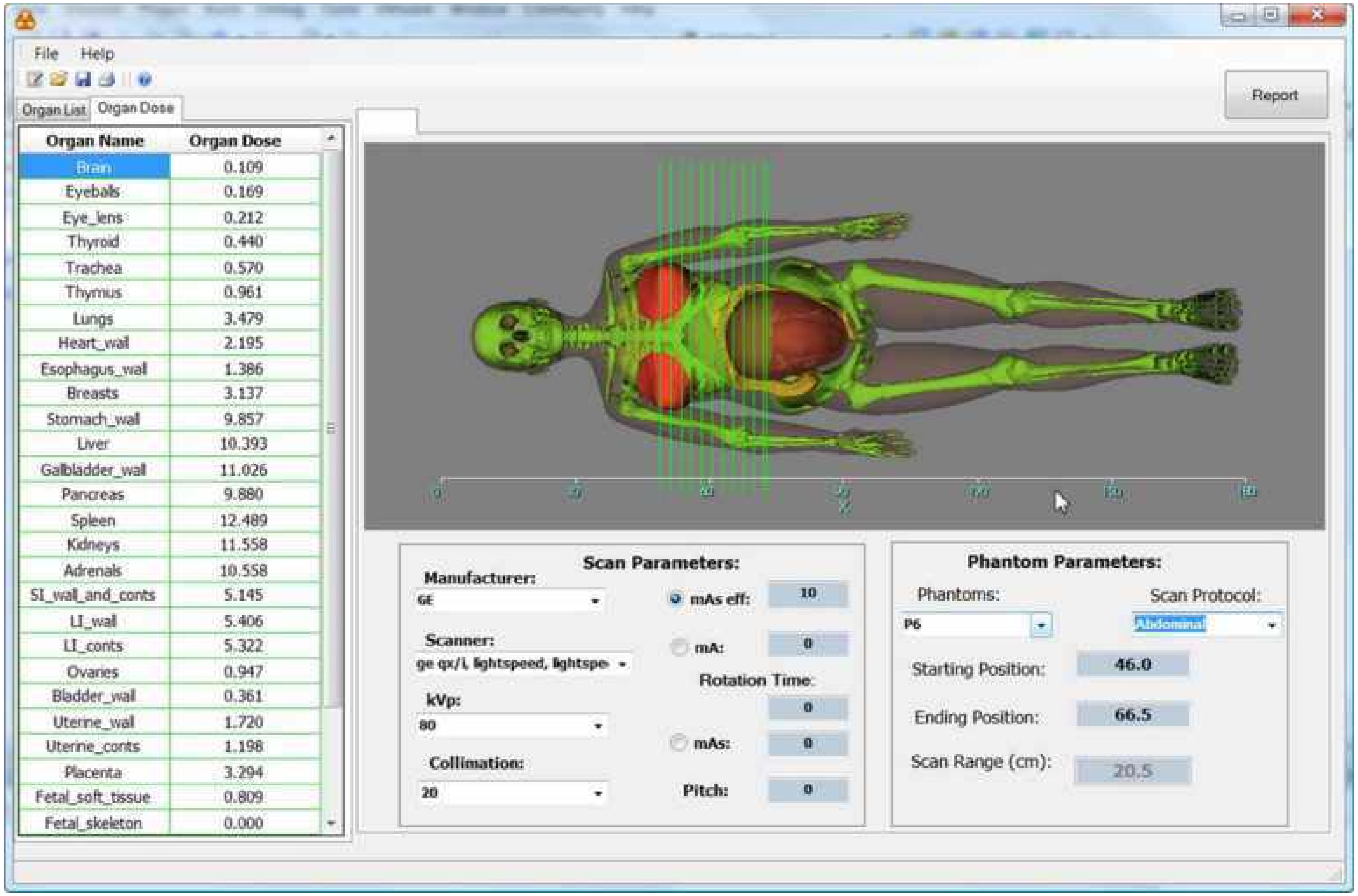
VirtualDose, A New Software for CT Dose Reporting



- A easy to use graphical user interface (GUI)
- Interactive 3D phantom rendering
- Scan parameters can be interactively specified on GUI

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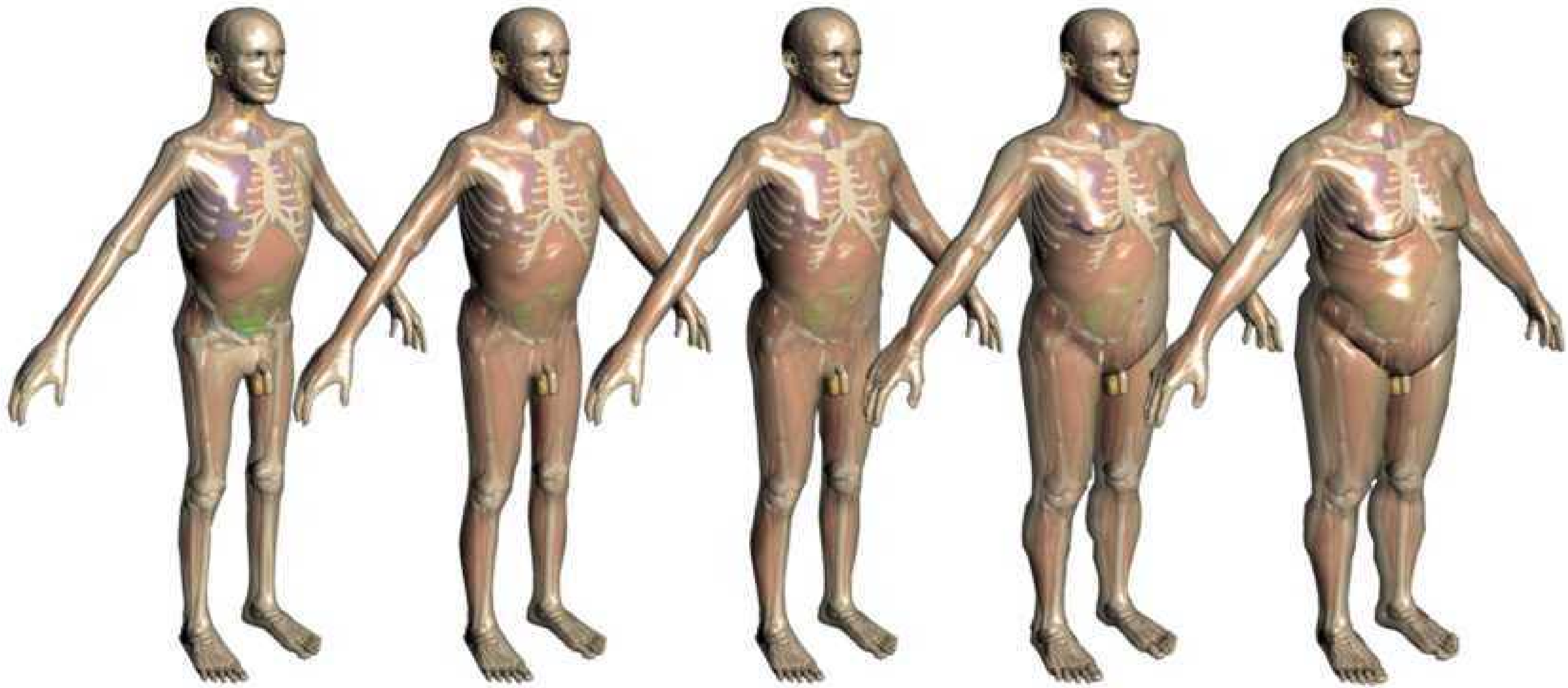
Size and Weight Adjustable Phantoms

Na YH, Zhang B, Zhang J, Caracappa PF, Xu XG. Deformable Adult Human Phantoms for Radiation Protection Dosimetry: Anthropometric data representing size distributions of adult worker populations and software algorithms. Phys. Med. Biol. 55: 3789-3811, 2010.

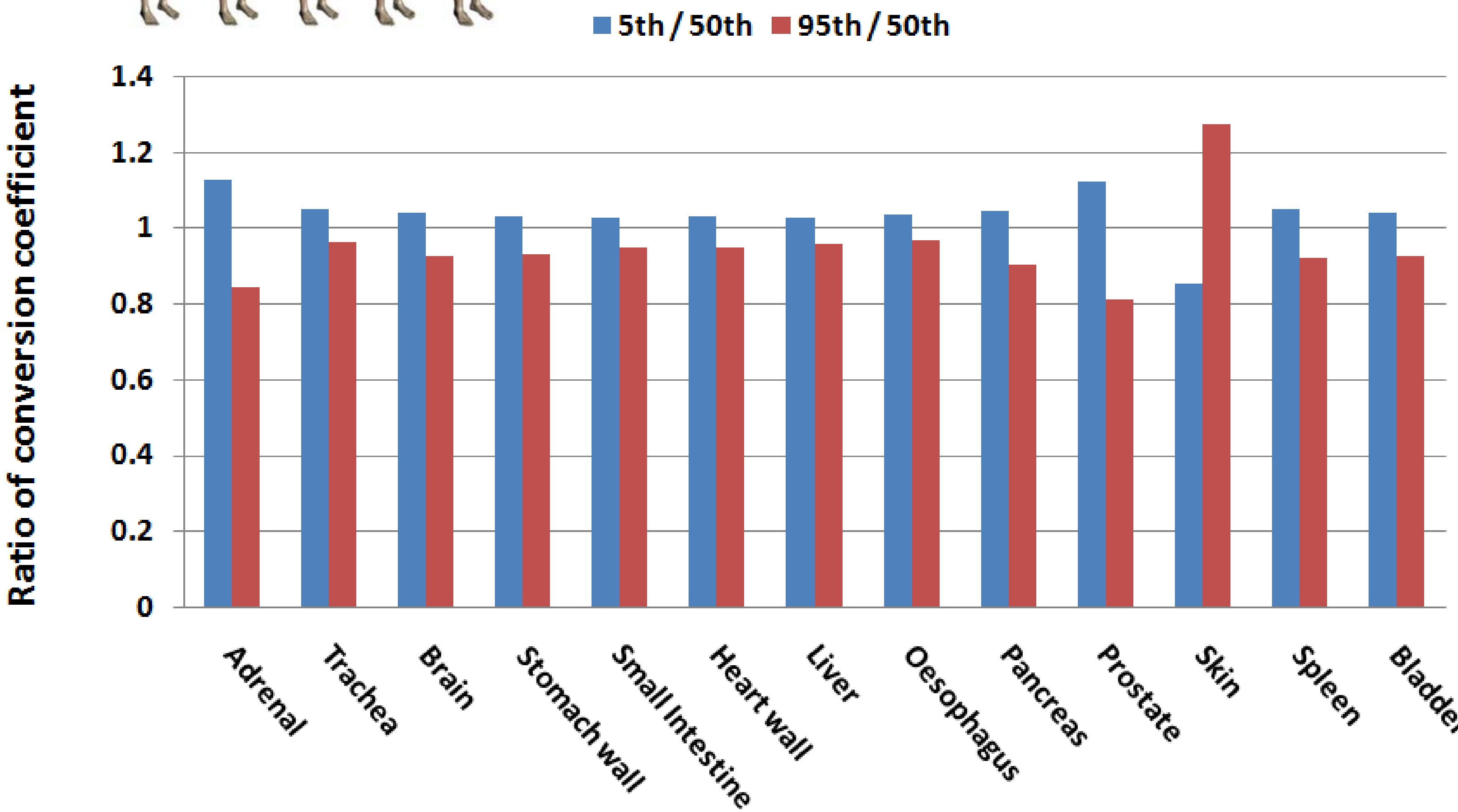
- **Same height (e.g. 176cm Male), but different weights:**



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/)

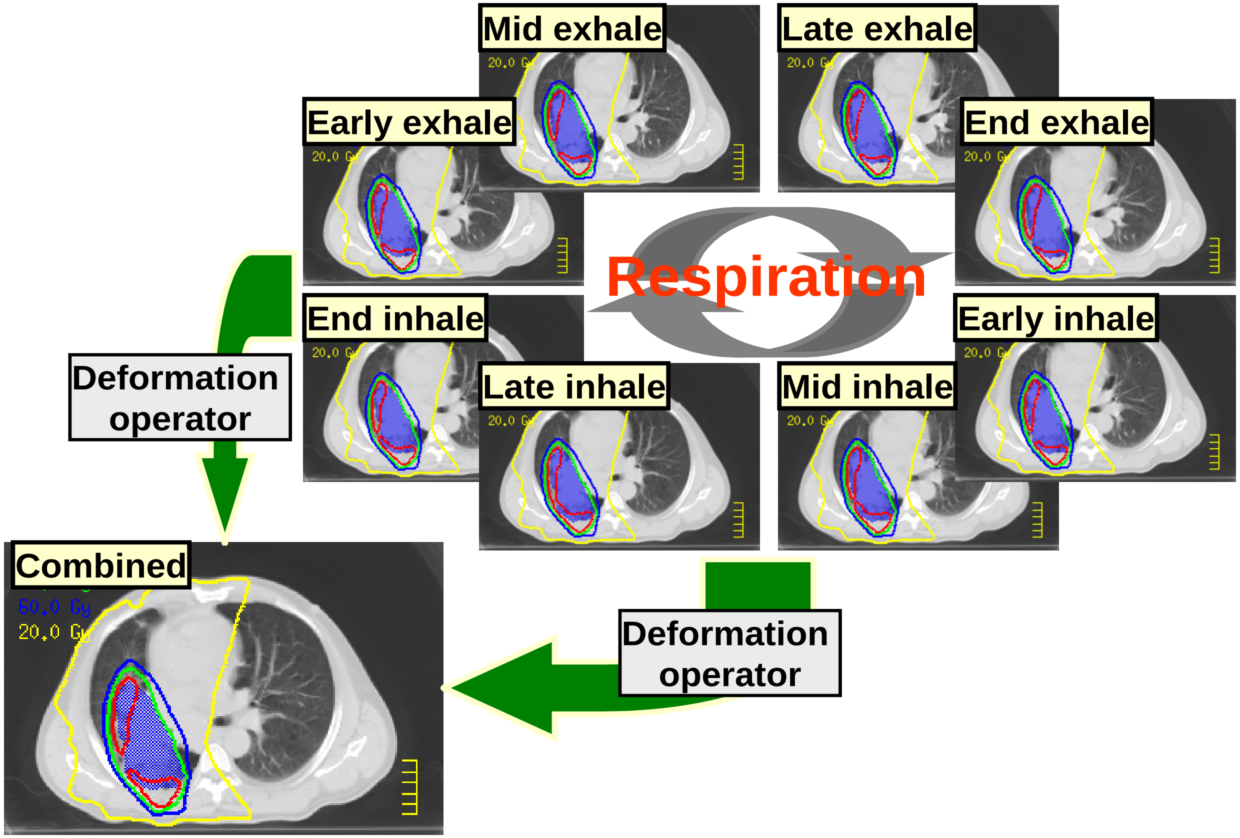
Results: Organ dose differences of 5th-, 50th-, 95th-weight percentile phantoms for the AP irradiation with 0.5-MeV photon beams



Applications to Radiotherapy:
(1) Respiration in Treatment Planning
(2) Proton Radiography

Medical Physics Applications Are Challenging (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



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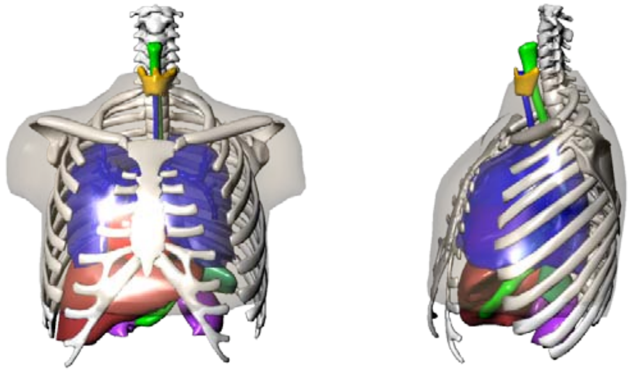
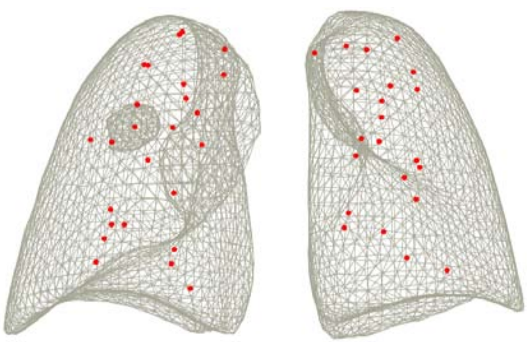
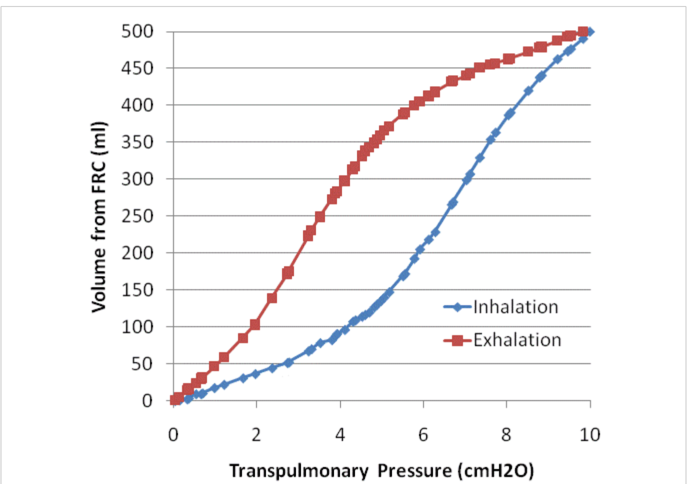
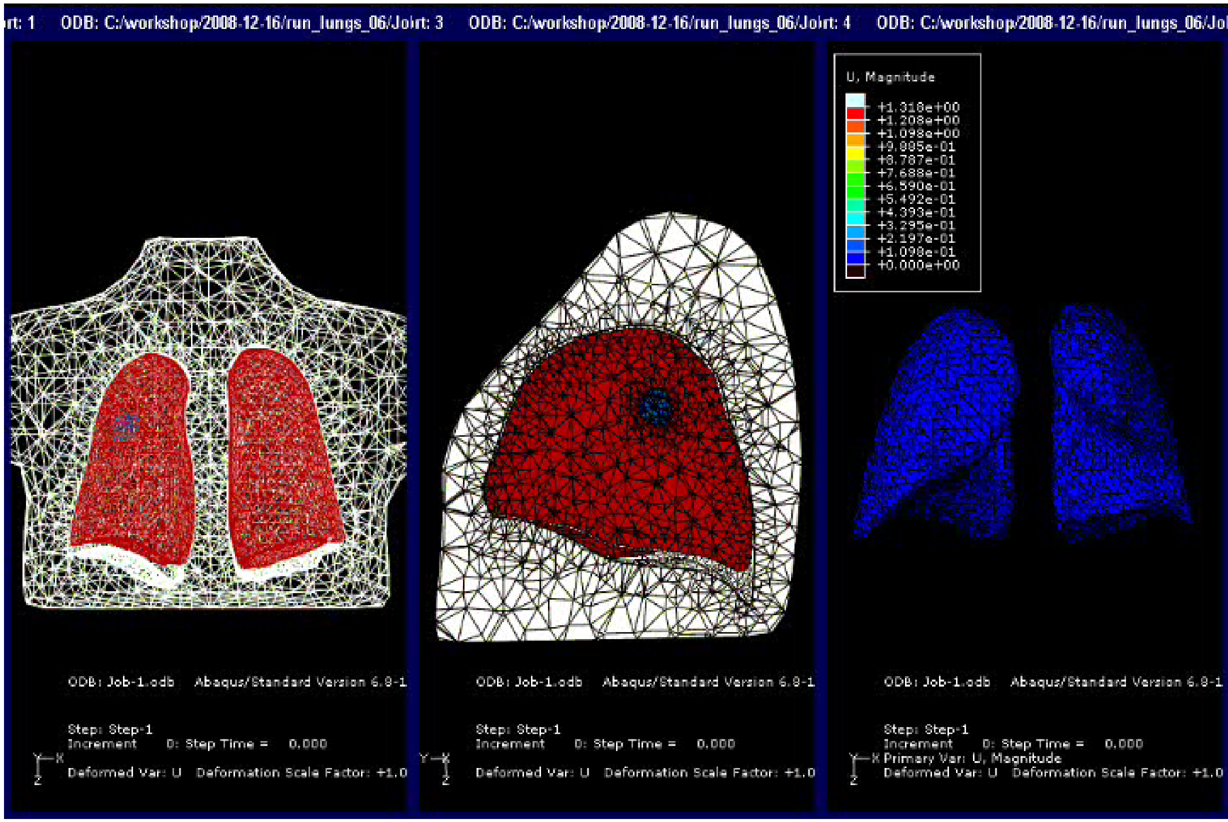
Respiration Modeling Involving Geometry + Physics + Physiology
(More detail in poster at MC2010)



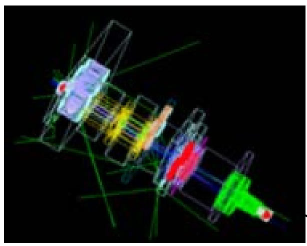






Finite Element Analysis

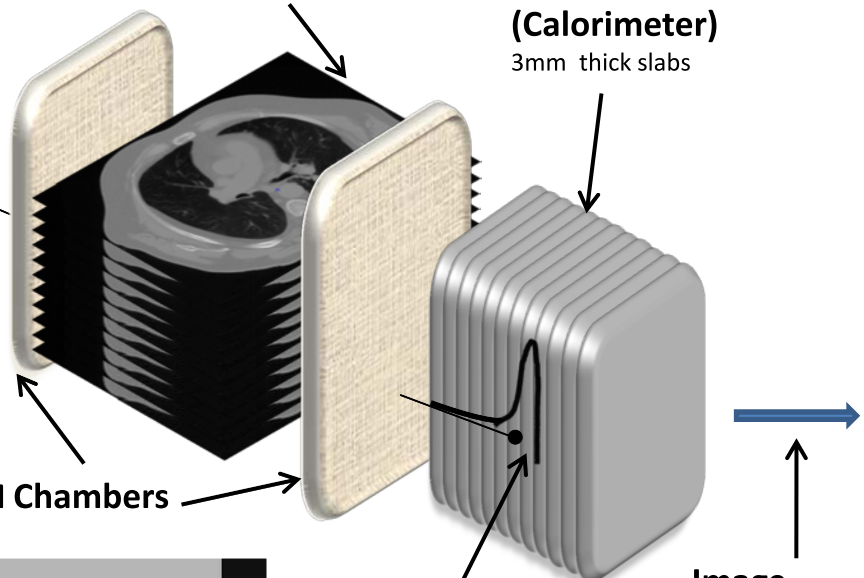
MC Modeling of Proton Radiography (“Range Telescope”)



Proton beam
(230 MeV
(0.5% FWHM)

Patient Phantom (3D and 4D)

Energy detector (Calorimeter)
3mm thick slabs

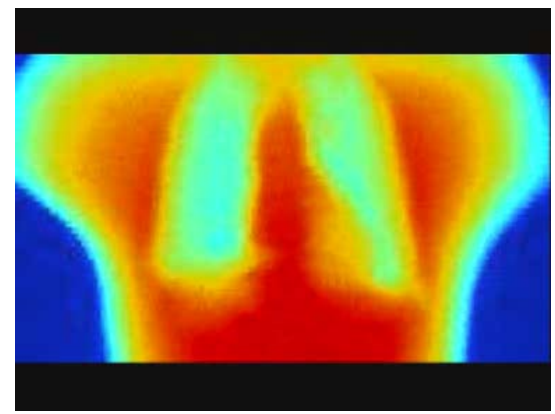


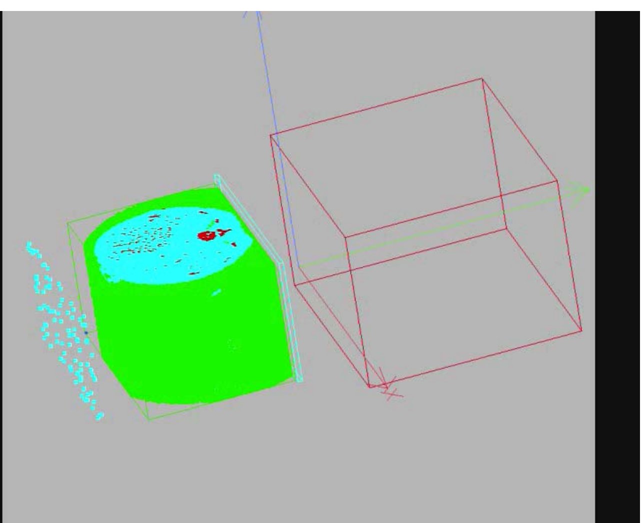
GEM Chambers

Bragg peak

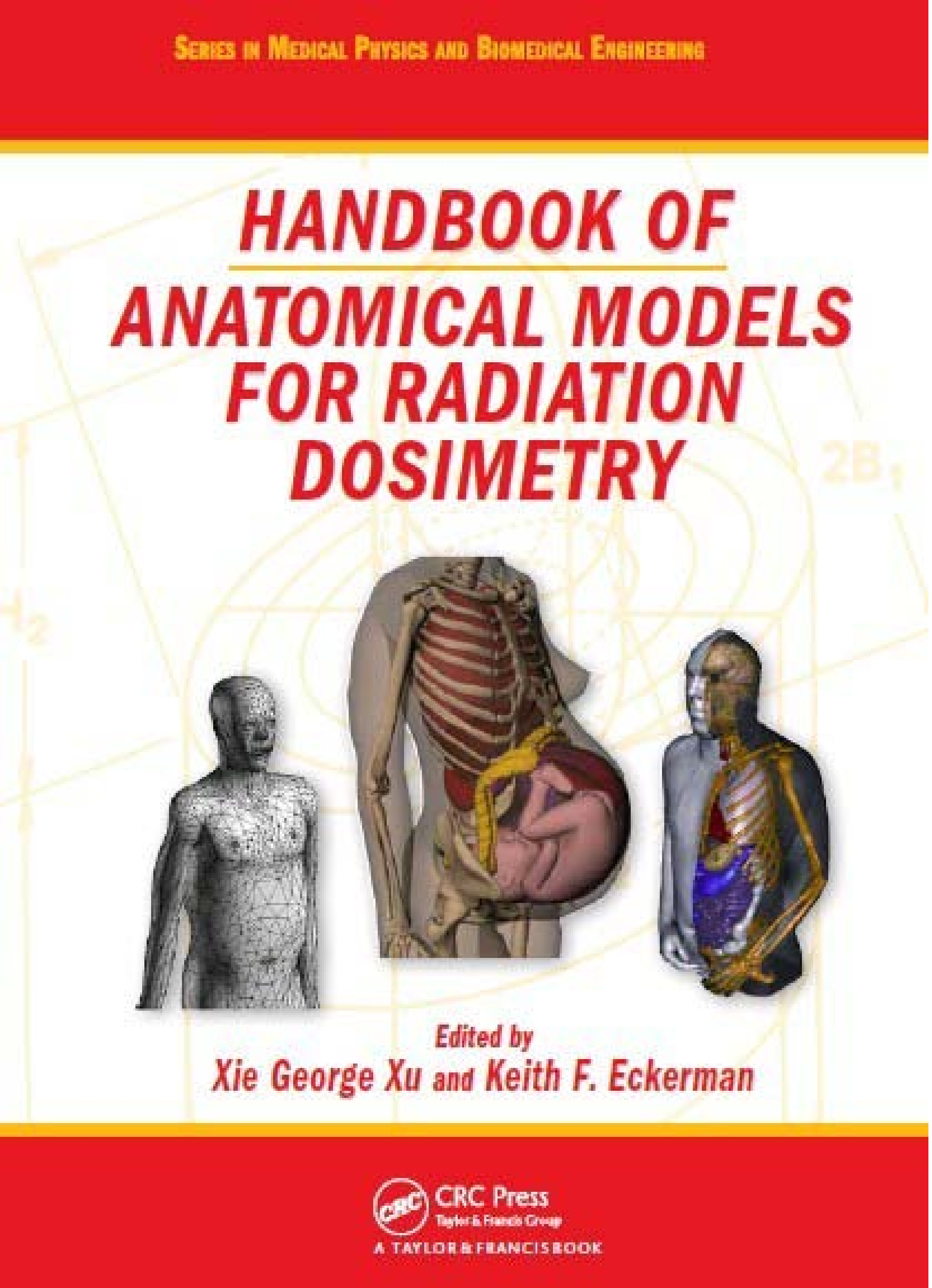
Image Reconstruction

Proton Radiograph/Fluoroscopy Showing change in radiological pathlength





Moritz software tracks multiple-Coulomb scattering



Published in late 2009

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

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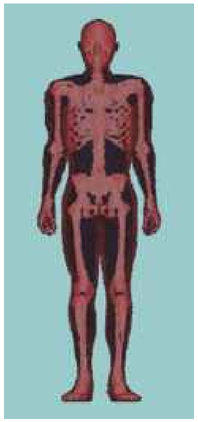
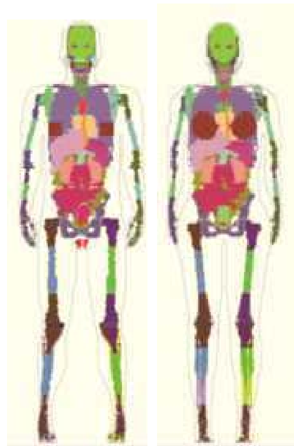
<<Handbook of Anatomical Models for Radiation Dosimetry>>

– curtsey images from various authors

REX & REGINA (ICRP)

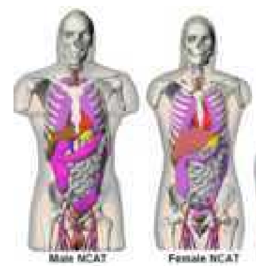


NORMAN

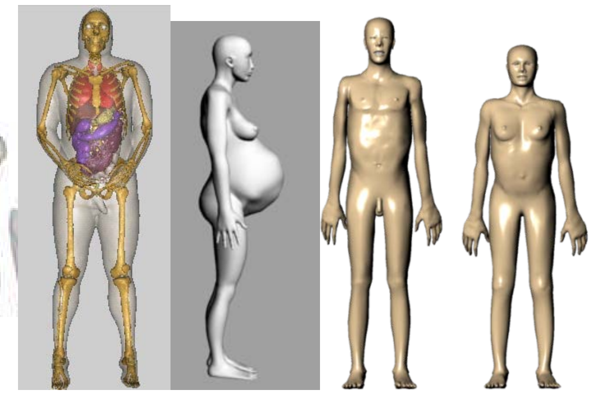


MAX06 FAX06

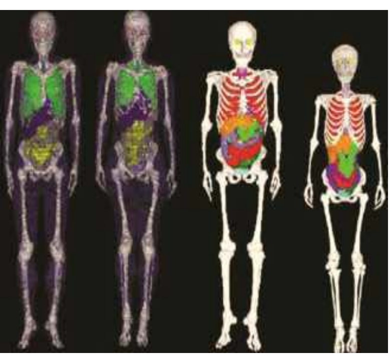
Zubal



NCAT



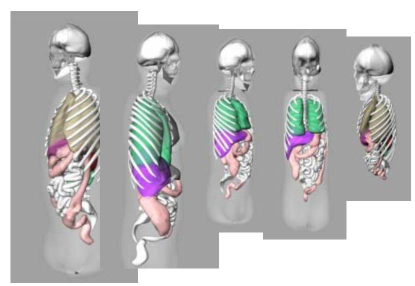
VIP-Man, Pregnant, Adult M/F



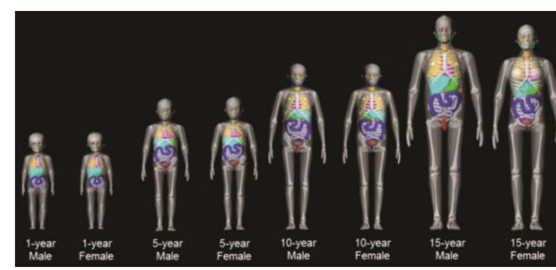
Otoko Onago JM KF

KTMAN 1, 2

CNMAN VCH

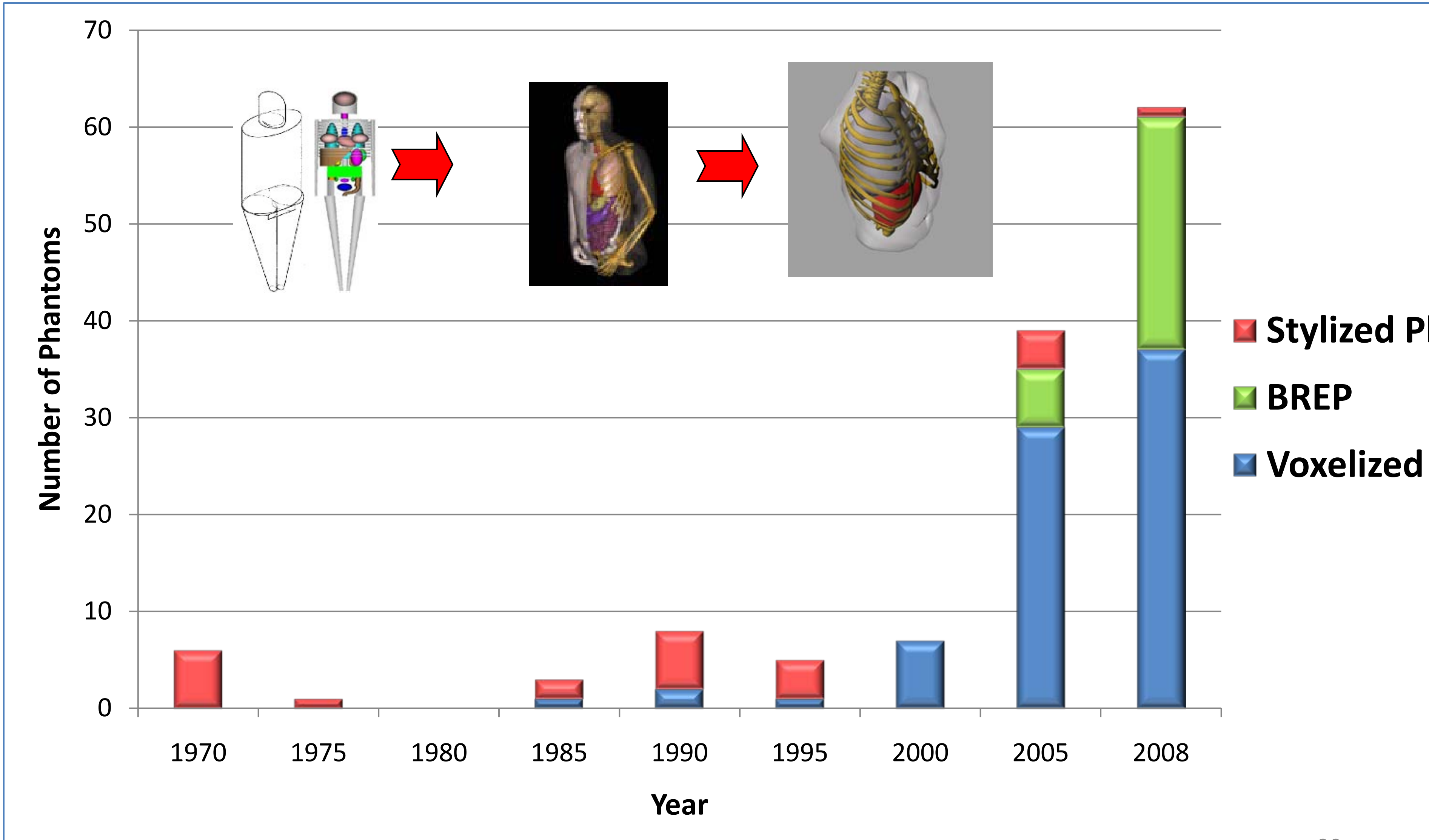


Vanderbilt Family



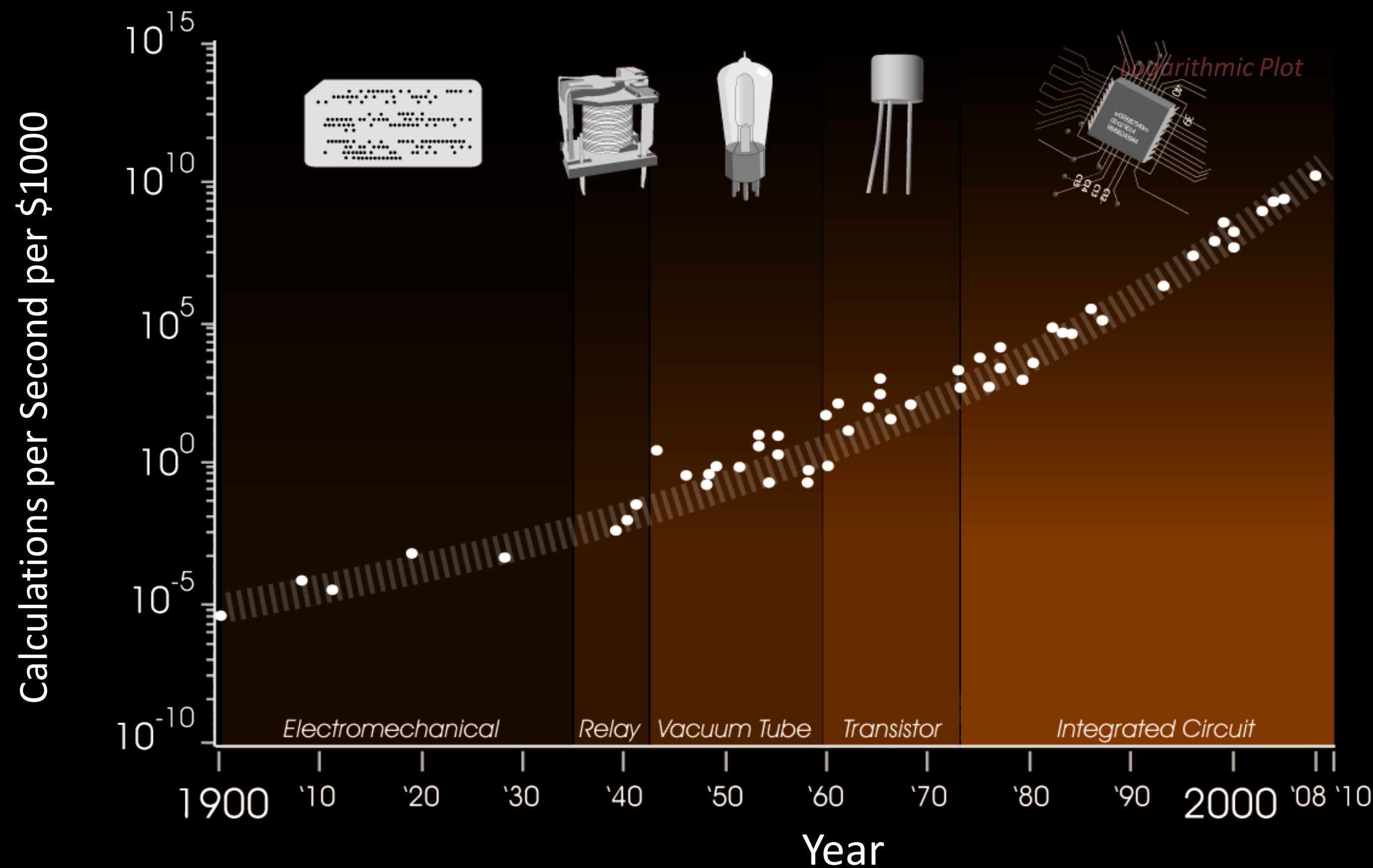
UF Family

The Number of New Phantoms Increased Exponentially

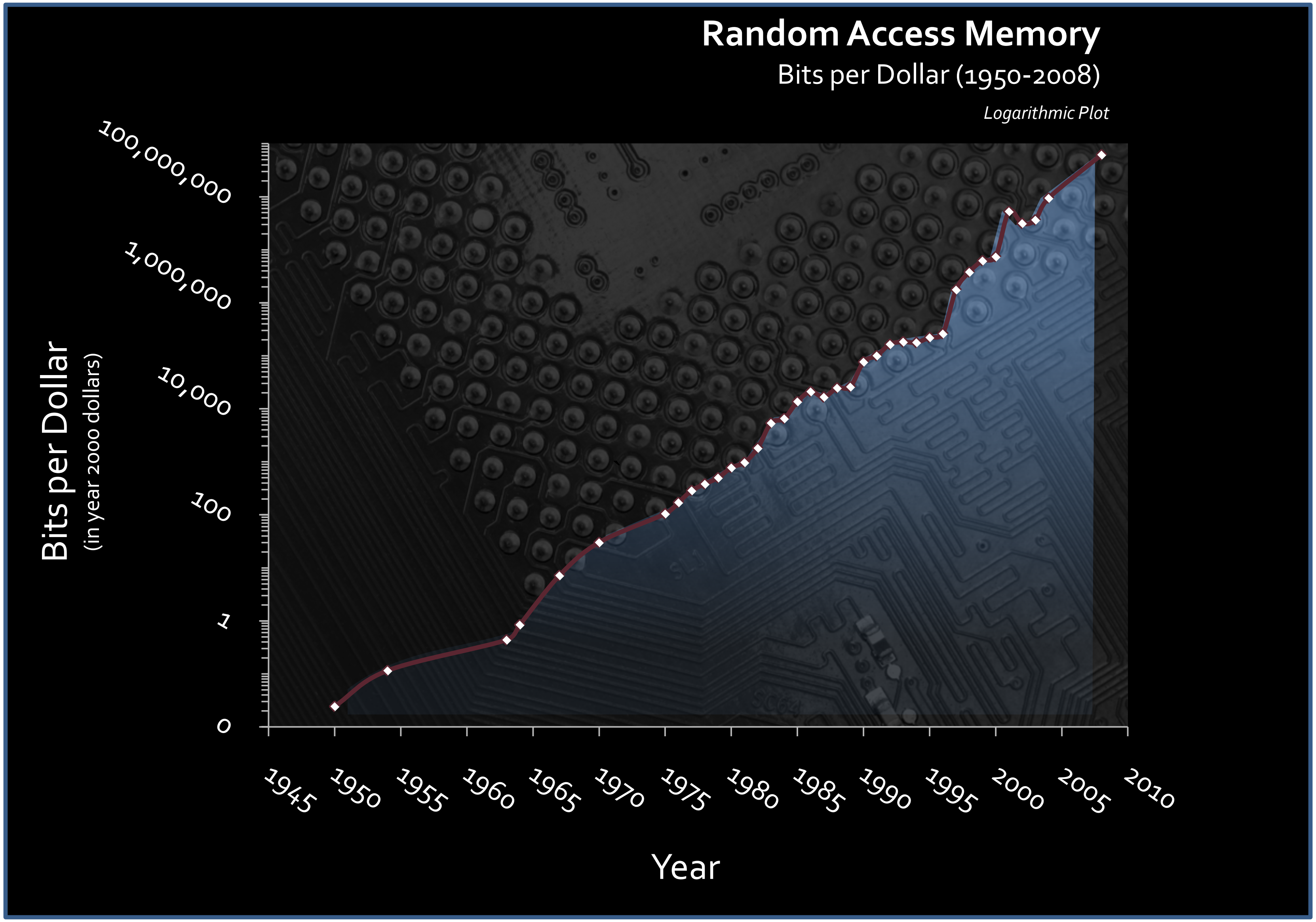


Moore's Law is Universal

Logarithmic Plot

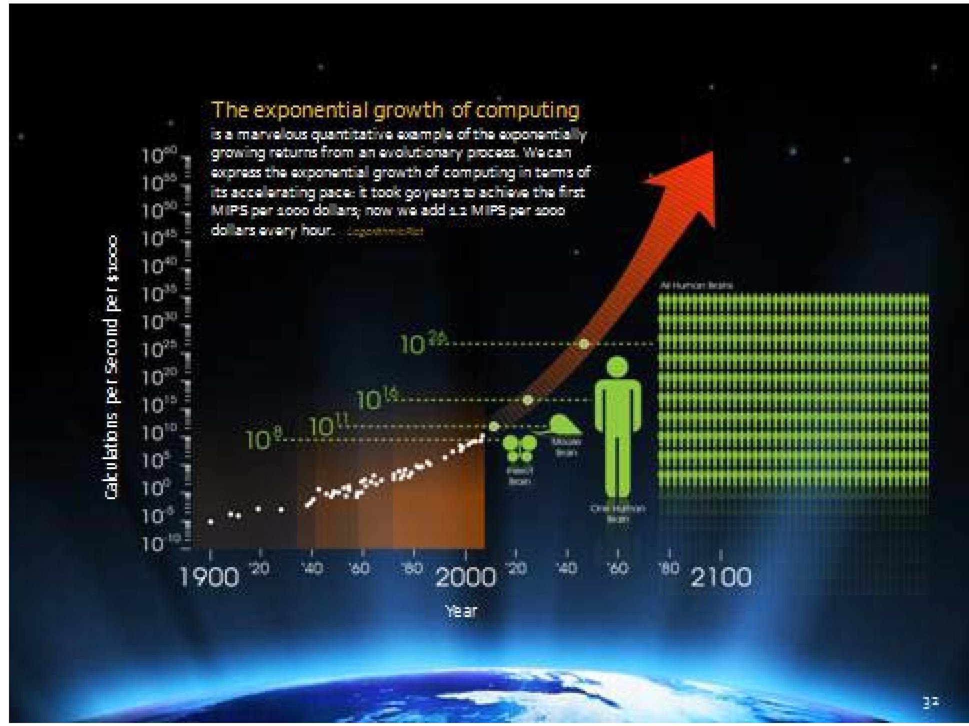


Adopted from Ray Kurzweil



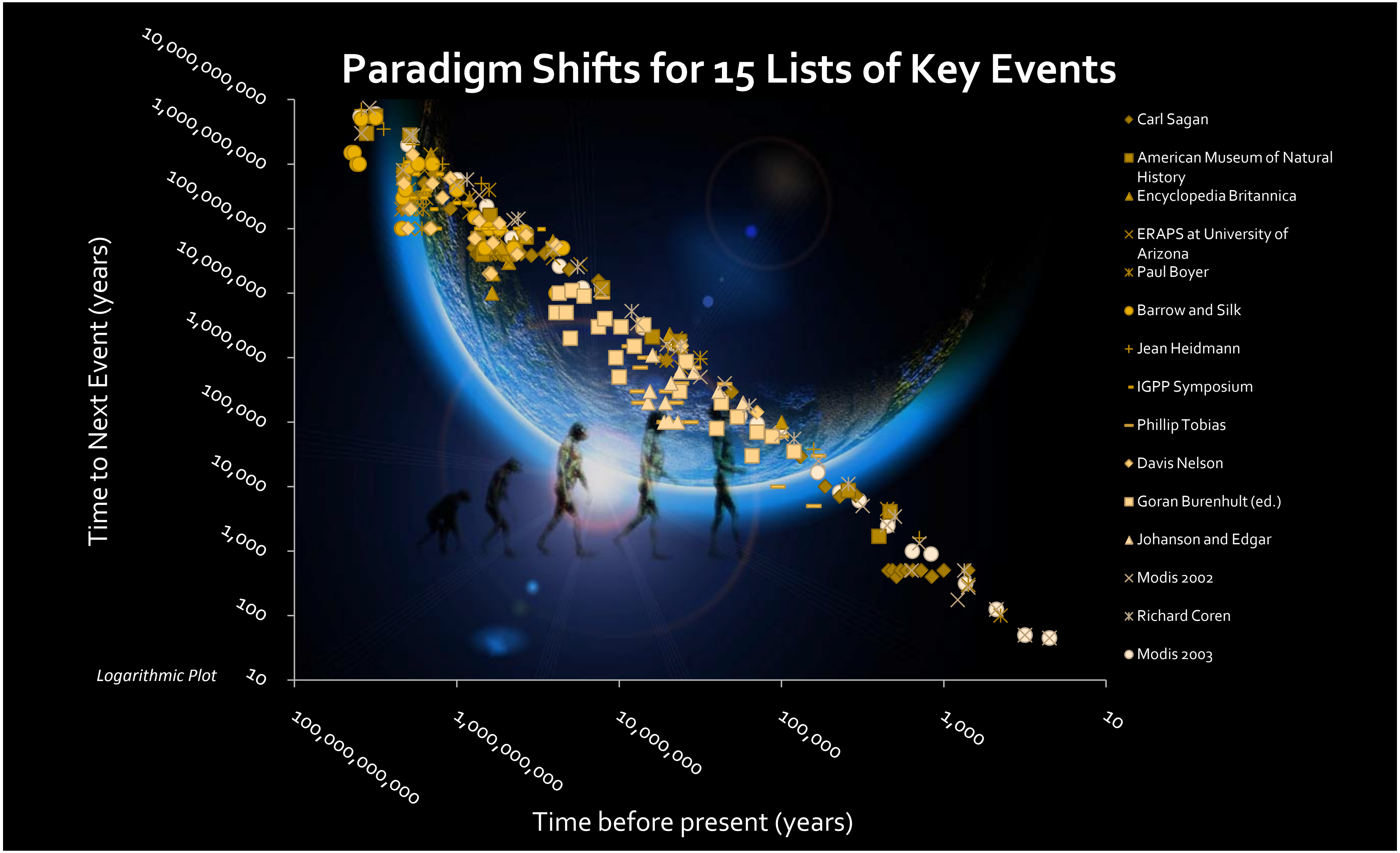
Adopted from Ray Kurzweil

"The Singularity Is Near: When Humans Transcend Biology" by Ray Kurzweil



"singularity" — an era in which technologies will have advanced so far beyond what is imaginable today that our lives will be transformed at a rate most people are unprepared.

Are you part of it or risking being “cut out of the loop?”



Adopted from Ray Kurzweil

Conclusions

- Think exponentially
- Be bold and aggressive
- Be visionary
- Be smart
- Be realistic