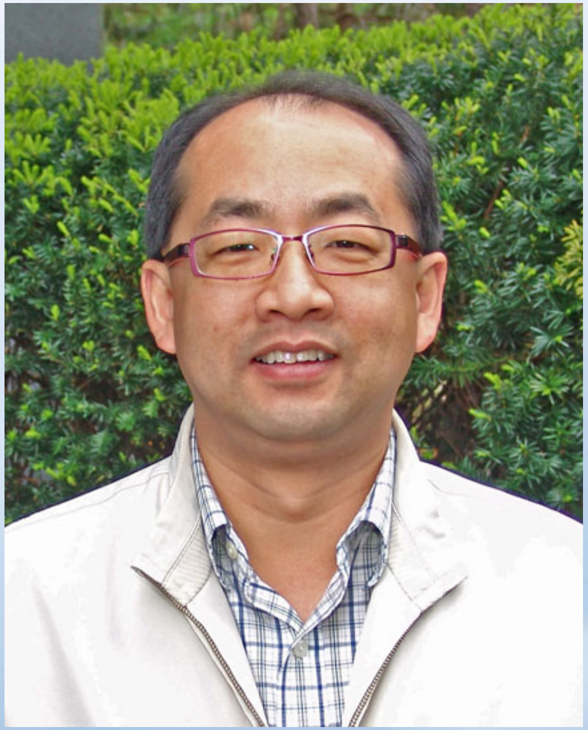
Choonsik Lee, Ph.D.
Investigator, DCEG

Dosimetry Tools for Medical Radiation Studies



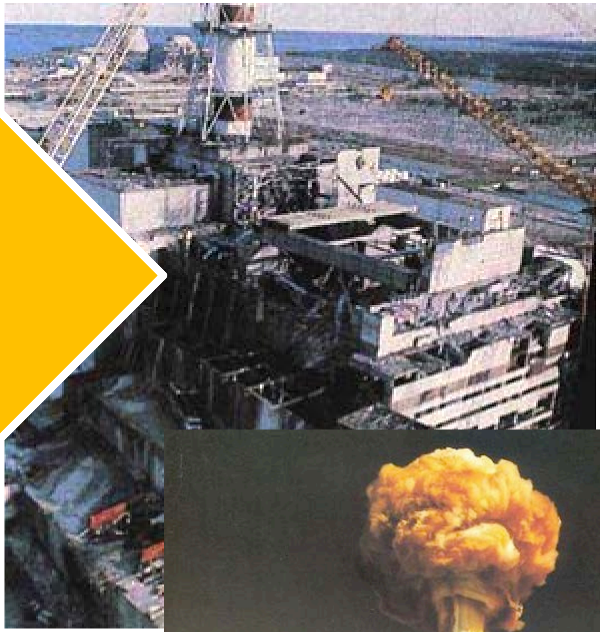
Radiation Epidemiology & Dosimetry Course

National Cancer Institute www.dceg.cancer.gov/RadEpiCourse

Content

- **Background**
- Computational phantoms
- Monte Carlo radiation transport
- Diagnostic radiation dosimetry tools
- Therapeutic radiation dosimetry tools

Organ dose estimation for medical exposure



- Planned and controlled
- Relatively well documented

Dosimetric quantities*

Kinetic energy deposited in matter

Organ Absorbed Dose (Gy) → w_R (Radiation Weighting Factor) → Equivalent Dose (Sv) → w_T (Tissue Weighting Factor) → Effective Dose (Sv)

Organ Absorbed Dose (Gy) ↔ Kerma (Gy)

$$H_T = \sum_R w_R D_{T,R}$$

$$E = \sum_T w_T \left[\frac{H_T^M + H_T^F}{2} \right]$$

Kinetic energy released in matter

* ICRP Publication 103 (2007)

Radiation weighting factor*

Table 2. Recommended radiation weighting factors.

Radiation type	**Radiation weighting factor, w_R**
Photons	1
Electrons[a] and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy (see Fig. 1 and Eq. 4.3)

$$w_R = \begin{cases} 2.5 + 18.2\, e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0\, e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leqslant E_n \leqslant 50 \text{ MeV} \\ 2.5 + 3.25\, e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases}$$

* ICRP Publication 103 (2007)

Tissue weighting factor*

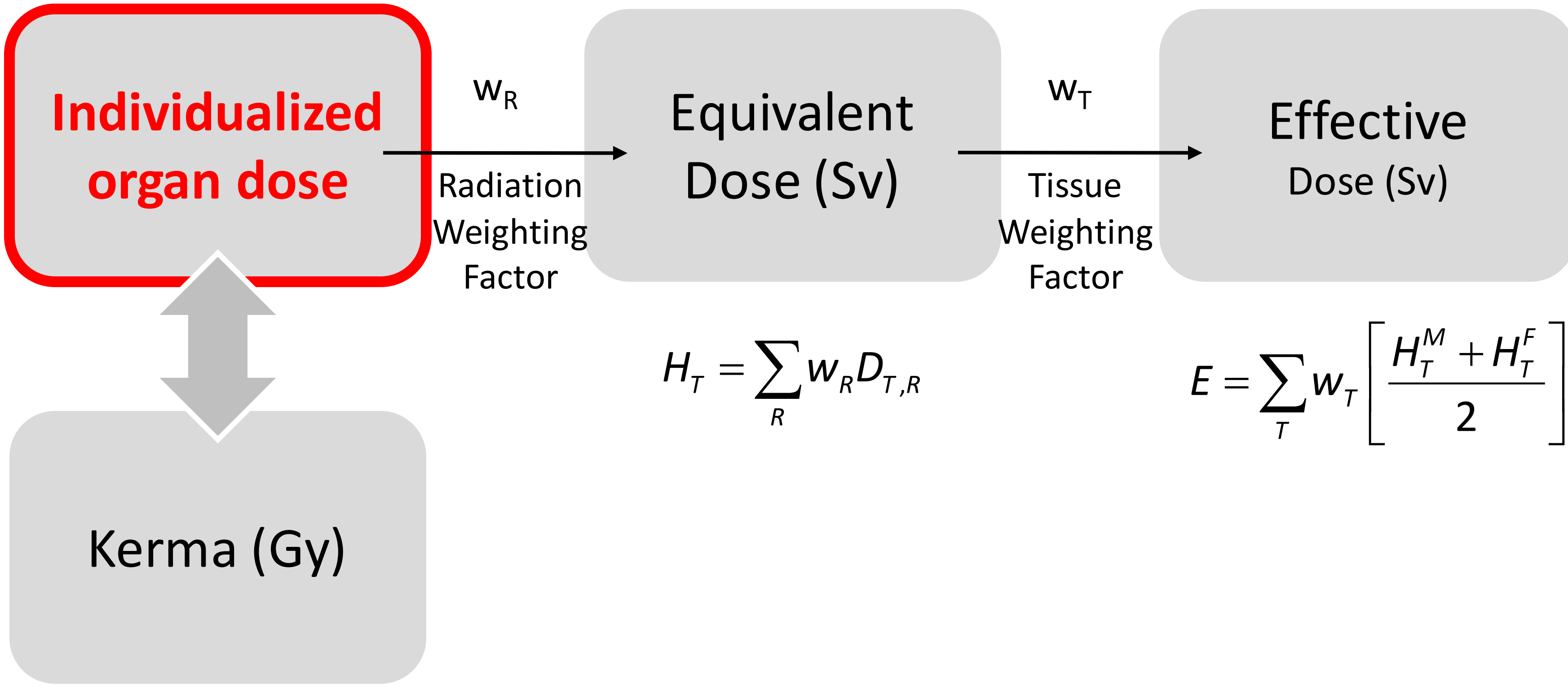
Table 3. Recommended tissue weighting factors.

Tissue	w_T	$\sum w_T$
Bone-marrow (red), Colon, Lung, Stomach, Breast, Remainder tissues*	0.12	0.72
Gonads	0.08	0.08
Bladder, Oesophagus, Liver, Thyroid	0.04	0.16
Bone surface, Brain, Salivary glands, Skin	0.01	0.04
	Total	1.00

* Remainder tissues: Adrenals, Extrathoracic (ET) region, Gall bladder, Heart, Kidneys, Lymphatic nodes, Muscle, Oral mucosa, Pancreas, Prostate (♂), Small intestine, Spleen, Thymus, Uterus/cervix (♀).

* ICRP Publication 103 (2007)

Dosimetric quantities*



Kinetic energy released in matter

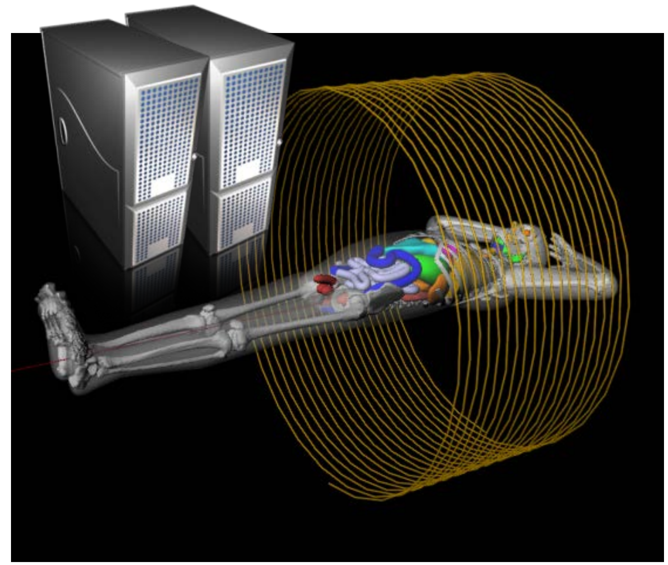
* ICRP Publication 103 (2007)

Two approaches to estimate organ dose

MEASUREMENT

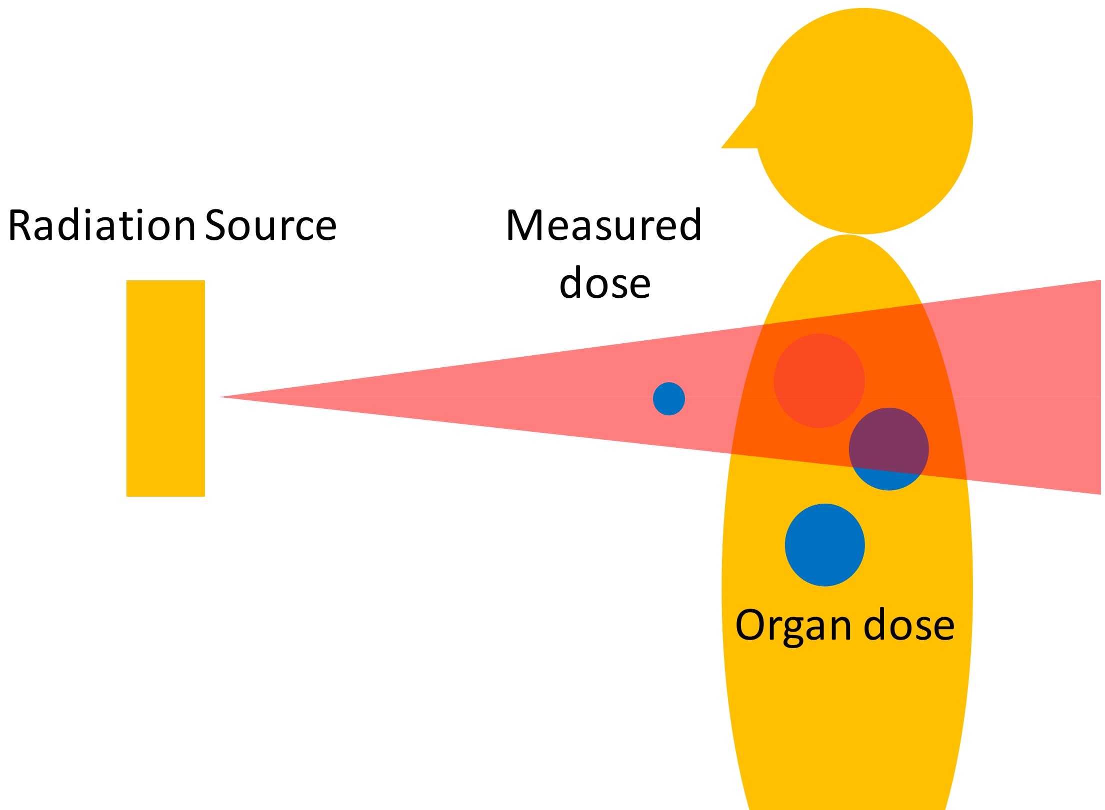
- Expensive
- Substantial person-hour
- Not flexible

CALCULATION



- Cost-effective
- Fewer person-hour
- More flexible

Conversion coefficients



$$\text{Conversion coefficients} = \frac{\text{Organ dose}}{\text{Measured dose}}$$

Measured dose:

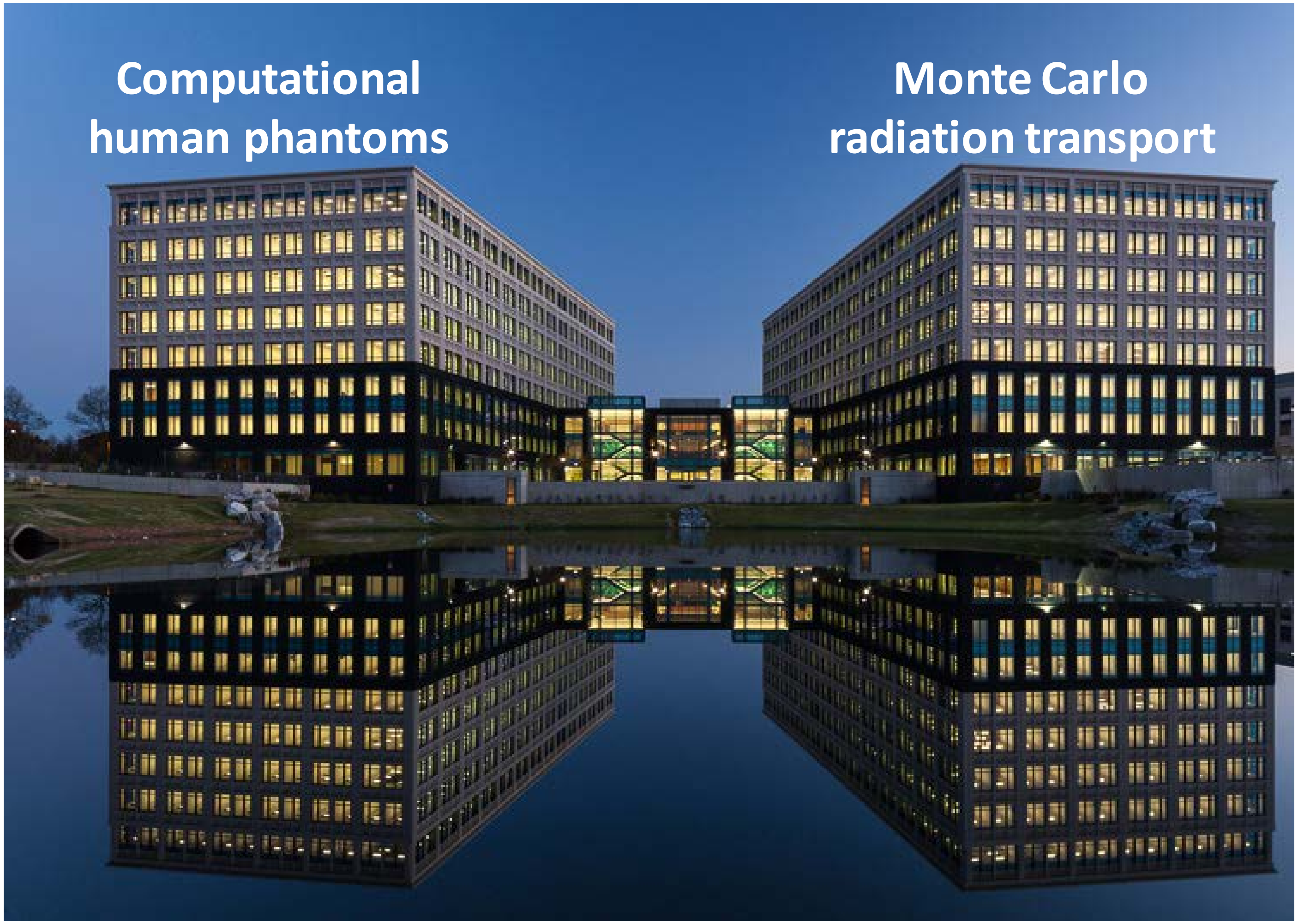
- Air Kerma
- Dose Area Product
- CTDI

Conversion coefficients

- Dependent on
  - Patient characteristics: age, gender, body size
  - Machine settings: beam energy, direction, collimation, and etc.

- Two approaches in dose calculation tools
  - Look-up-table approach: simple geometry (e.g., CT scan)
  - Exposure scenario-specific calculation: complex geometry (e.g., radiography, radiotherapy)

Two components in Medical Dosimetry Tools



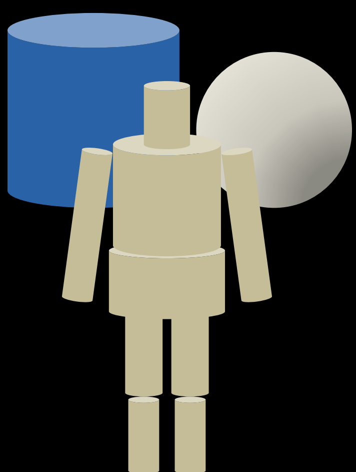
Content

- Background
- **Computational phantoms**
- Monte Carlo radiation transport
- Diagnostic radiation dosimetry tools
- Therapeutic radiation dosimetry tools

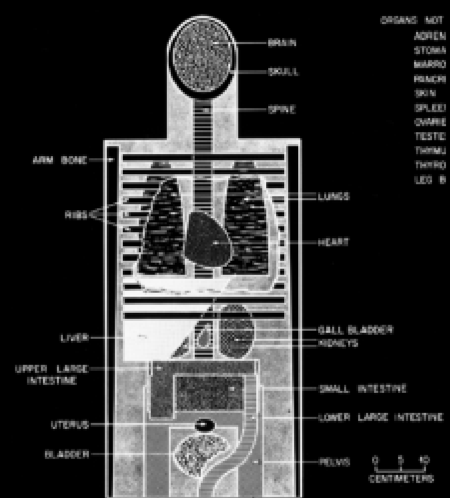
Evolution of Computational Human Phantoms

More accurate anatomy

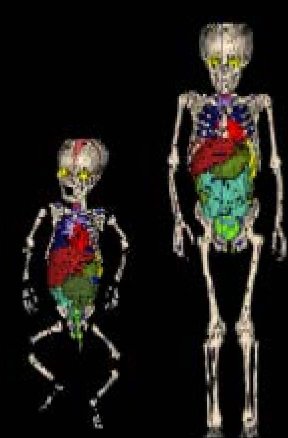
1950s	1960s	1980s	2000s
Simple phantoms	Stylized phantoms	Voxel phantoms	Hybrid phantoms



BOMAB phantom



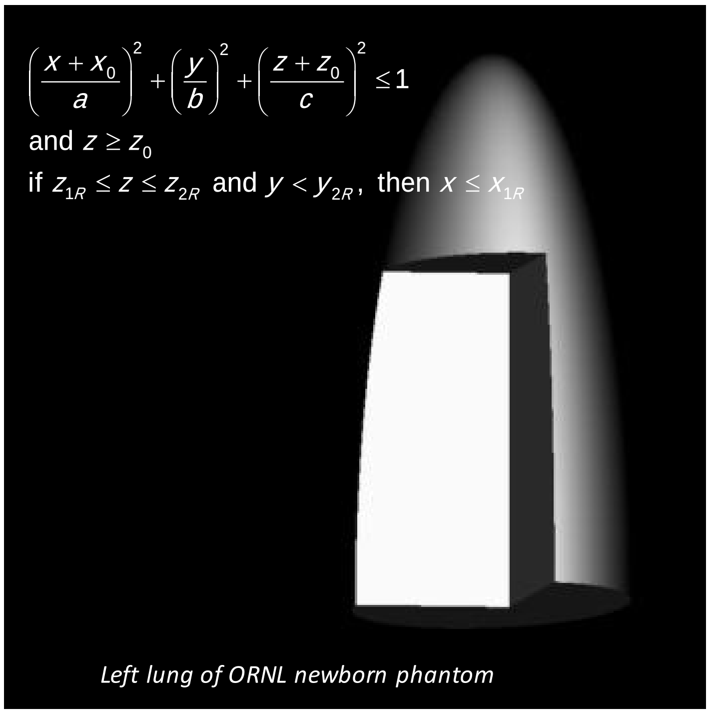
ORNL adult phantom



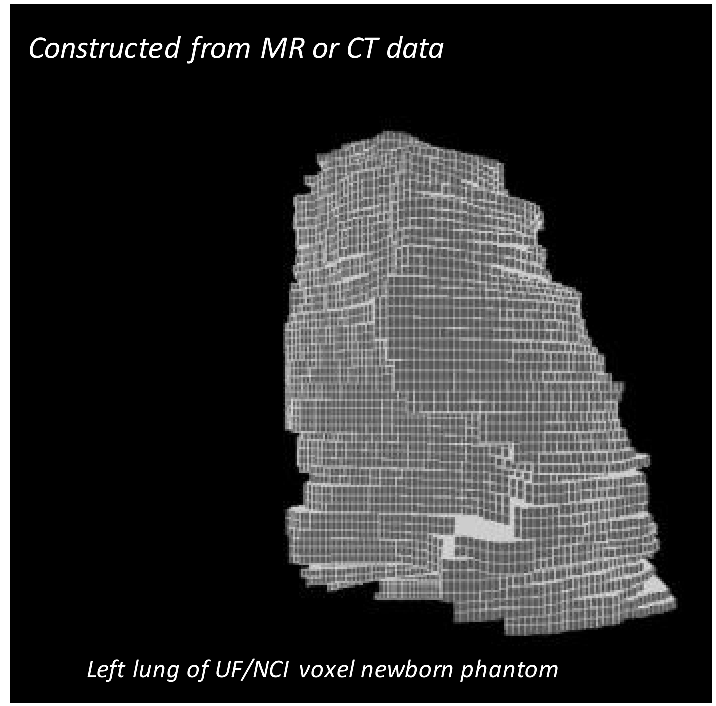
GSF BABY and CHILD voxel phantoms

UF/NCI Hybrid phantoms

First vs. Second generation phantoms

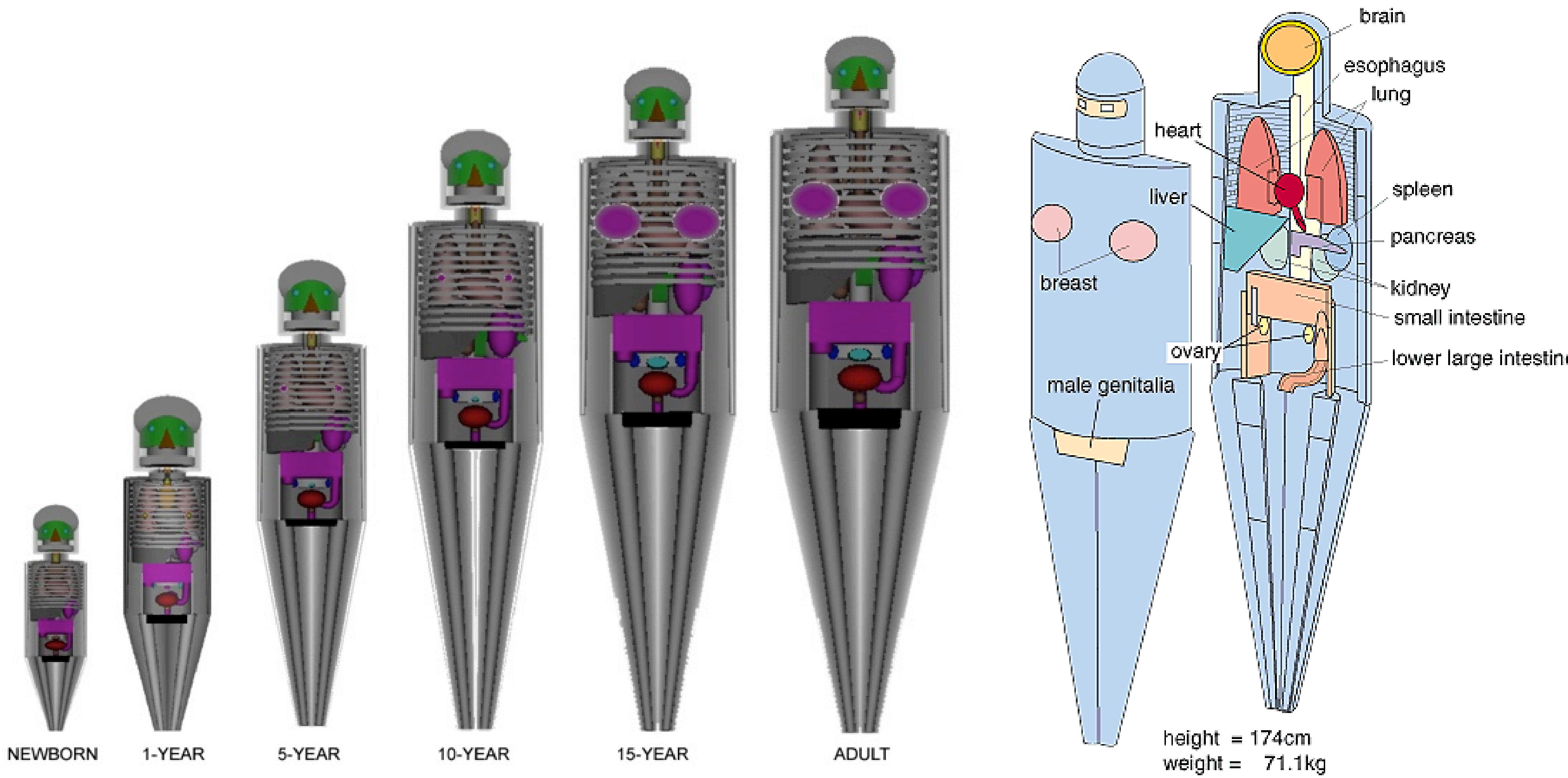


Stylized (mathematical) phantom
Since 1960s



Voxel (tomographic) phantom
Since 1980s

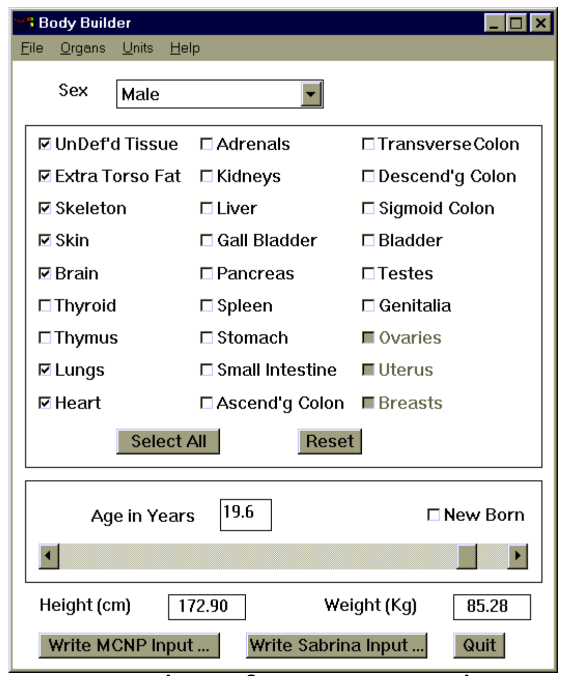
Oak Ridge National Laboratory phantoms*

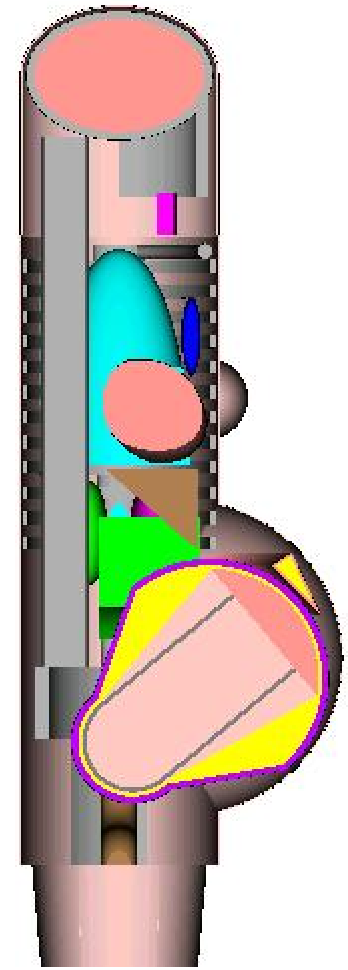


*ORNL/TM 8381 (1987)

Stylized phantom generator

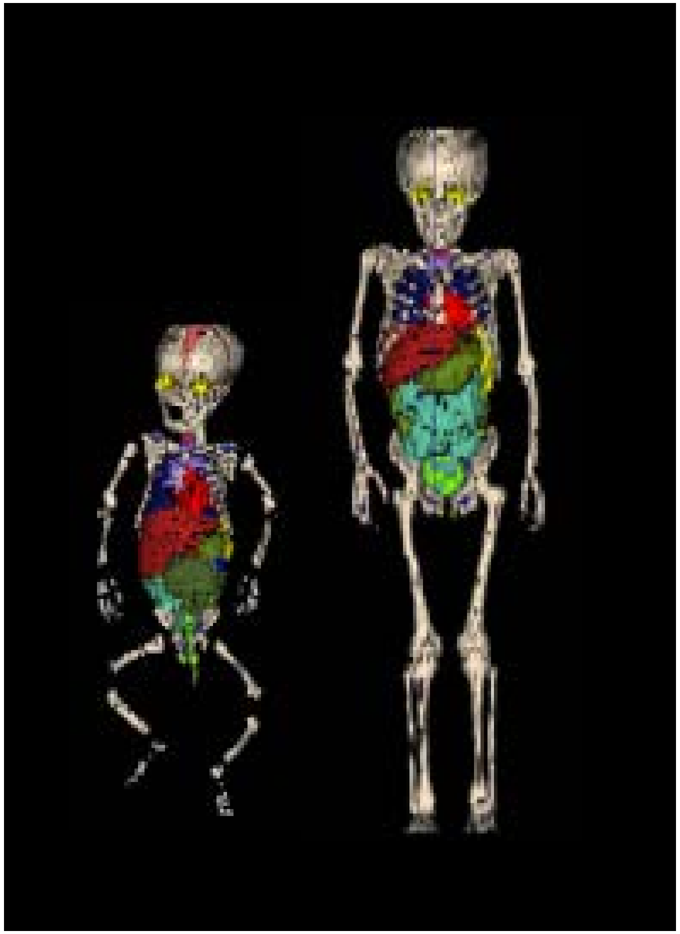
- Body Builder (White Rock Science)
  - Generate human phantoms (stylized)
  - Pregnant female (3, 6, and 9 months)
  - Gender-specific phantoms





Graphics from www.whiterockscience.com

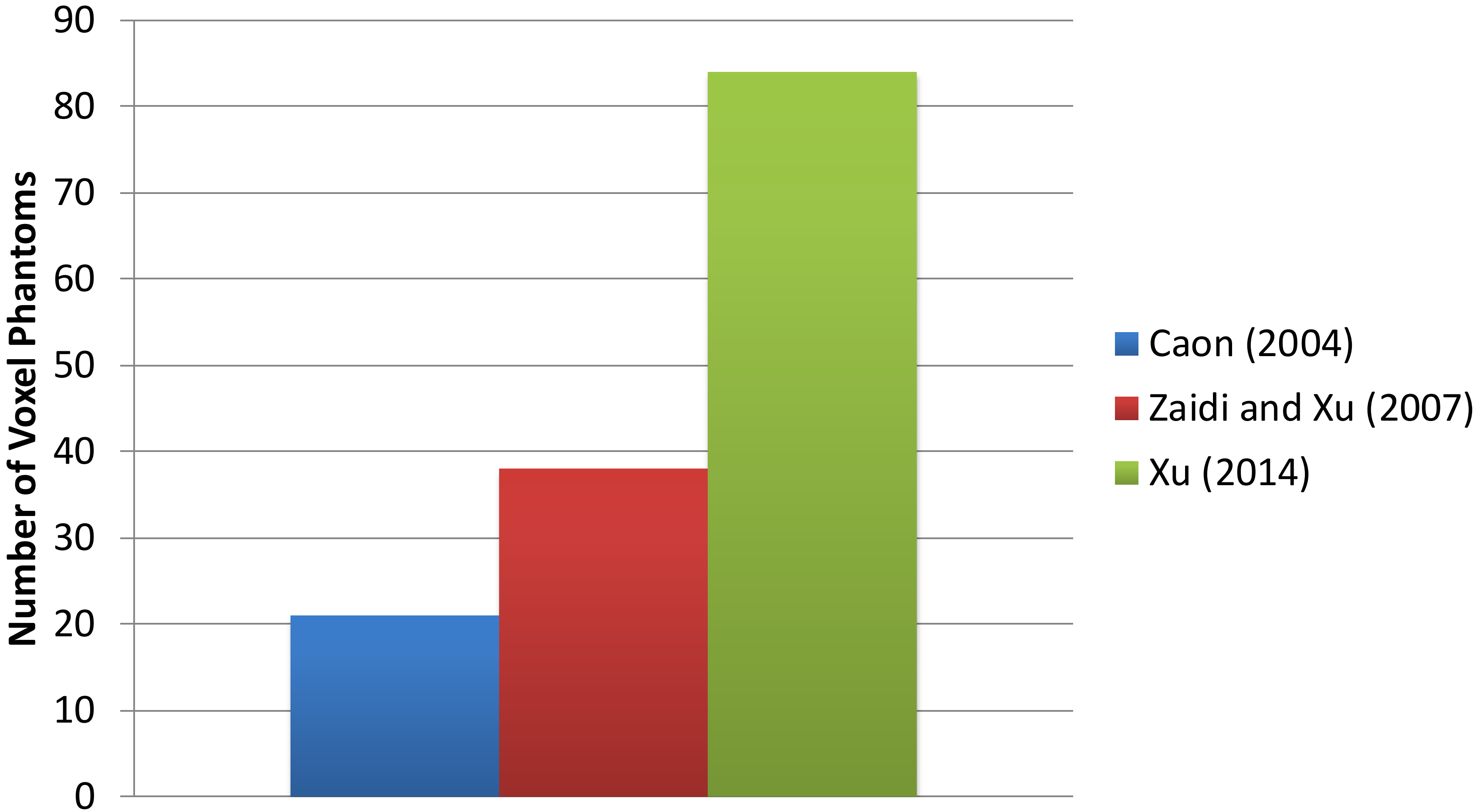
World-First Voxel Phantoms*



2-month BABY (left) and 7-year CHILD (right) pediatric voxel phantoms

*Zankl et al. Radiation Environment & Biophysics (1988)

Status of Voxel Phantoms*

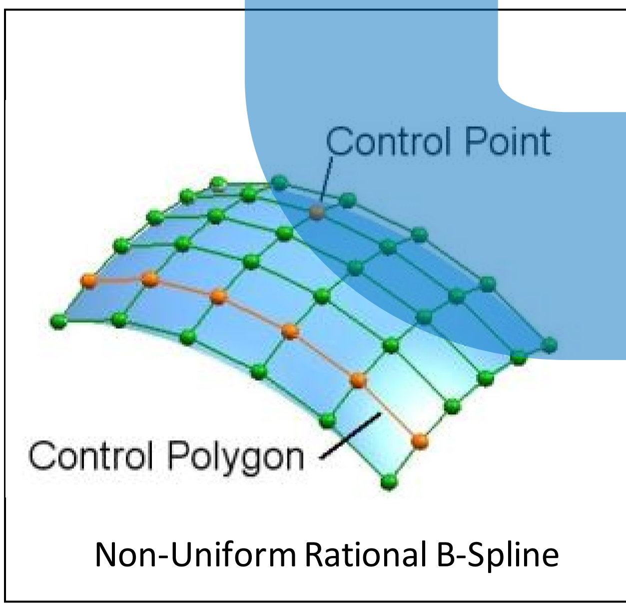


*Xu Physics in Medicine and Biology 2014

Third generation phantoms: Hybrid approach*

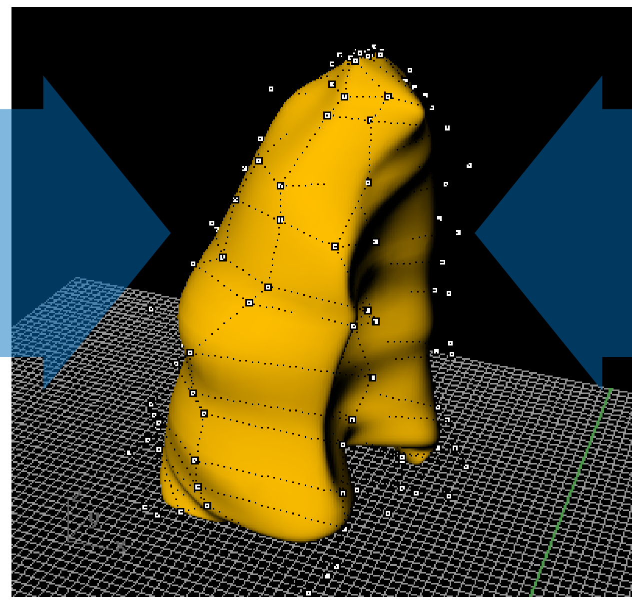
Stylized phantom

Mathematical Flexibility
(NURBS surface)



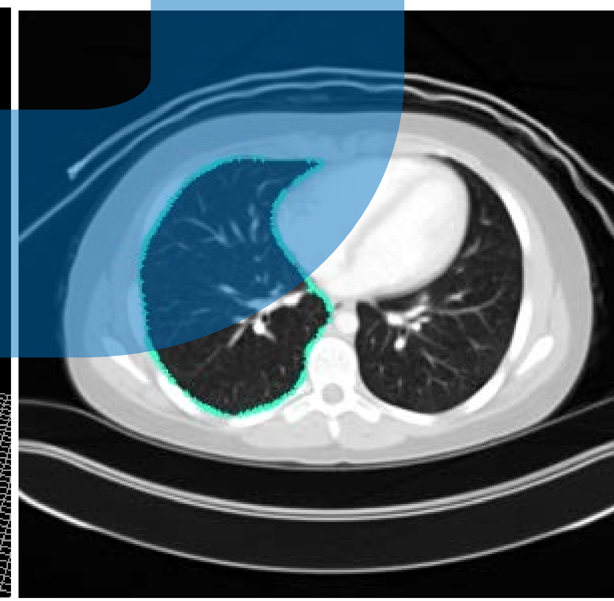
Non-Uniform Rational B-Spline

Hybrid**



Voxel phantom

Anatomical Realism
(CT images of patient)

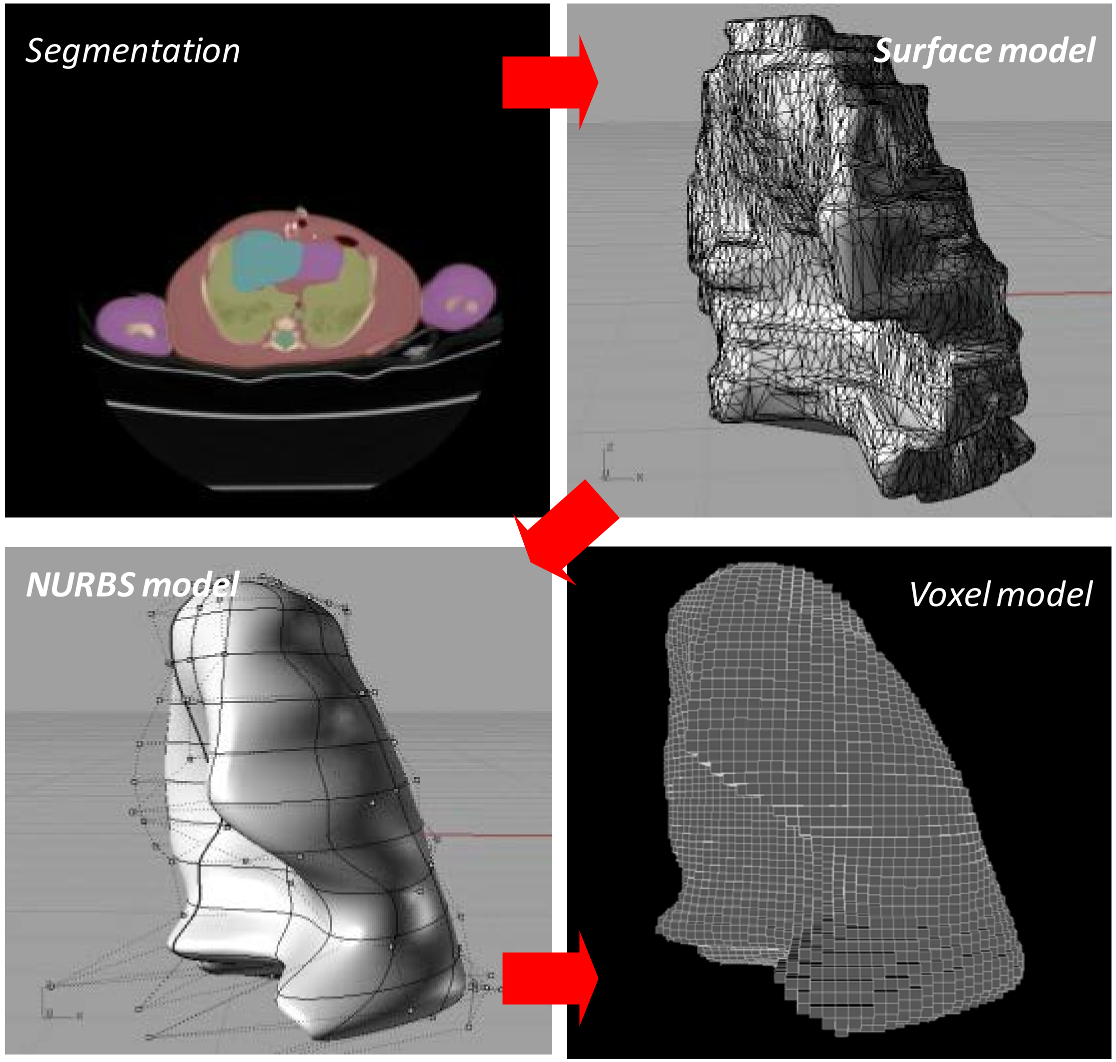


*Segars et al. Nuclear Science 2001, Lee et al. Radiation Protection Dosimetry 2007
**Also known as Boundary Representation (BREP)

Procedure to develop hybrid phantom

Contour organs from CT images of real patients

Build surface models from organ contours



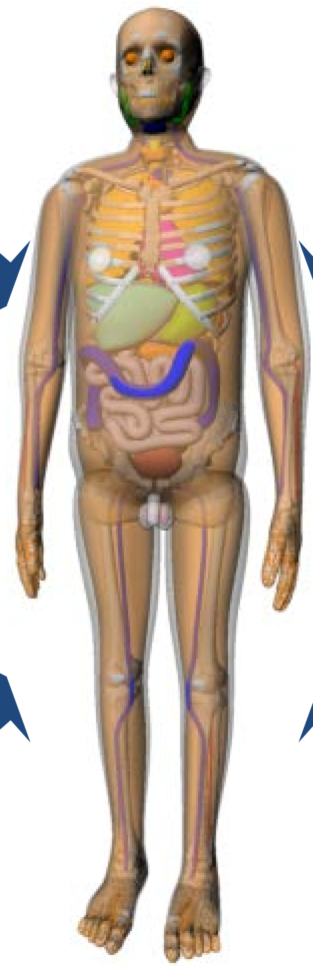
Smoother and more flexible than surface models

Convert to voxel models for Monte Carlo calculations

Reference data incorporated

Reference organ volume
(ICRP Publication 89)

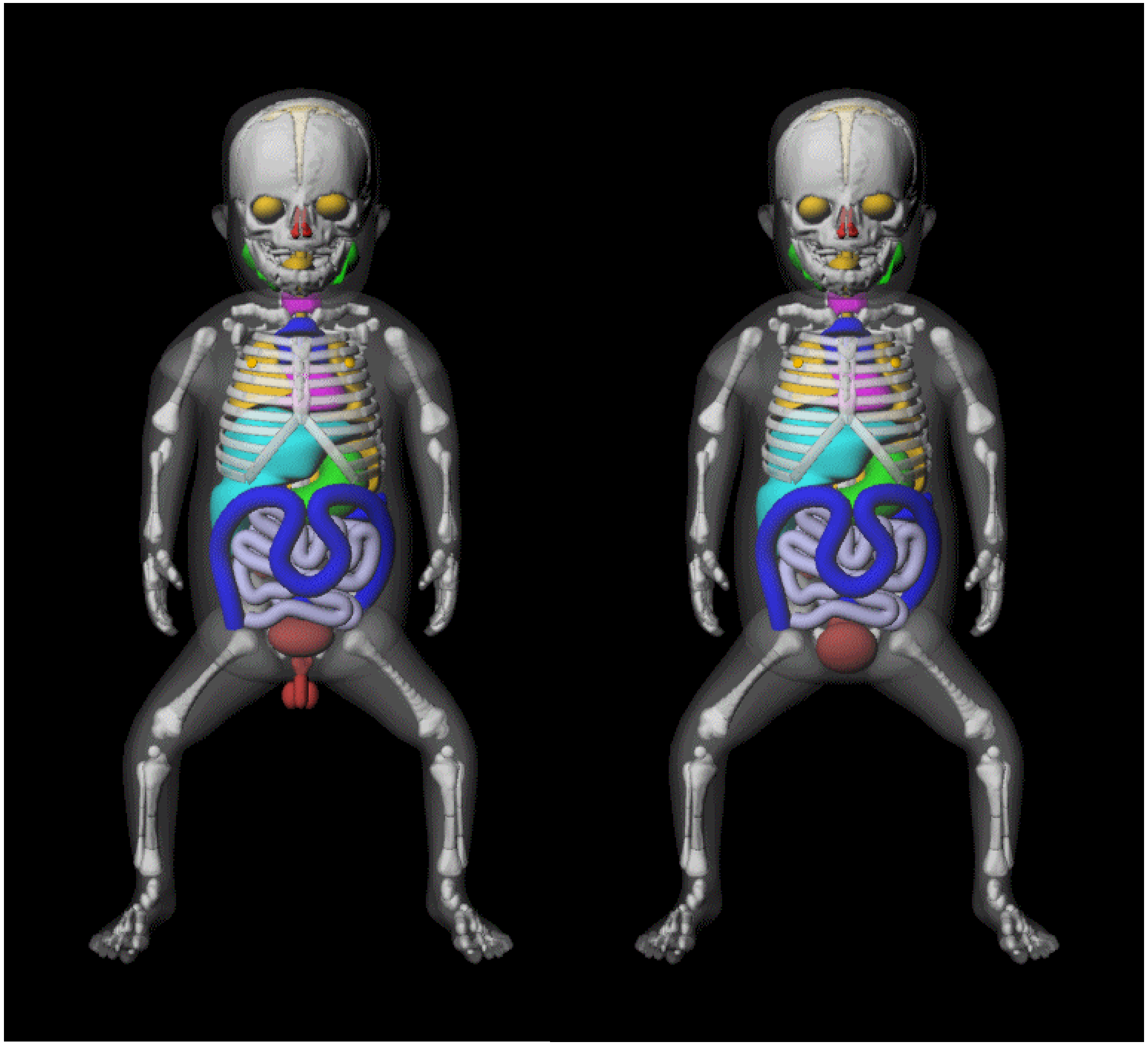
Reference organ composition
(ICRU Report 46 & ICRP Publication 89)



Reference gastro-intestine
(ICRP Publication 100)

Reference anthropometry
(CDC NHANES data)

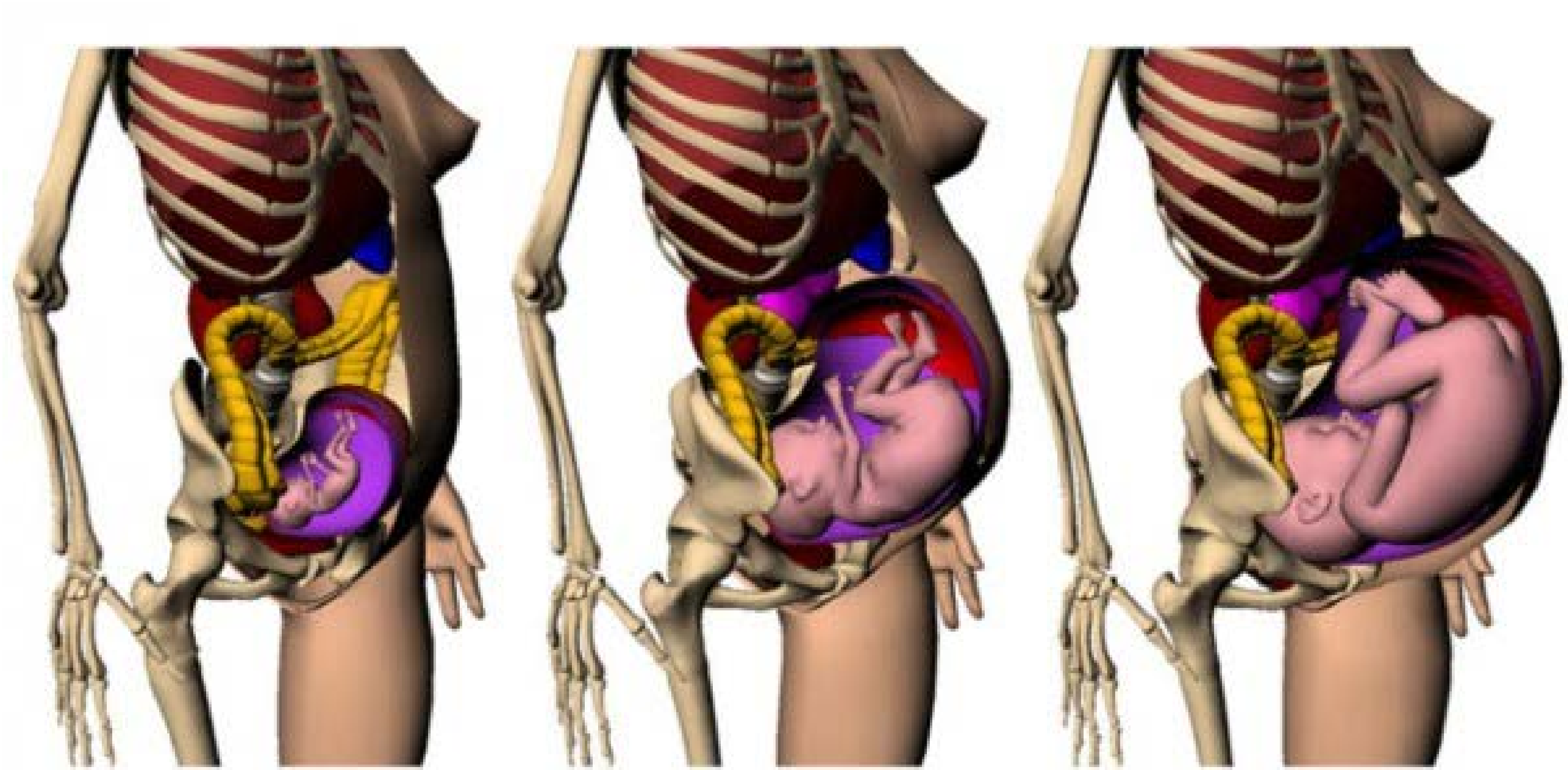
World-first newborn hybrid phantom*



UF/NCI hybrid male (left) and female (right) newborn phantoms

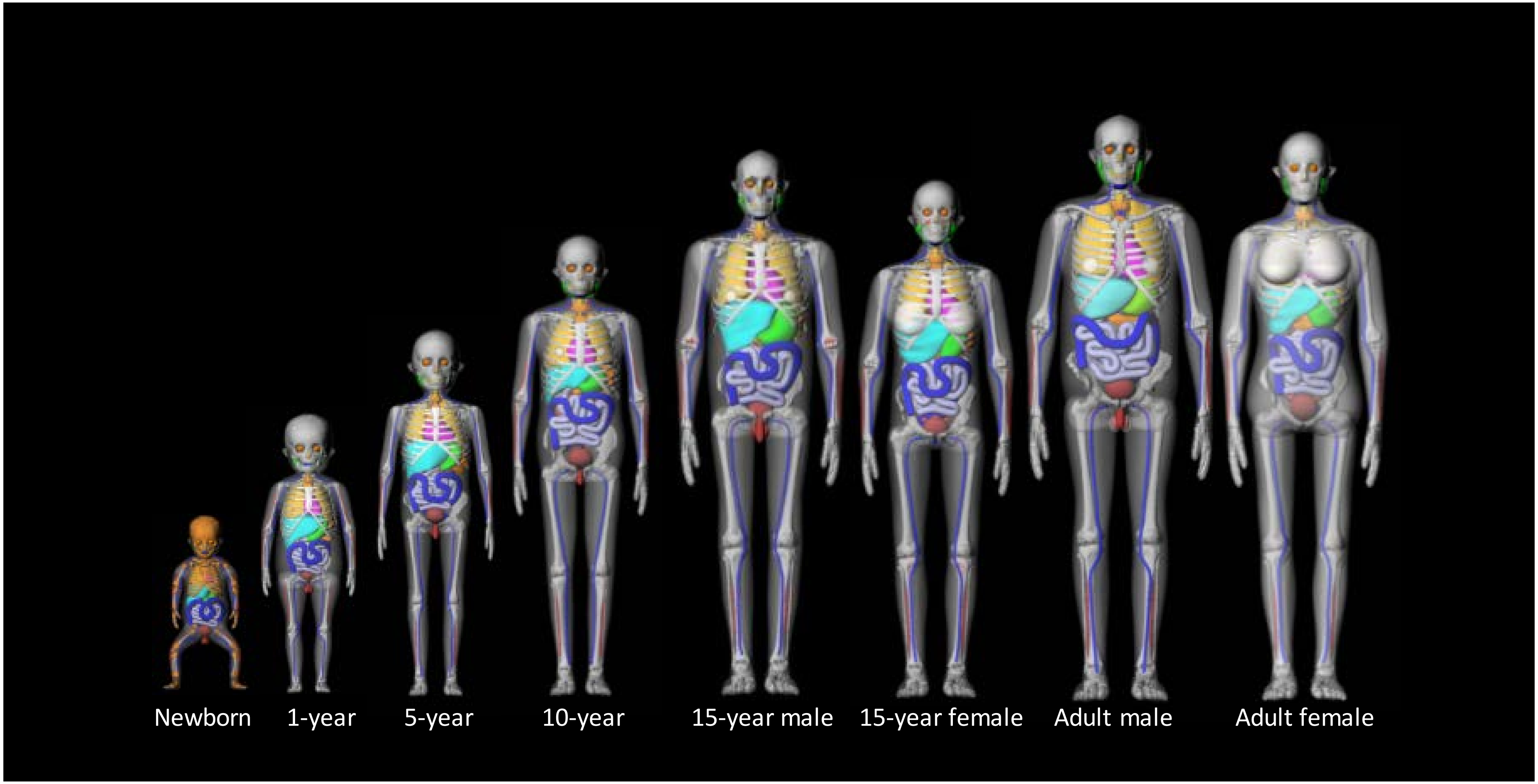
*Lee et al. PMB 2007

Pregnant Phantom Series*



*Xu et al. PMB 2007

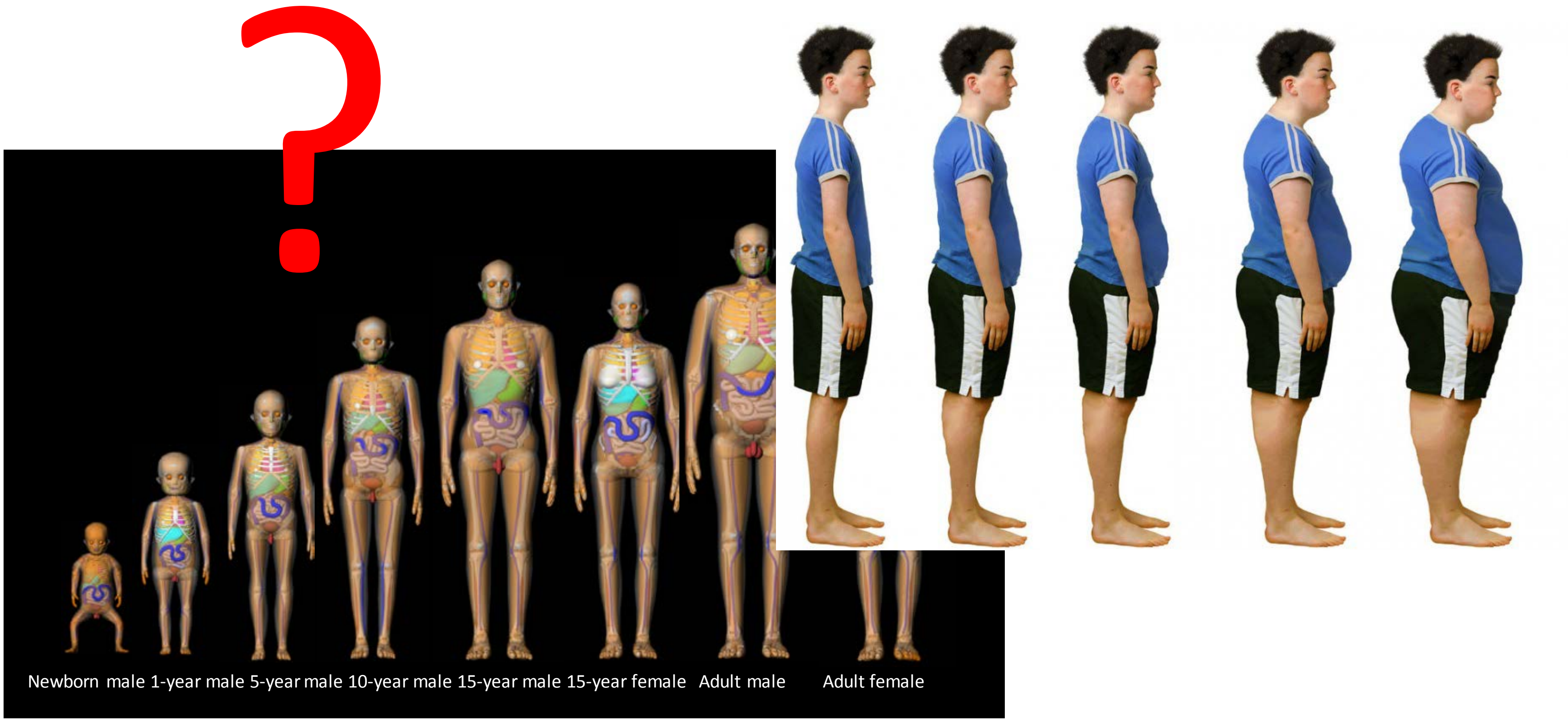
A series of Hybrid Phantoms (2006-2013)



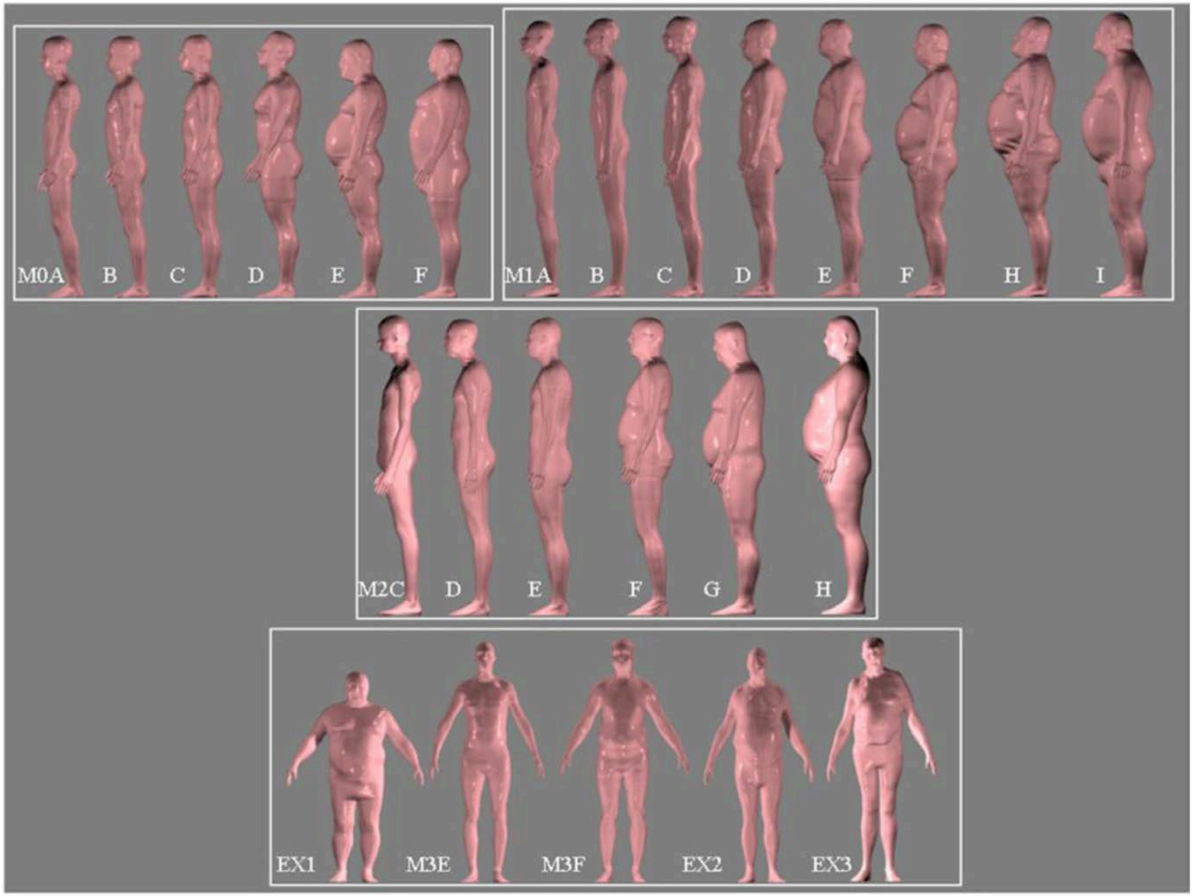
* Lee et al, PMB 2007, MP 2008, PMB 2010

Body size-specific phantoms

- Body size significantly varies among patients at the same age
- Radiation dose depends on body size



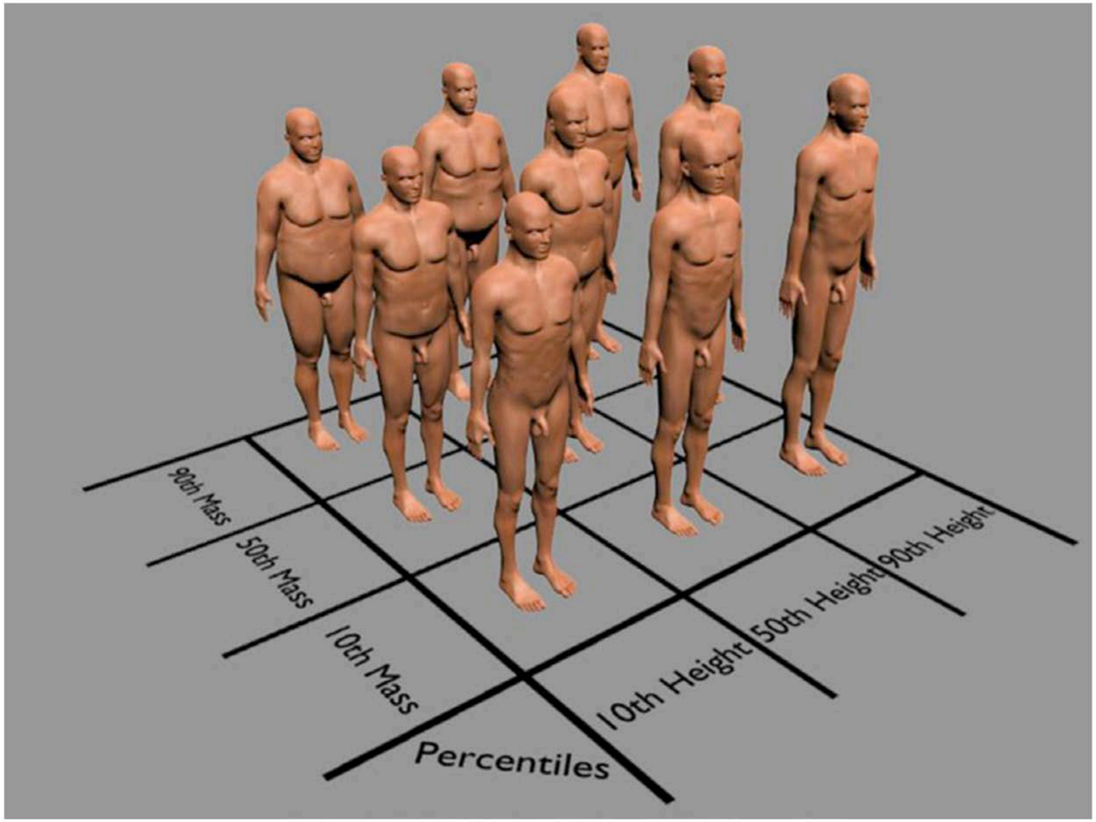
Body size-specific phantoms



Library of **adult male/female** phantoms with different BMI

*Broggio et al. PMB 2011

Body size-specific phantoms



Extension of MASH and FASH **adult male/female** phantoms

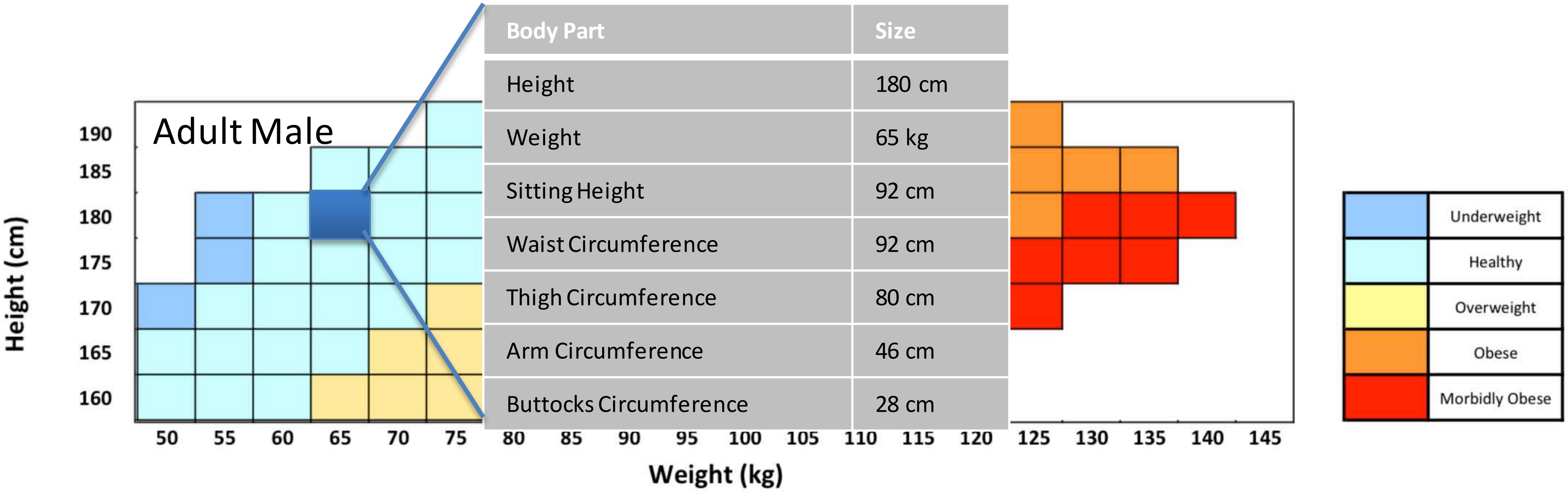
*Cassola et al. PMB 2011

Body size-specific phantoms

Extension of RPI **adult male/female** phantoms

*Ding et al. PMB 2012

UF/NCI Phantom Library*

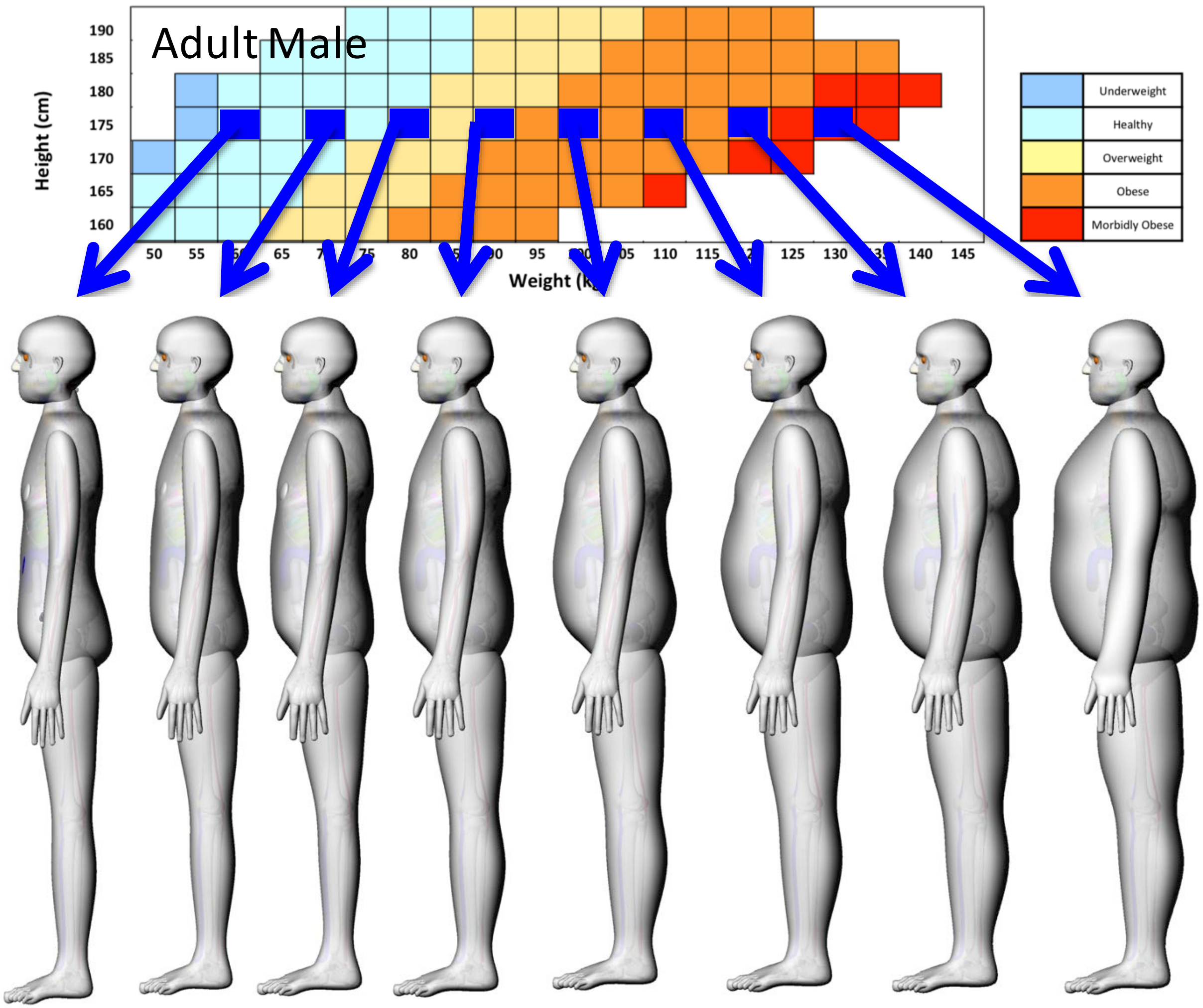


Body Part	Size
Height	180 cm
Weight	65 kg
Sitting Height	92 cm
Waist Circumference	92 cm
Thigh Circumference	80 cm
Arm Circumference	46 cm
Buttocks Circumference	28 cm

- BMI distribution grid developed from US CDC survey data
- Seven different body dimensions assigned to each cell
- Body size-dependent phantoms developed by deforming the reference phantoms

*Geyer et al. PMB 2014

UF/NCI Phantom Library*

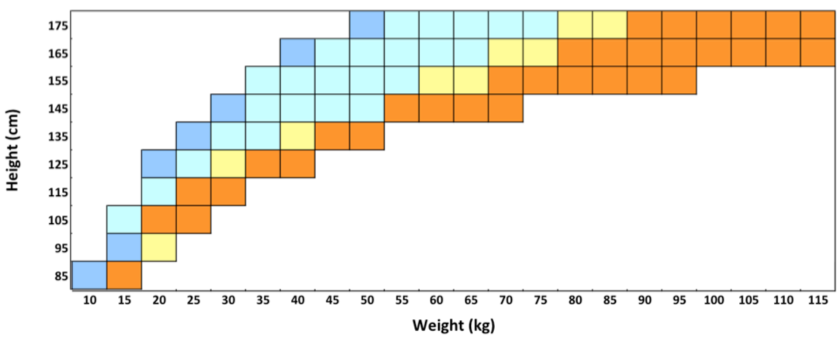


A series of the adult male phantoms at 175 cm high and different weights, 60 – 130 kg

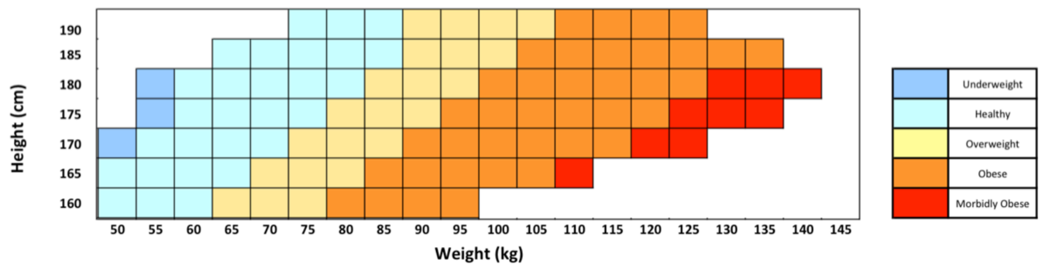
*Geyer et al. PMB 2014

UF/NCI Phantom Library*

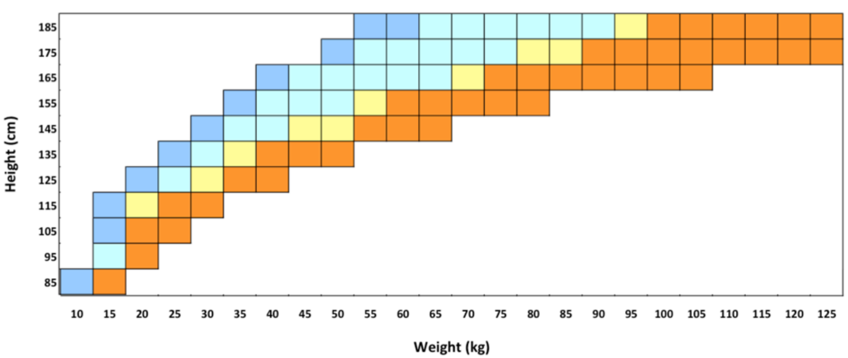
Pediatric Female



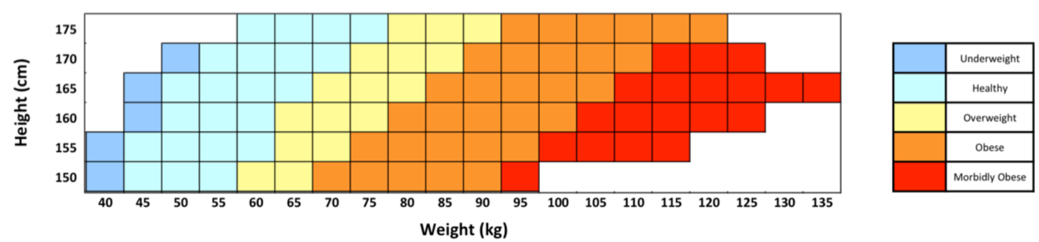
Adult Female



Pediatric Male

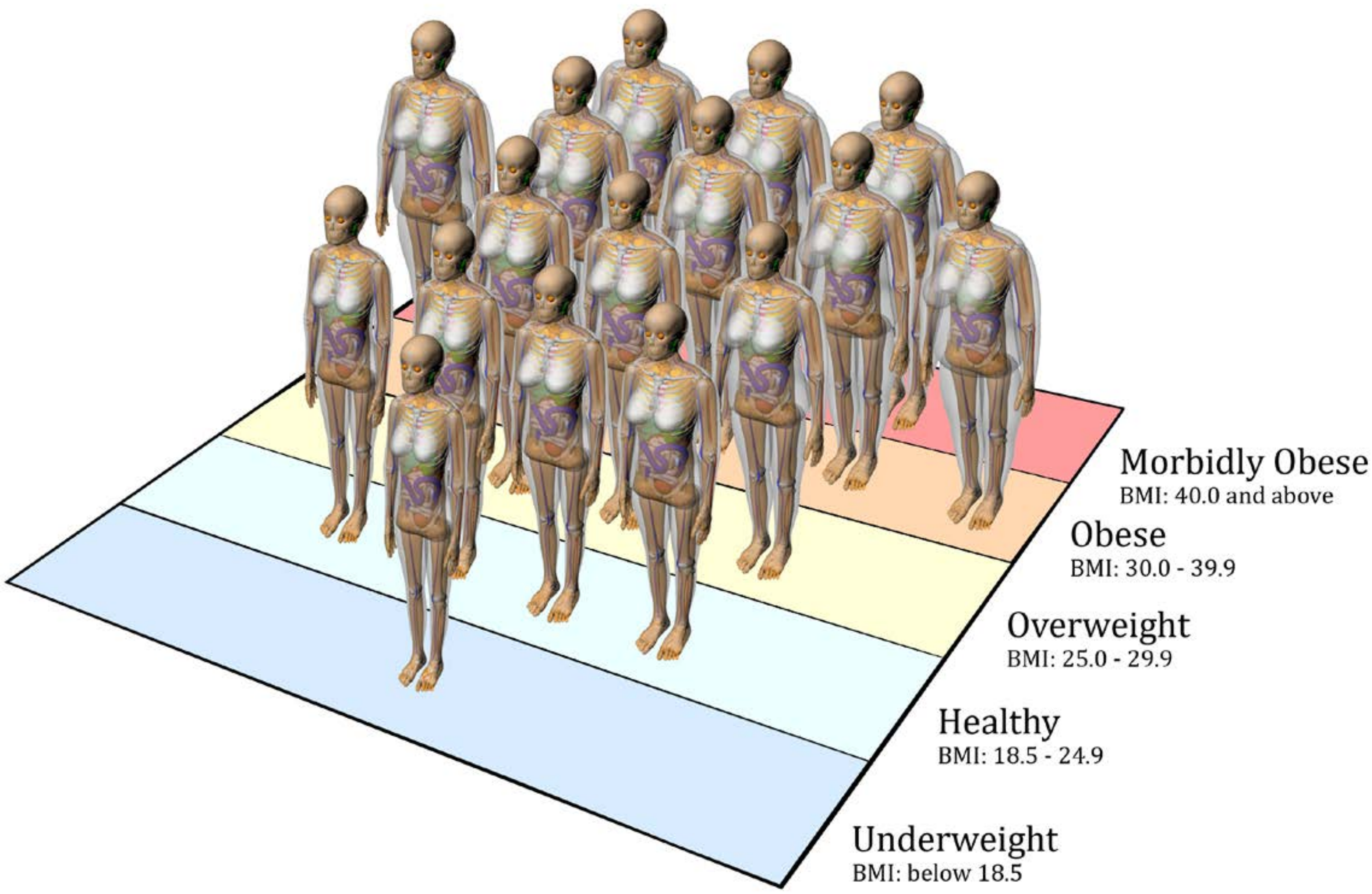


Adult Male



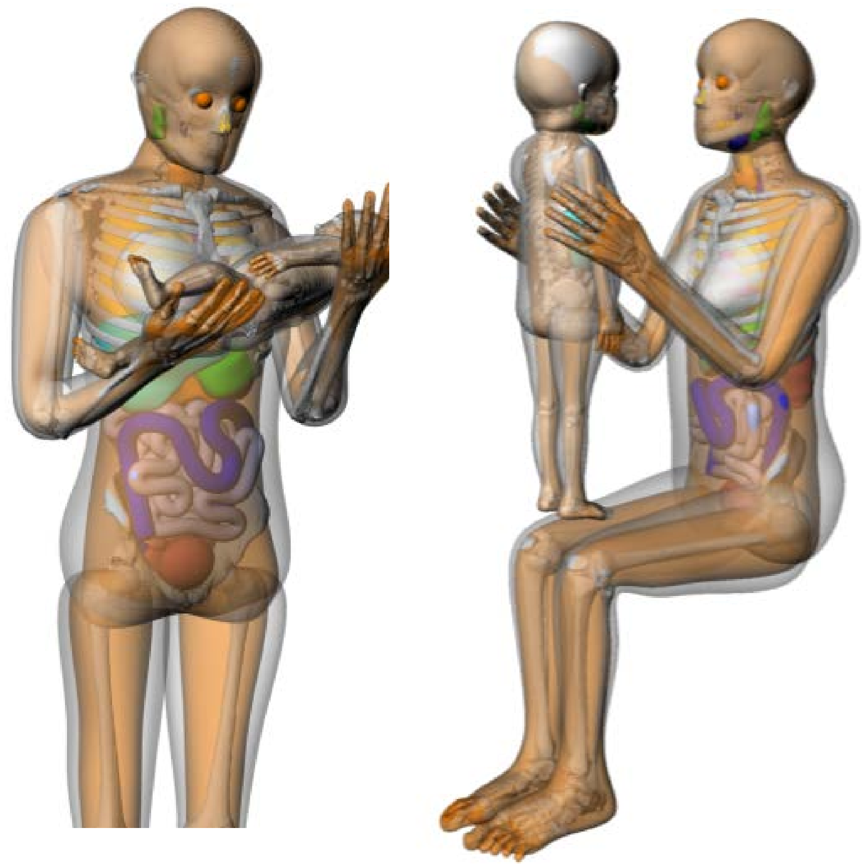
*Geyer et al. PMB 2014

UF/NCI Phantom Library: 351 phantoms



*Geyer et al. PMB 2014

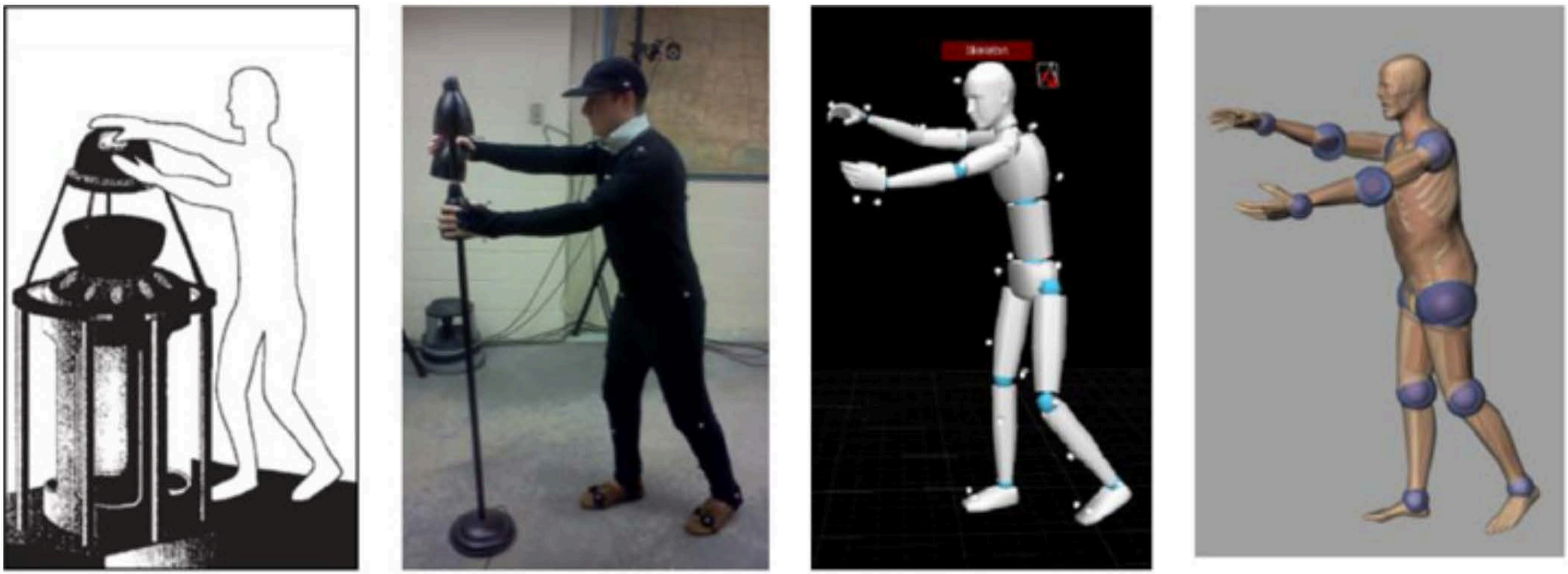
Phantoms in different postures



Patient and baby phantoms used in the study of release criteria for patients treated by I-131*

*Han et al. MP 2013

Phantoms in different postures



Body posture-specific phantom developed from motion capture technology

*Vazquez et al. PMB 2014

ICRP Reference Adult Phantoms*

- Developed from Golem (male) and Laura (female) adult phantoms.
- ICRP Committee II Task Group DOCAL**
- External dose conversion coefficients (ICRP 116)
- Internal dose coefficients (ICRP 1XX, coming soon)

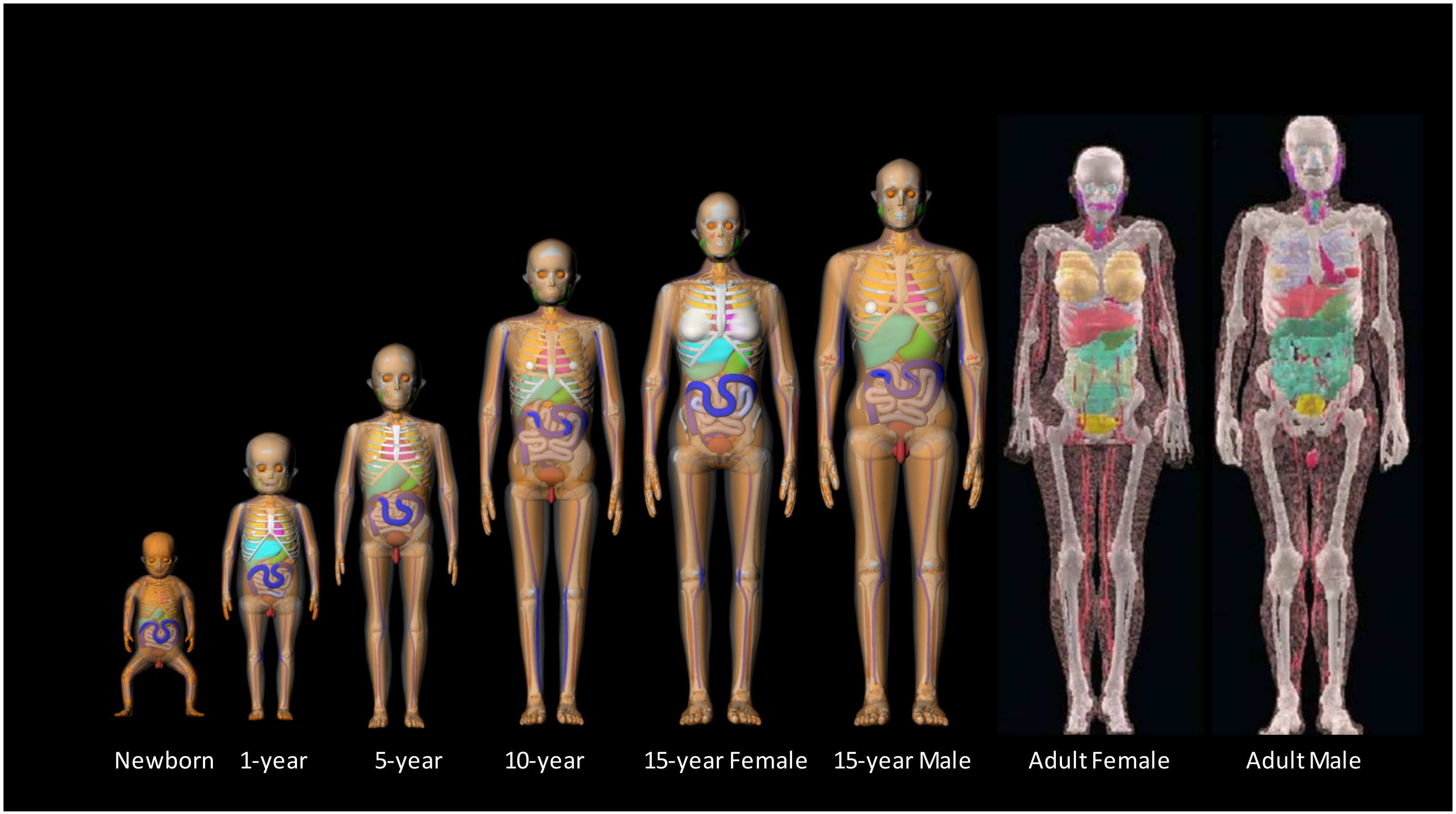
*ICRP Publication 110 (2009)
**DOCAL: Dose Calculation

ICRP Reference Pediatric Phantoms

- ICRP Committee II Task Group CPRT*
- Adopt UF/NCI pediatric phantoms as a template
- Additional modeling
  - Oral mucosa, lips and cheeks
  - Breast: glandular + adipose
  - Lung blood
  - Ureters
  - Lymphatic nodes
  - Muscle model

*CPRT: Computational Phantom and Radiation Transport

ICRP Reference Pediatric and Adult Phantoms



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

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Received , revised
Accepted for publication 7 July 2014
Published 21 August 2014

Abstract

Radiation dose calculation using models of the human anatomy has been a subject of great interest to radiation protection, medical imaging, and radiotherapy. However, early pioneers of this field did not foresee the exponential growth of research activity as observed today. This review article walks the reader through the history of the research and development in this field of study which started some 50 years ago. This review identifies a clear progression of computational phantom complexity which can be denoted by three distinct generations. The

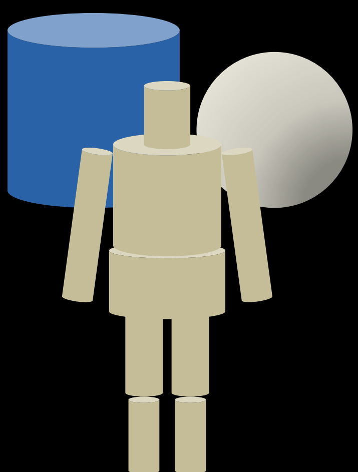
Use phantoms depending on your need

1950s
Simple phantoms

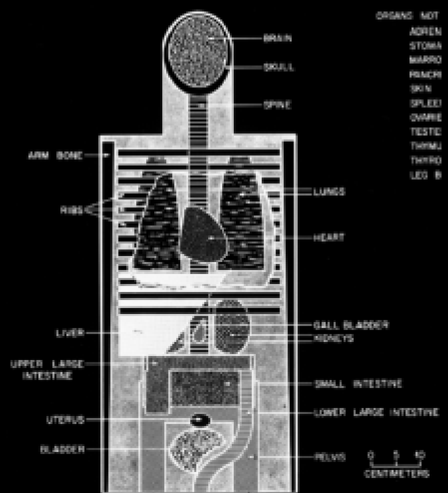
1960s
Stylized phantoms

1980s
Voxel phantoms

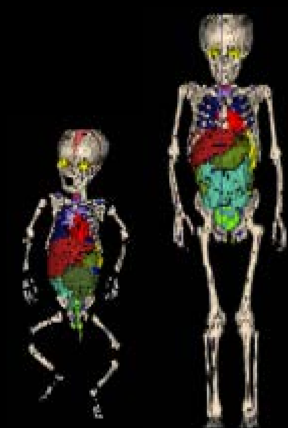
2000s
Hybrid phantoms



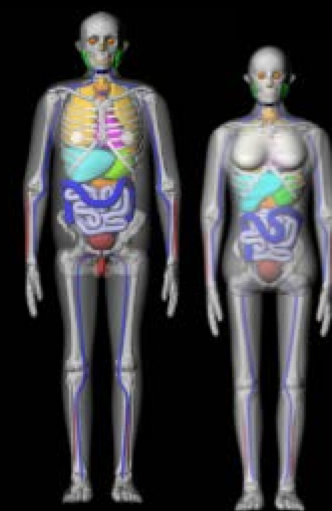
BOMAB phantom



ORNL adult phantom



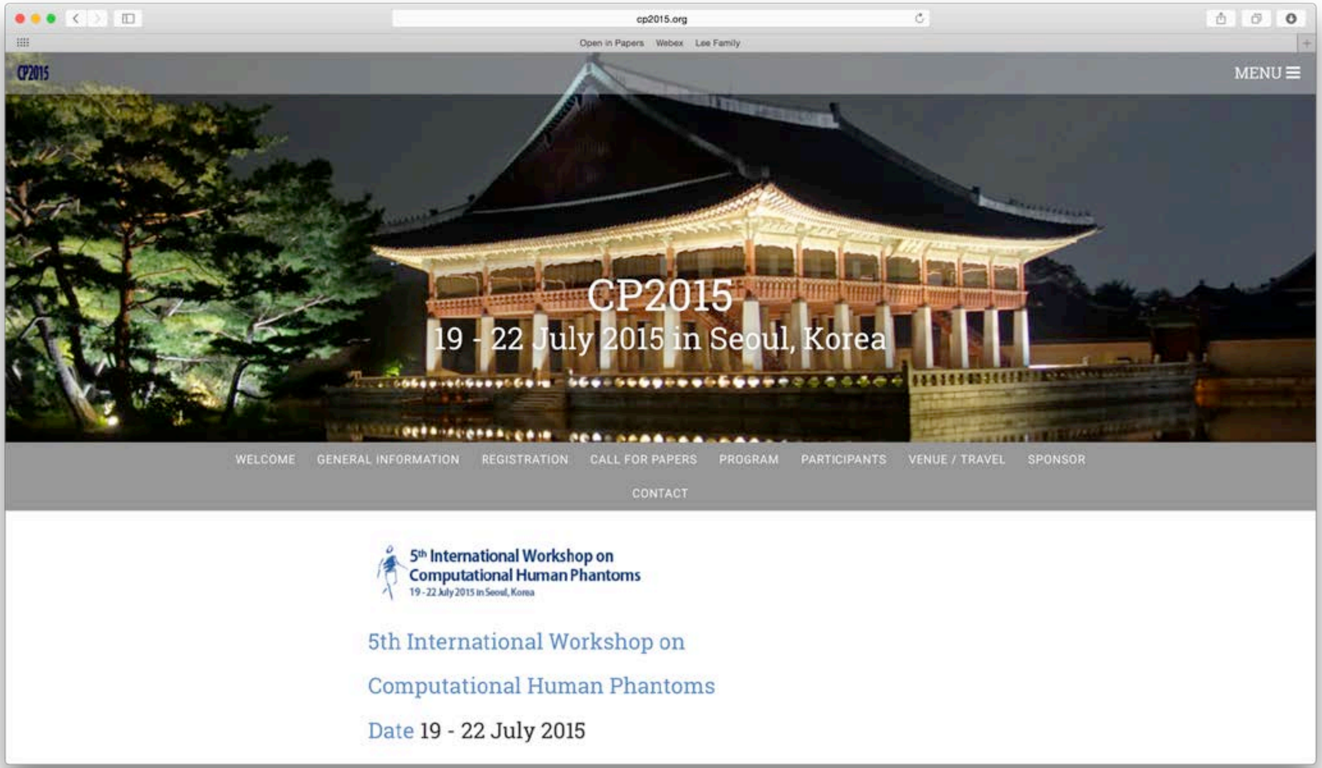
GSF BABY and CHILD
voxel phantoms



UF/NCI
Hybrid phantoms

Phantom Consortium (www.virtualphantoms.org)

- Founded in 2005 by 10+ founding members
- Meet every two years
- Release phantoms for research purposes



Content

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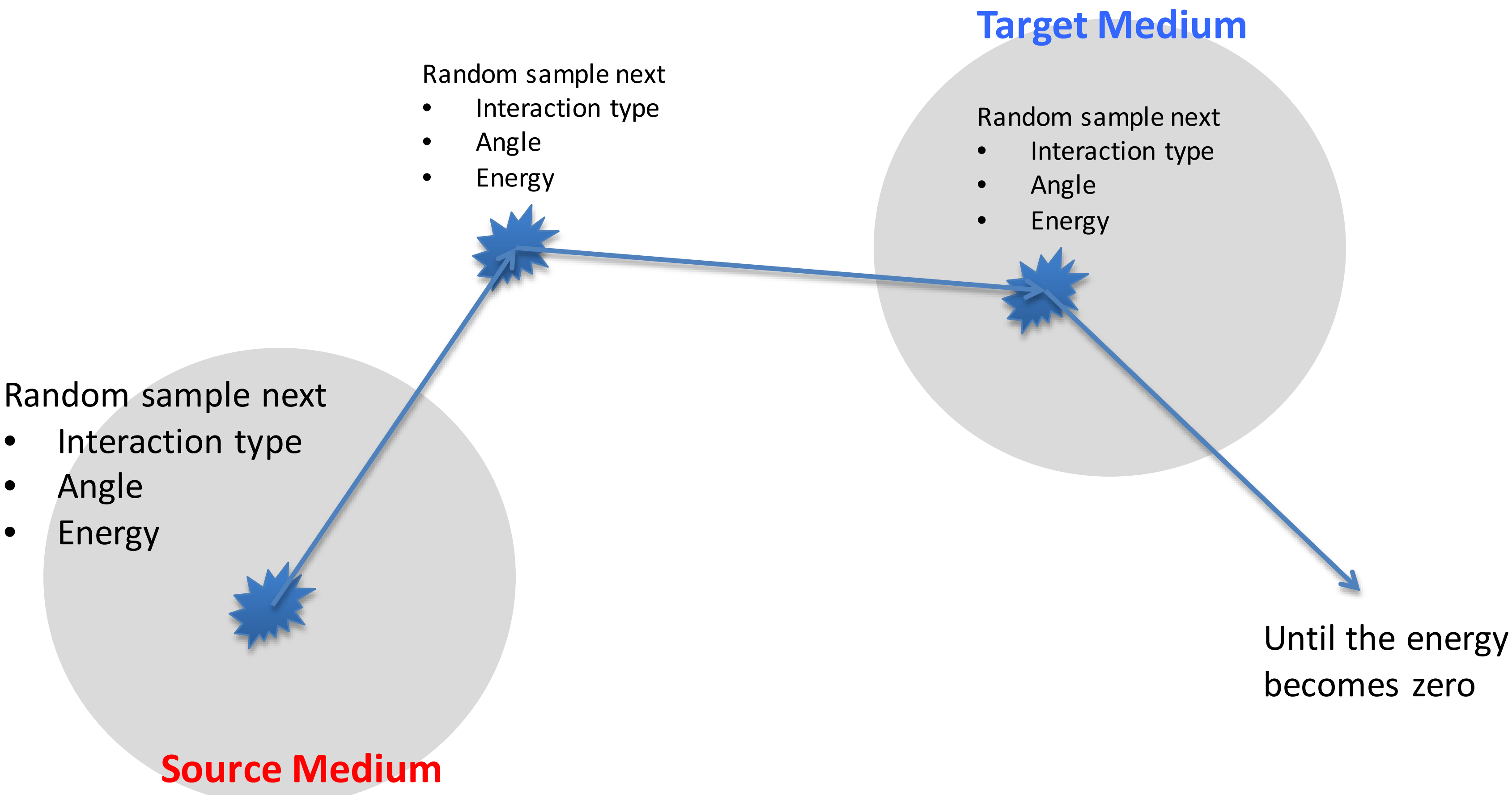
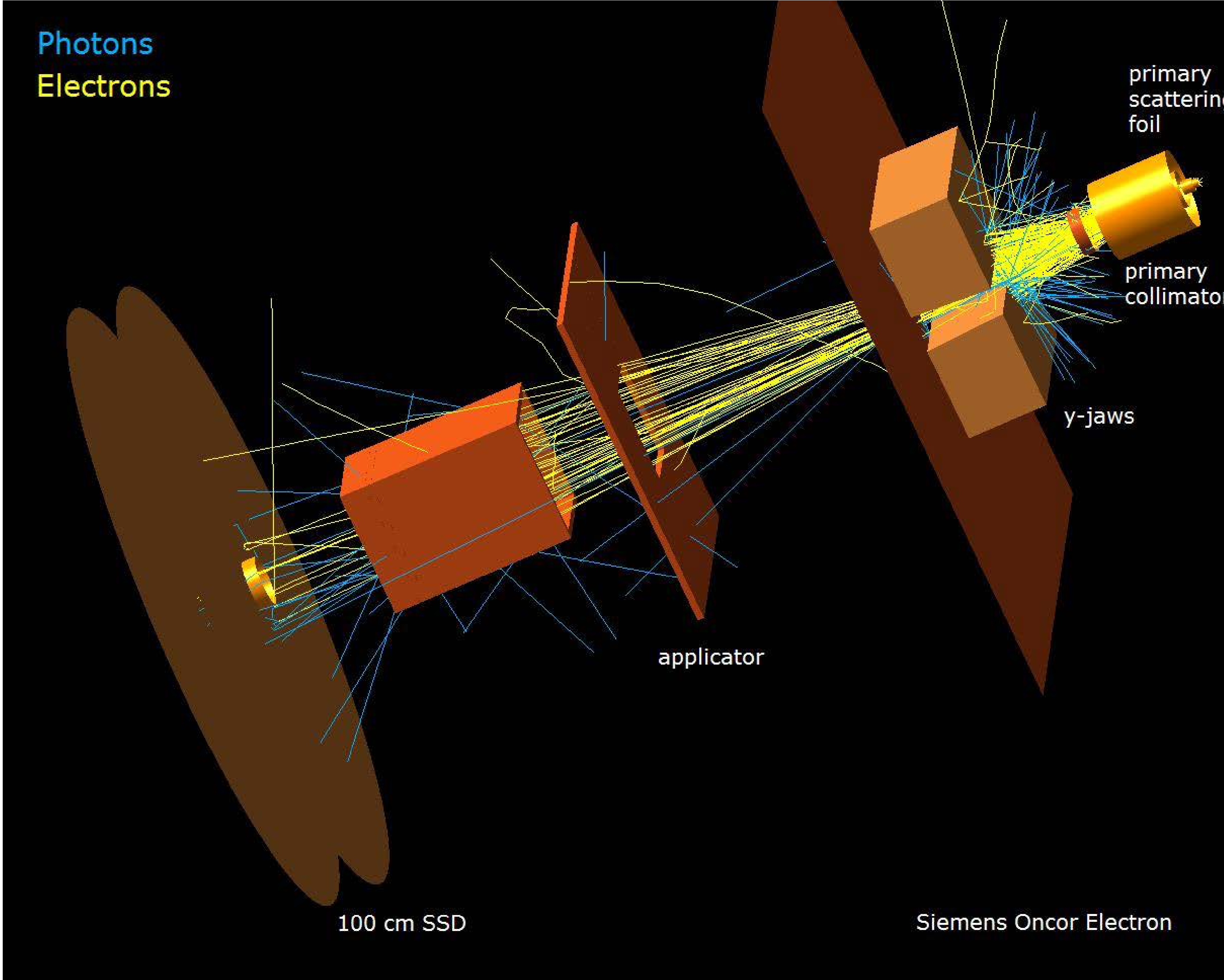
- Computational phantoms
- **Monte Carlo radiation transport**
- Diagnostic radiation dosimetry tools
- Therapeutic radiation dosimetry tools

3D Monte Carlo radiation transport

- A statistical approach for the physical phenomena based upon random number and the probability functions




Photons
Electrons
primary
scattering
foil
primary
collimator
y-jaws
applicator
100 cm SSD
Siemens Oncor Electron

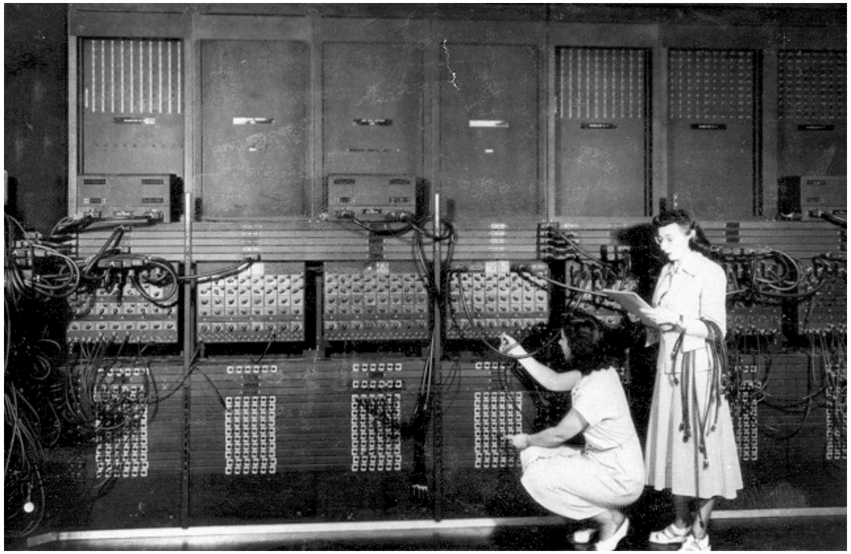
Monte Carlo simulation codes

- FLUKA – CERN and INFN's particle physics
- GEANT4 – CERN's simulation of high energy particles
- EGS – Stanford's simulation code for photon/electron
- PEREGRINE – LLNL's Monte Carlo tool for radiotherapy
- BEAMnrc – MC code system for radiotherapy
- PENELOPE – MC code for coupled transport of photons and electrons, with applications in radiotherapy
- MCNP – LANL's radiation transport codes
- …….
- Streamlined Monte Carlo transport code at NCI!

Brief introduction to MCNP

- MCNP: Monte Carlo N-Particle
  - Neutron, photon, electron, or coupled transport
  - Operable on PC, Unix, Linux, Mac, and parallel computing machine
  - Developed at Los Alamos National Laboratory

- History
  - MCNP4 (1990)
  - MCNP4A (1993)
  - MCNP4B (1997)
  - MCNP4C (2000)
  - MCNP5 (2003)
  - MCNP6 (up-to-date version)



The first electronic computer, ENIAC (1946)

Brief introduction to MCNP

- MCNPX (Monte Carlo N-Particle eXtended)
  - Extension to 34 particles up to 150 MeV
  - Operable on PC, Unix, Linux, and parallel computing machine
  - Developed at Los Alamos National Laboratory

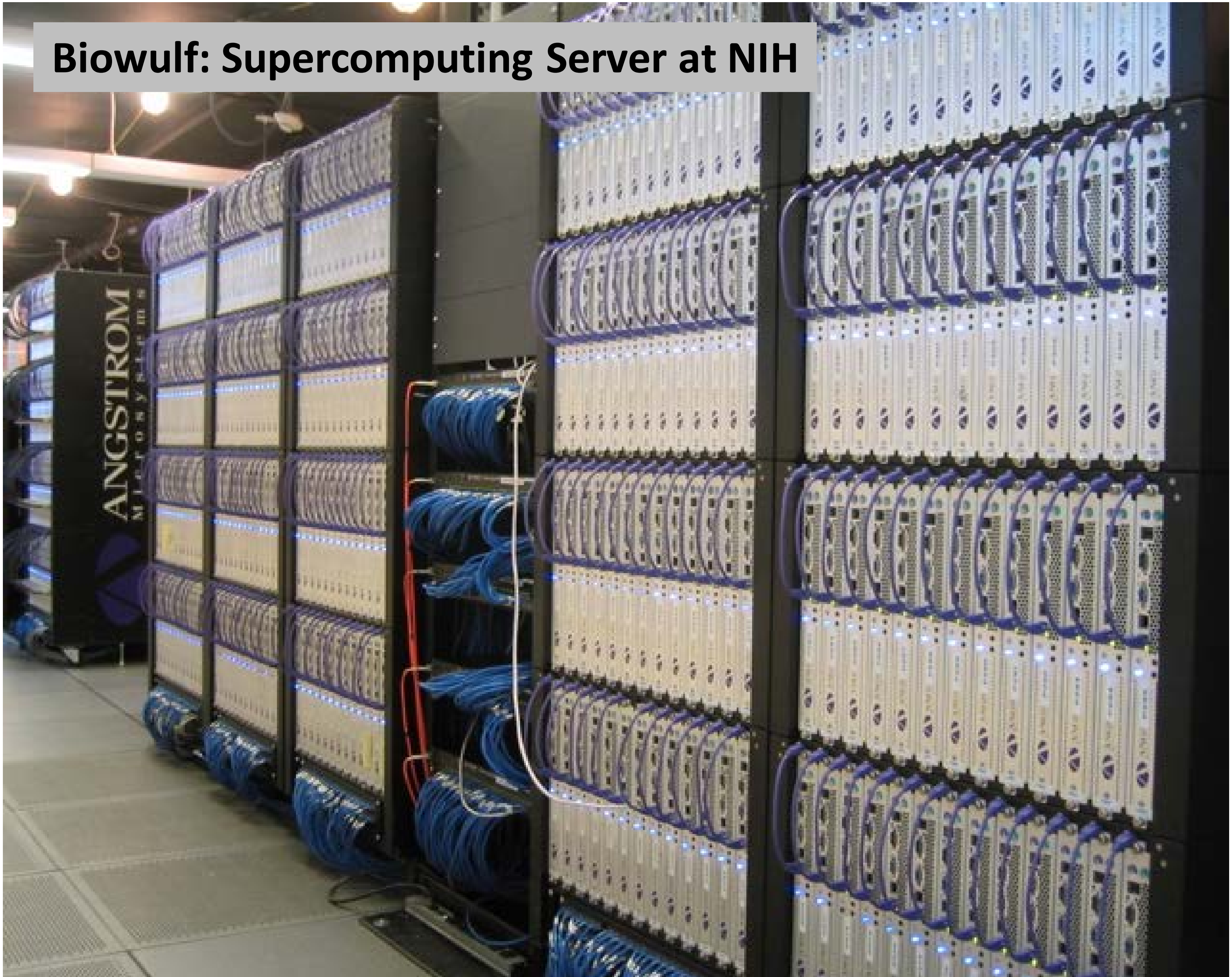
- History
  - MCNPX2.1 (October 1997)
  - MCNPX2.5 (April 2004)
  - MCNPX2.7 (up-to-date version)

$2 Cash Award to the person who finds any bug!

Maes, Tractebel, Brussels, Belgiu ... -055, 4/15/07)

44. Translations on the mesh tally RMESH or CMESH with a TRANS keyword can fail in all MCNPX versions. $2 awarded Choonsik Lee, University of Florida (GWM) (X-3-MCC:JSH-2007-56, 4/15/07)
45. Repeated structures lose particles with surfaces sources. $2 awarded Steven van der Marck, NRG, Petten, Netherlands (GWM) (X-3-MCC:JSH-2007-57, 4/16/07)

Biowulf: Supercomputing Server at NIH

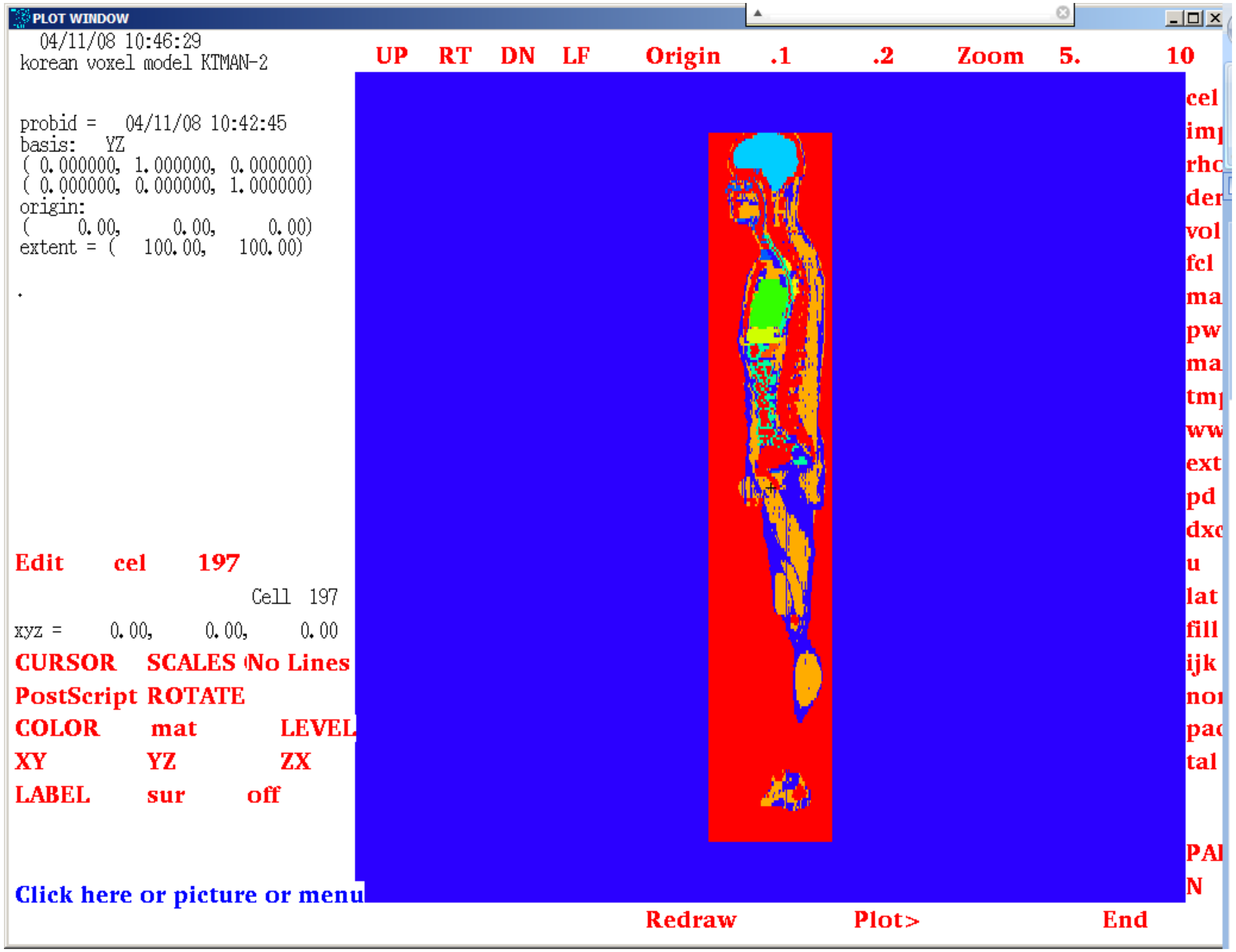


Applications of Monte Carlo codes

- Specific areas of application include
  - Radiation protection and dosimetry
  - Radiation shielding
  - <u>Radiography and medical physics</u>
  - Nuclear criticality safety, detector design and analysis
  - Accelerator target design
  - Fission and fusion reactor design
  - Decontamination and decommissioning reactor

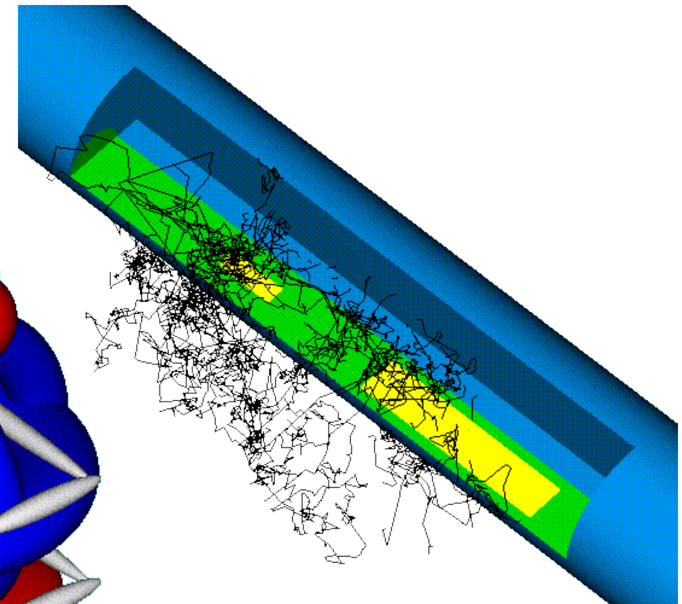
Visualization

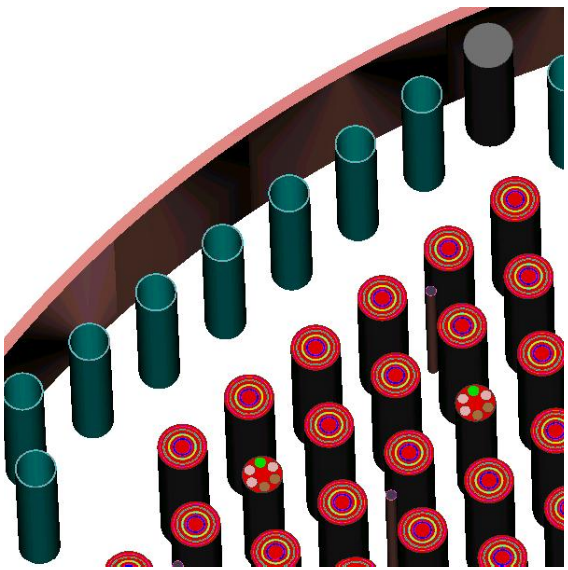
- MCNP/MCNPX built-in tool

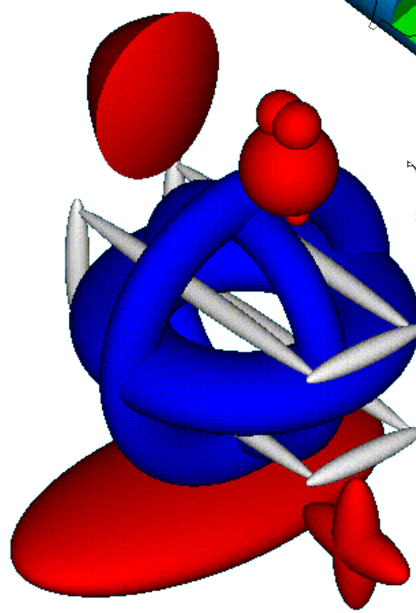


Visualization

- Sabrina (White Rock Science)
  - Visualize 3D geometries based on ray-tracing
  - Visualize particle track
  - Windows and UNIX



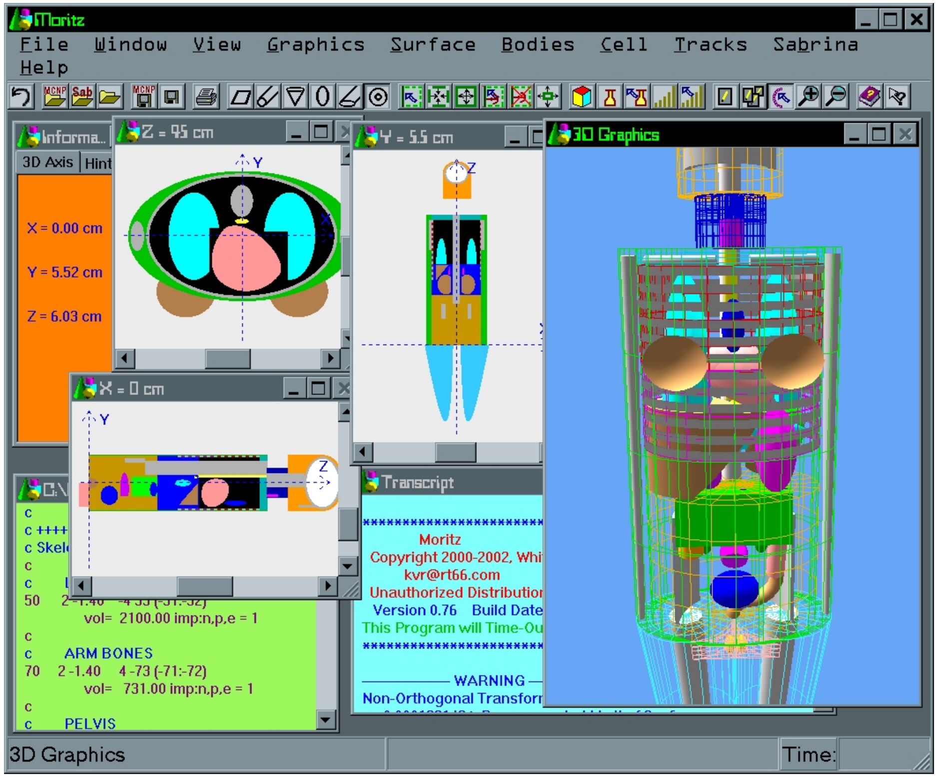




Graphics from www.whiterockscience.com

Visualization

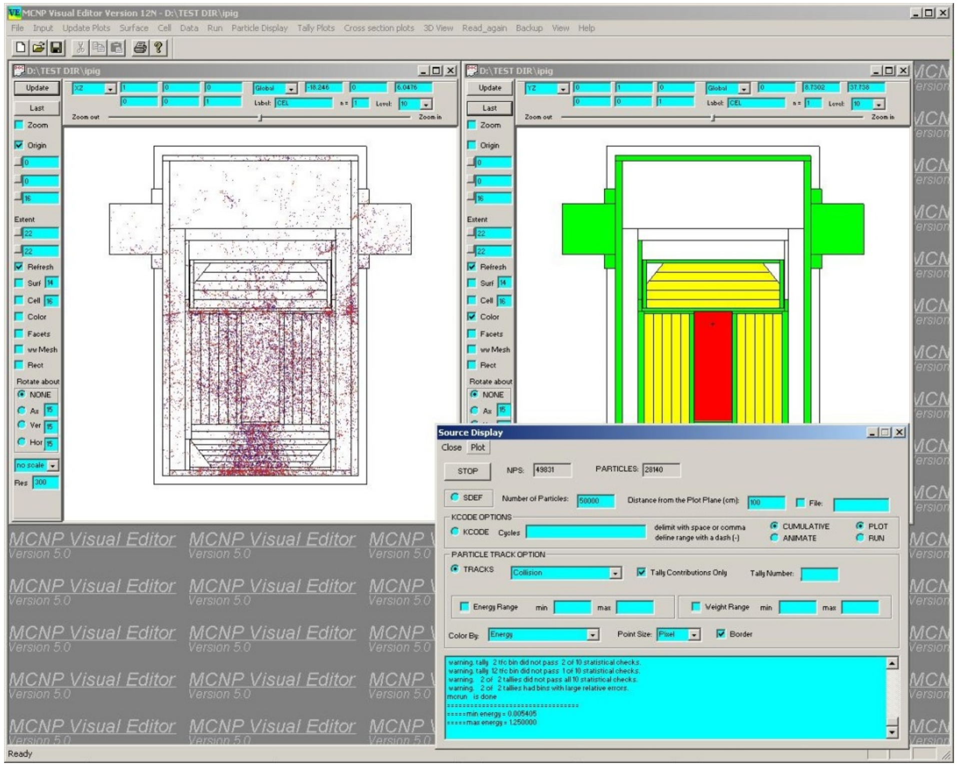
- Moritz (White Rock Science)
  - Real-time interactive visualization tool
  - Macrobody and voxel geometry supported
  - Mesh tally plotting



Graphics from www.whiterockscience.com

Visualization

- VISED (Visual Editor Consultants)
  - 3D visualization tool
  - Source and collision plotting
  - Write MCNP input and run

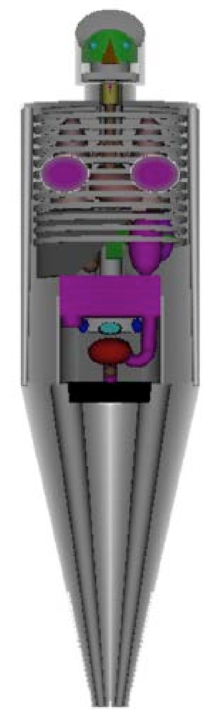


Graphics from www.mcnpvised.com

Example input file for a phantom in MCNP

```
ANDROGYNOUS PHANTOM AT  21.0 YEARS
C ++++++++++++++++++++++++++++++++++++++++
C
C    FILE PREPARED BY BODY BUILDER
C    COPYRIGHT 1996-2004, WHITE ROCK SCIENCE
C
C    THIS INPUT FILE IS FOR THE USE OF
C    BODYBUILDER LICENSE HOLDER ONLY.
C    DISTRIBUTION IS PROHIBITED.
C
C ++++++++++++++++++++++++++++++++++++++++
C
C +++++++++++++++++++++++++++++++++++++++++++++
C           CELLS
C +++++++++++++++++++++++++++++++++++++++++++++
C SKELETONVOLUME = 7218.700000, SKEL_VOL = 7142.857143
C
C         LEG BONES
50      2 -1.40    -4 53 (-51 : -52)
                 VOL=  2800.00 IMP:P = 1
C
C         ARM BONES
70     2 -1.40     4 -73 (-71 : -72)
                 VOL=   956.00 IMP:P = 1
C
C         PELVIS
90     2 -1.40     91 -92 93 4 -101 (95 : -94)
                 VOL=   606.00 IMP:P = 1
C
C         SPINE
100    2 -1.40   -100 -103 101 IMP:P = 1 VOL = 206.349
101    2 -1.40   -100 -8   103 IMP:P = 1 VOL = 547.404
102    2 -1.40   -105 -102 8   IMP:P = 1 VOL = 233.376
C               TOTAL SPINE VOL=   983.00
C
C         SKULL & FACE
110    2 -1.40   (111 -110):(121 -120 122 -1 -123 110)
                 VOL=   923.00 IMP:P = 1
C
C         RIBS
130    2 -1.40    132 -131 ((134 -133):(136 -135):(138 -137):(74 -139):
                 (76 -75):(78 -77):(80 -79):(82 -81):(332 -83):
                 (86 -85):(88 -87):(98 -89))
                 VOL=   694.00 IMP:P = 1
C
C         CLAVICLES
140    2 -1.40    -140 ((141 -143):(-142 144))
                 VOL=    54.70 IMP:P = 1
C
C         SCAPULAE
150    2 -1.40     131 -156 154 -155 ((150 -152):(-151 153))
                 VOL=   202.00 IMP:P = 1
C
C         ADRENALS
160     1 -1.04     162 (-160:-161)
                  VOL=    15.70 IMP:P = 1
```

```
C          STOMACH
210     SQ   576.0000  1024.0000   144.0000 0 0 0 -9216.0000
               8.0000    -4.0000    35.0000
C          STOMACH CONTENTS
211     SQ   310.9145   625.9888    65.3635 0 0 0 -3566.7398
               8.0000    -4.0000    35.0000
C EXTENT     4.0000    12.0000    -7.0000    -1.0000    27.0000    43.000
C
C          SMALL INTESTINE
221     PY    -4.8600
222     PY     2.2000
223     PZ    17.0000
C
C          ASCENDING COLON
230     SQ     6.2500     6.2500 0 0 0 0    -39.0625    -8.5000    -2.3600
C          ASCENDING COLON CONTENTS
233     SQ     3.2095     3.2095 0 0 0 0    -10.3007    -8.5000    -2.3600
231     PZ    14.4500
232     PZ    24.0000
C
C          TRANSVERSE COLON
240     SQ  0   2.250000     6.2500 0 0 0    -14.0625 0    -2.3600    25.50
C          TRANSVERSE COLON CONTENTS
243     SQ  0   0.946729     3.8927 0 0 0    -3.6854 0    -2.3600    25.50
241     PX    10.5000
242     PX   -10.5000
C
C
C          DESCENDING COLON
251      PZ     8.7200
250     GQ   4.536900   3.534400     0.106435 0      1.156545    -0.463191
             -72.816057    -10.085068        2.067006   283.328636
C          DESCENDING COLON CONTENTS
252     GQ   2.528100   1.795600     0.054654 0      0.587565    -0.258104
             -40.575343     -5.123571        1.232974   161.921356
C
C
C          SIGMOID COLON
282     PX     3.0000
280     TY     3.0000 0     8.7200     5.7200     1.5700     1.5700
281     TY      3.000 0 0      3.000     1.5700     1.5700
C          SIGMOID COLON CONTENTS
283     TY     3.0000 0     8.7200     5.7200     0.9100     0.9100
284     TY      3.000 0 0      3.000     0.9100     0.9100
C
C          HEART
C
290   4 PX 0
291   4 PZ 0
```

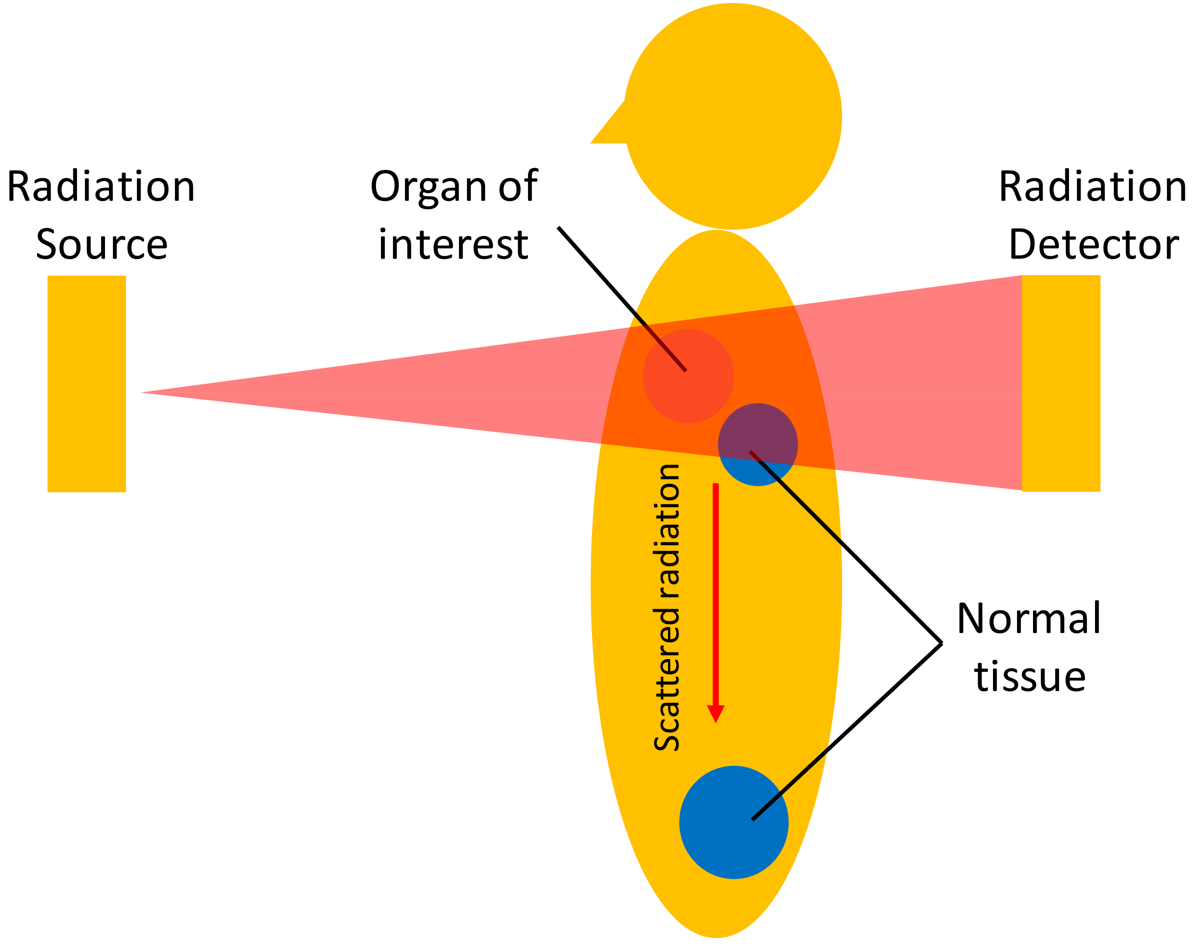


ADULT

Content

- Background
- Computational phantoms
- Monte Carlo radiation transport
- **Diagnostic radiation dosimetry tools**
- Therapeutic radiation dosimetry tools

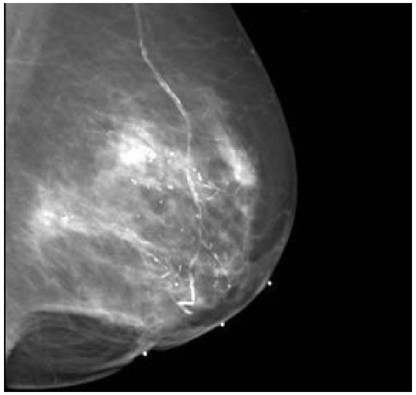
Normal tissue dose in diagnostic radiation procedures



Different imaging modalities

Radiography: projection image

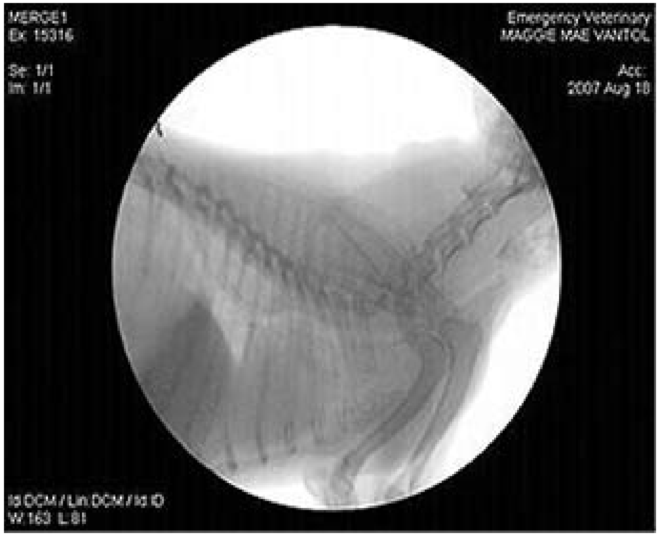
Mammography



Different imaging modalities

Fluoroscopy: real-time moving image

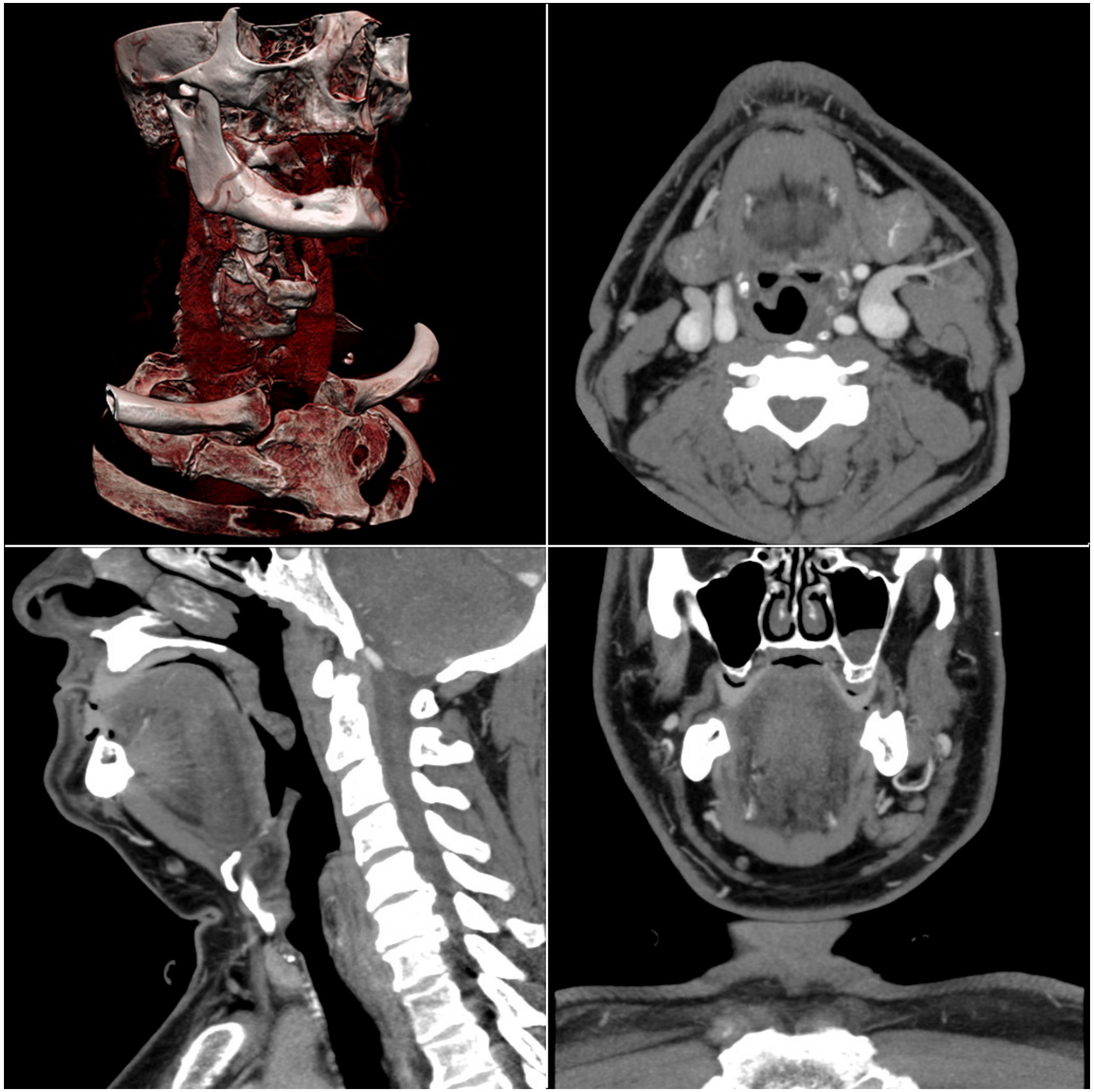
Diagnostic fluoroscopy



Interventional fluoroscopy

Different imaging modalities

Computed Tomography: cross-sectional image



Different imaging modalities

Nuclear Medicine Imaging: anatomy + function

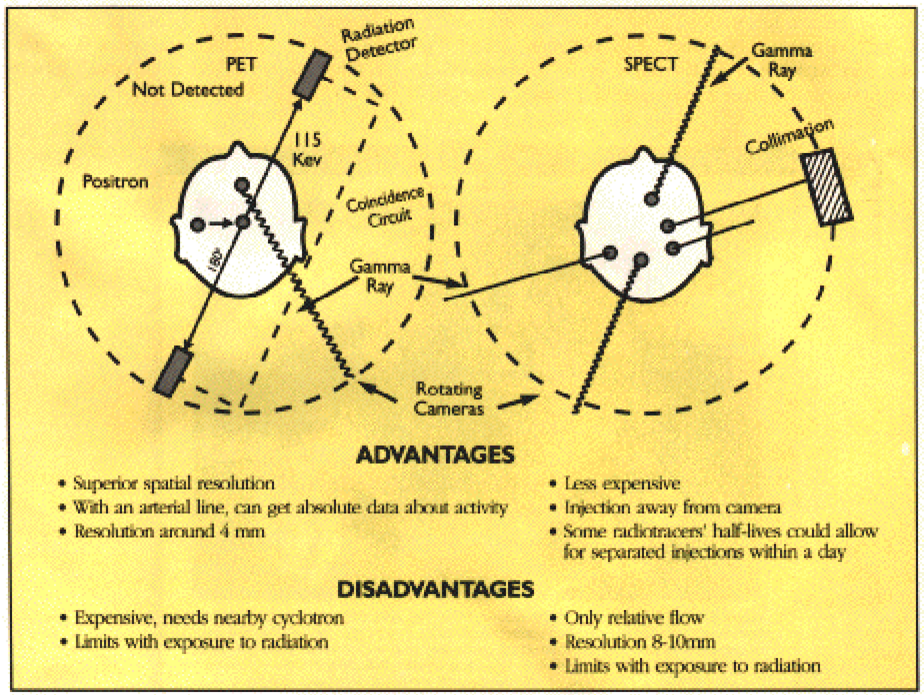
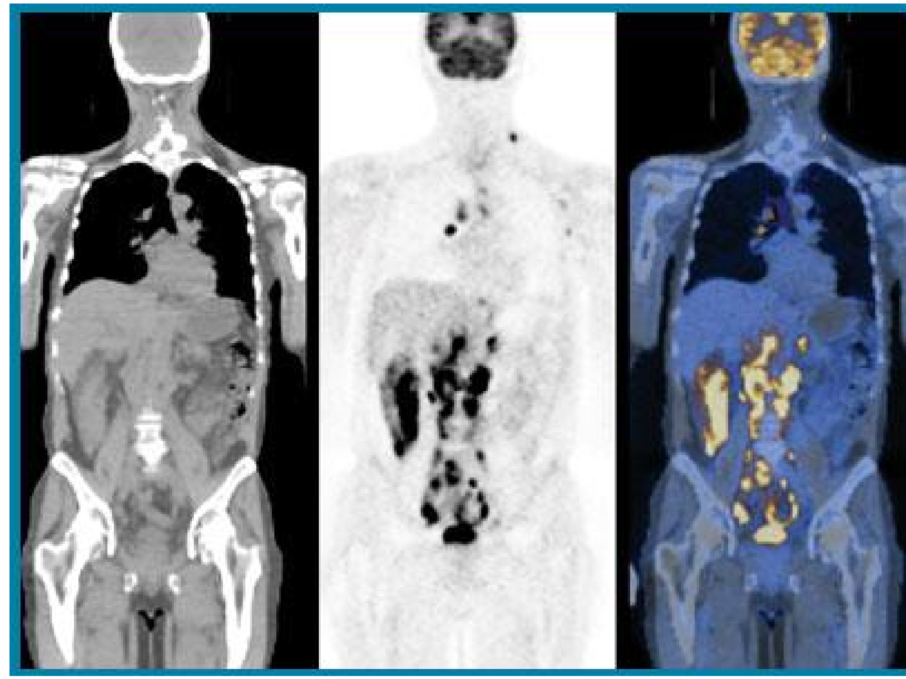


Figure 1 - This is a diagram of the imaging technique behind SPECT (right of image) and PET (left of image).

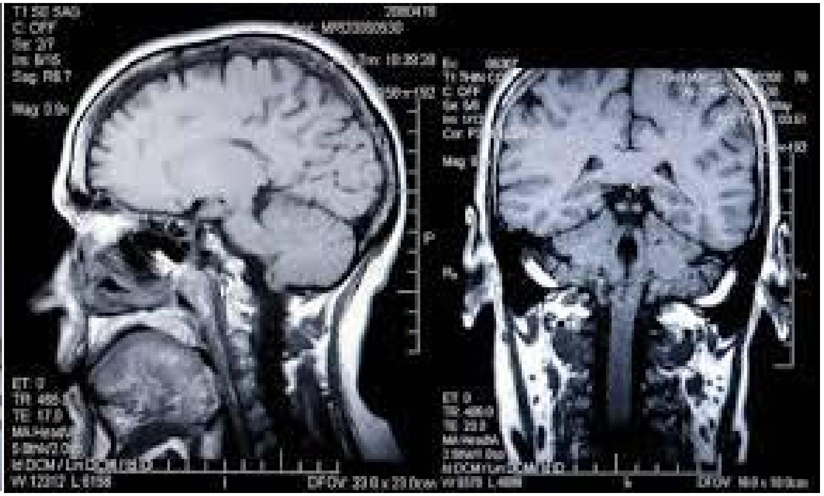


CT PET PET/CT

Ultrasound imaging

No Radiation Exposure!

Magnetic Resonance Imaging



Diagnostic radiation dosimetry tools

- **Radiography/Fluoroscopy**
- Mammography
- Computed Tomography

Organ dose estimation: Conversion coefficient

- "Handbook of selected tissue doses for projections common in diagnostic radiology" (Rosenstein, FDA89-8031, 1988)
  - Developed from adult male and female computational phantoms coupled with Monte Carlo transport technique
  - Provide organ doses per unit exposure (measurement) for comprehensive technique factors

Organ dose estimation: Conversion coefficient

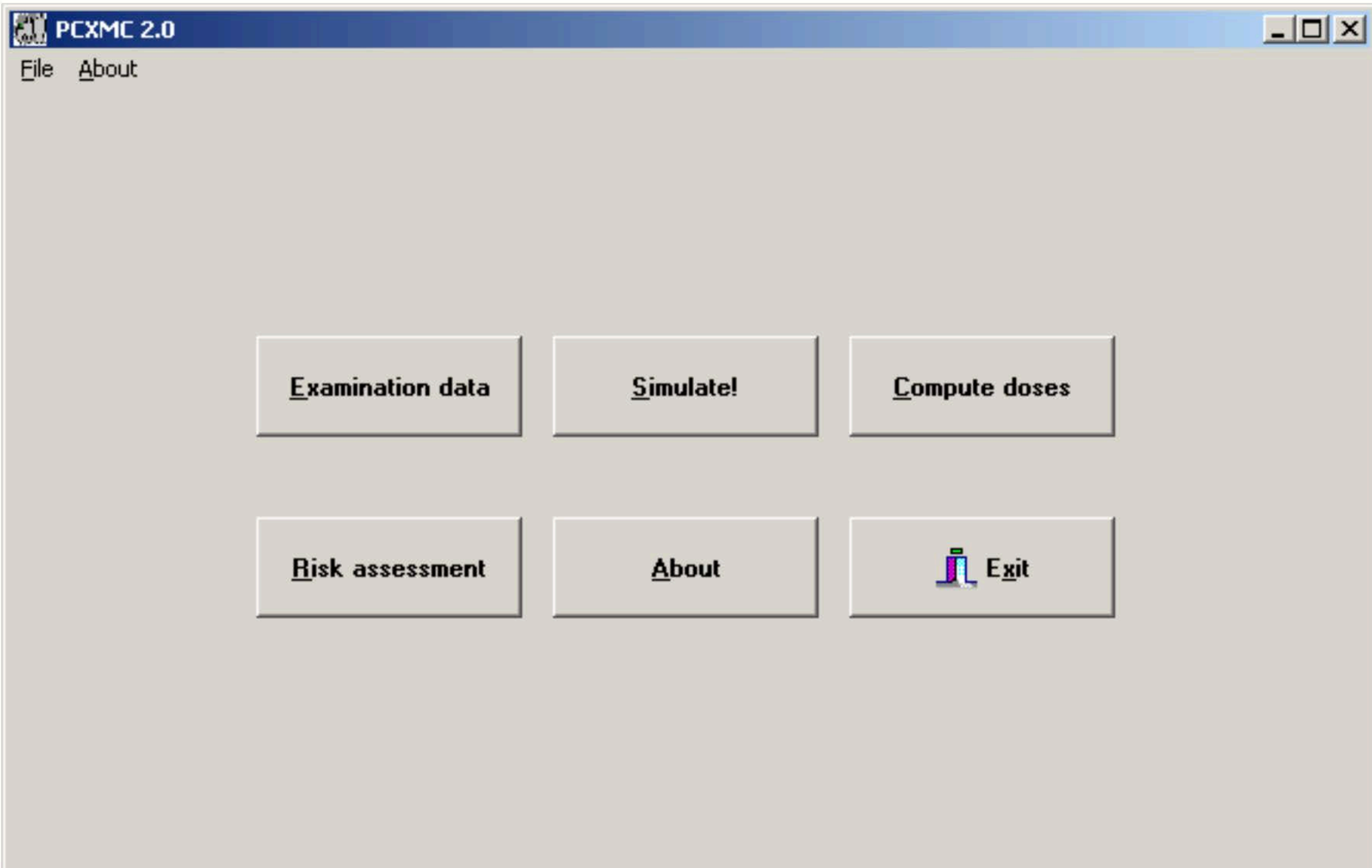
TABLE 24. PA CHEST - SID: 72" (183 cm); FIELD SIZE at FILM: 14" X 17" (35.6 cm X 43.2 cm)

MALE	TISSUE DOSES (mrad) and CANCER DETRIMENT INDEX for 1 R EXPOSURE at SKIN ENTRANCE (FREE-IN-AIR)[a,b]											
HVL (mm Al) ⟶	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5
LUNGS	124	216	301	375	439	493	539	578	610	637	660	678
ACTIVE BONE MARROW	27	49	71	92	113	131	149	165	180	194	207	219
THYROID	4.0	11	21	30	40	49	57	64	70	75	79	82
TRUNK TISSUE	52	82	109	132	152	170	185	199	210	221	230	238
CDI (10^{-5})	0.65	1.09	1.49	1.85	2.16	2.44	2.68	2.88	3.06	3.22	3.36	3.48
TESTES	+	+	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1	0.2

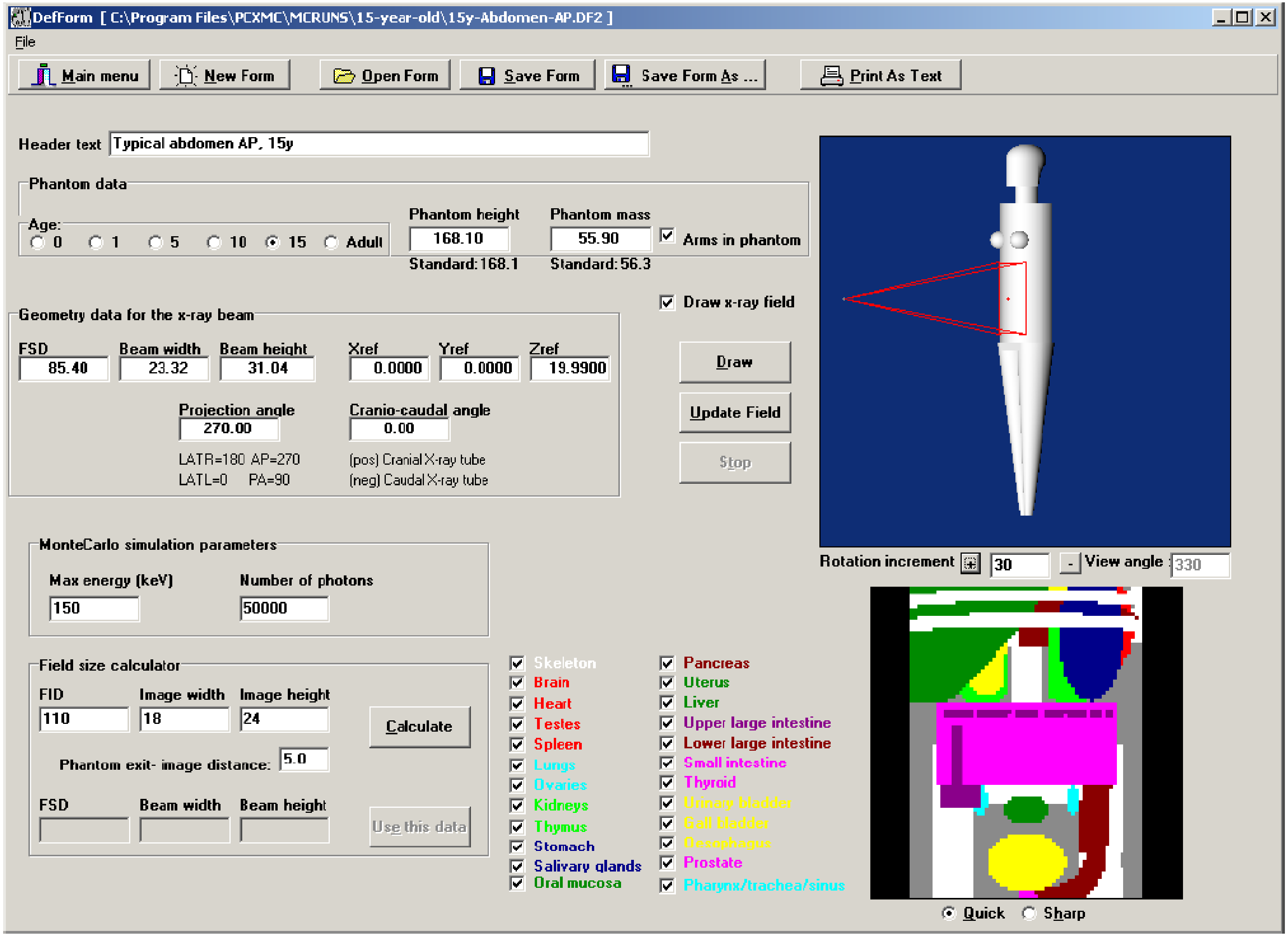
Organ dose estimation: PCXMC

- A commercial computer program for calculating patients' organ and effective doses in radiography examinations
  - Developed by Tapiovaara et al. (STUK, Finland)
  - Current version, PCXMC 2.0 (released in Nov 2008)
  - Based on the computational phantoms (Cristy and Eckerman, 1987) coupled with Monte Carlo transport technique

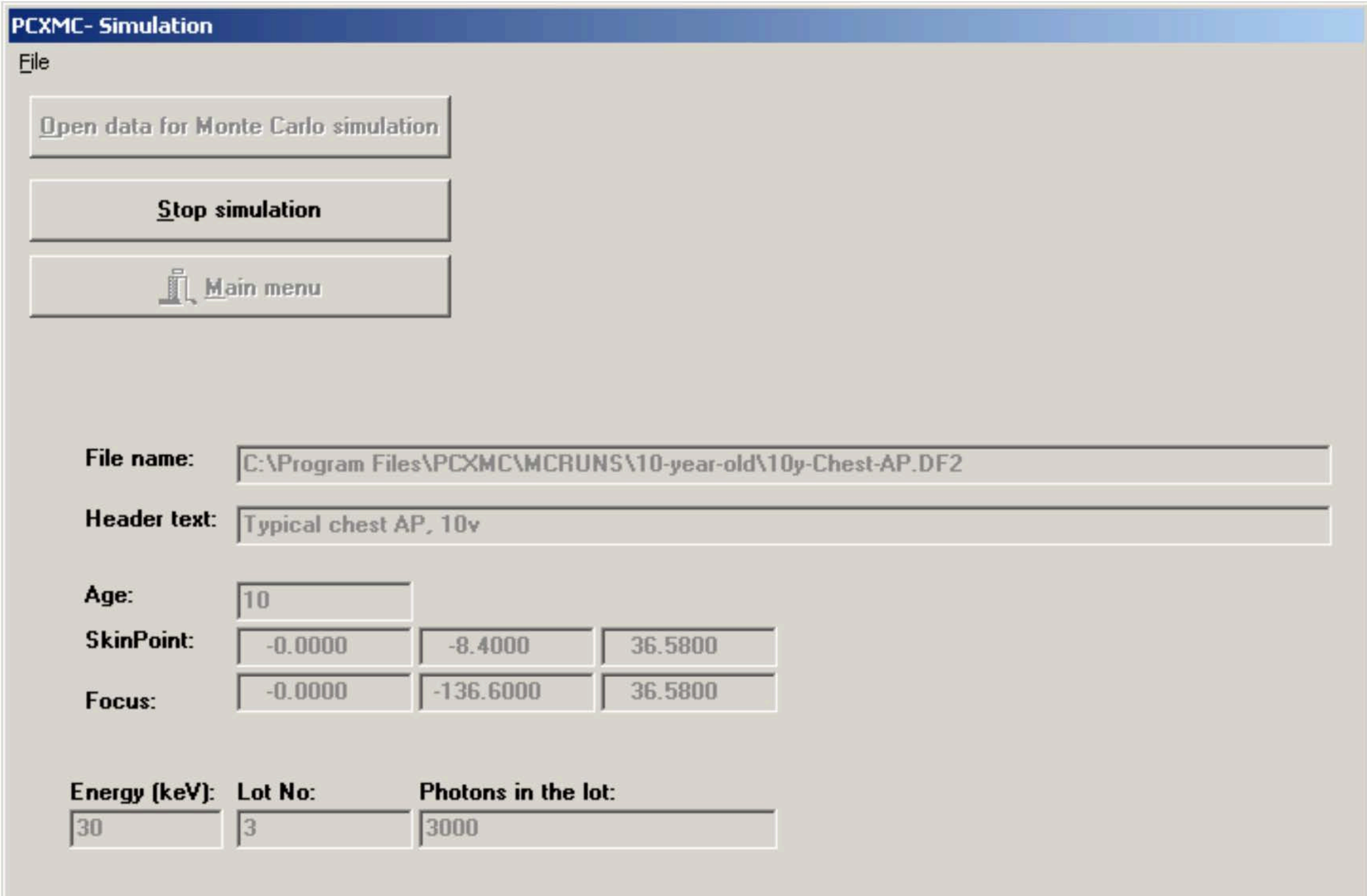
Four Different Modules in PCXMC



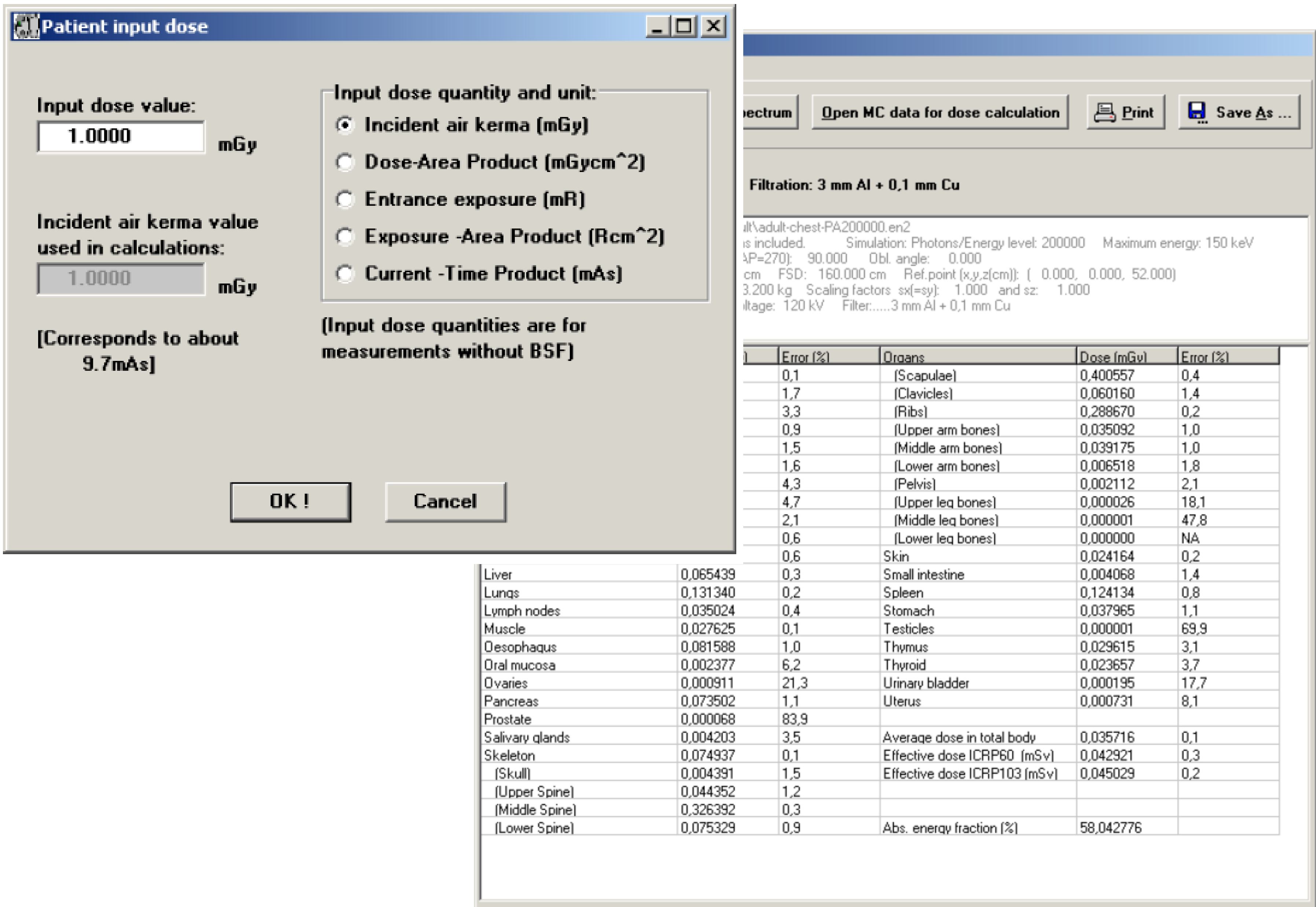
Examination Data Module (User input)



Simulation Module (Monte Carlo transport)

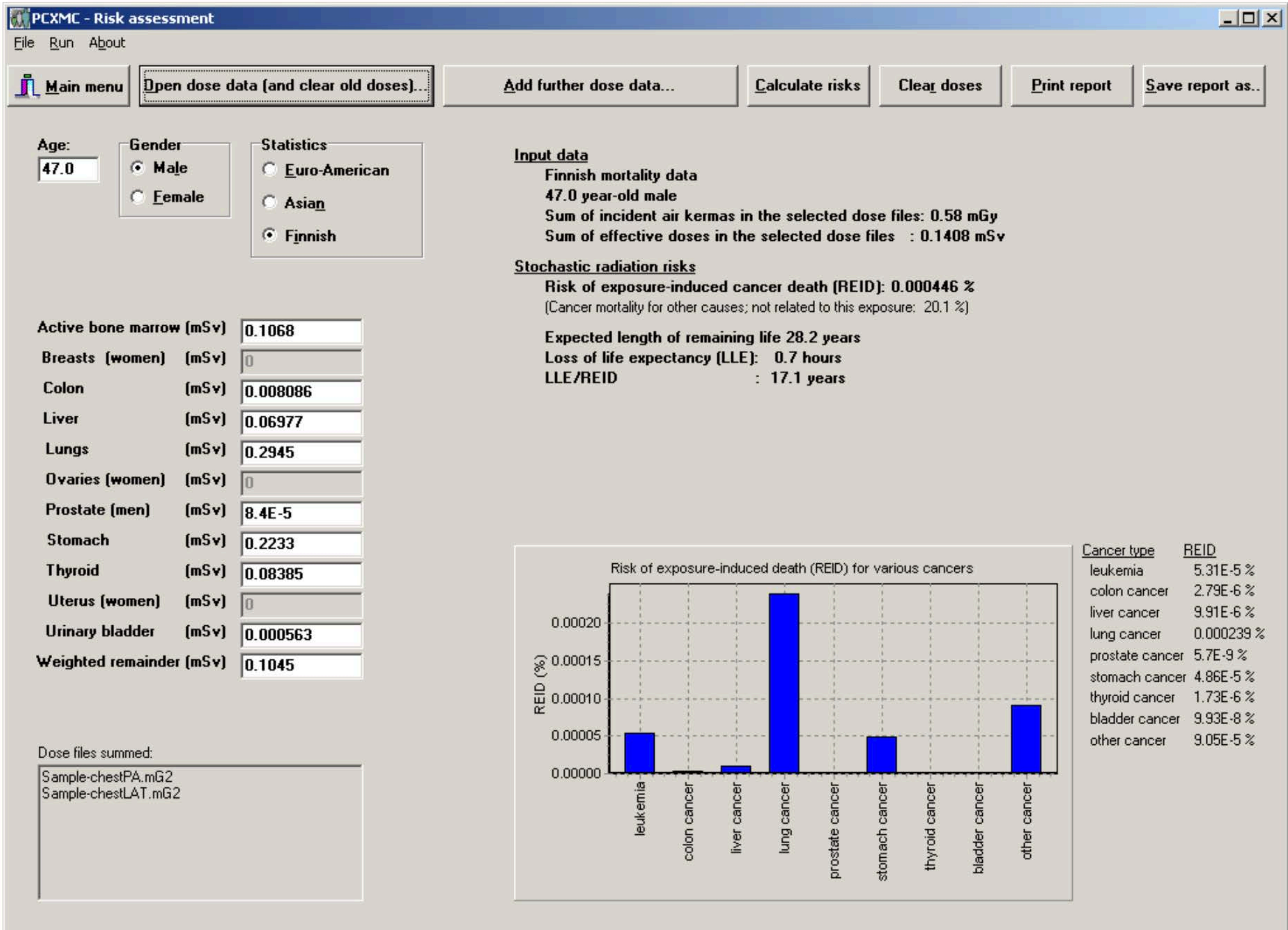


Dose Calculation Module (input measurements)



	)	Error (%)	Organs	Dose (mGy)	Error (%)
		0,1	(Scapulae)	0,400557	0,4
		1,7	(Clavicles)	0,060160	1,4
		3,3	(Ribs)	0,288670	0,2
		0,9	(Upper arm bones)	0,035092	1,0
		1,5	(Middle arm bones)	0,039175	1,0
		1,6	(Lower arm bones)	0,006518	1,8
		4,3	(Pelvis)	0,002112	2,1
		4,7	(Upper leg bones)	0,000026	18,1
		2,1	(Middle leg bones)	0,000001	47,8
		0,6	(Lower leg bones)	0,000000	NA
		0,6	Skin	0,024164	0,2
Liver	0,065439	0,3	Small intestine	0,004068	1,4
Lungs	0,131340	0,2	Spleen	0,124134	0,8
Lymph nodes	0,035024	0,4	Stomach	0,037965	1,1
Muscle	0,027625	0,1	Testicles	0,000001	69,9
Oesophagus	0,081588	1,0	Thymus	0,029615	3,1
Oral mucosa	0,002377	6,2	Thyroid	0,023657	3,7
Ovaries	0,000911	21,3	Urinary bladder	0,000195	17,7
Pancreas	0,073502	1,1	Uterus	0,000731	8,1
Prostate	0,000068	83,9			
Salivary glands	0,004203	3,5	Average dose in total body	0,035716	0,1
Skeleton	0,074937	0,1	Effective dose ICRP60 (mSv)	0,042921	0,3
(Skull)	0,004391	1,5	Effective dose ICRP103 (mSv)	0,045029	0,2
(Upper Spine)	0,044352	1,2			
(Middle Spine)	0,326392	0,3			
(Lower Spine)	0,075329	0,9	Abs. energy fraction (%)	58,042776	

Risk Assessment Module (based on BEIR VII models)

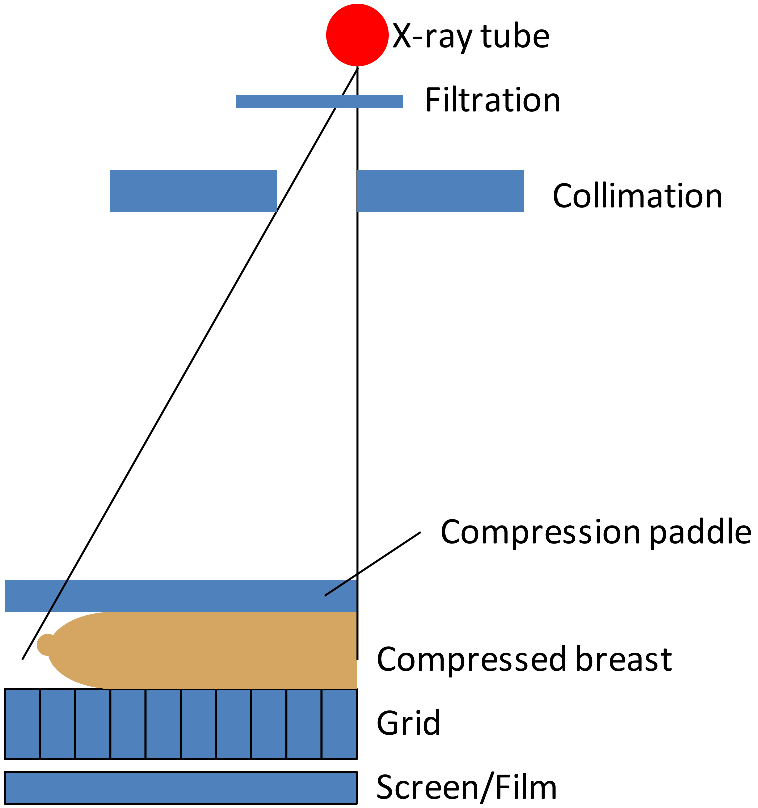


Diagnostic radiation dosimetry tools

- Radiography/Fluoroscopy
- **Mammography**
- Computed Tomography

Mammography

- Average (or mean) glandular dose (AGD)
  - Breast dose (at greatest risk)
  - Replaced traditional quantities (skin dose, midplane breast dose, and etc.)



Organ dose estimation: Conversion coefficient

- The average glandular dose, D_g (mGy) = D_{gN} (mGy/R) x X (R)

  X: entrance exposure (measurement)

  D_{gN}: Exposure-to-AGD conversion coefficient (obtained from Monte Carlo simulation)

TABLE 8-6. DgN CONVERSION FACTOR (mRAD PER ROENTGEN) AS A FUNCTION OF HVL AND kVp FOR Mo TARGET/FILTER: 4.5-CM BREAST THICKNESS OF 50% GLANDULAR AND 50% ADIPOSE BREAST TISSUE COMPOSITION*

	kVp							
HVL (mm)	25	26	27	28	29	30	31	32
0.25	122							
0.26	126	128						
0.27	130	132	134					
0.28	134	136	138	139				
0.29	139	141	142	143	144			
0.30	143	145	146	147	148	149		
0.31	147	149	150	151	152	153	154	
0.32	151	153	154	155	156	158	159	160
0.33	155	157	158	159	160	162	163	164
0.34	160	161	162	163	164	166	167	168
0.35	164	166	167	168	169	170	171	172
0.36	168	170	171	172	173	174	175	176
0.37		174	175	176	177	178	178	179
0.38			179	180	181	182	182	183
0.39				184	185	186	186	187
0.40					189	190	191	192

*Adapted from ACR QC Manual, 1999.

Advanced conversion coefficient*

TABLE A3
Conversion Coefficients (this work) Derived for Typical Protocols by Period and Compressed Breast Thickness (CBT)

Period	Technique	Target-filter	HVL[a] or filtration	CBT (cm)	kV[b] min	kV[b] max	Conversion coefficient (D_{gN}) min	Conversion coefficient (D_{gN}) max
1960–1964	Egan	W-Al	0.9 mm Al inherent	3	22	24	0.305	0.353
				5	26	35	0.258	0.377
				8	26	35	0.169	0.255
	Gershon-Cohen	W-Al	1.5 mm Al	3	25	30	0.449	0.535
			1 mm inherent	5	25	30	0.294	0.365
				8	25	30	0.192	0.243
1965–1969	Egan	Mo-Mo	HVL = 0.4	3	26	30	0.305	0.309
				5	26	30	0.190	0.194
				8	26	30	0.123	0.126
			HVL = 0.61	3	26	30	0.449	0.453
				5	26	30	0.290	0.297
				8	26	30	0.189	0.195
			0.78 mm Al	3	26	30	0.347	0.375
				5	26	30	0.217	0.238
				8	26	30	0.141	0.156
1970–1974	Egan	W-Al	HVL = 0.44	3	30	32	0.367	0.373
				5	30	32	0.242	0.249
				8	30	32	0.160	0.166
			HVL = 0.66	3	30	32	0.493	0.496
				5	30	32	0.333	0.338
				8	30	32	0.222	0.226
		Mo-Mo	HVL = 0.36	3	26	35	0.277	0.291
				5	26	35	0.172	0.186
				8	26	35	0.111	0.118
			HVL = 0.6	3	26	35	0.442	0.465
				5	26	35	0.285	0.309
				8	26	35	0.186	0.205
			0.78 mm Al	3	26	35	0.347	0.425
				5	26	35	0.217	0.278
				8	26	35	0.141	0.183

* Thierry-Chef et al. Rad Res (2012)

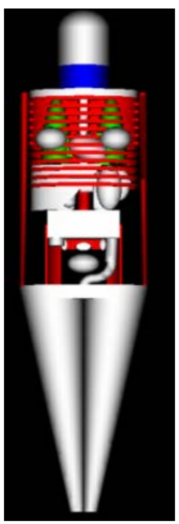
Diagnostic radiation dosimetry tools

- Radiography/Fluoroscopy
- Mammography
- **Computed Tomography**

Conventional CT dosimetry tools (developed in 1980s)

CTDosimetry

- NRPB database (UK)
- Hermaphrodite adult
- **<u>No children</u>**

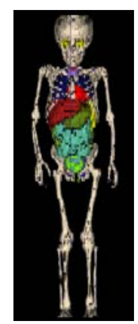


ORNL adult hermaphrodite phantom

CT-Expo

- GSF database (Germany)
- Male and female adult
- **<u>Two children</u>**

BABY



CHILD

ADAM EVA

CTDosimetry

ImPACT CT Patient Dosimetry Calculator
Version 1.0.2 12/11/2009

Scanner Model:		
Manufacturer:	Siemens	
Scanner:	Siemens Sensation 16	
kV:	120	
Scan Region:	Head	
Data Set	MCSET21	Update Data Set
Current Data	MCSET21	
Scan range		
Start Position	0 cm	Get From Phantom Diagram
End Position	43 cm	

Organ weighting scheme	ICRP 60

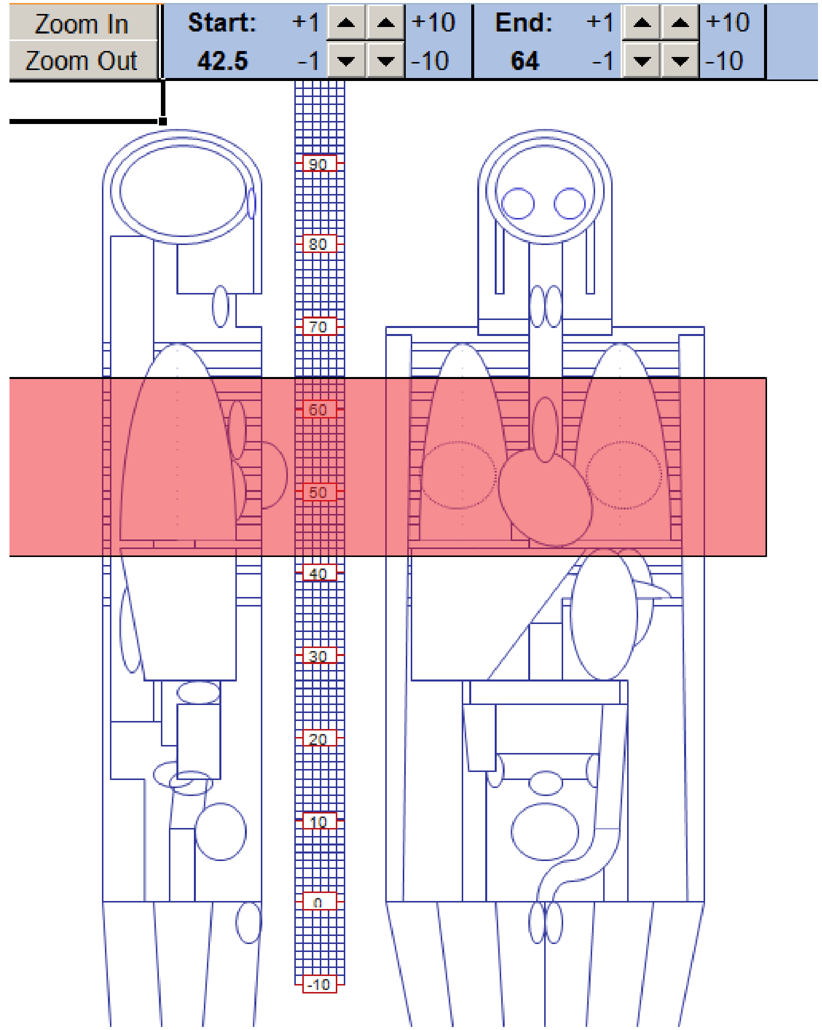
Acquisition Parameters:			
Tube current		100	mA
Rotation time		1	s
Spiral pitch		1	
mAs / Rotation		100	mAs
Effective mAs		100	mAs
Collimation			mm
Rel. CTDI	Look up	1.00	(assumed)
CTDI (air)	Look up	21.8	mGy/100mAs
CTDI (soft tissue)		23.3	mGy/100mAs
$_nCTDI_w$	Look up	16.6	mGy/100mAs

$CTDI_w$	16.6	mGy
$CTDI_{vol}$	16.6	mGy
DLP	713	mGy.cm

Organ	w_T	H_T (mGy)	$w_T.H_T$
Gonads	0.2	6.5	1.3
Bone Marrow	0.12	4.8	0.57
Colon	0.12	11	1.3
Lung	0.12	1.2	0.15
Stomach	0.12	11	1.3
Bladder	0.05	12	0.61
Breast	0.05	0.35	0.018
Liver	0.05	10	0.5
Oesophagus (Thymus)	0.05	0.26	0.013
Thyroid	0.05	0.031	0.0016
Skin	0.01	3.3	0.033
Bone Surface	0.01	5.8	0.058
Not Applicable	0	0	0
Not Applicable	0	0	0
Remainder	0.025	4.7	0.12
Kidneys	0.025	13	0.31
Total Effective Dose (mSv)			6.3

Remainder Organs	H_T (mGy)
Adrenals	9.4
Small Intestine	11
Kidney	13
Pancreas	9.4
Spleen	10
Thymus	0.26
Uterus	12
Muscle	4.7
Brain	0.0016
Not Applicable	N/A
Not Applicable	N/A
Not Applicable	N/A
Not Applicable	N/A
Other organs of interest	**H_T (mGy)**
Eye lenses	0.0027
Testes	2.3
Ovaries	11
Uterus	12
Prostate	12

Scan Description / Comments	



Conversion factors for pediatric effective doses in CTDosimetry

	Head and Neck	Chest	Abdo & Pelvis
Adult	1.0	1.0	1.0
15 y	1.1	1.0 - 1.1	1.0 - 1.1
10 y	1.2 - 1.3	1.1 - 1.4	1.2 - 1.5
5 y	1.6 - 1.7	1.2 - 1.6	1.2 - 1.6
1 y	2.2	1.3 - 1.9	1.3 - 2.0
Newborn (0 y)	2.3 - 2.6	1.4 - 2.2	1.4 - 2.4

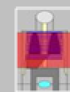
Typical normalised effective doses to paediatric patients relative to adults

CT-Expo

Calculate

1. Age Group: Adult — Gender: (•) male ( ) female

2. Scan Range



Get Values

Scan Range Data (Slice Positions)		
Scan Range z from z-	to z+	L [cm]
40	70	30

3. Scanner Model

Manufacturer	General Electric
Scanner	9800

Scanner Data for Scan Region "Body"

${}_nCTDI_w$ [mGy/mAs]	U_{ref} [kV]	$P_{B,H}$	k_{CT}	k_{OB}	ΔL [cm]
0.062	120	0.24	0.50	1.00	0.0

4. Select mode — [ ] Body mode for head/neck region — [x] Spiral mode

5. Scan Parameters

Please Enter Actual Settings:

U [kV]	I [mA]	t [s]	Q_{el} [mAs]	Q [mAs]	$N * h_{col}$ [mm]	TF [mm]	h_{rec} [mm]	p	Ser.
120	120	2	240	0	10.0	10.0	1.0	1.0	1

6. Results

Dose Values per Scan or per Series*

$CTDI_w$ [mGy]	$CTDI_{vol}$ [mGy]	DLP_w* [mGy*cm]	E* [mSv]	D_{uterus}* [mSv]
14.9	14.9	448	**6.4**	n.a.

Child/Baby: all CTDI and DLP values refer to 16cm head phantom !

Dose Values per Examination

DLP_w [mGy*cm]	E [mSv]	D_{uterus} [mSv]
448	**6.4**	n.a.

Effective dose E refers to ICRP 60

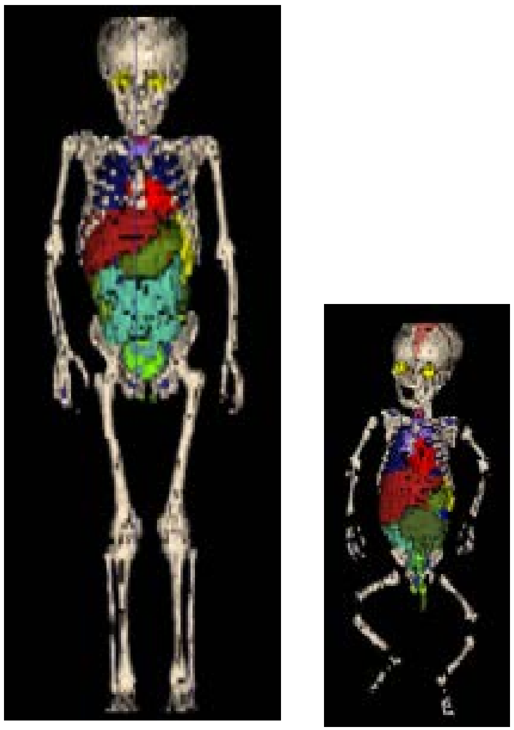
Please note:
All organ doses H_T are based on conversion coefficients for stand-ard patients (ADAM, EVA, CHILD, BABY) and serve for information purposes only (in particular organs outside the scan range) !

Tissue or Organ	H_T per Series [mSv]
Thyroid	6.4
Breasts	0.0
Oesophagus	22.7
Lungs	23.4
Liver	7.4
Stomach	4.8
Colon	0.0
Testicles	0.0
Ovaries	0.0
Bladder	0.0
Bone marrow	5.6
Bone surface	15.0
Skin	5.4

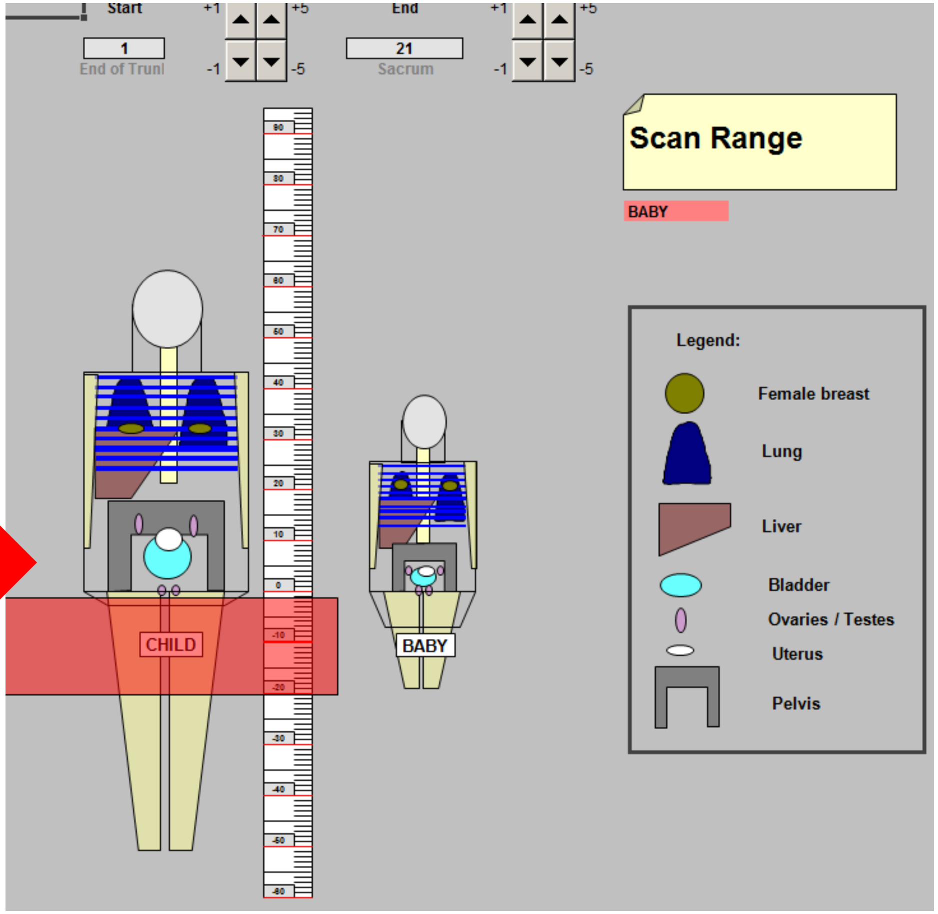
Remainder Organs	H_T per Series [mSv]
Brain	0.3
Thymus	22.7
Spleen	5.8
Pancreas	5.2
Adrenals	9.3
Kidneys	1.5
Small intest.	0.2
Upp. large int.	0.3
Uterus	0.0

Misc.	H_T per Series [mSv]
Eye lenses	0.4

CT-Expo



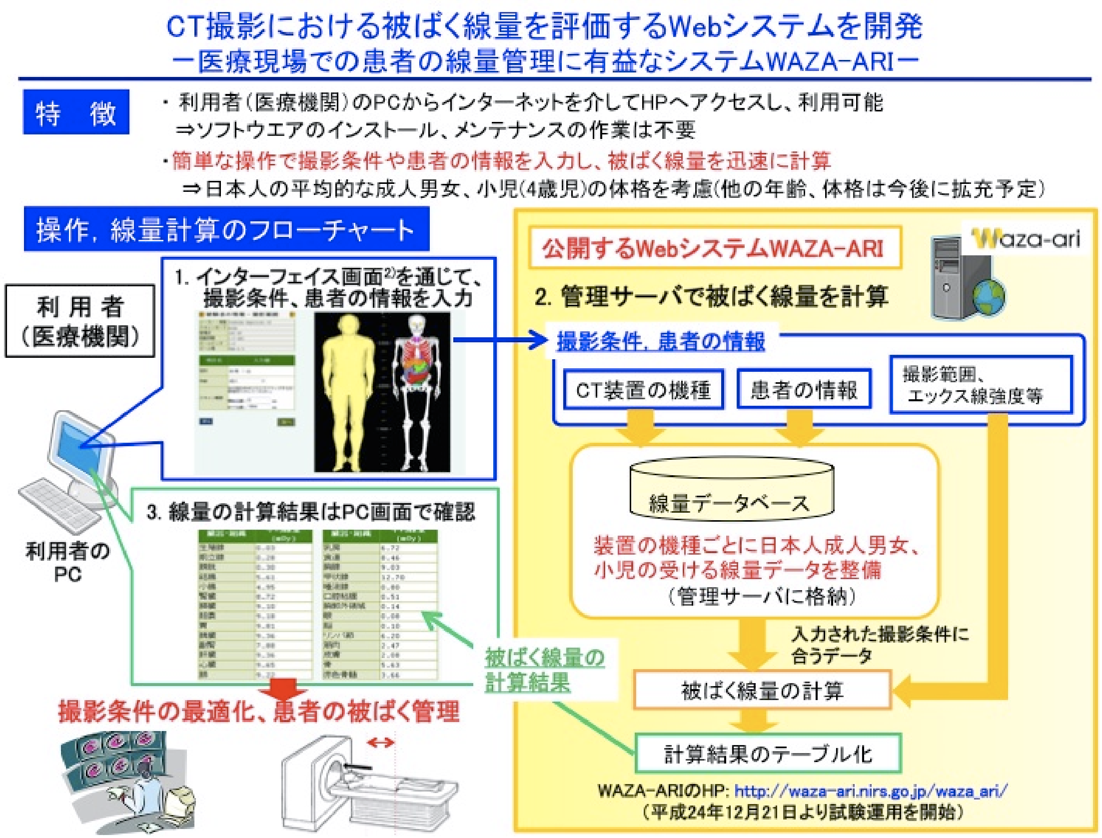
Actual phantoms
Used in calculation



Phantoms displayed in CT-Expo
to define scan range

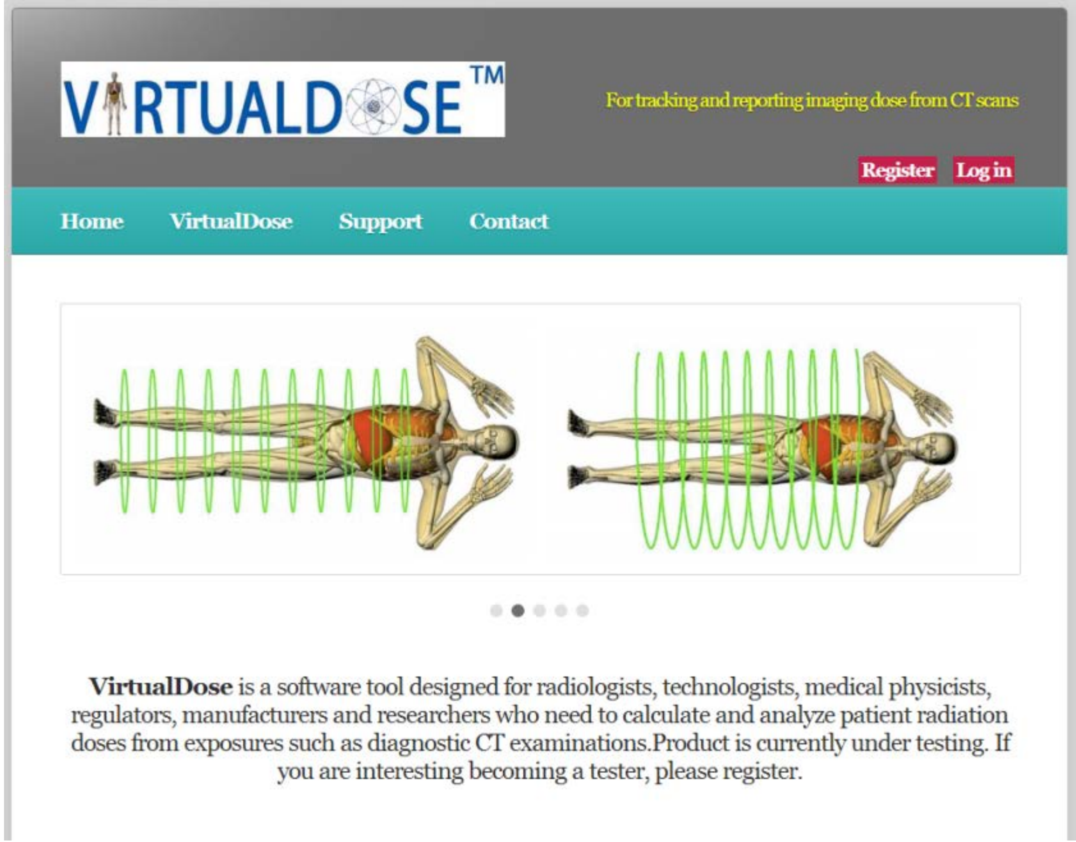
More recent developments:
WAZA-ARI (Japan)

- Under beta test
- Japanese adult male only
- Limited CT scanner models
- Web-interface



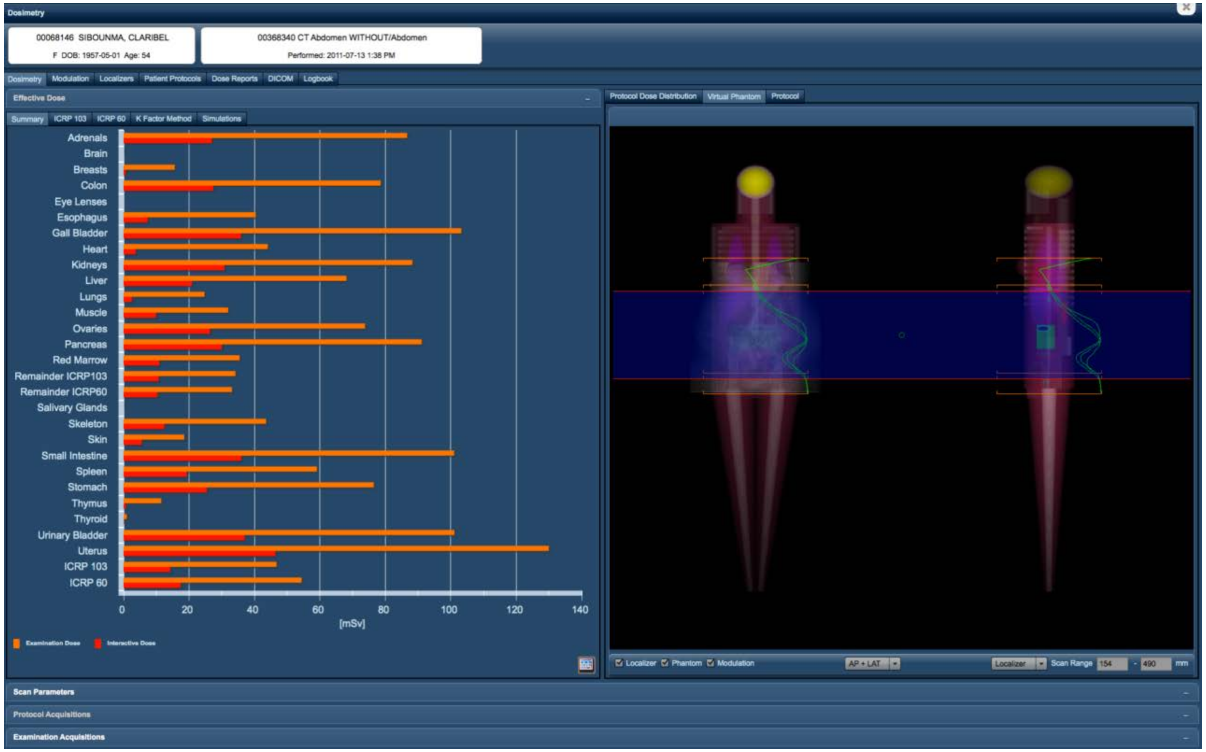
More recent developments: **VirtualDose^{TM}CT** (RPI, USA)

- Commercial solution
- RPI pediatric/adult phantoms
- Limited CT scanner model



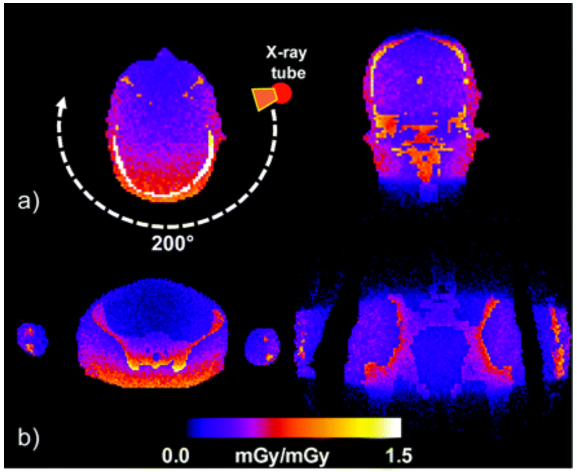
More recent developments:
eXposure™ (Radimetrics, inc)

- Advanced interface between dosimetry tool and PACS
- Adopted by a large number of clinical centers worldwide
- Old stylized phantoms



More recent developments: **GPU-based** on-site dose calculation

- Calculate dose distribution right after CT images are reconstructed.
  - Kalender et al. (Germany)
  - Xu et al. (RPI, USA)

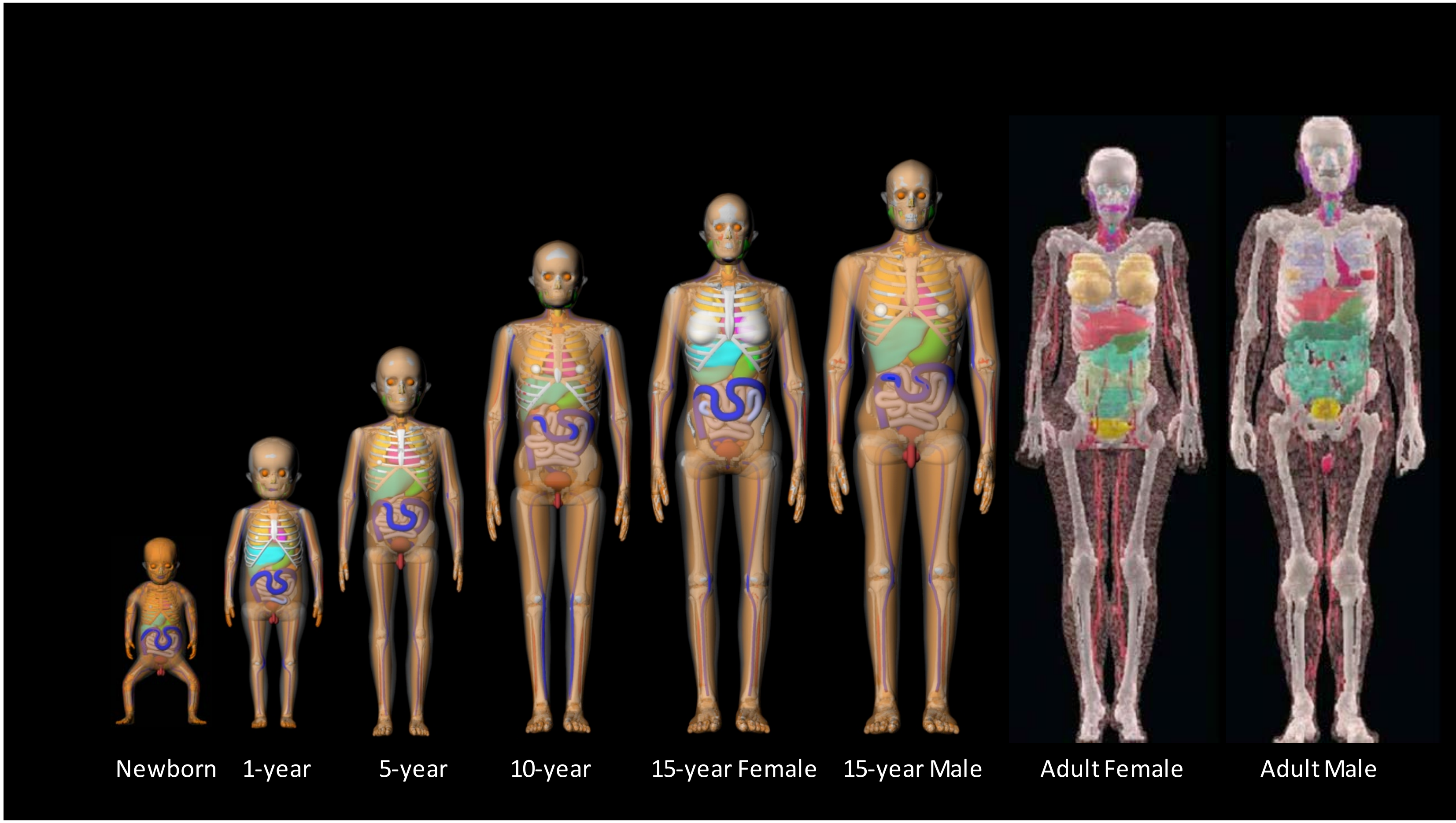


- Not appropriate for epidemiologic study
  - Only provide 3D dose distribution
  - Organ segmentation is required for organ dose calculation

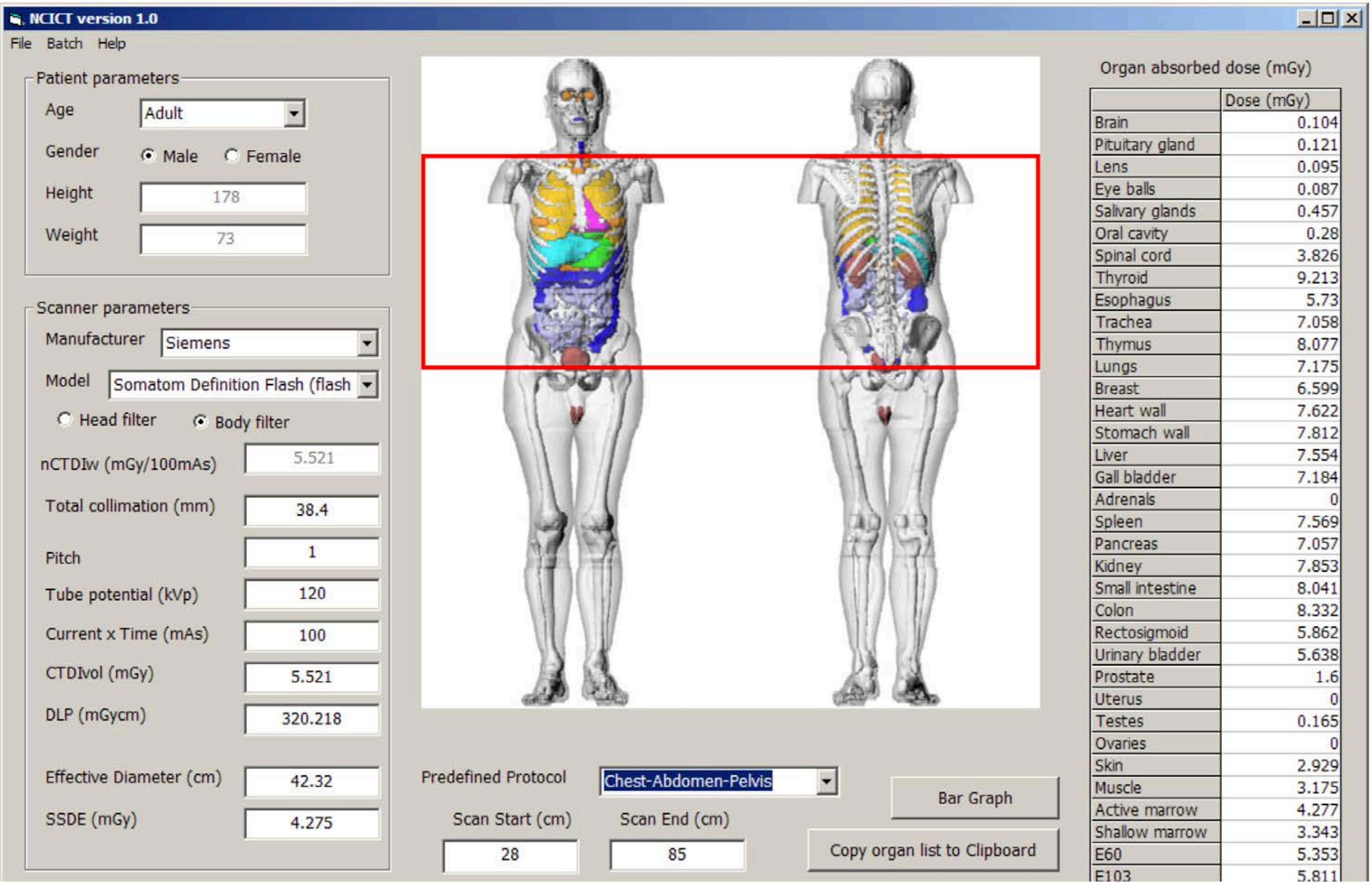
NCICT

- National Cancer Institute Dosimetry System for CT Patients
- ICRP Reference pediatric and adult phantoms adopted
- Validation of the CT x-ray simulation
- CT scanner output library for +150 scanner model
- Based on +10 journal publications

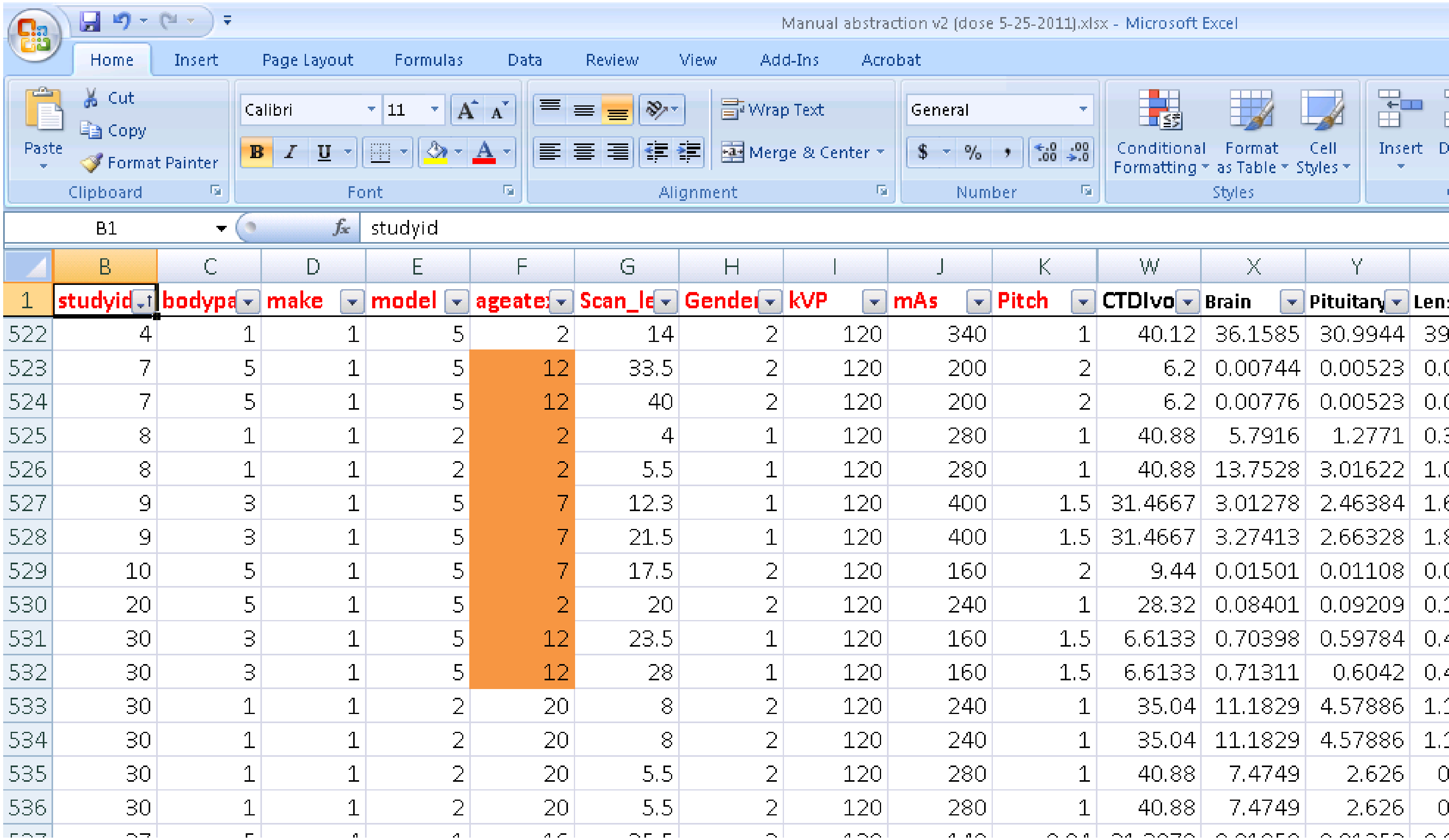
ICRP Reference Pediatric and Adult Phantoms



User interface of NCICT



Batch Module in NCICT (with/without $CTDI_{vol}$)



	studyid	bodypa	make	model	ageate	Scan_le	Gender	kVP	mAs	Pitch	CTDIvo	Brain	Pituitary	Lens
522	4	1	1	5	2	14	2	120	340	1	40.12	36.1585	30.9944	39.4
523	7	5	1	5	12	33.5	2	120	200	2	6.2	0.00744	0.00523	0.00
524	7	5	1	5	12	40	2	120	200	2	6.2	0.00776	0.00523	0.00
525	8	1	1	2	2	4	1	120	280	1	40.88	5.7916	1.2771	0.36
526	8	1	1	2	2	5.5	1	120	280	1	40.88	13.7528	3.01622	1.01
527	9	3	1	5	7	12.3	1	120	400	1.5	31.4667	3.01278	2.46384	1.64
528	9	3	1	5	7	21.5	1	120	400	1.5	31.4667	3.27413	2.66328	1.83
529	10	5	1	5	7	17.5	2	120	160	2	9.44	0.01501	0.01108	0.01
530	20	5	1	5	2	20	2	120	240	1	28.32	0.08401	0.09209	0.10
531	30	3	1	5	12	23.5	1	120	160	1.5	6.6133	0.70398	0.59784	0.41
532	30	3	1	5	12	28	1	120	160	1.5	6.6133	0.71311	0.6042	0.42
533	30	1	1	2	20	8	2	120	240	1	35.04	11.1829	4.57886	1.14
534	30	1	1	2	20	8	2	120	240	1	35.04	11.1829	4.57886	1.14
535	30	1	1	2	20	5.5	2	120	280	1	40.88	7.4749	2.626	0.5
536	30	1	1	2	20	5.5	2	120	280	1	40.88	7.4749	2.626	0.5

Beta testing (2010 –)

Name	Institution	Country
Maccia Carlo	CAATS	France
Andreas Jahnen	CRP Tudor	Luxemburg
Isabelle Thierry-Chef	IARC	France
Marie-Odile Bernier	IRSN	France
Jean-Luc Rehel	IRSN	France
Eva Godske Friberg	NRPA	Norway
Hilde Olerud	NRPA	Norway
Lucian Krille	UMC	Germany
Henryk Wicke	Johannes Gutenberg University Mainz	Germany
Michael Hauptmann	Netherlands Cancer Institute	Netherland
Zoe Brady	Alfred Health	Autralia
Georg Stamm	Institut für Radiologie	Germany
Jinsung Kim	Samsung Medical Center	Korea
Thalia Mills	FDA	USA
David Spelic	FDA	USA
Stanley Stern	FDA	USA
Amir Bahadori	NASA	USA
Kwang Pyo Kim	KHU	Korea
Roberto Maass	NCI	USA
Eliseo vano	University of Madrid, Spain	Spain
Paul Shrimpton	HPA UK	UK
Akira Endo	JAEA	Japan
Xizeng Wu	U of Alabama	USA
Koji Ono	Oita University	Japan
Fumiaki Takahashi	JAEA	Japan
Takayasu Yoshitake	Shinbeppu Hospital	Japan
Mark Smekhov	Ministry of Health, Israel	Israel
Klaus Bacher	Ghent University	Belgium

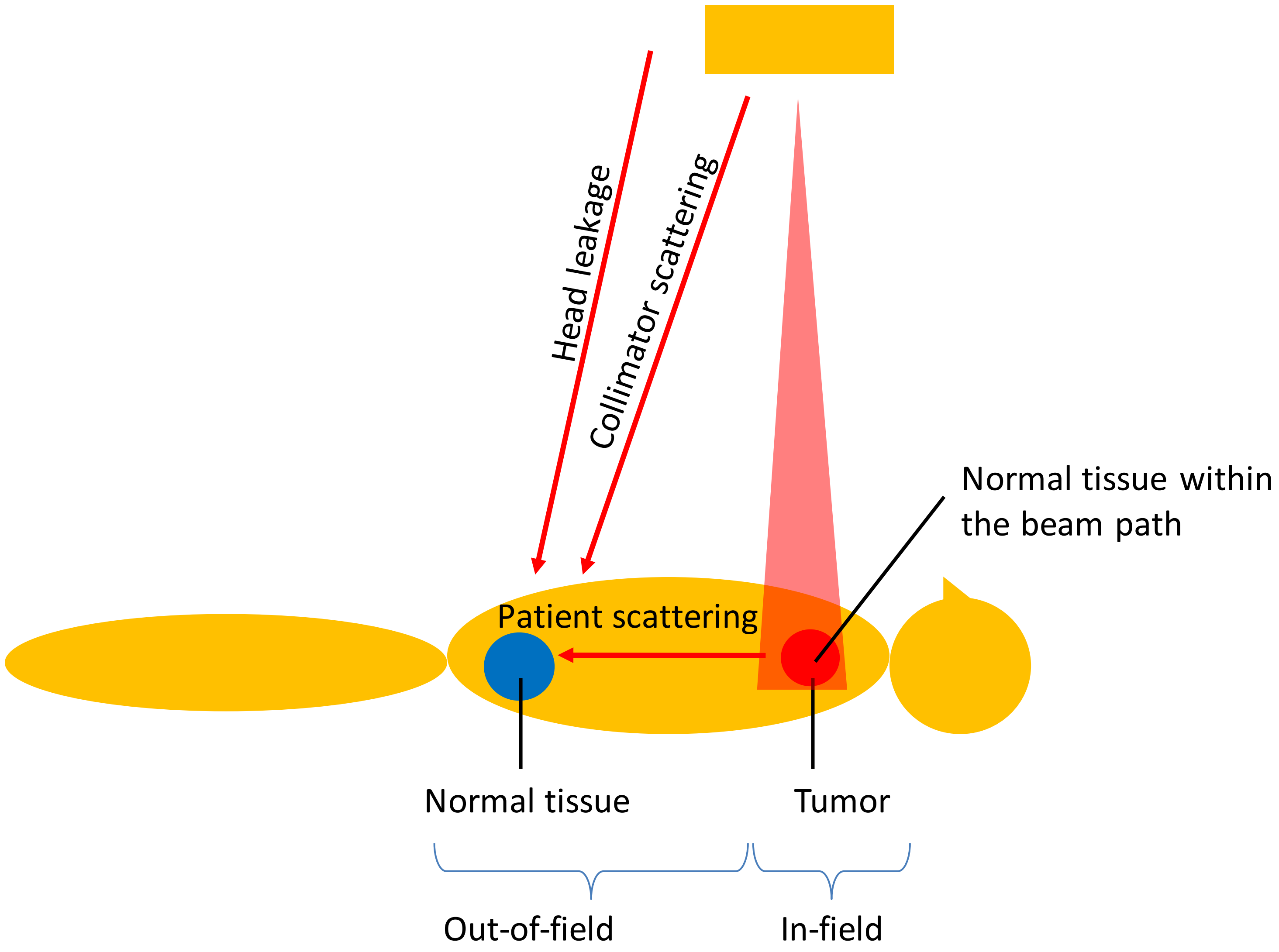
Future Plan

- Further developments
  - NCICT-eXtended: 351 body size dependent phantoms
  - Translation of the original Visual Basic 6.0 (Windows) into Python language (multi platform) in progress
- Release plan
  - Publication on NCICT (Mid 2015)
  - Public release of NCICT from NCI (early 2016)

Content

- Background
- Computational phantoms
- Monte Carlo radiation transport
- Diagnostic radiation dosimetry tools
- **Therapeutic radiation dosimetry tools**

Unintended radiation dose to normal tissues



Therapeutic radiation dosimetry tools

- **Treatment Planning System (in-field dosimetry)**
- Measurement-based methods
- Monte Carlo radiation transport

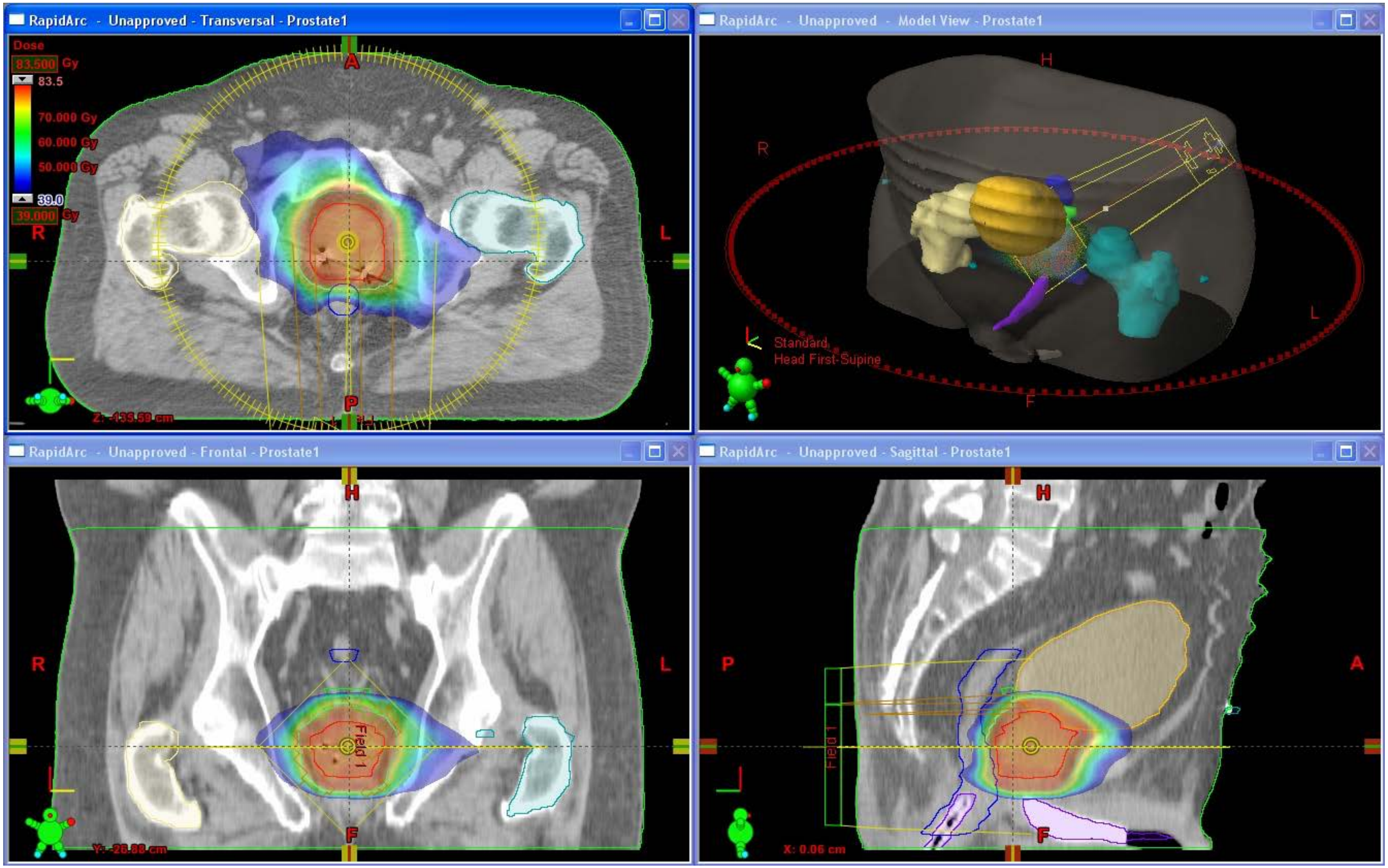
Treatment Planning System

- A computer software to design radiotherapy procedures to maximize tumor dose but minimize normal tissue dose

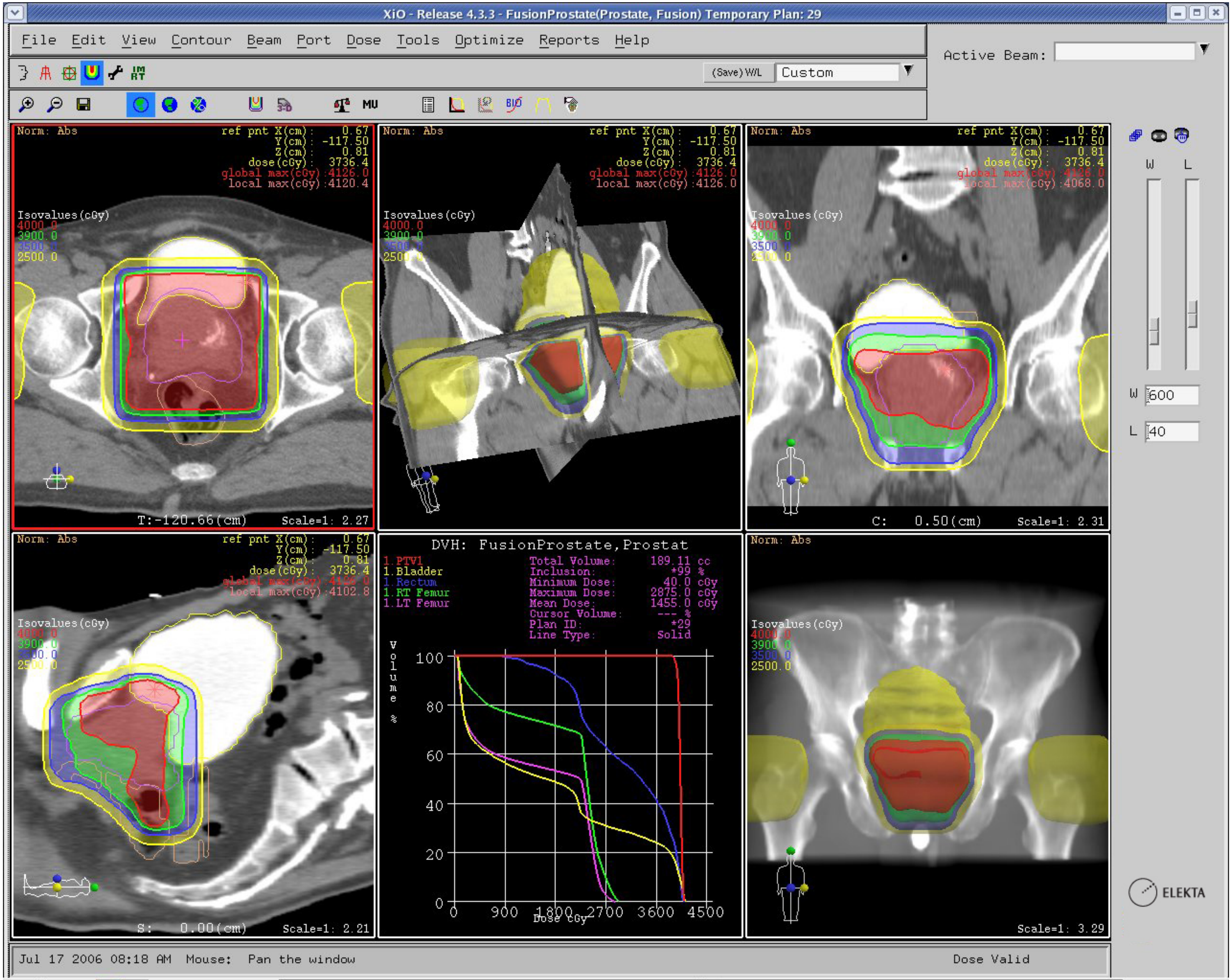
- iPlan (Brainlab)
- XiO (Elekta)
- Pinnacle (Phillips)
- RayStation (RaySearch)
- Eclipse (Varian)

http://www.healthcare.philips.com

Eclipse (Varian Medical System, Inc.)

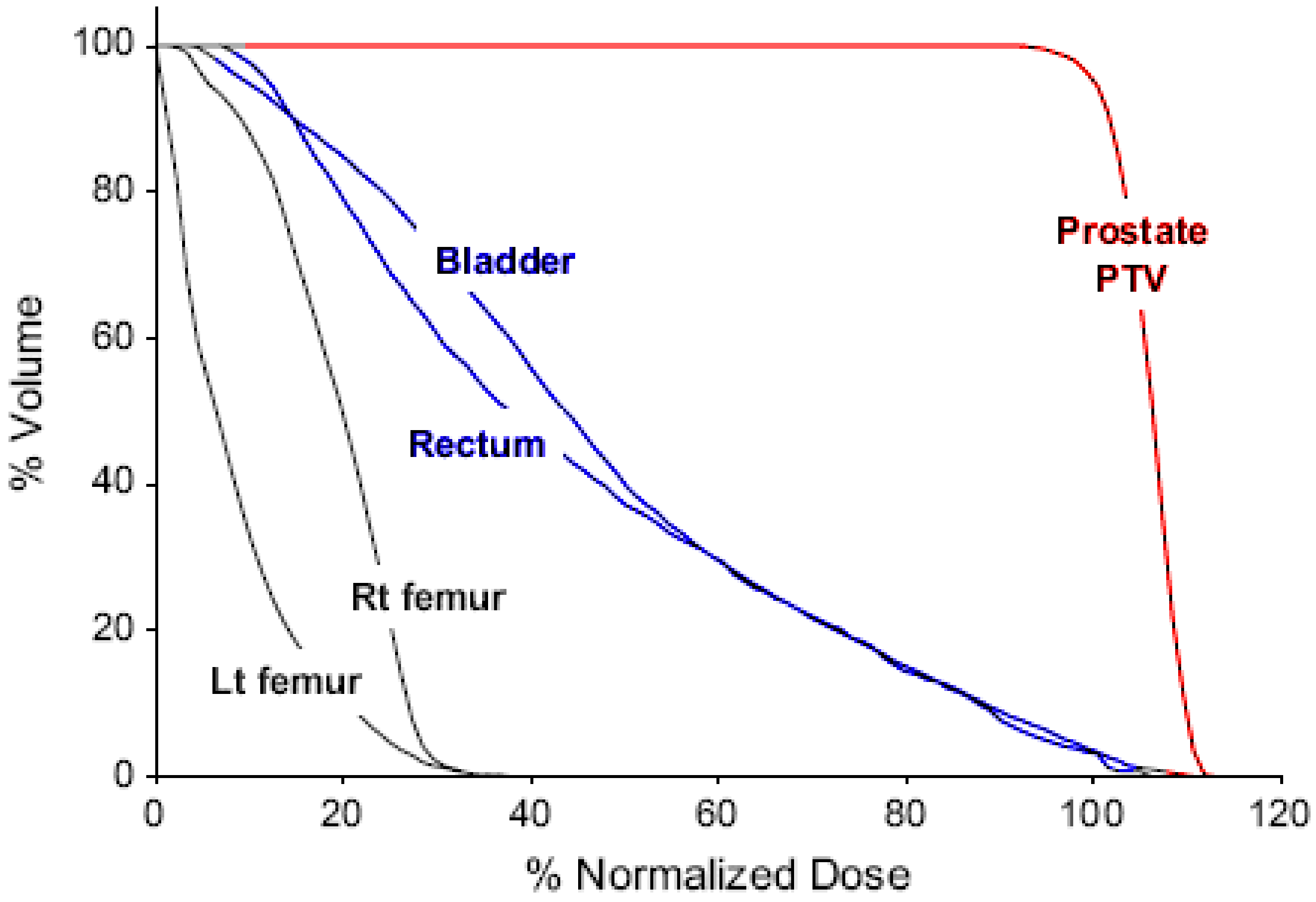


XiO (Elekta)



XiO - Release 4.3.3 - FusionProstate(Prostate, Fusion) Temporary Plan: 29
File Edit View Contour Beam Port Dose Tools Optimize Reports Help
Active Beam:
(Save) W/L Custom
Norm: Abs
ref pnt X(cm): 0.67
Y(cm): -117.50
Z(cm): 0.81
dose(cGy): 3736.4
global max(cGy): 4126.0
Isovalues(cGy)
4000.0
3900.0
3500.0
2500.0
T:-120.66(cm) Scale=1: 2.27
C: 0.50(cm) Scale=1: 2.31
S: 0.00(cm) Scale=1: 2.21
Scale=1: 3.29
DVH: FusionProstate,Prostat
1.PTV1
1.Bladder
1.Rectum
1.RT Femur
1.LT Femur
Total Volume: 189.11 cc
Minimum Dose: 40.0 cGy
Maximum Dose: 2875.0 cGy
Mean Dose: 1455.0 cGy
Plan ID: +29
Line Type: Solid
Volume %
Dose cGy
W 600
L 40
ELEKTA
Jul 17 2006 08:18 AM Mouse: Pan the window
Dose Valid

Dose-volume Histogram

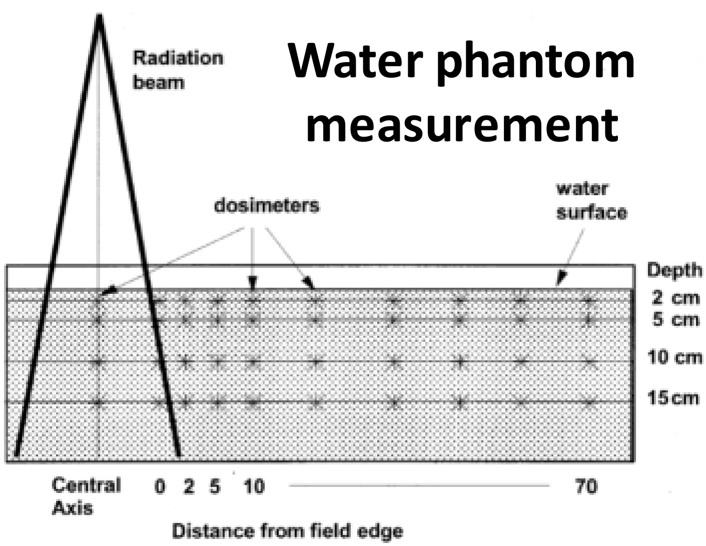


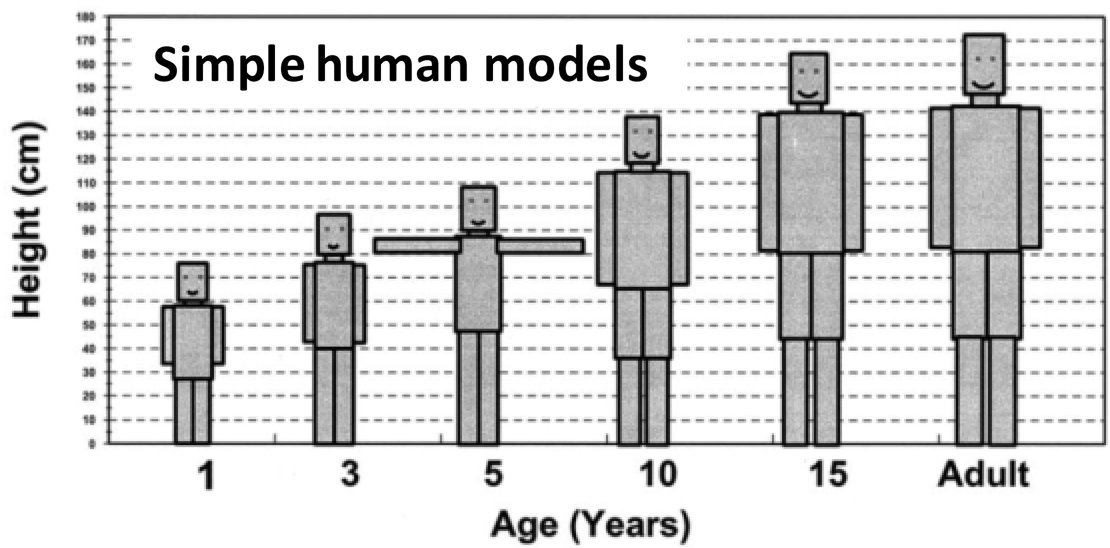
Therapeutic radiation dosimetry tools

- Treatment Planning System
- **Measurement-based methods (out-of-field dosimetry)**
- Monte Carlo radiation transport

Measurement-based methods

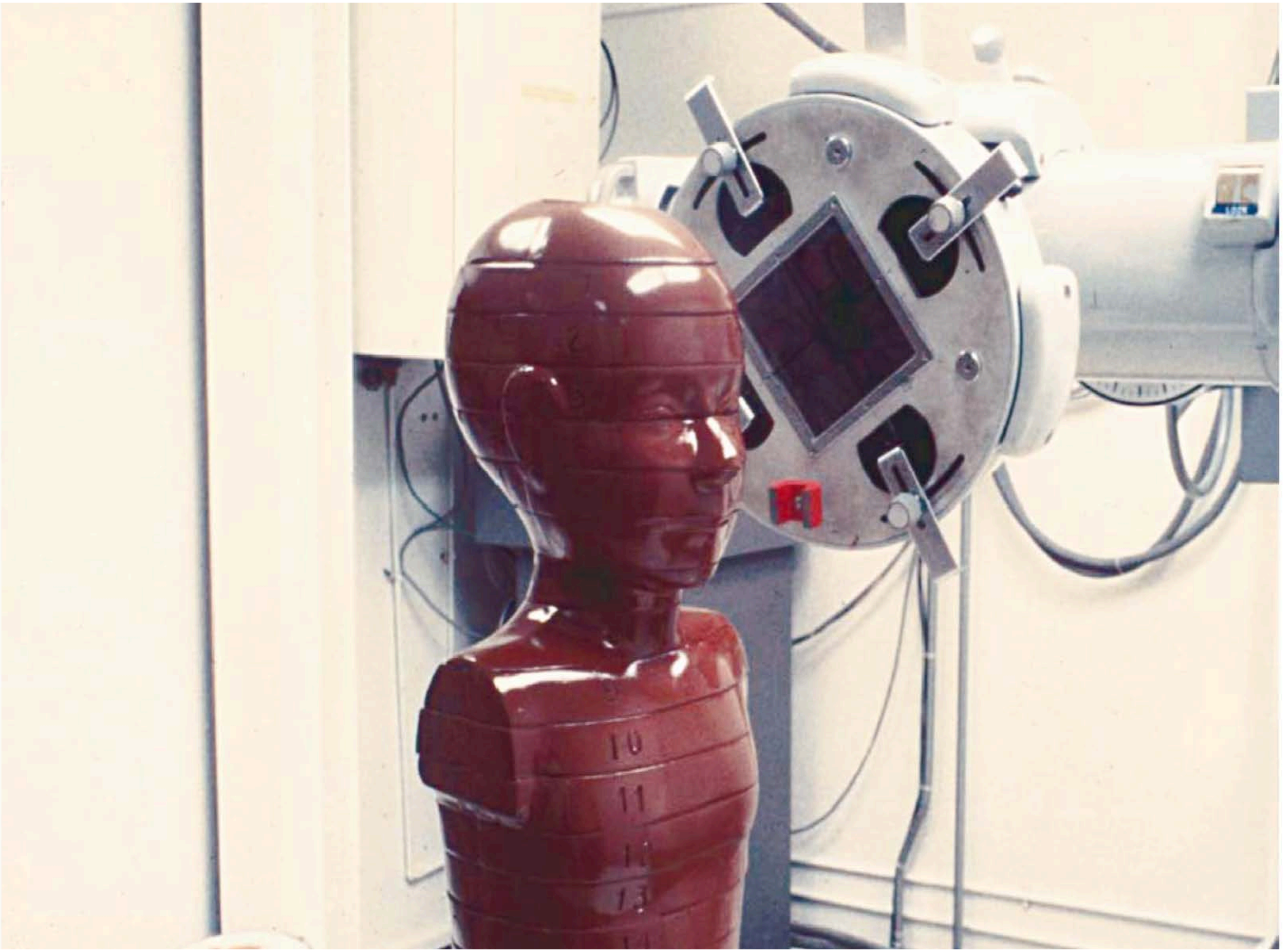
- Based on water phantom measurement
- Computational human models with 3D grids





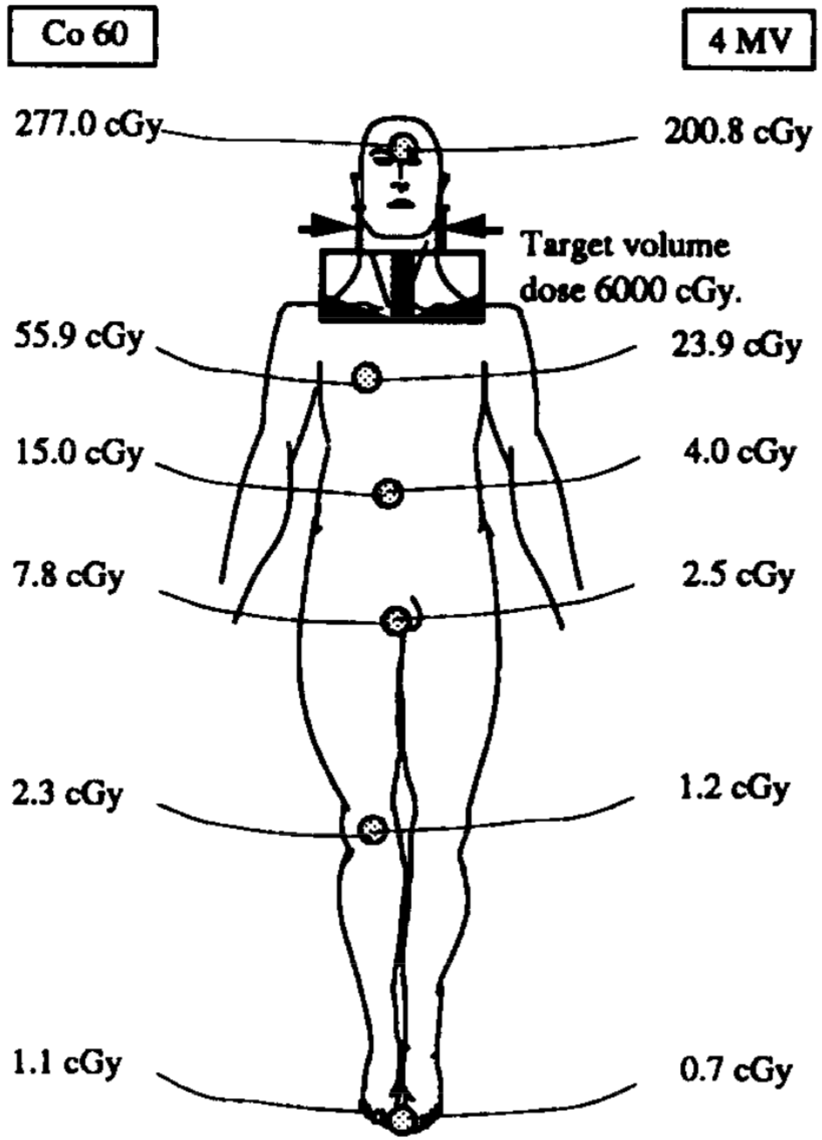
* Stovall et al, Rad Res 2006

Physical phantom to simulate the tonsil irradiation



* Stovall et al, Rad Res 2006

Dos_EG program*



* Diallo et al. Radiotherapy and Oncology 1996

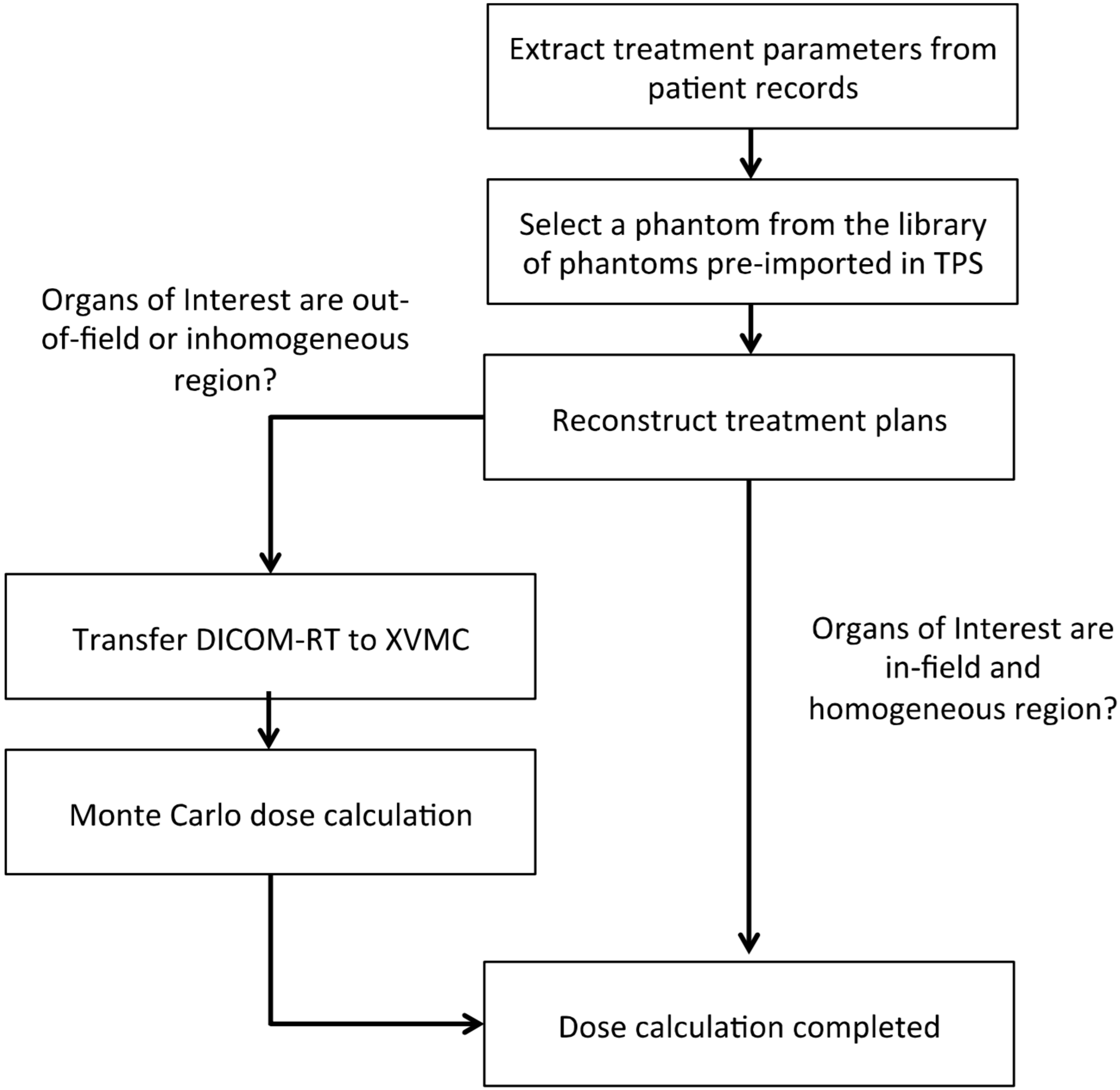
Therapeutic radiation dosimetry tools

- Treatment Planning System
- Measurement-based methods
- **Monte Carlo radiation transport (out-of-field dosimetry)**

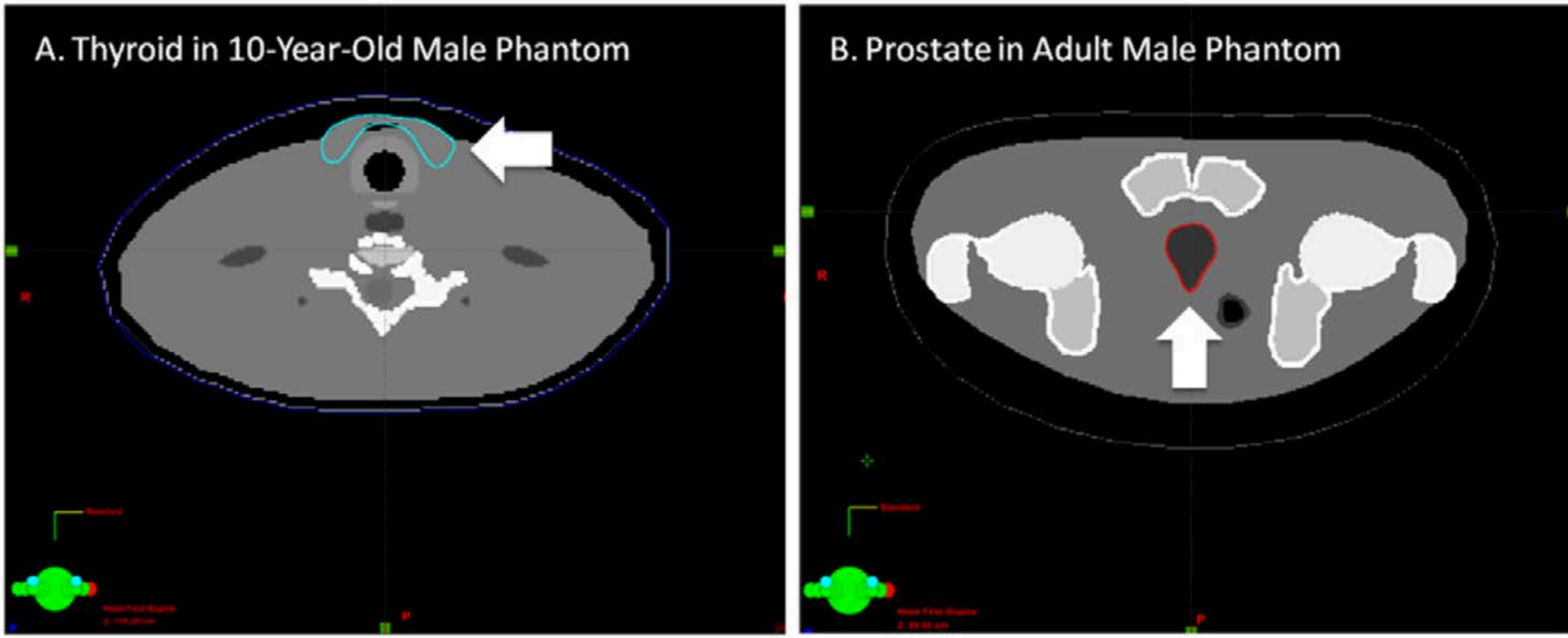
National Cancer Institute Dosimetry Tool for Radiation Treatment: NCIRT*

- Comprehensive dosimetry tool to estimate dose to normal tissues in patients undergoing radiation treatment
- Developed by the multi-institutional consortium
  - National Cancer Institute
  - University of Michigan
  - East Carolina University
  - University of California San Francisco

* Lee et al, Phys Med Biol 2015


Extract treatment parameters from patient records
Select a phantom from the library of phantoms pre-imported in TPS
Organs of Interest are out-of-field or inhomogeneous region?
Reconstruct treatment plans
Transfer DICOM-RT to XVMC
Organs of Interest are in-field and homogeneous region?
Monte Carlo dose calculation
Dose calculation completed

Converted the organ contours in the UF/NCI computational phantoms into DICOM-RT*

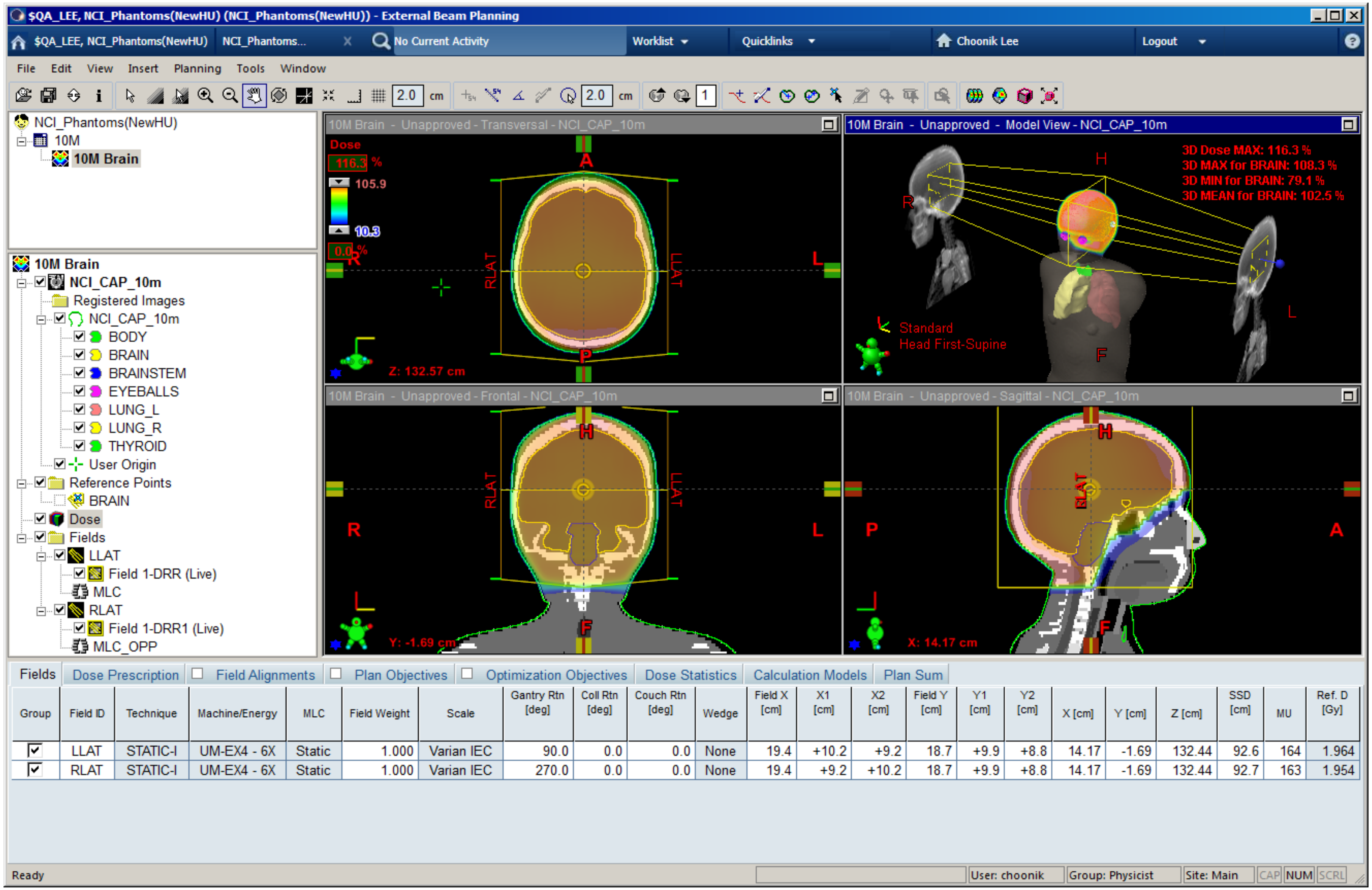


* Pyakuryal et al (in preparation)

Illustrative organ dose calculations

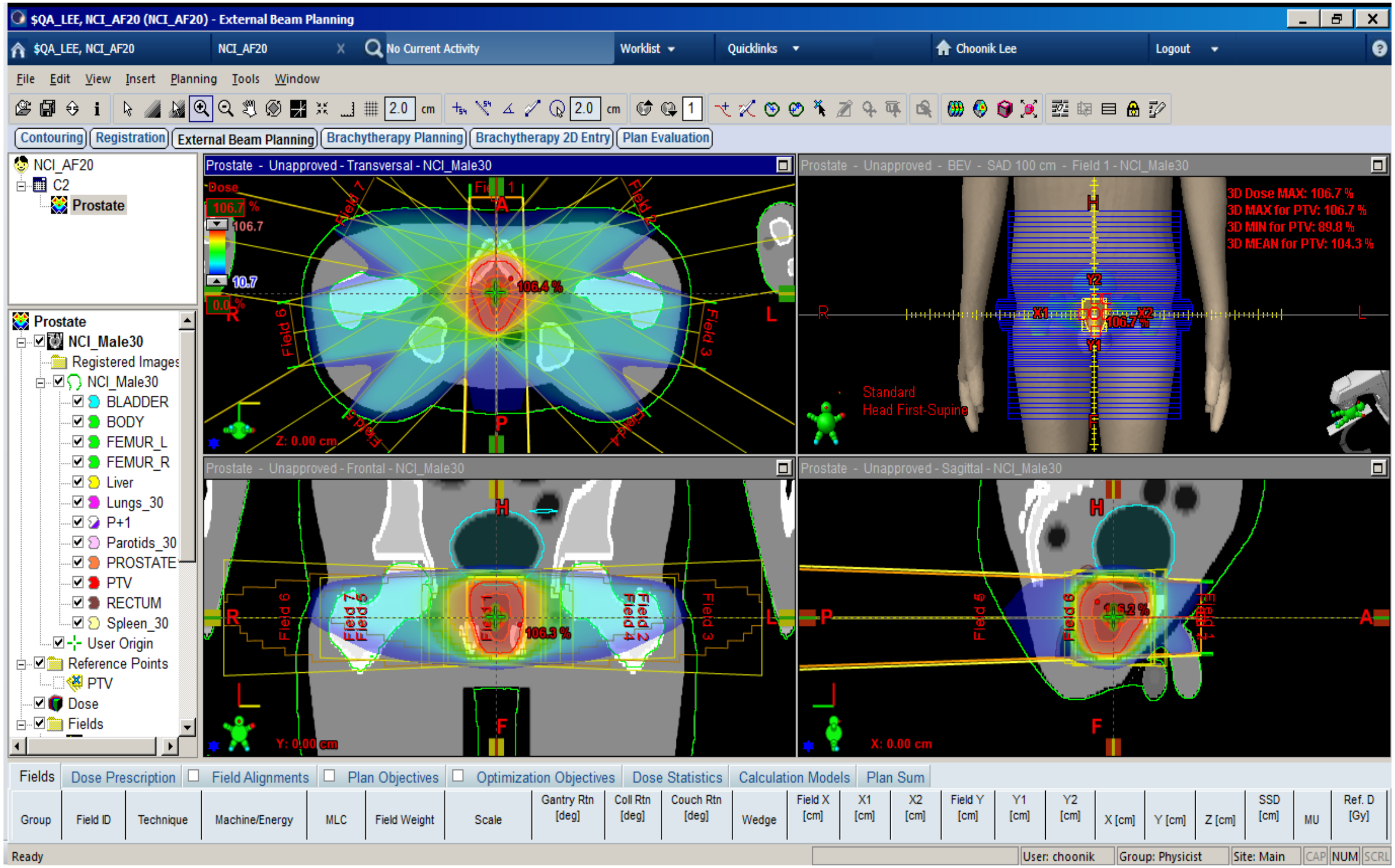
- Two cases of cancer treatment
  - Brain tumor in 10-year-old phantom
  - Prostate cancer in adult male phantom
- Steps
  - Convert 10-year-old male and adult male Hybrid Phantoms
  - Treatment planning and generate DICOM-RT
  - Monte Carlo calculation using DICOM-RT

Treatment plan: 10-year-old brain tumor

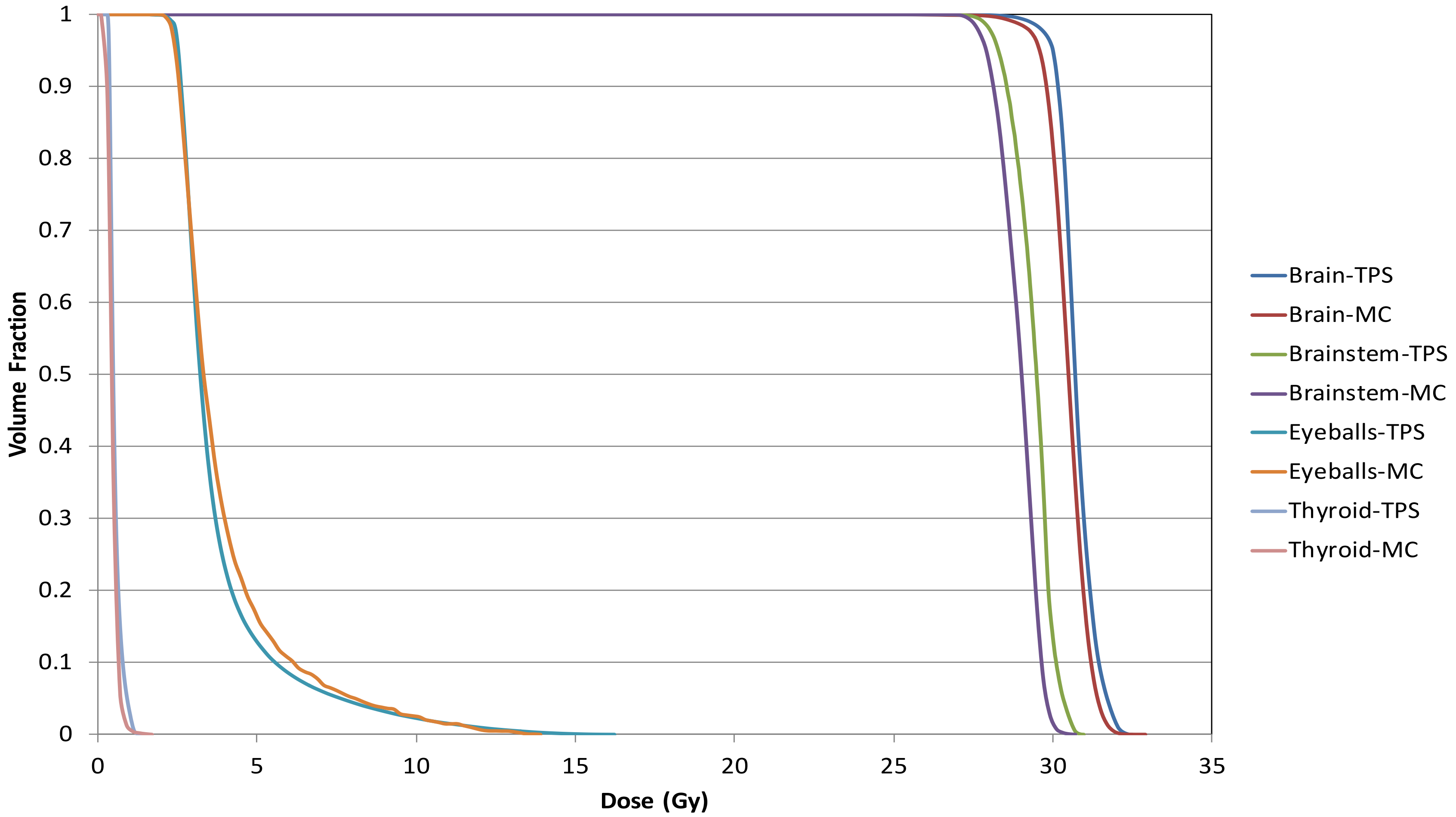


Group	Field ID	Technique	Machine/Energy	MLC	Field Weight	Scale	Gantry Rtn [deg]	Coll Rtn [deg]	Couch Rtn [deg]	Wedge	Field X [cm]	X1 [cm]	X2 [cm]	Field Y [cm]	Y1 [cm]	Y2 [cm]	X [cm]	Y [cm]	Z [cm]	SSD [cm]	MU	Ref. D [Gy]
☑	LLAT	STATIC-I	UM-EX4 - 6X	Static	1.000	Varian IEC	90.0	0.0	0.0	None	19.4	+10.2	+9.2	18.7	+9.9	+8.8	14.17	-1.69	132.44	92.6	164	1.964
☑	RLAT	STATIC-I	UM-EX4 - 6X	Static	1.000	Varian IEC	270.0	0.0	0.0	None	19.4	+9.2	+10.2	18.7	+9.9	+8.8	14.17	-1.69	132.44	92.7	163	1.954

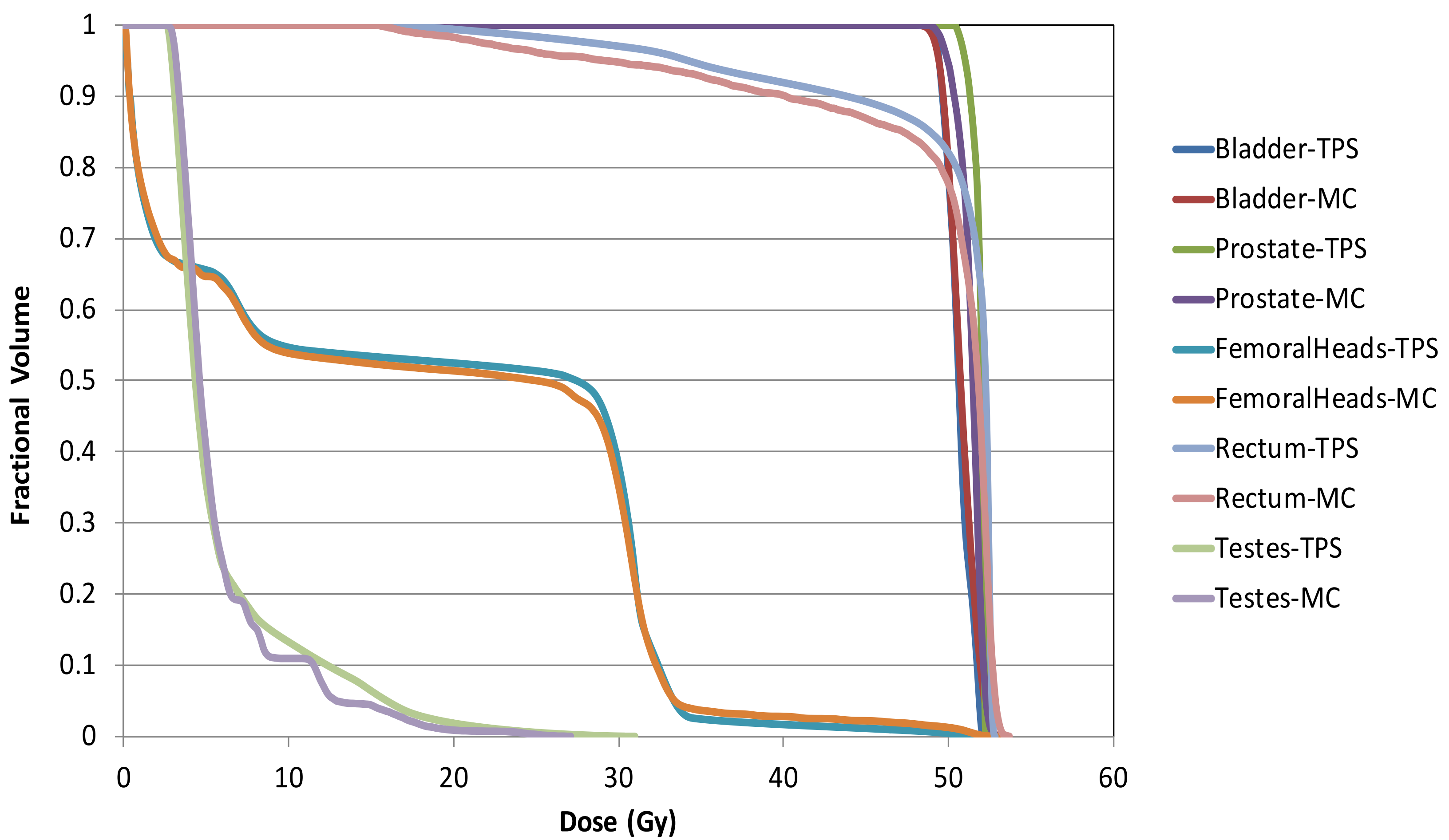
Treatment plan: Adult male prostate tumor



DVH for 10-year-old brain tumor treatment



DVH for adult male prostate tumor treatment



Example of Intensity Modulated Radiation Treatment (IMRT) dose calculations

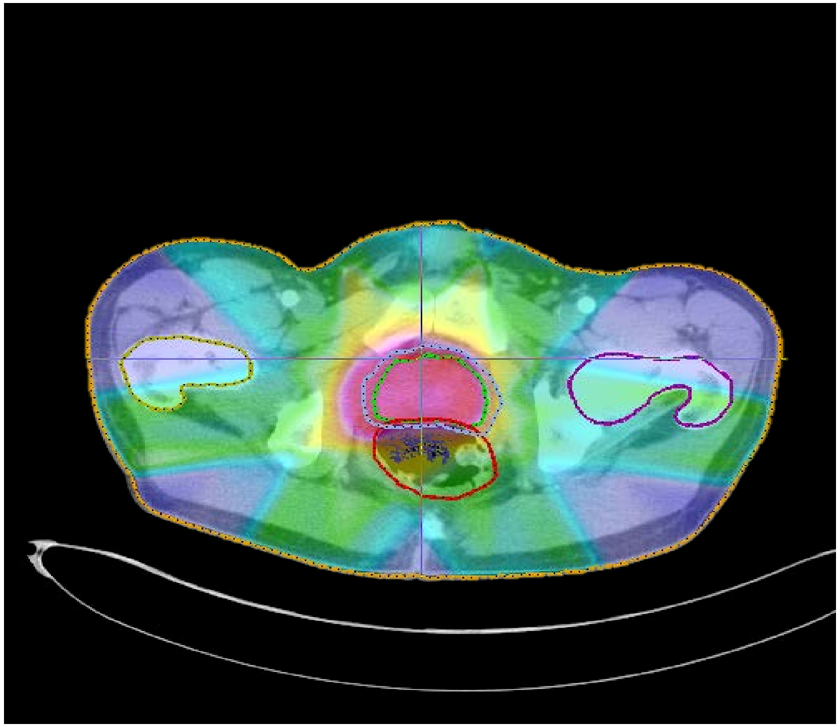


Figure 1: Dose distribution at the isocenter for the 7-field IMRT plan on the patient CT calculated by XVMC.

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

- Background
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Test problem #1

Which one of the following phantoms is most up-to-date?

1. ORNL stylized phantoms
2. GSF pediatric voxel phantoms
3. Hybrid (BREP) phantoms
4. BOMAB phantoms

Test problem #1

Which one of the following phantoms is most up-to-date?

1. ORNL stylized phantoms
2. GSF pediatric voxel phantoms
3. Hybrid (BREP) phantoms (Answer)
4. BOMAB phantoms

Test problem #2

Which is the project you cannot do using Monte Carlo radiation transport codes?

1. Calculate organ dose for CT patients
2. Simulate the aerodynamics of an automotive model
3. Nuclear reactor shielding calculations
4. Calculate normal tissue doses for radiotherapy patients

Test problem #2

Which is the project you cannot do using Monte Carlo radiation transport codes?

1. Calculate organ dose for CT patients
2. Simulate the aerodynamics of an automotive model (answer)
3. Nuclear reactor shielding calculations
4. Calculate normal tissue doses for radiotherapy patients

Test problem #3

You want to calculate stomach dose for a radiography patient. You have a stomach dose coefficient, 4 mGy/mGy, and the measurement of entrance air kerma, 5 mGy. What is the stomach dose?

1. 40 mGy
2. 30 mGy
3. 20 mGy
4. 10 mGy

Test problem #3

You want to calculate stomach dose for a radiography patient. You have a stomach dose coefficient, 4 mGy/mGy, and the measurement of entrance air kerma, 5 mGy. What is the stomach dose?

1. 40 mGy
2. 30 mGy
3. 20 mGy (answer)
4. 10 mGy

Test problem #4

Which of the following dose descriptors will you see on a CT scanner console?

1. Air kerma (mGy)
2. Dose-Area Product (mGy-cm^2)
3. $CTDI_{vol}$ (mGy)
4. Effective dose (mSv)

Test problem #4

Which of the following dose descriptors will you see on a CT scanner console?

1. Air kerma (mGy)
2. Dose-Area Product (mGy-cm^2)
3. $CTDI_{vol}$ (mGy) (answer)
4. Effective dose (mSv)

Test problem #5

Which of the following radiation sources can you ignore in normal tissue dose for radiotherapy patient?

1. Scatter radiation from machine head
2. Scatter radiation from beam collimation
3. Scatter radiation from the patient him/herself
4. Scatter radiation from the treatment room wall

Test problem #5

Which of the following radiation sources can you ignore in normal tissue dose for radiotherapy patient?

1. Scatter radiation from machine head
2. Scatter radiation from beam collimation
3. Scatter radiation from the patient him/herself
4. Scatter radiation from the treatment room wall (answer)

Questions and Answers

U.S. Department of Health and Human Services
National Institutes of Health | National Cancer Institute
www.dceg.cancer.gov/RadEpiCourse
1-800-4-CANCER
Produced May 2015