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Computational Phantoms for Radiation Dosimetry

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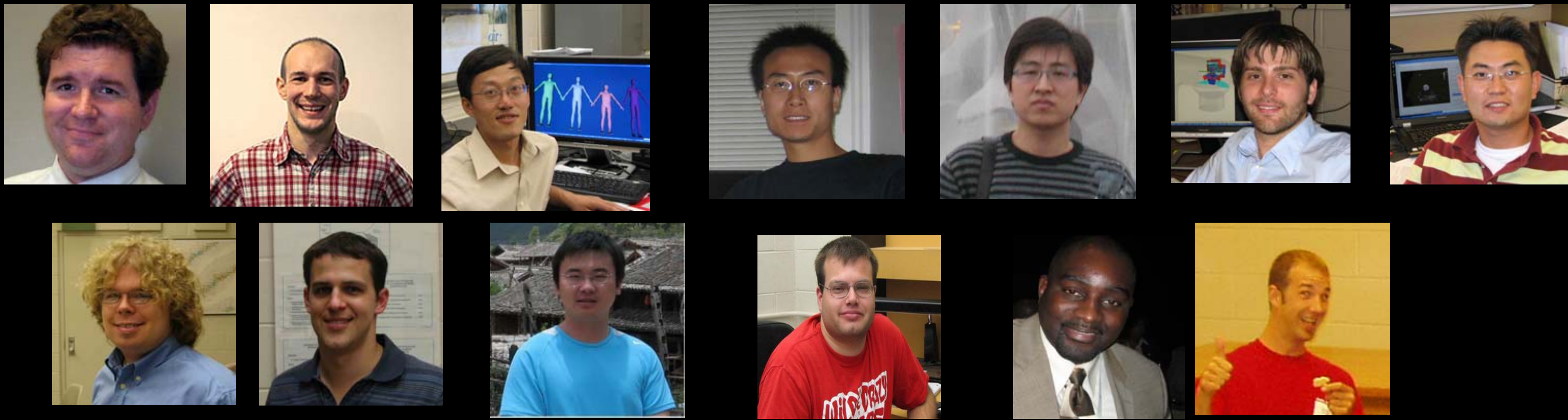
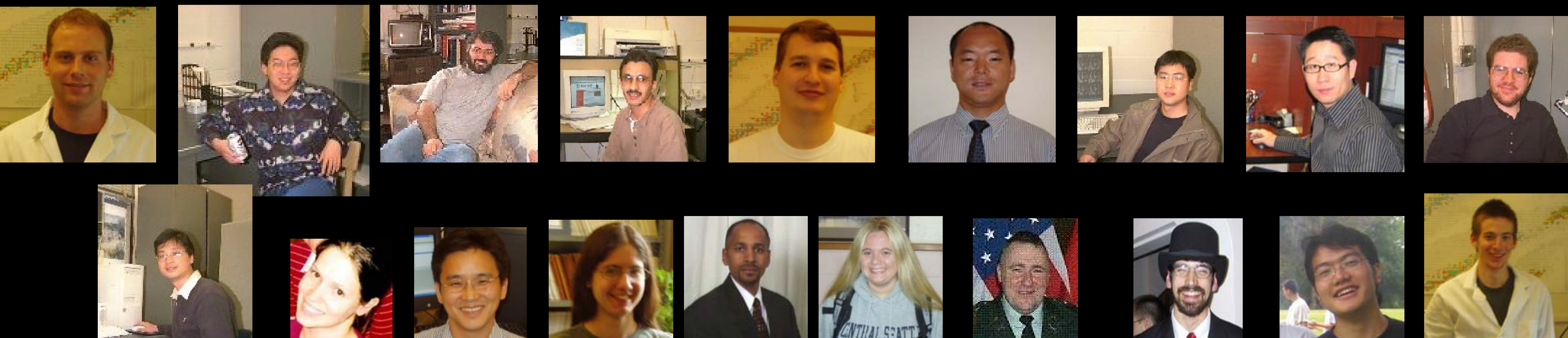
Rensselaer Radiation Measurements and Dosimetry Group (RRMDG)

http://RRMDG.rpi.edu

Current Students/Research Staff



Past Students



Basic of Radiation Dosimetry

Absorbed Dose (J/kg, or Gy) = Energy / Mass

Ionizing Radiation

- Photons (X-rays)
- Electrons
- Positrons
- Neutrons
- Protons
- etc

Radiation Risk Based on Organ Doses

Effective Dos (ED) defined in ICRP-60 (1991)

1) Organ "Equivalent Dose ": $H_T = \Sigma_R w_R D_{T,R}$
2) Total Body "Effective Dose" = $\Sigma_T w_T H_T$

Organ (T)	w_T(ICRP-60)
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder*	0.05

*Definition of the "remainder" follows ICRP 60.

Occupational dose limits:

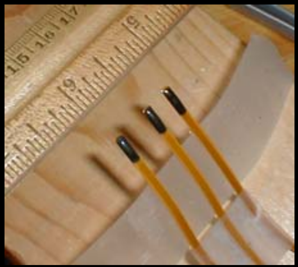
0.5 Sv per year for an organ

0.02 Sv per year total body

Two Ways to Determine Organ Doses

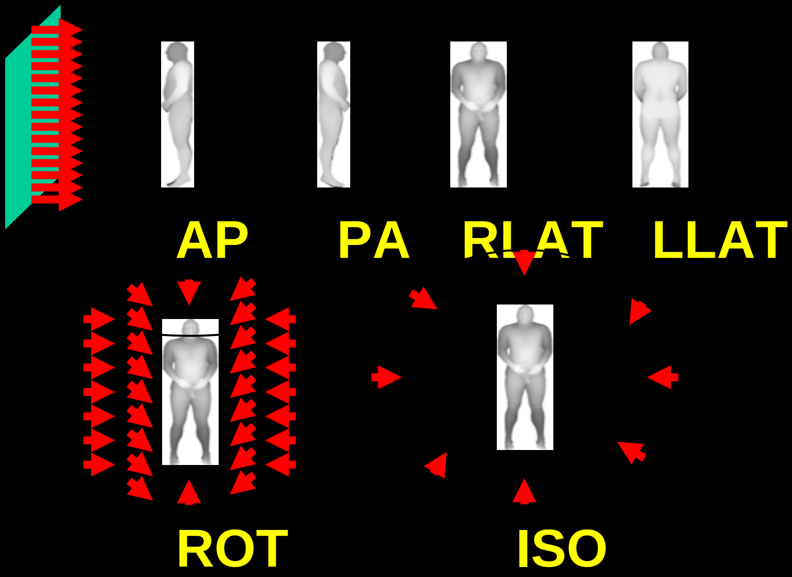
Measurements

- Dosimeters
- Physical phantom

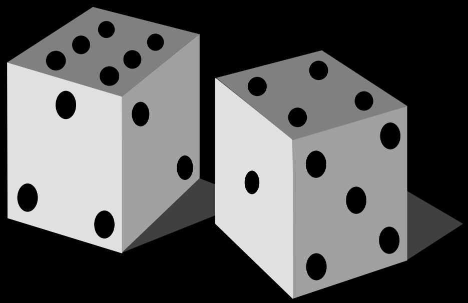


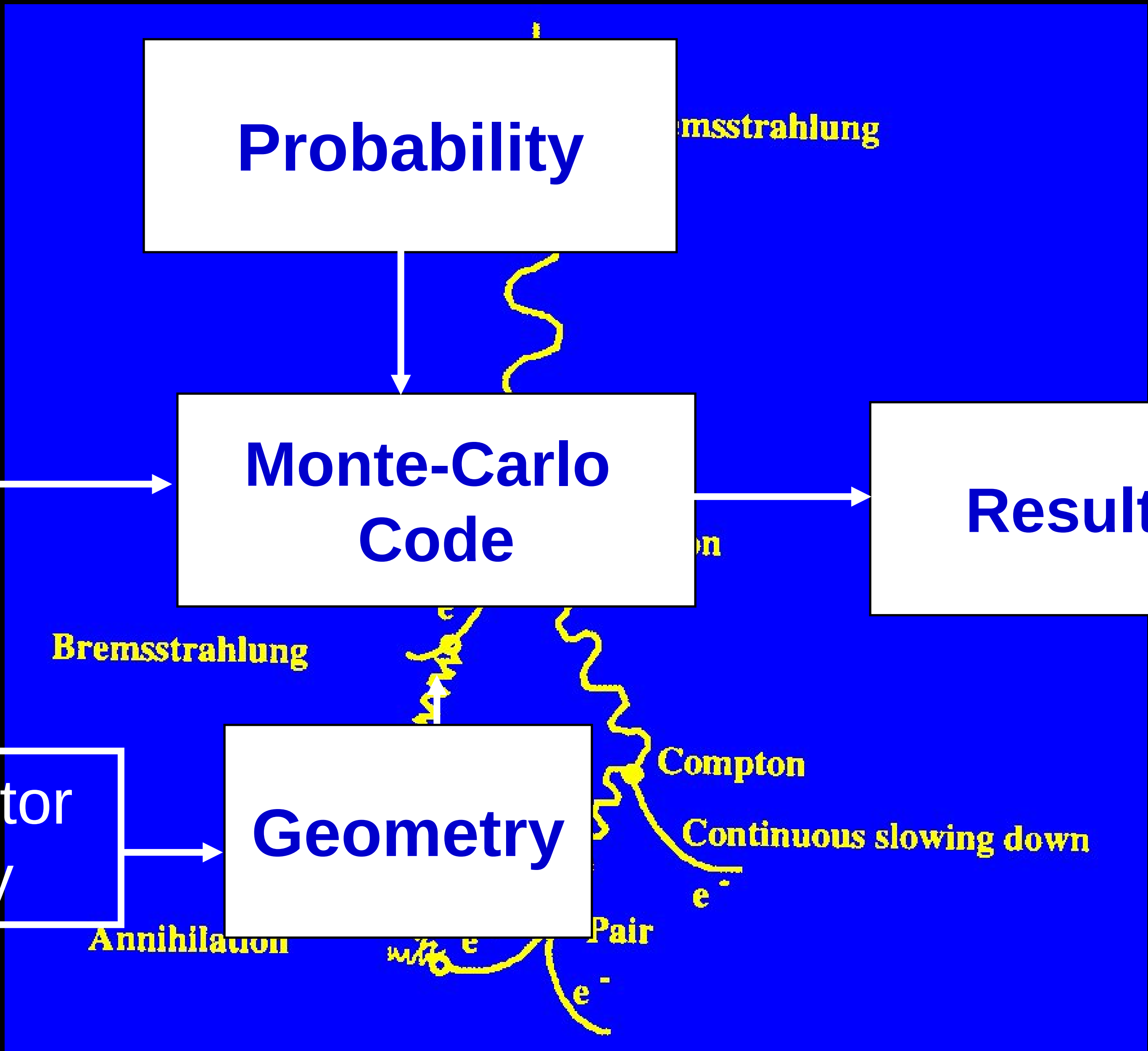
Monte Carlo Simulations

- Computational phantoms
- Monte Carlo codes



Monte Carlo Methods





Probability

Random Number

Monte-Carlo Code

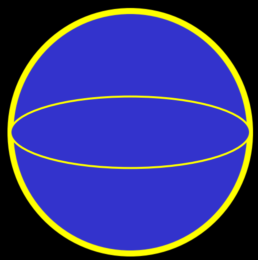
Result

A nuclear reactor or human body

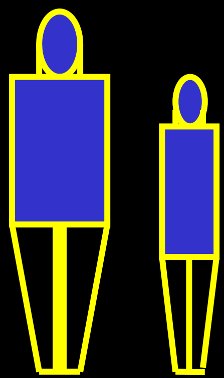
Geometry

The History of Computational Phantoms

- Simple to complex
- Homogeneous to heterogeneous
- Rigid to deformable
- Stationary to moving
- “Reference Man” to “reference library” or “person-specific” (?)

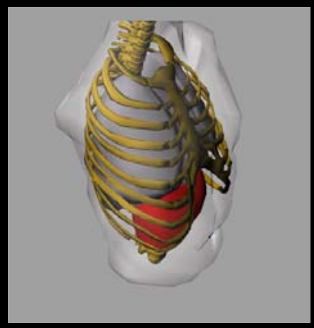


ICRU sphere
1960s

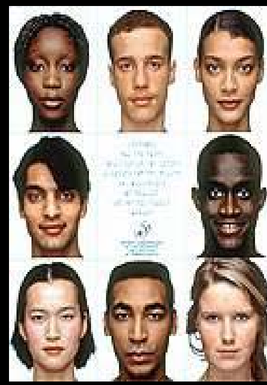


MIRD anthropomorphic
models in 1980s

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



Near Future
Deformable and
moving 4D models
2008-2010



Future?

Phantoms at RPI

1. VIP-Man Adult Male
   - developed 1997-1999

2. Pregnant Females (3, 6 and 9 months)
   – developed 2006-2007

3. Motion-simulating model (4-D)
   - on-going

Visible Human Project

Visible Man

39 Y

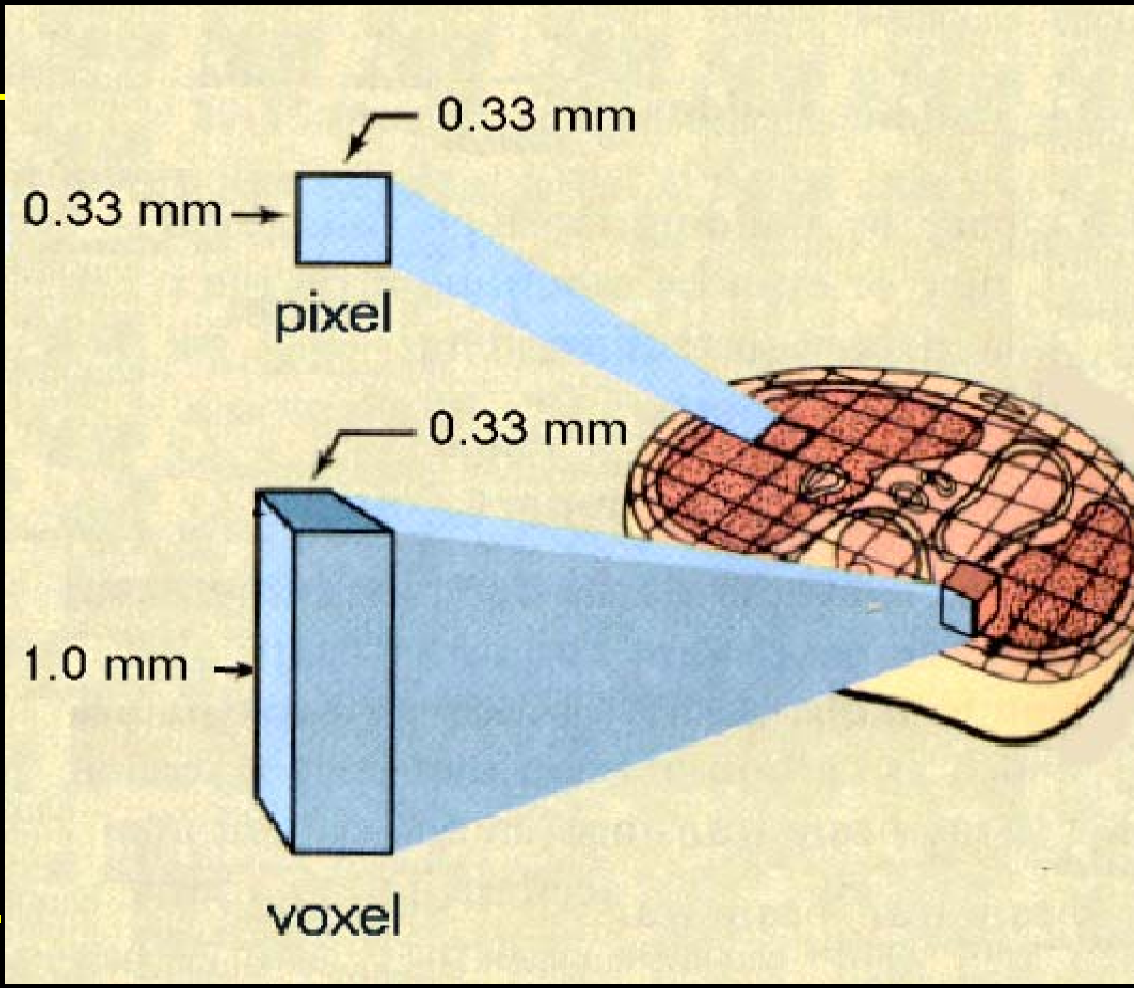
186-cm

90 Kg

0.33 mm× 0.33 mm

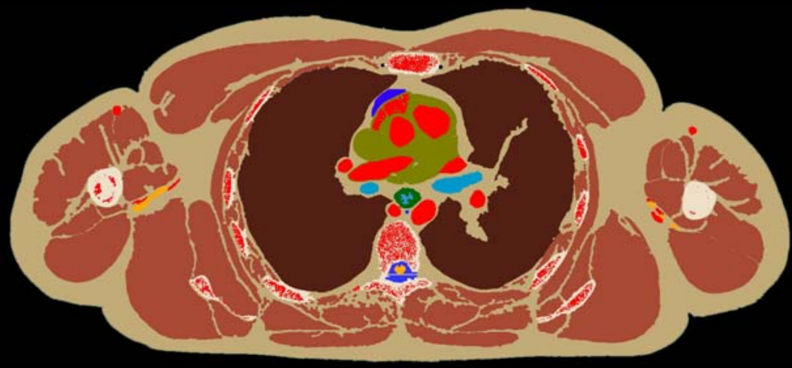
1-mm-thick slice

WB contains 2,048×1,216 ×1,871 = 4.7 billion voxels.

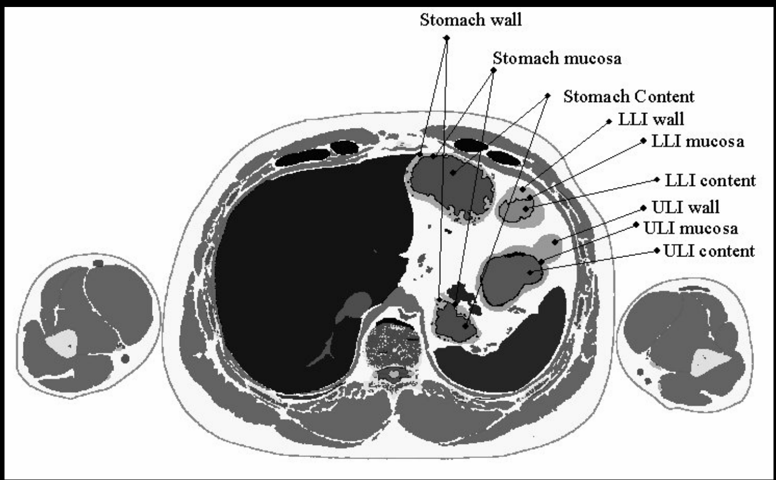


Segmentation and Labeling

Original Color Photo



Segmented Slice



Labeled

3D Rendering

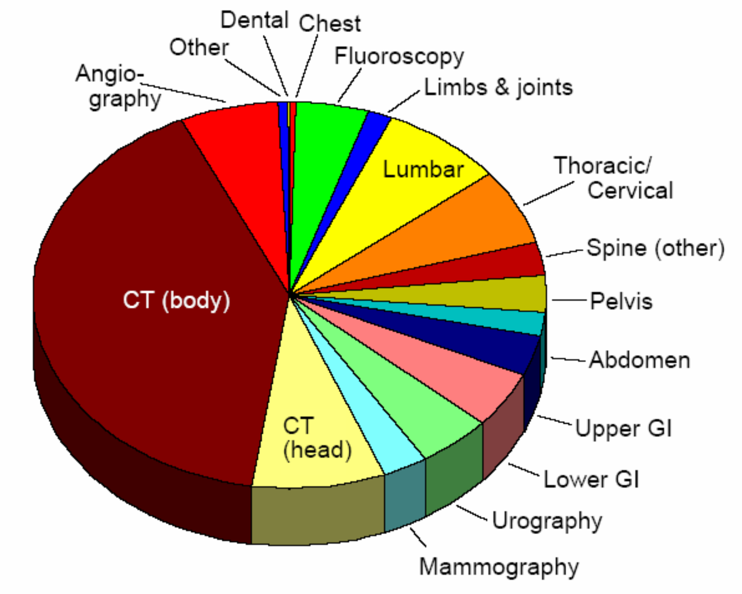
~30 Papers Involving the VIP-Man (1999-2007)

- External photons, electrons, neutrons and protons
- Internal photons and electrons
- Nuclear medicine dosimetry
- X-ray diagnostic imaging
- Radiation treatment of cancers
- Surgical simulations

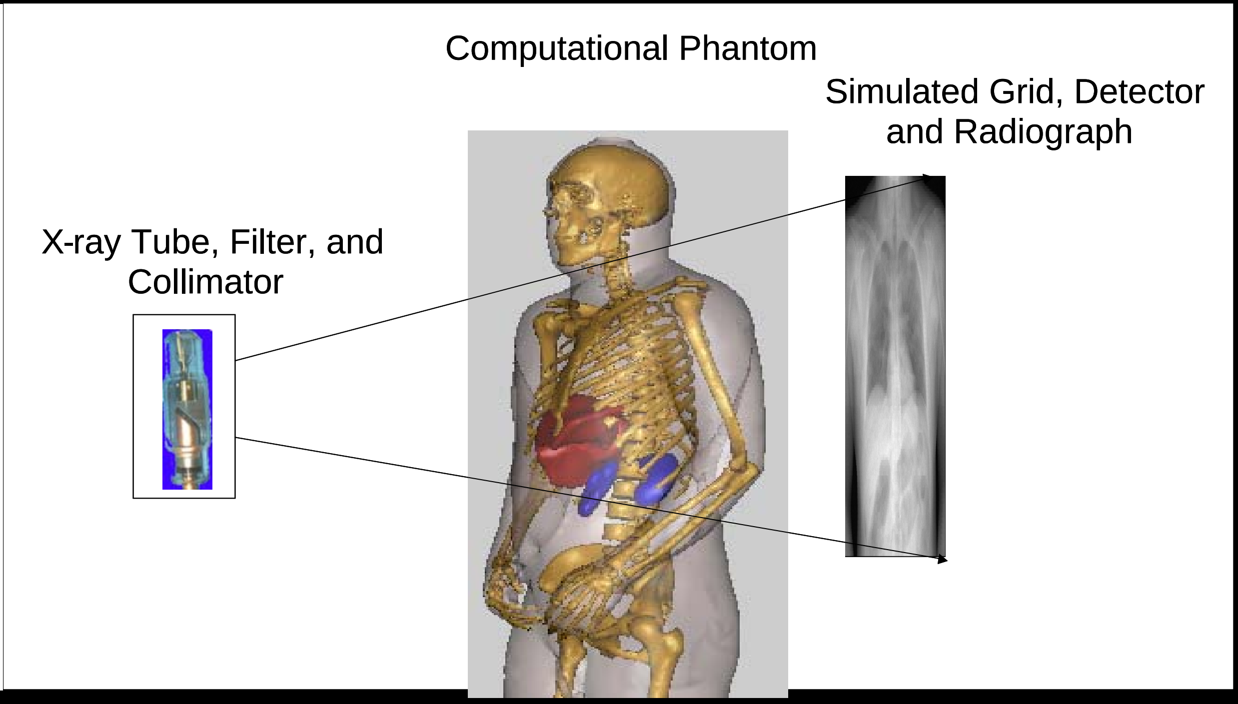
http://RRMDG.rpi.edu

Radiograph Image Optimization

- 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**

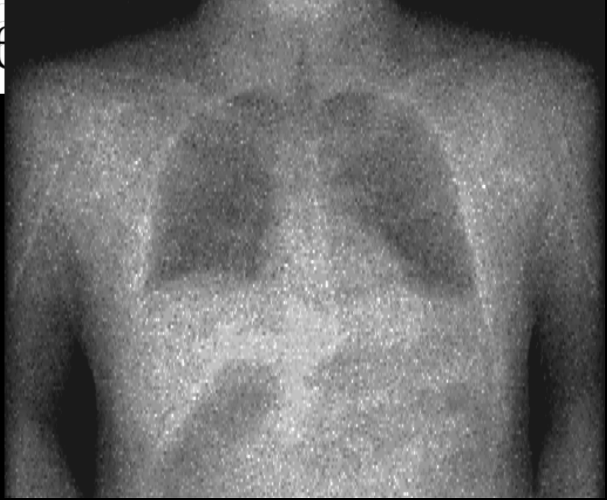


The relative contribution of diagnostic procedures to the collective medical dose estimated for the year 1996.



Results

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



Low dose and low resolution

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.

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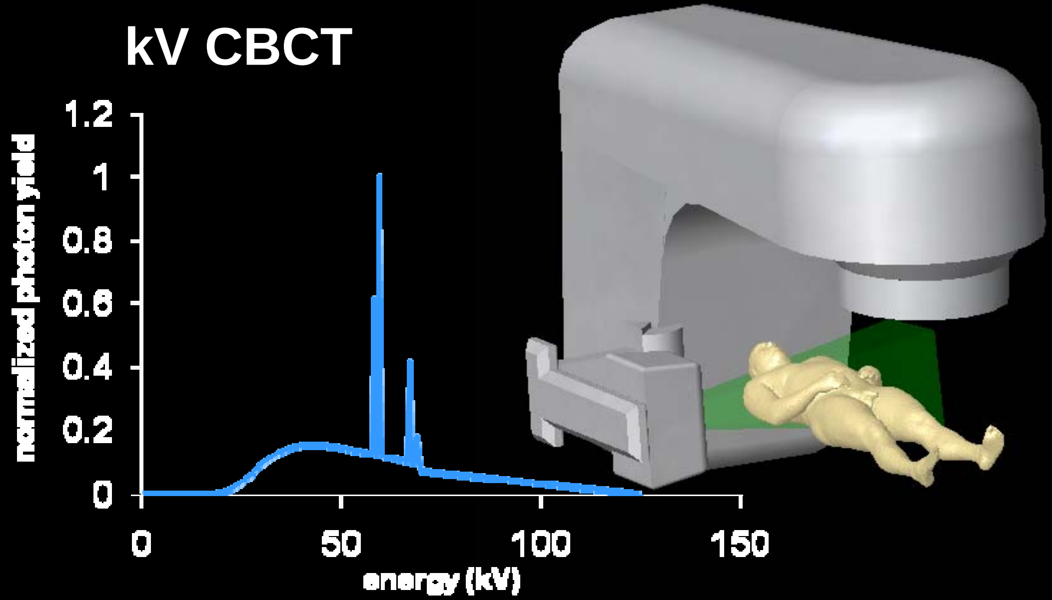
Dose from Image-Guided Radiotherapy

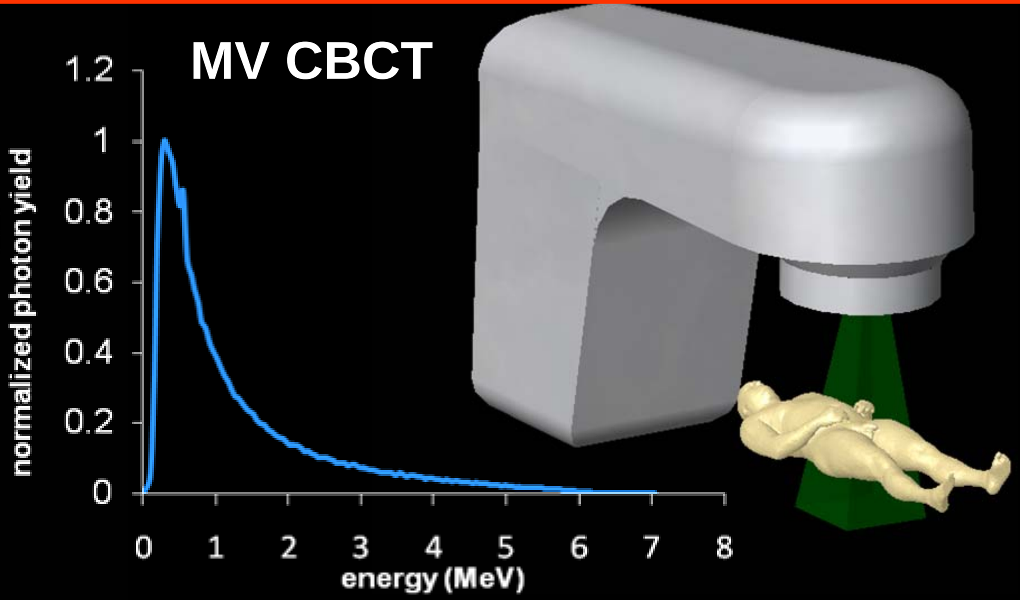
Mr. Jianwei Gu, Student Presentation, CIRMS 2007

kV CBCT



(The photon energy spectrum for 125 kVp, courtesy of Steve B. Jiang)

MV CBCT



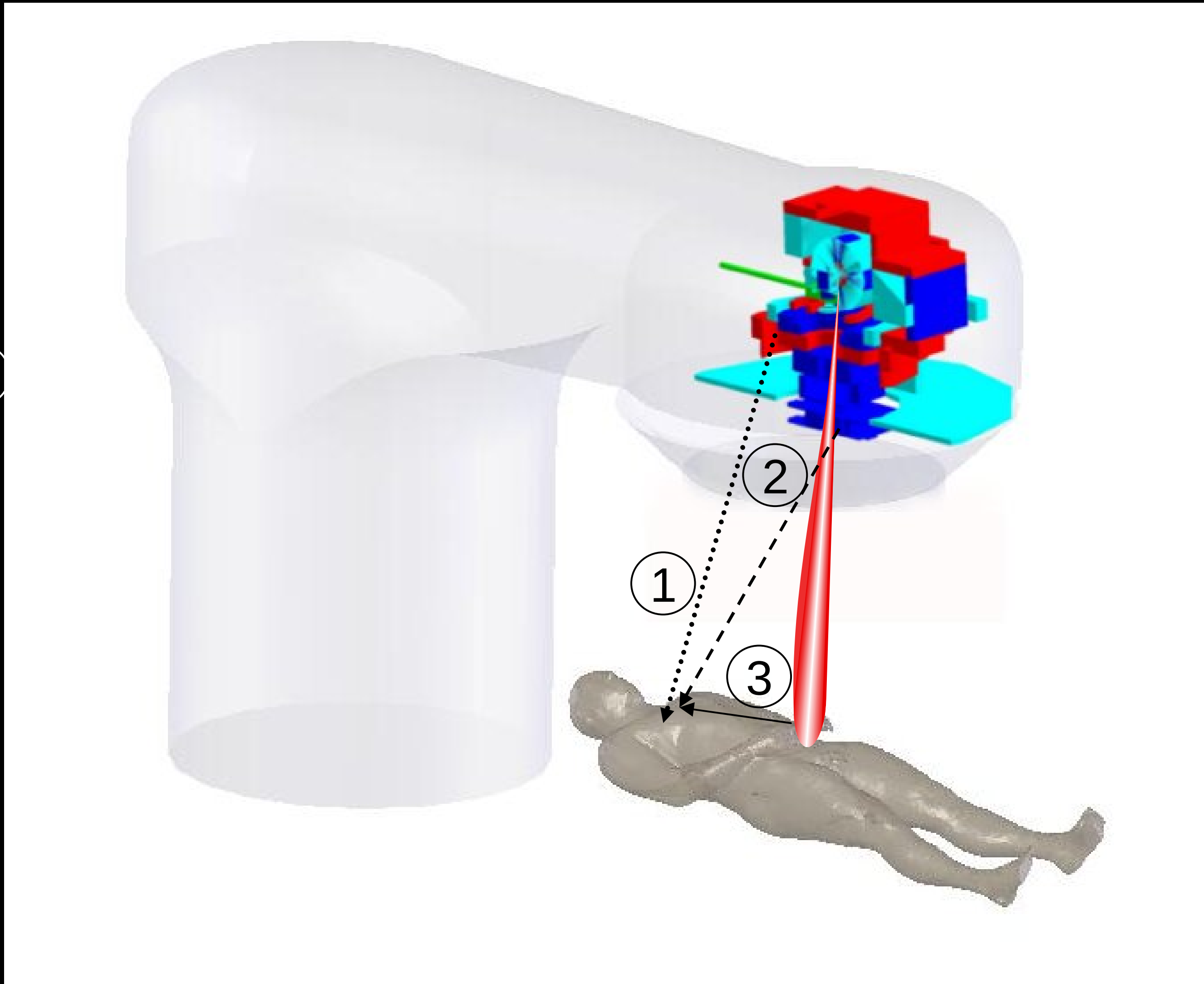
(The photon energy spectrum for 6 MV, courtesy of Bryan Bednarz)

Effective Dose	kV CBCT	MV CBCT
Head and Neck (mSv)	37.9	369.6
Prostate (mSv)	36.5	574.4

Projection number	675	200
Total mAs for CBCT acquisition	5400 mAs	~ 2 MUs
Angular range of projection views	364	200 (rotation from 270-110)

Detailed accelerator model used for radiation-induced second cancer research

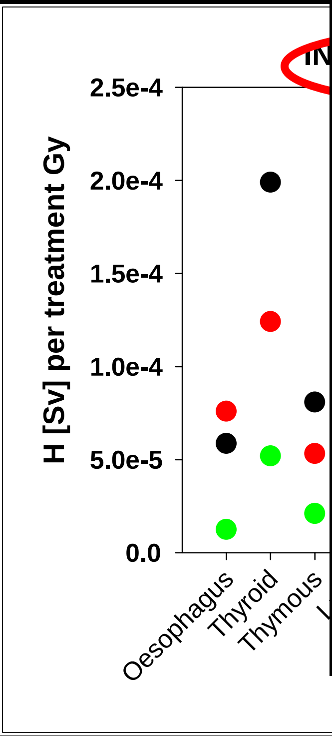
- out-of-field photon dose from:
  - leakage ①
  - collimator scatter ②
  - patient scatter ③

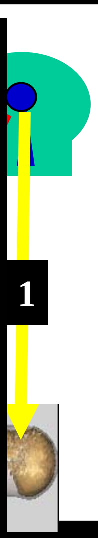


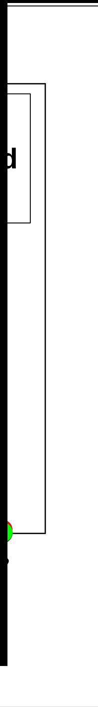
Due

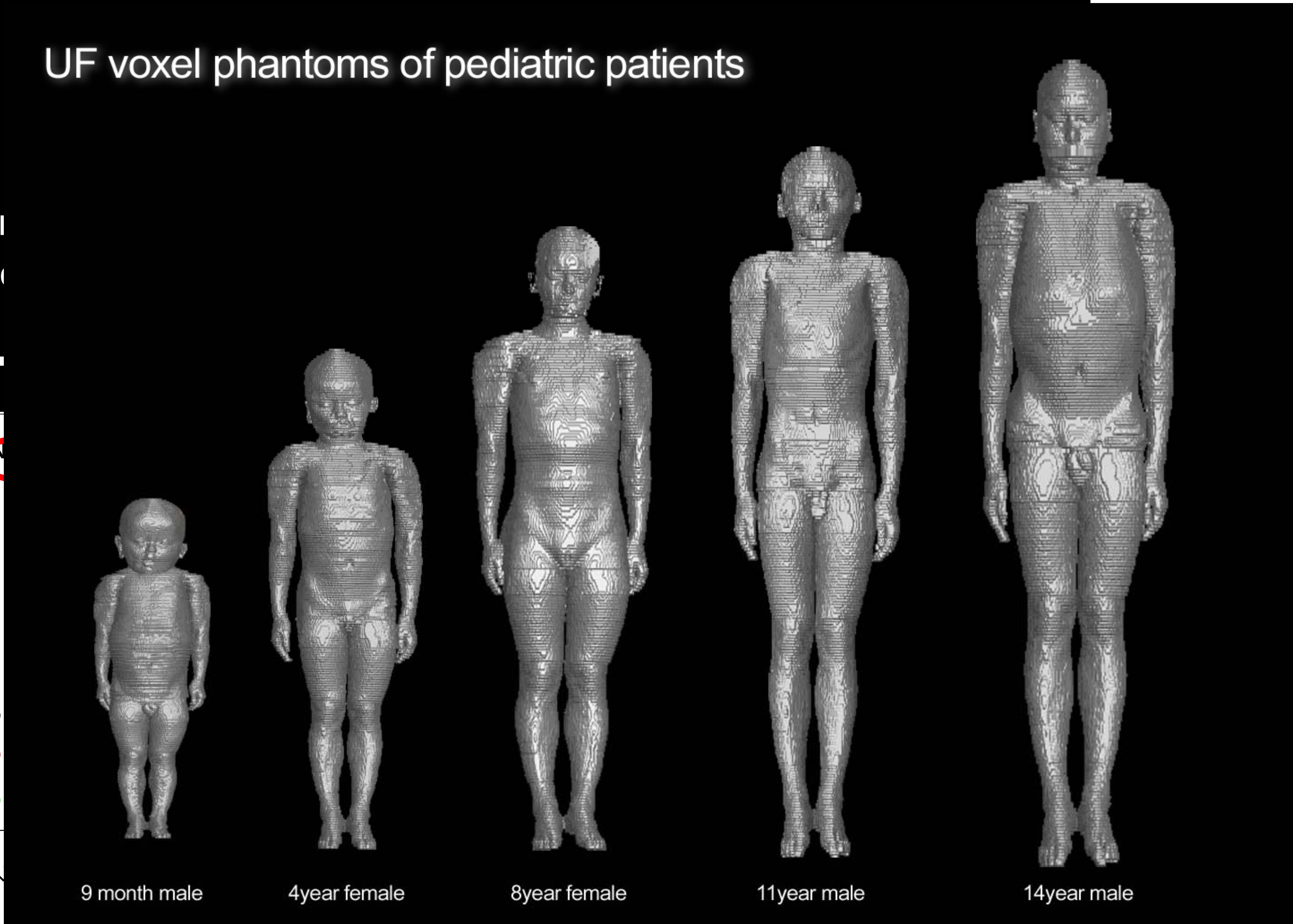
(Brain tumor, I

The organ
the adu





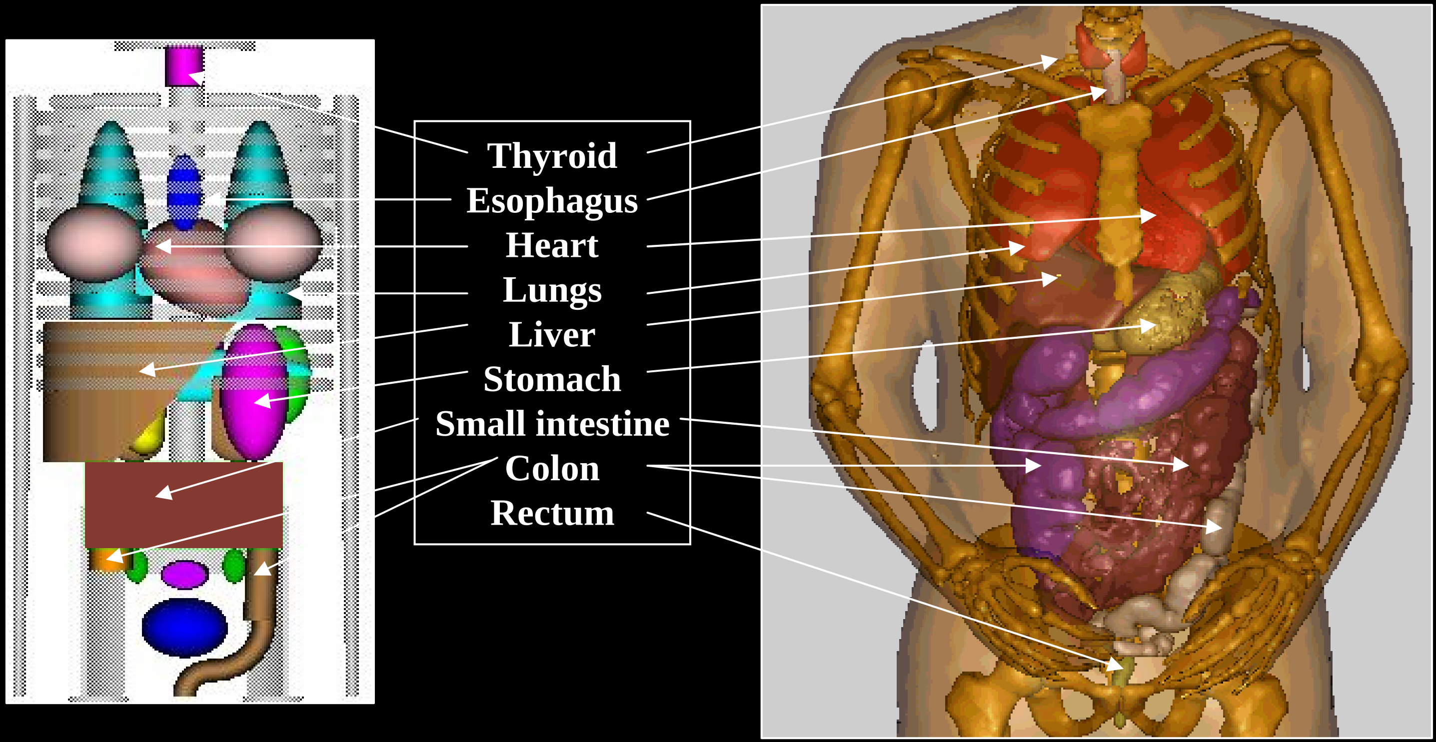


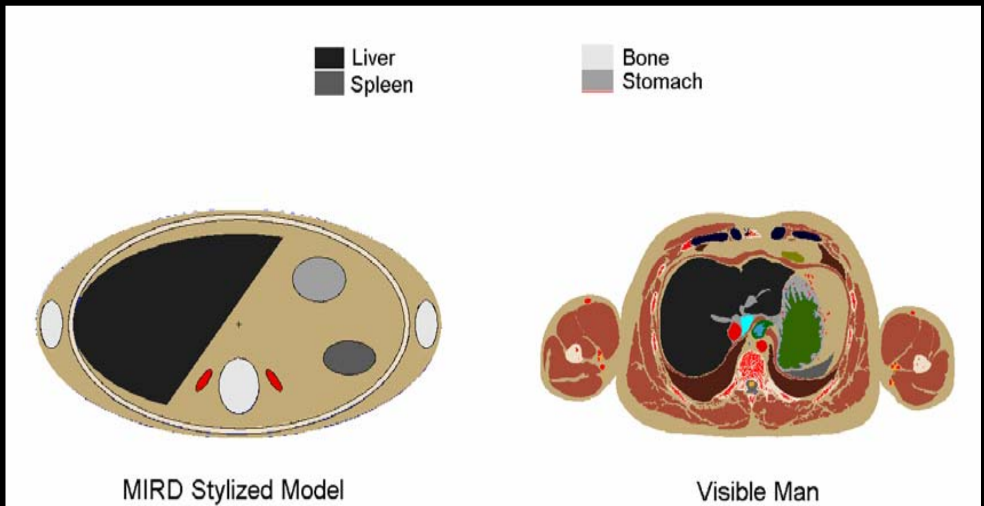


Zacharatou-Jarlskog, Lee, Jiang, Bolch, Xu, Paganetti. Monte Carlo simulations using whole-body pediatric and adult phantoms as virtual patients to assess secondary organ doses in proton radiation therapy. Poster at 48th AAPM Annual Meeting 2006

Paradigm Change in Nuclear Medicine Dosimetry

- From Stylized to Realistic Models





Results: S-Values (Sources in Caudate Nucleus)

Chao T. C. and Xu X. G. S-values Calculated from a Tomographic Head/brain Model For Brain Imaging. Phys. Med. Biol. (49) 4971-4984. 2004.

TABLE 2.1 S-Values (nGy MBq-1 s-1) for Radionuclides Emitted from Caudate Nucleus.

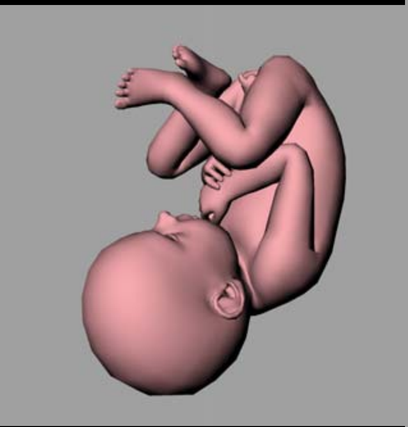
Target Organ	^{11}C		^{15}O		^{18}F		^{99m}Tc		^{123}I	
	VIP-Man	V/M	VIP-Man	V/M	VIP-Man	V/M	VIP-Man	V/M	VIP-Man	V/M
Caudate Nucleus	6,538	(1.13)	10,775	(1.10)	4,426.6	(1.10)	86.4	(0.31)	221.0	(0.43)
Cerebellum	6.79	(1.27)	6.88	(1.28)	6.60	(1.23)	1.027	(1.41)	1.469	(1.48)
Cerebral Cortex	20.12	(1.86)	27.32	(2.51)	17.32	(1.60)	2.340	(1.64)	3.991	(1.82)
Cerebral White Matter	29.33	(0.87)	43.58	(0.88)	25.88	(0.85)	3.621	(0.97)	6.582	(0.98)
Corpus Callosum	99.6		150.4		93.2		13.00		25.87	
Eyes	7.14	(0.96)	7.01	(0.94)	6.74	(0.90)	0.97	(1.09)	1.31	(1.16)
Lenses	5.3		5.5		5.2		0.74		0.90	
Lentiform Nucleus	110.5	(0.90)	167.7	(0.66)	96.5	(1.00)	12.87	(1.21)	26.35	(1.25)
Optic Chiasma	55		55		53		7.6		14.0	
Optic Nerve	35.0		36.1		33.9		4.9		8.5	
Pons & Middle Cerebellar Peduncle	9.09		9.11		8.79		1.35		1.89	
Thalamus	60.5	(0.95)	61.8	(0.89)	58.6	(0.92)	8.33	(1.02)	15.94	(1.02)
Thyroid	0.52	(0.46)	0.51	(0.44)	0.51	(0.45)	0.062	(0.48)	0.080	(0.50)

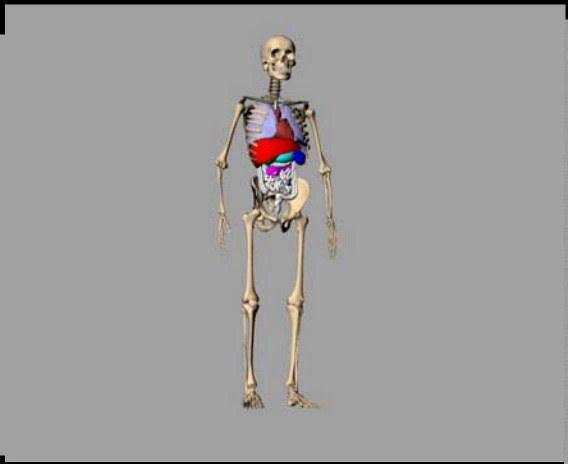
*V/M is the ratio of S-Values from VIP-Man head and brain model to those from MIRD revised head and brain model.

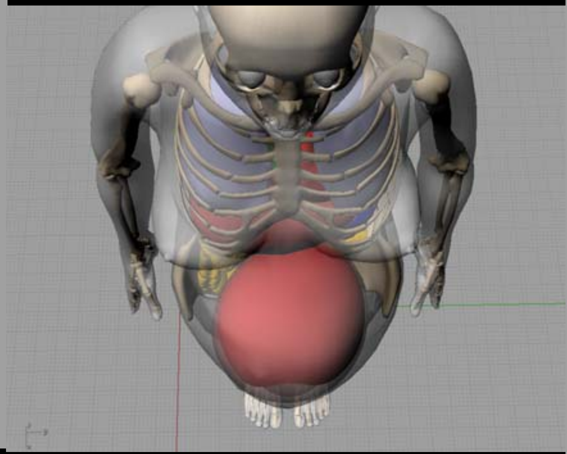
* Bouchet LG, Bolch WE, Weber DA, Atkins HL, Poston, JW. MIRD Pamphlet No. 15: Radionuclide S values in a revised dosimetric model of the adult head and brain. J Nucl Med 1999; 40:62S-101S.

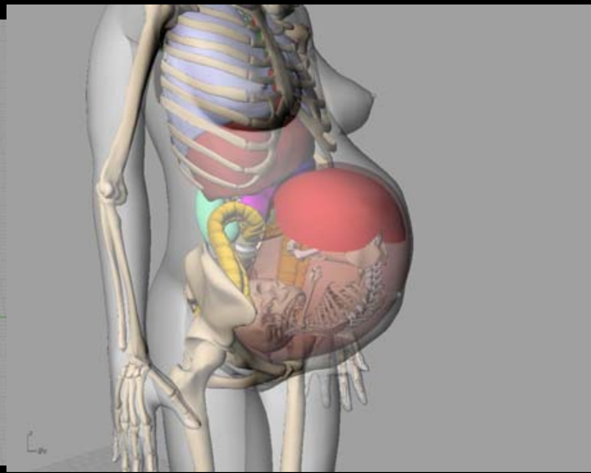
A New Method for Phantom Design: Pregnant Female Models

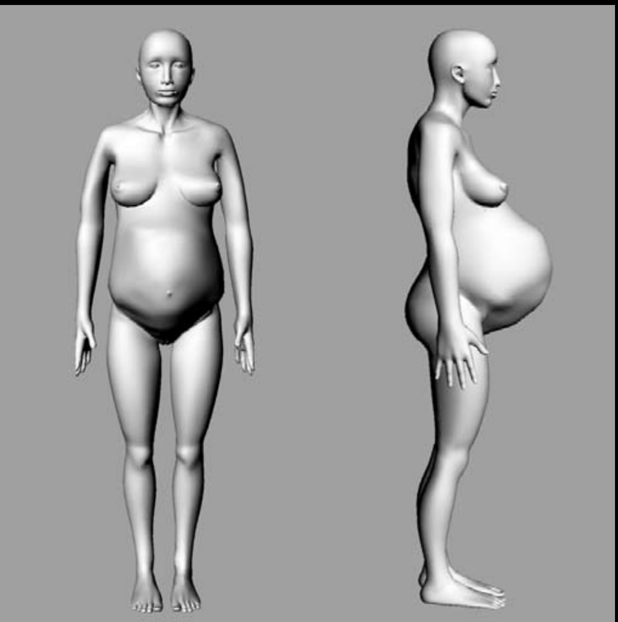
Xu et al. A boundary-representation method for designing whole-body radiation dosimetry models: pregnant females representing three gestational periods, RPI-P3, -P6 and –P9. Phys. Med. Biol. (accepted October 2007)

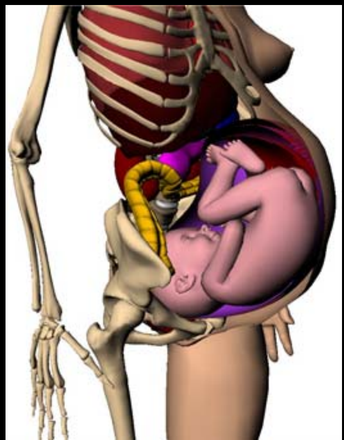




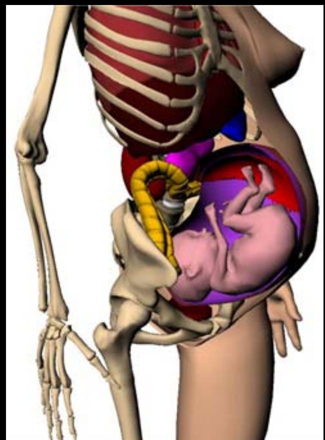




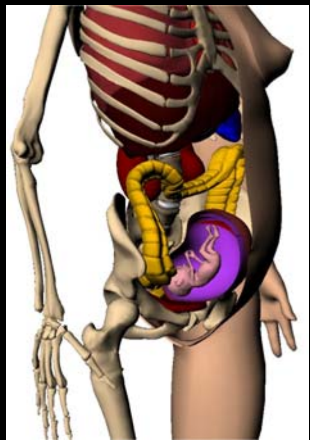




9-month



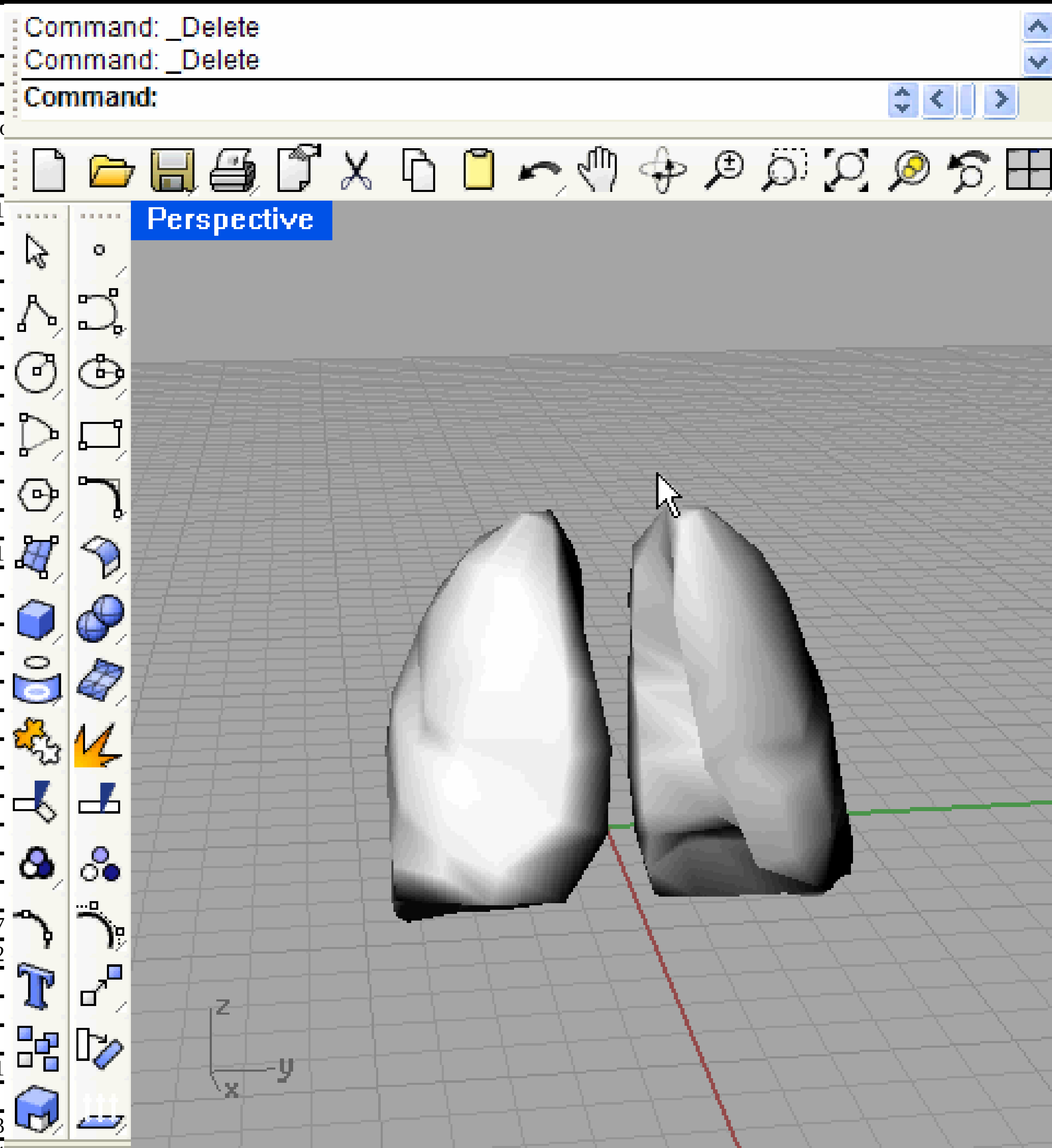
6-month



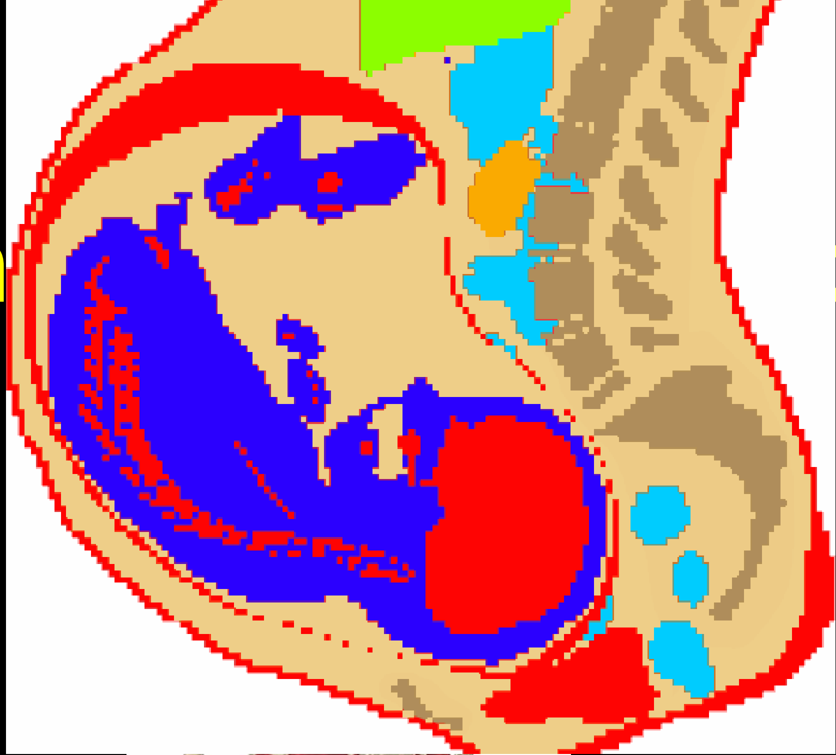
3-month

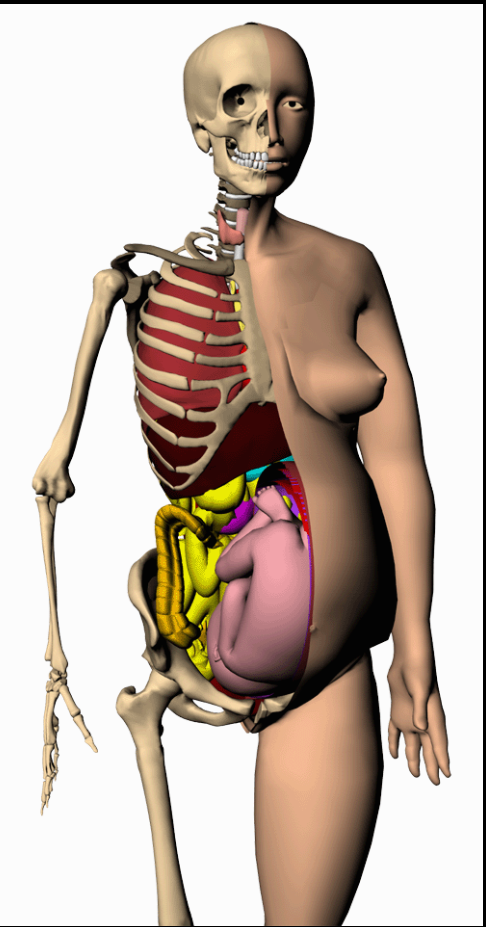
Organ Masses Adjusted to ICRP References

Organ		
	RPI	
	RPI-3DModel	RPI-vo
Fixed volume organs		
Brain	1,299.49	1
Eyeballs	14.63	
Eye lens	0.40	
Thyroid	17.00	
Trachea	7.99	
Thymus	20.00	
Lungs	950.34	
Heart wall	250.15	
Heart cont.	369.96	
Esophagus	35.00	
Stomach wall	139.56	
Stomach cont.	230.67	
Liver	1,399.81	1
Gallbladder wall	8.00	
Gallbladder cont.	48.19	
Pancreas	119.68	
Spleen	129.58	
Kidneys	275.04	
Adrenals	13.00	
SI wall and cont.	N/A	
LI wall	682.24	
LI cont.	N/A	
Ovaries	11.00	
Bladder wall	40.11	
Bladder cont.	129.37	
Skeleton	7,862.62	7
Skin	N/A	2
Variable volume organs		
Uterine wall 3 m	270.11	
6 m	549.94	
9 m	1,046.85	1
Uterine cont. 3 m	859.61	
6 m	3,657.42	3

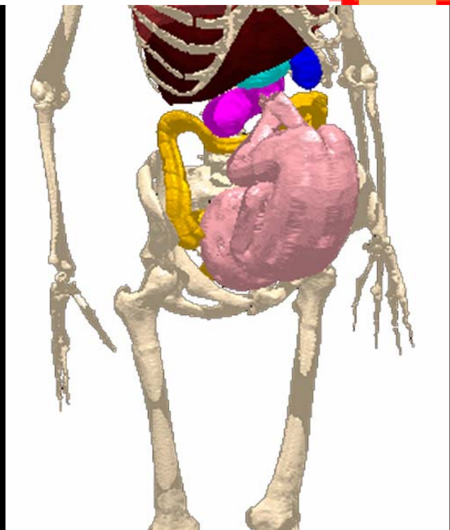


From xels

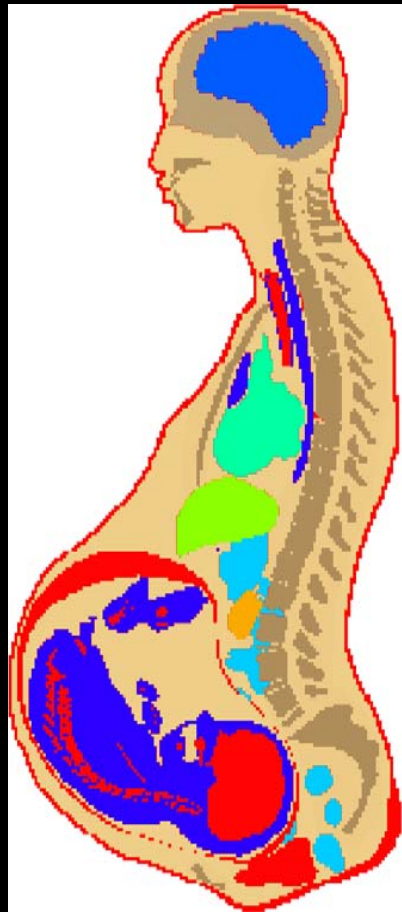




Re-voxelize at any size (1mm shown here)



Put into MC codes
- MCNPX
- EGSnrc



Surface Model Adjusted to ICRP reference values

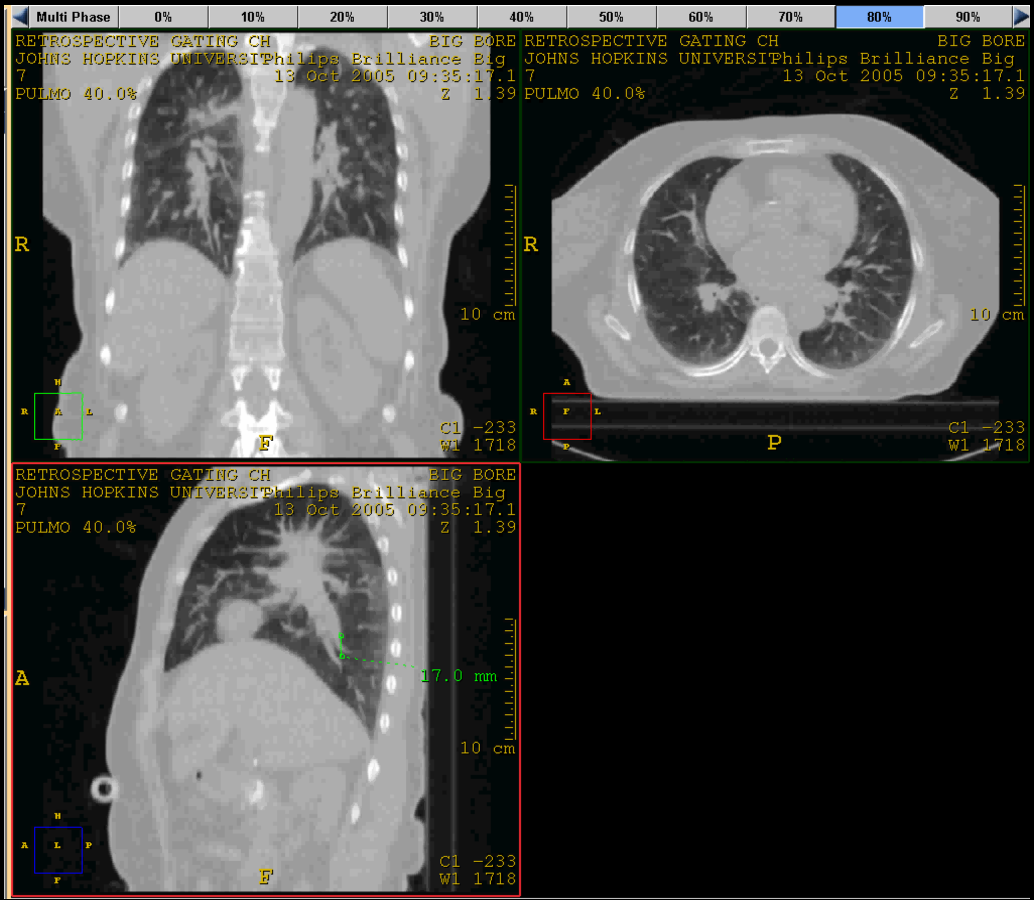
Voxel Model

Geometry in MCNPX code

Nuclear Medicine Dosimetry

- MIRDose replaced by OLINDA
- OLINDA/EXM approved by FDA 2005 (distribution via Vanderbilt)
- NIH STTR grant (Stabin, Brill and Xu)
- OLINDA/EXM 2 will include voxel family phantoms in 2007/2006
- …

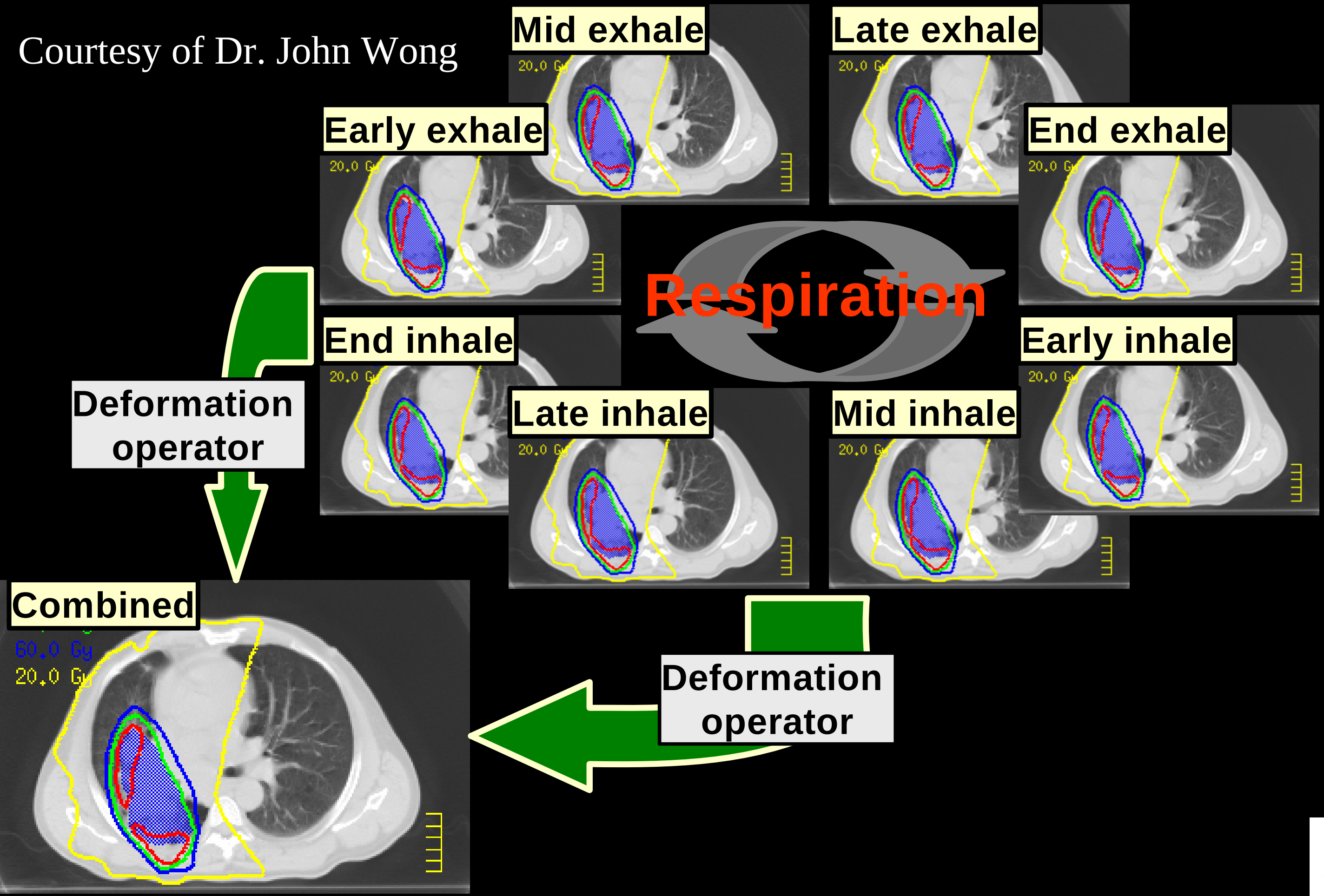
4D Models for Management of Respiratory Motion in RT (On-going)



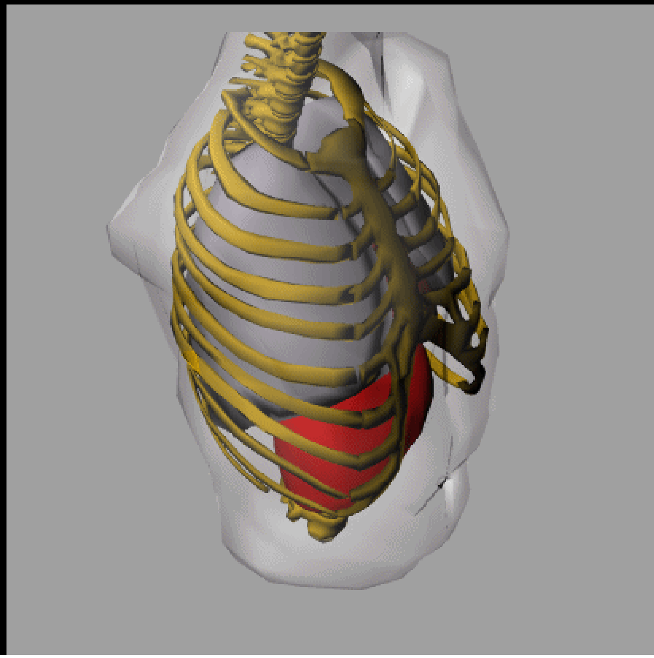
- Techniques for coping with respiratory motion:
  - Conventional 3D plan increases PTV size
  - Breath-hold techniques (ABC/DIBH)
  - Respiratory gating
  - Others (couch synchronization etc.)
- 4D planning is the future

NURBS-Based 4D- Modeling

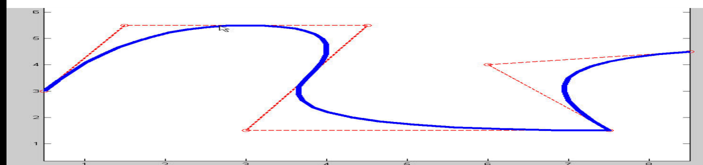
Courtesy of Dr. John Wong



- Xu and Shi, Monte Carlo 2005
- Shi and Xu, AAPM 2005

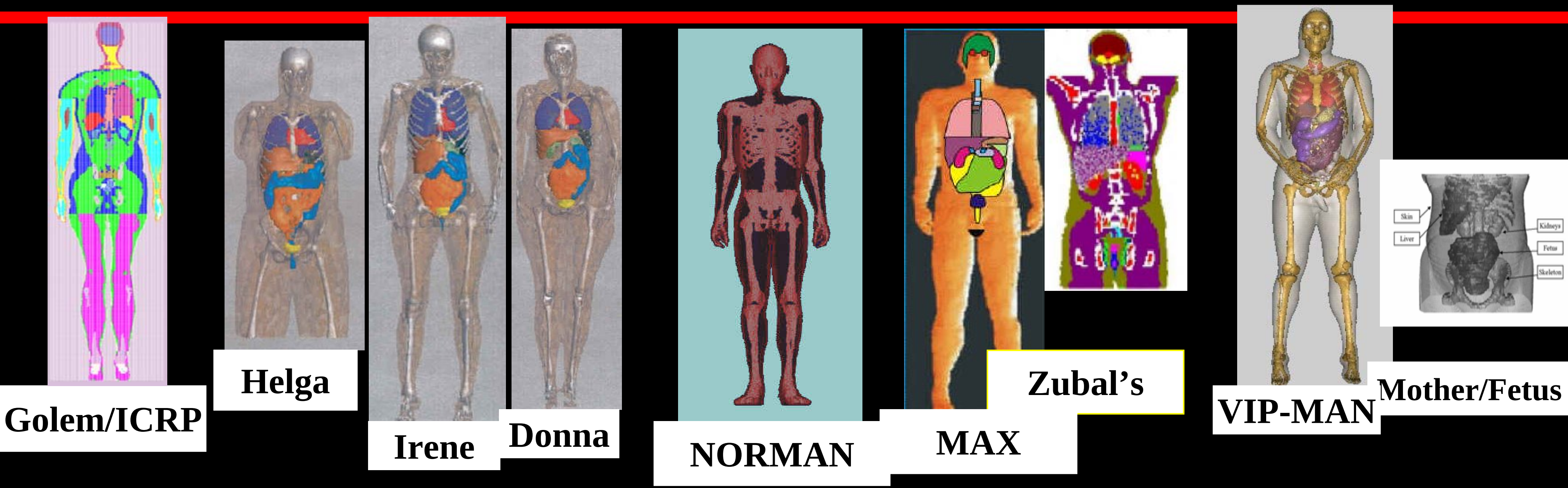


$$S^w(u,v) = \sum_{i=0}^{n}\sum_{j=0}^{m} N_{i,p}(u)N_{j,q}(v)P^w_{i,j}$$

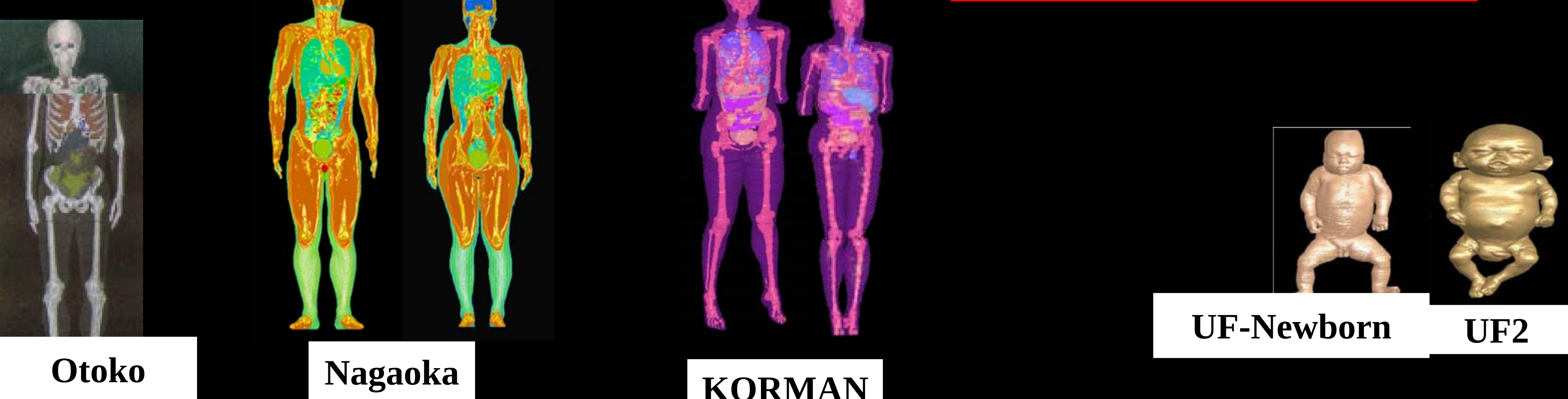


Consortium of Computational Human Phantoms (CCHP)

Samples from different groups from Germany, UK, USA, Japan, Korea and Brazil



www.virtualphantoms.org



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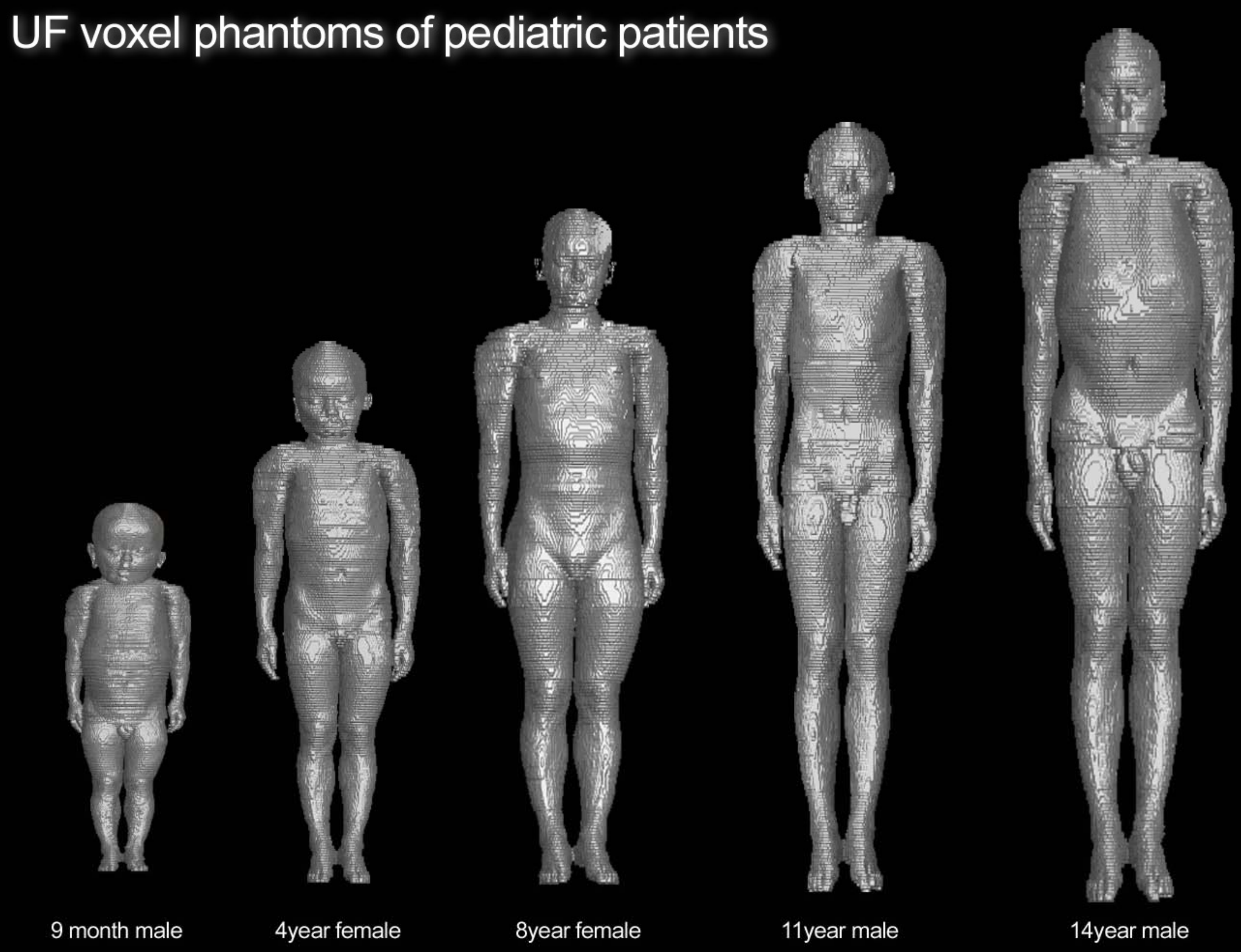
Computational Phantoms for Younger Patients



Courtesy of Dr. Wesley Bolch of University of Florida via joint R01 project National Cancer Institute (R01CA116743)

Founding members of The Consortium of Computational Human Phantoms (CCHP):

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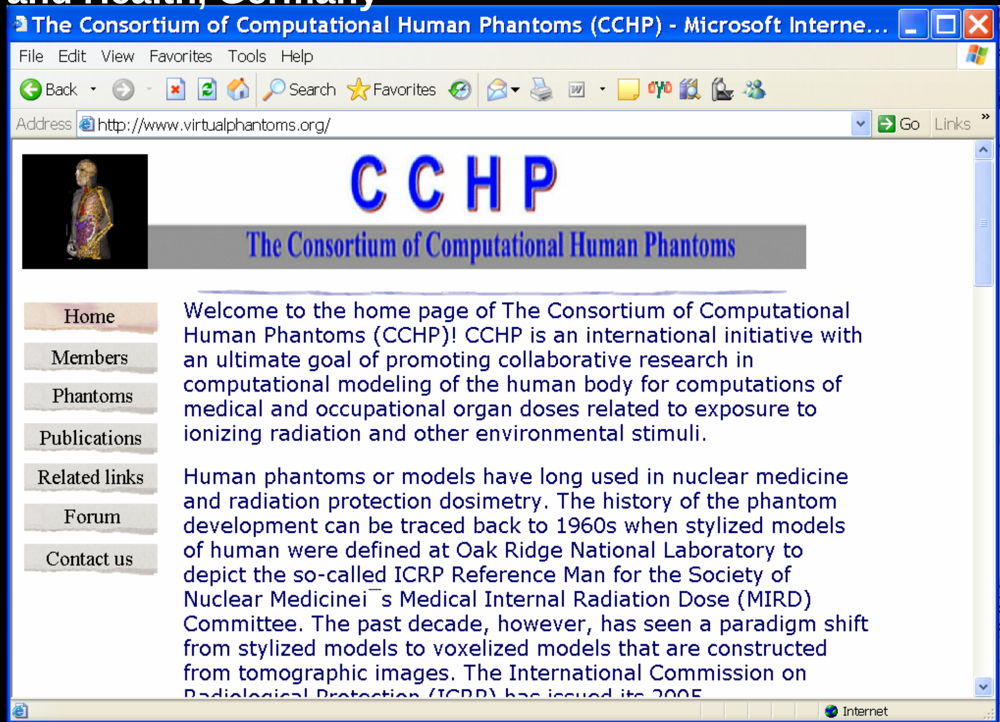
Wesley E. Bolch, University of Florida, USA
Loic de Carlan, IRSN -Institute of Nuclear Safety and Radiation Protection, France
Martin Caon, Flinders University, Australia
Keith F. Eckerman, Oak Ridge National Laboratory, USA
Rickard Kramer, Federal University of Pernambuco, Brazil
Choonsik Lee, Hanyang University, Korea
Tomoaki Nagaoka, Kitasato University Graduate School of Medical Sciences, Japan
Lawrence S. Pinsky, University of Houston, USA
Kimiaki Saito, Japan Atomic Energy Research Institute, Japan
William Segars, Johns Hopkins University, USA
Michael G. Stabin, Vanderbilt University, USA
Maria Zankl, GSF - National Research Center for Environment and Health, Germany
George Zubal, Yale University, USA

www.virtualphantoms.org



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<<Handbook of Anatomical Models for Radiation Dosimetry>>

(To be published as part of "Series in Medical Physics and Biomedical Engineering")

Edited by

X. George Xu, Ph.D., Rensselaer Polytechnic Institute, Troy, New York, USA

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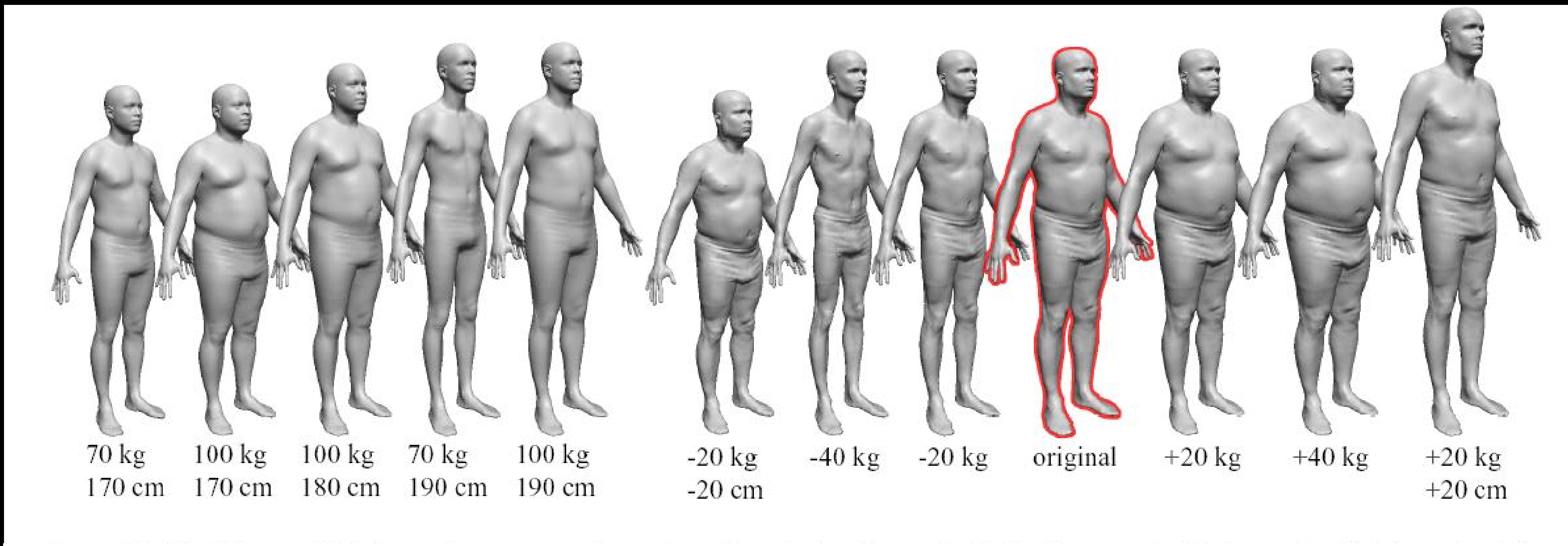
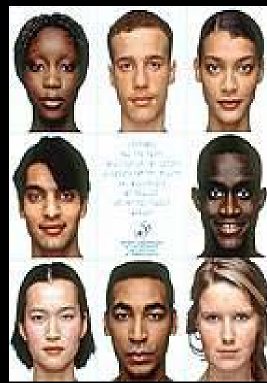
The Journey of Computational Phantoms

- Simple to complex
- Homogeneous to heterogeneous
- Rigid to deformable
- Stationary to moving
- “Reference Man” to “reference library” or “person-specific” (?)

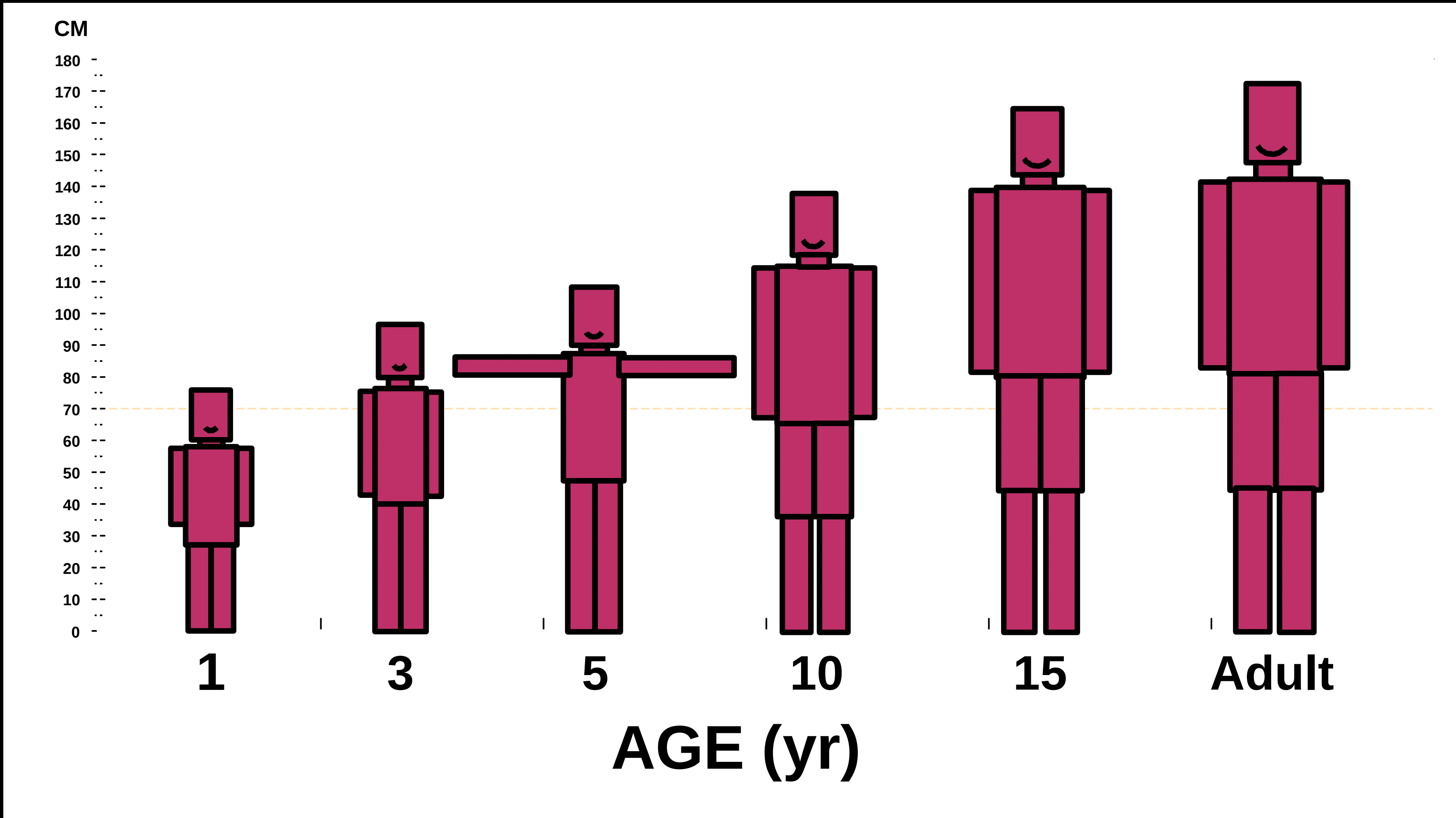


Curtsey of Dr. Q Wang of NIST (JHU Workshop 2006)



Future?

A Paradigm Change from Simplified Models Used To Study Secondary Cancers of Patients for 25 Years

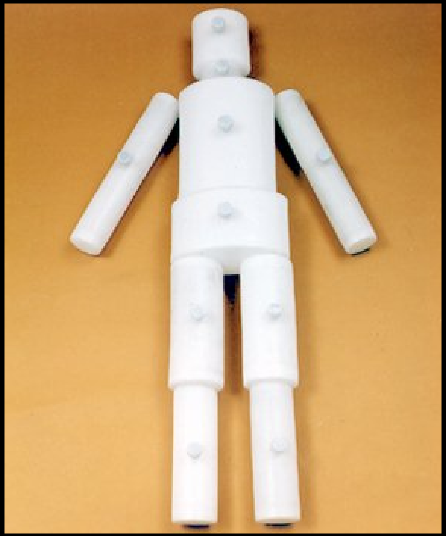


Stovall M, Smith SA and Rosenstein M. Tissue doses from radiotherapy of cancer of the uterine cervix, Medical Physics 16(5): 726-733, 1989.

A Paradigm Change from Simplified Models Used In Bio-assay Phantom Fabrication

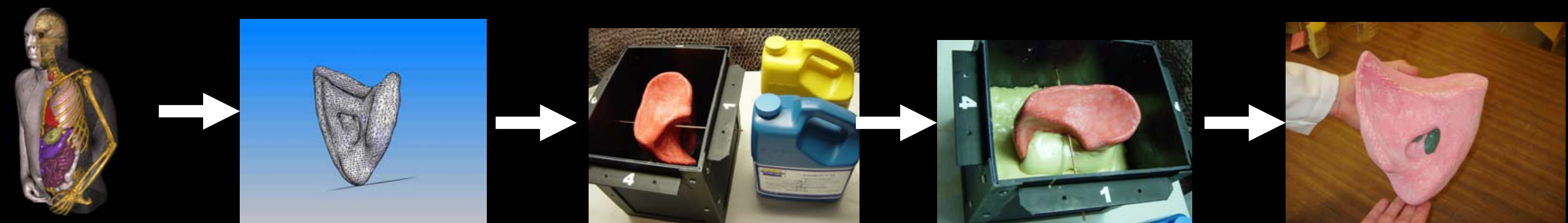
The calibration of whole-body counter relies on a standard phantom called the Bottle Manikin Absorption (BOMAB) phantom

- 10 high-density polyethylene containers representing ICRP 23 Reference Man
- The plastic matrix contains NIST Standard Reference Materials uniformly
- It has been used for over 25 years in the United States.



BOMAB

Rapid-Prototyping for Realistic Phantoms



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Summary

- A paradigm change in "computational phantoms" has occurred

- A number of new phantoms are available to various needs
  – Age- and gender-specific
  – Pregnant females
  – 4D motion simulating phantoms

- International collaboration and standardization are critical

- Future directions
  - Cope with limits on speed and voxel numbers
  – Geometry input (voxel, CAD, etc)
  – Monte Carlo methods for motion-simulations (4D)
  – Patient-specific information
  – Sub-organ, cellular/molecular, biological simulations

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