Reference Organ and Effective Dose Coefficients for Common Radiographic Examinations

Calculation of Dose Coefficients
Webinar
22 July 2024

Please let us know what you think!

Yeon Soo Yeom, Ph.D.

Contents

- *Reference phantoms – Chapter 2*
- *Dose coefficients for monoenergetic photons – Chapter 4*
- *Dose coefficients for example X-ray spectra – Chapter 5*

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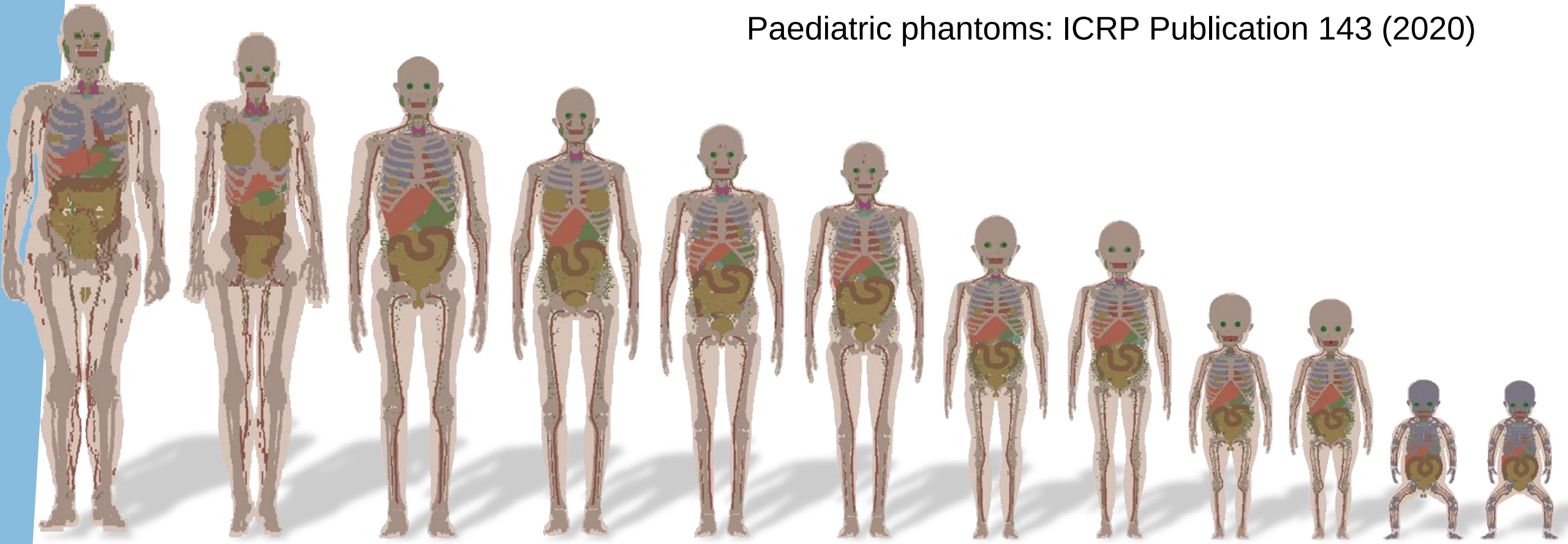
Reference Phantoms

Adult phantoms: ICRP Publication 110 (2009)

Paediatric phantoms: ICRP Publication 143 (2020)



Adult MF | 15MF | 10MF | 5MF | 1MF | 00MF

M: Male; F: Female

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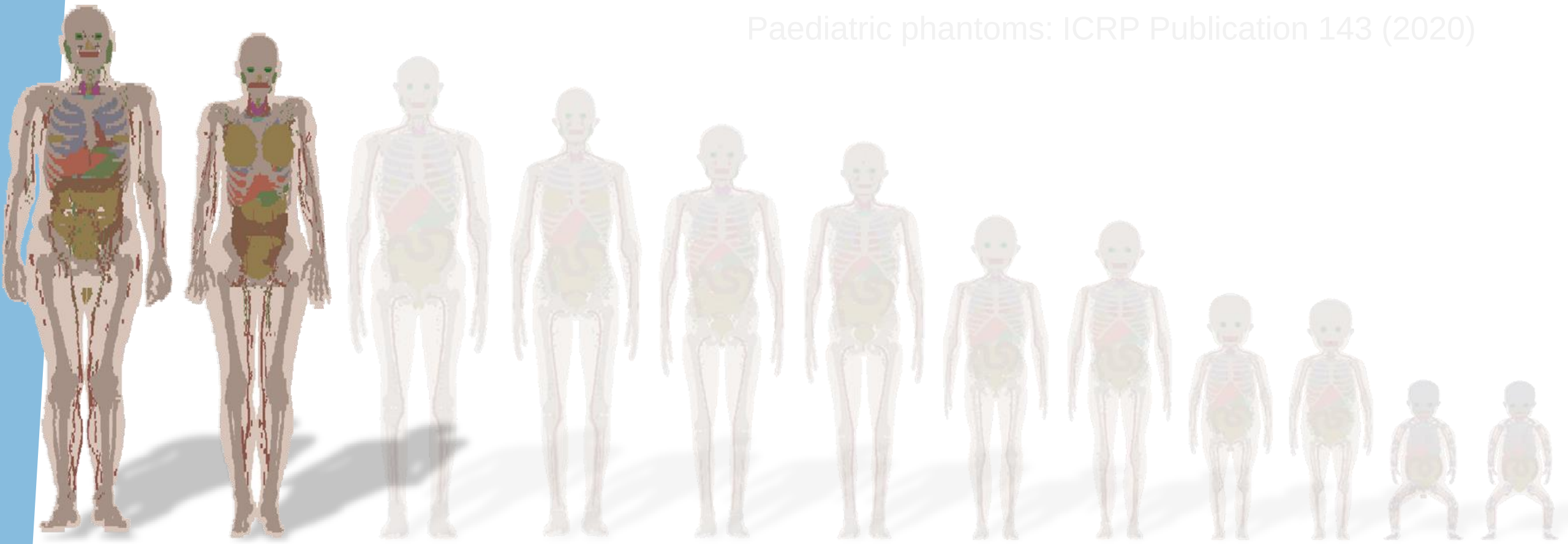

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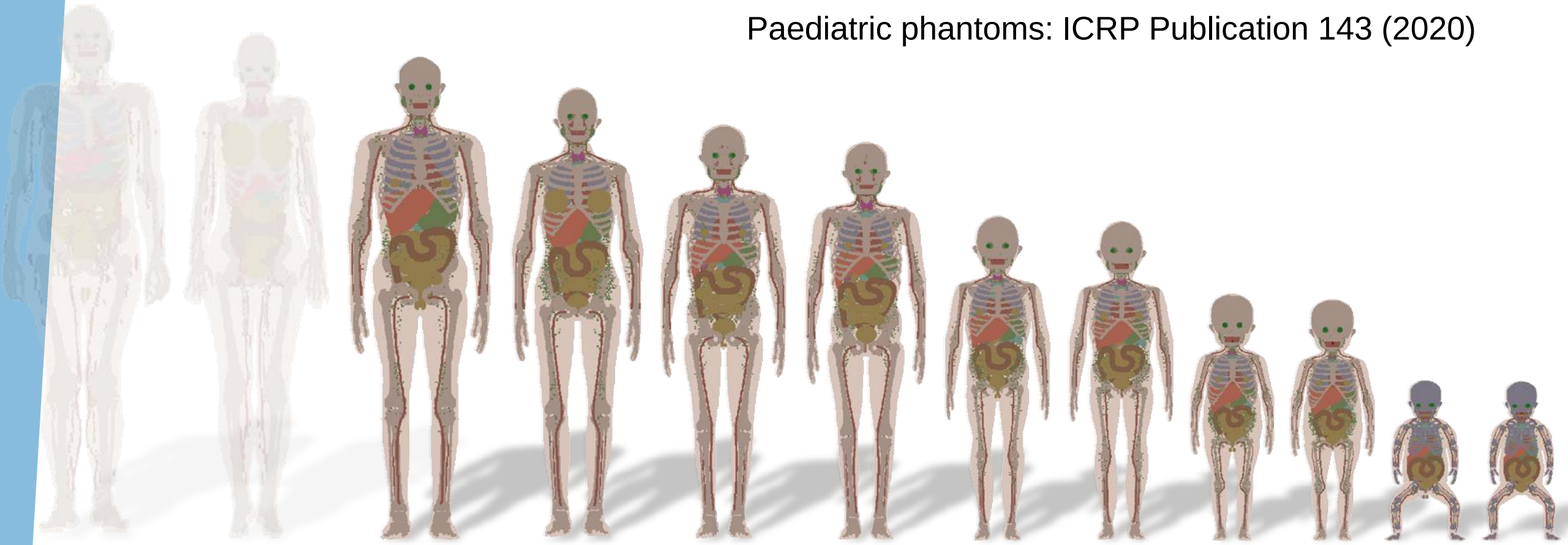

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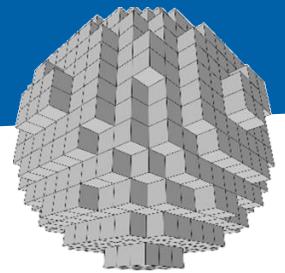
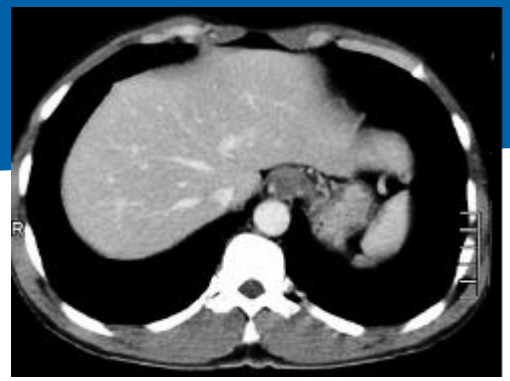
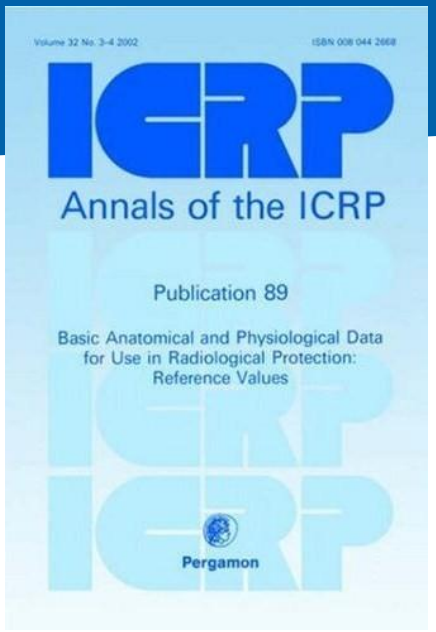
Reference Phantoms



Voxel model



CT images



ICRP P89 (2002)

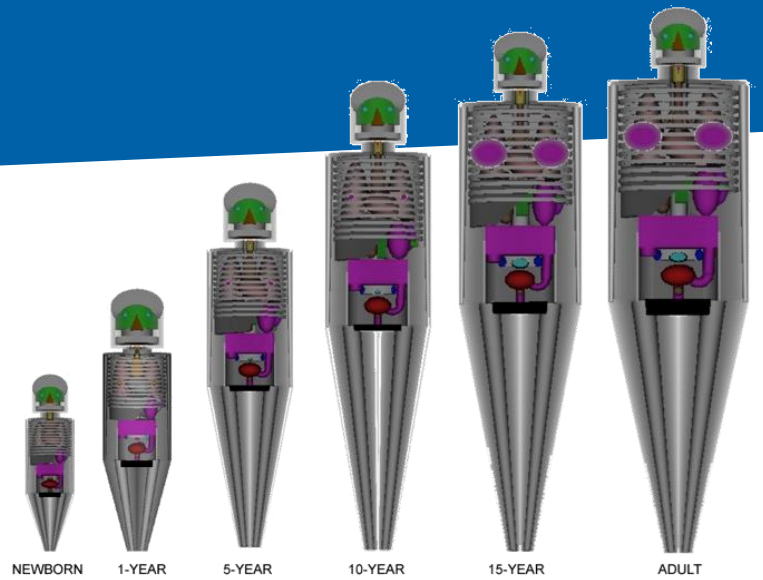
Adult MF **15MF** **10MF** **5MF** **1MF** **00MF**

ICRP *M: Male; F: Female*

ICRP P110 (2009) and P143 (2020)

Reference Phantoms

- **Significant improvement of anatomy and dosimetry** against mathematical phantoms (used prior to ICRP103 Recommendations)



ORNL TM-8381 (1987)

Adult MF **15MF** **10MF** **5MF** **1MF** **00MF**

M: Male; F: Female

ICRP P110 (2009) and P143 (2020)

Reference Phantoms – Numerical Information

	Voxel array			Voxel size (mm)			Standing height (cm)*	Body mass (kg)*
	Columns	Rows	Slices	X	Y	Z		
Adult M	245	127	222	2.137	2.137	8.000	176	73
Adult F	299	137	348	1.775	1.775	4.840	163	60
15-year M	407	225	586	1.250	1.250	2.832	167	56
15-year F	401	236	571	1.200	1.200	2.828	161	53
10-year M/F	419	226	576	0.990	0.990	2.425	138	32
5-year M/F	419	230	572	0.850	0.850	1.928	109	19
1-year M/F	393	248	546	0.663	0.663	1.400	76	10
Newborn M/F	345	211	716	0.663	0.663	0.663	51	3.5

**Reference values of ICRP Publication 89 (2002)*

Reference Phantoms – Organs and Tissues

Red bone marrow (RBM)
Colon
Lung
Stomach
Breast
Gonads
Urinary bladder
Oesophagus
Liver
Thyroid
Bone surface (endosteum)
Brain
Salivary glands
Skin

Adrenals
Extrathoracic (ET) region
Gall bladder
Heart
Kidneys
Lymphatic nodes
Muscle
Oral mucosa
Pancreas
Prostate (male only)
Small intestine
Spleen
Thymus
Uterus/cervix (female only)
Eye lens

- All organs and tissues considered at risk of stochastic and/or deterministic effects in the current ICRP Recommendations[1]
- Organ/tissue masses matched to the ICRP-89 reference values[2]
- Skeletal tissues ***implicitly*** included in the reference phantoms[3,4]

[1] *ICRP Publication 103 (2007)*
[2] *ICRP Publication 89 (2002)*
[3] *ICRP Publication 110 (2009)*
[4] *ICRP Publication 143 (2020)*

Reference Phantoms – Organs and Tissues

Red bone marrow (RBM)
Colon
Lung
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Urinary bladder
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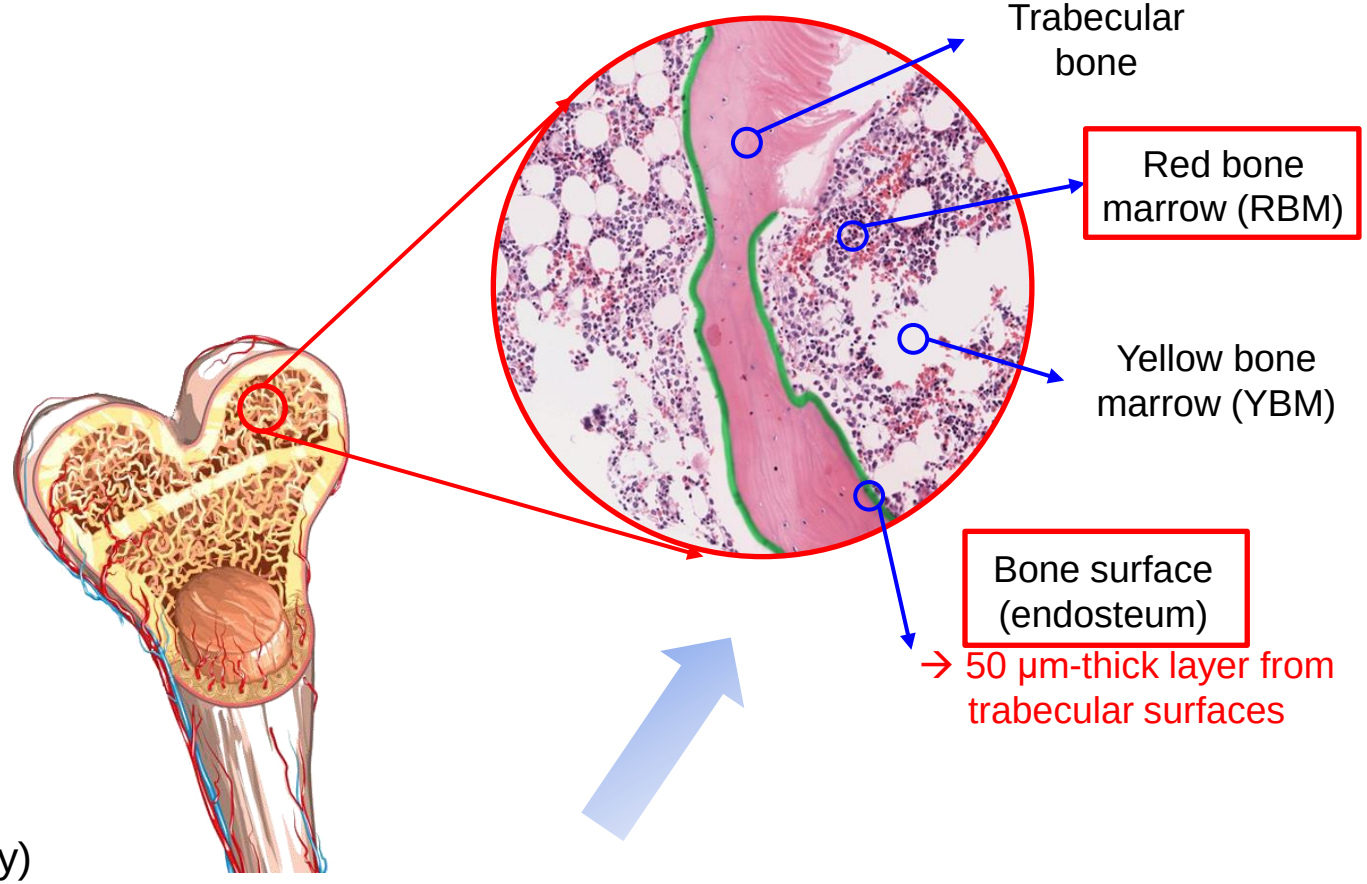

Highly complex and microscopic structures cannot be explicitly defined in the phantoms

Reference Phantoms – Organs and Tissues

Red bone marrow (RBM)	Adrenals
Colon	Extrathoracic (ET) region
Lung	Gall bladder
Stomach	Heart
Breast	Kidneys
Gonads	Lymphatic nodes
Urinary bladder	Muscle
Oesophagus	Oral mucosa
Liver	Pancreas
Thyroid	Prostate (male only)
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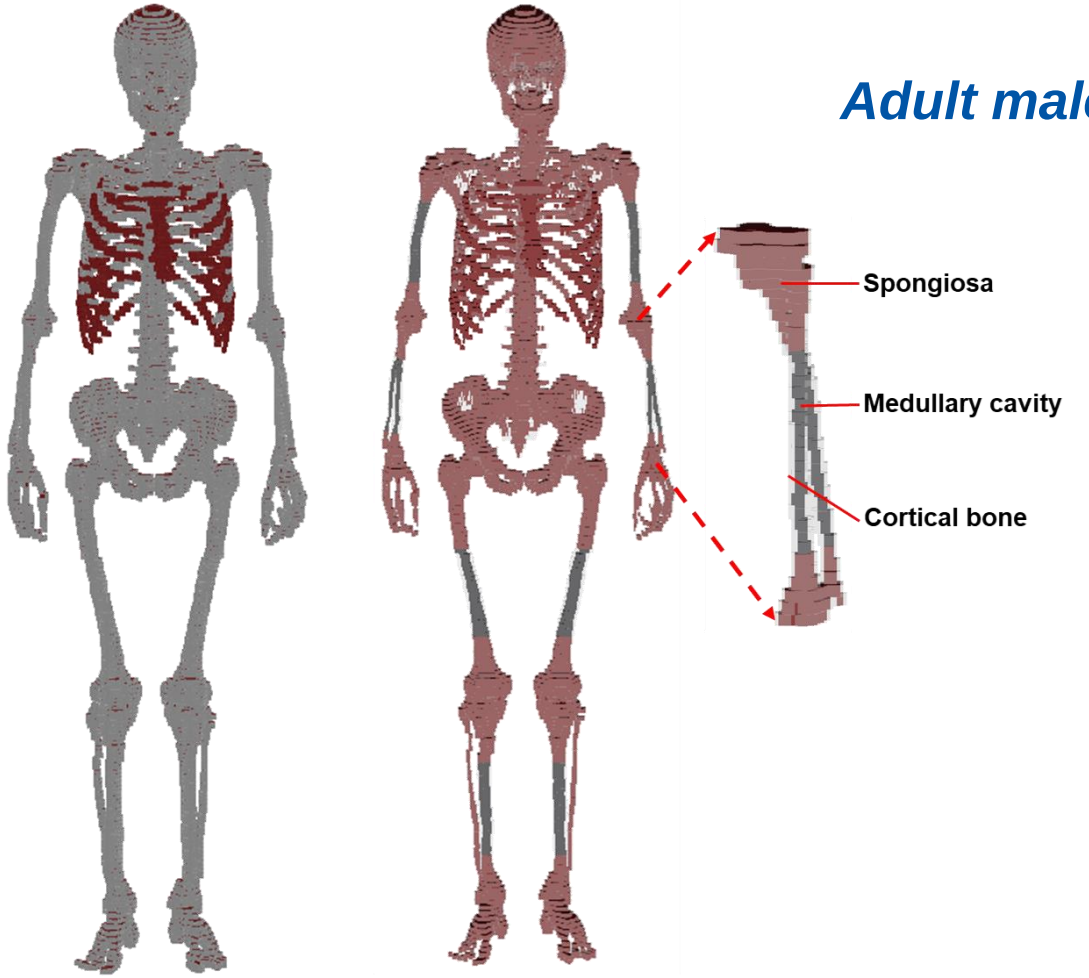

Macroscopic skeletal regions (cortical bone, spongiosa, and medullary cavity) defined in the phantoms → ***special consideration*** needed for skeletal dosimetry

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Dose coefficients for Monoenergetic Photons

- Air kerma per fluence at 1 m from source (Gy cm^2)
- Organ absorbed dose per fluence at 1 m from source (Gy cm^2)
- $\sum w_T \times H_T^M$ ($E_{103, M}$) or $\sum w_T \times H_T^F$ ($E_{103, F}$) per fluence at 1 m from source (Sv cm^2)

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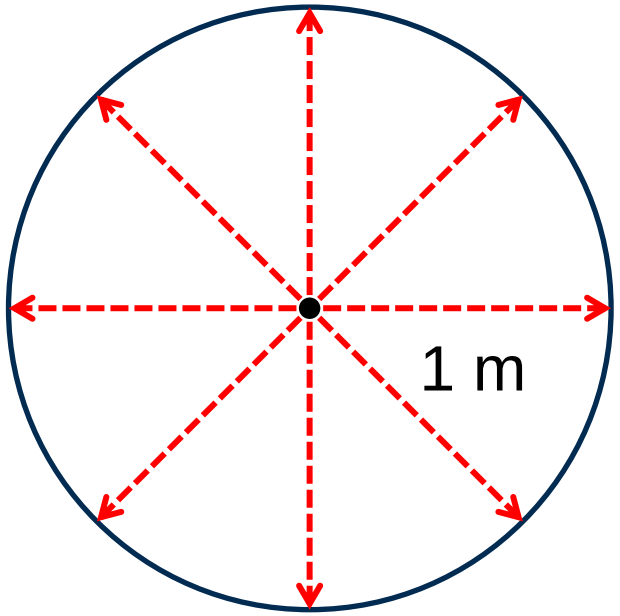

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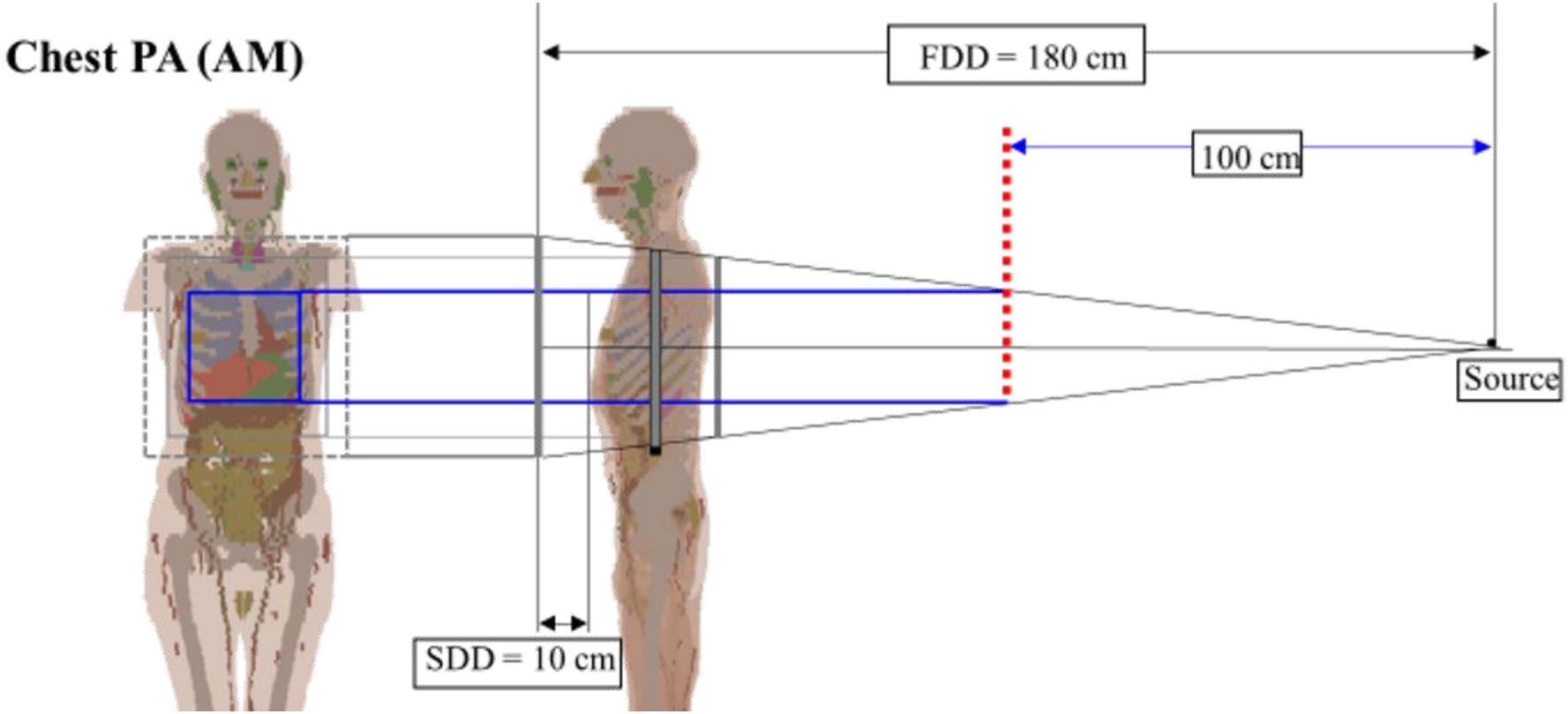

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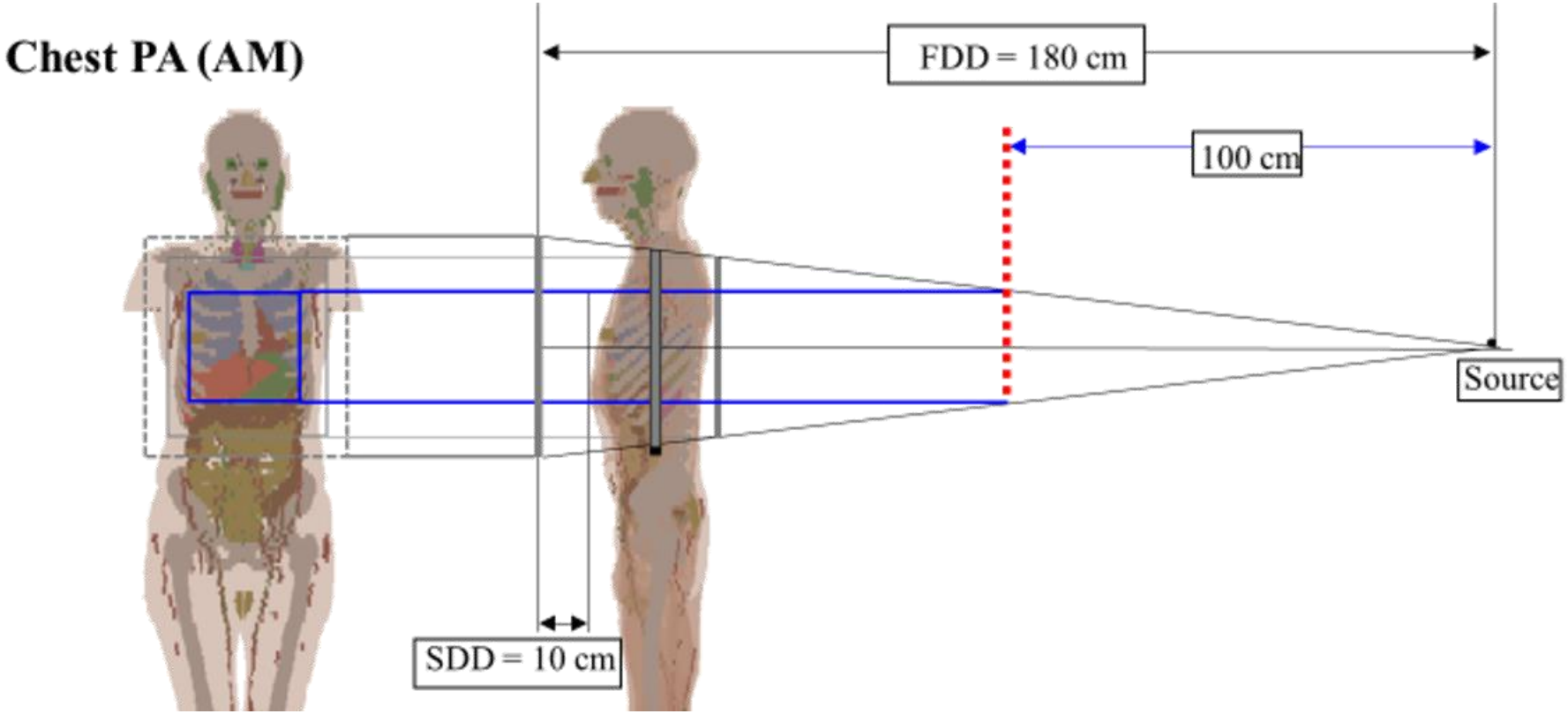


Different Posture between Phantom and Patient

For some imaging examinations, e.g., chest LAT, patients raised their arms

Different Posture between Phantom and Patient

For some imaging examinations, e.g., chest LAT, patients raised their arms

Adult MF | 15MF | 10MF | 5MF | 1MF | 00MF

ICRP *M: Male; F: Female*

Reference Phantoms without Arms

For some imaging examinations, e.g., chest LAT, patients raised their arms

Adult MF | 15MF | 10MF | 5MF | 1MF | 00MF

M: Male; F: Female

Table 4.1 *shows which examinations were simulated using the phantoms w/wo arms*

Monte Carlo Dose Calculations

❖ **Adult dose coefficients**

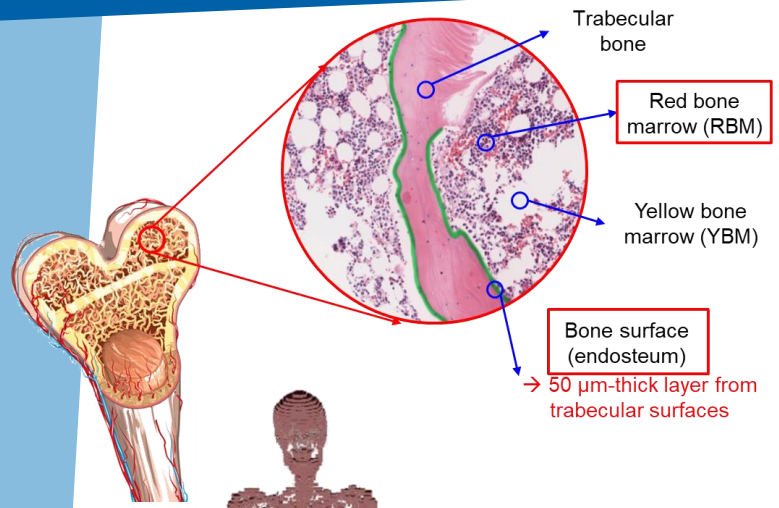
EGSnrc

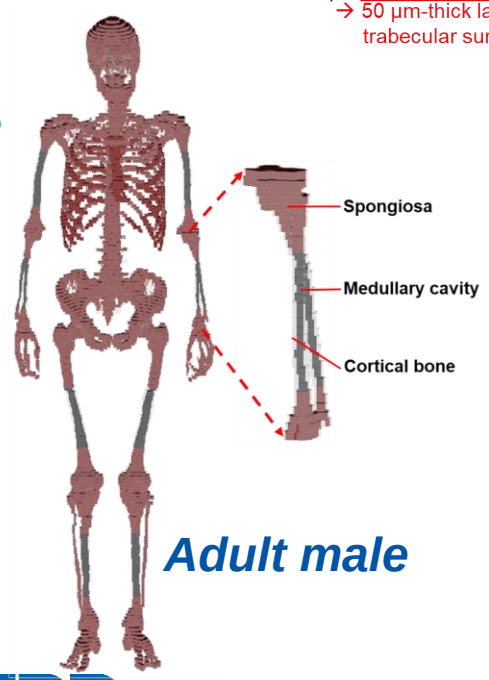
- Monte Carlo code: EGSnrc (ver. 4-2-3-1)
- Cross section library: XCOM database (Berger and Hubbell, 1987)
- Photon energy: 3-150 keV with 1-keV step
- Number of primary photons: 10^7
- Particles transported: photons and secondary electrons

❖ **Paediatric dose coefficients**

- Monte Carlo code: Geant4 (ver. 10.7.p03)
- Cross section library: Livermore data library (Perkins et al., 1991; Cullen et al., 1997)
- Photon energy: 1-80 keV (newborn), 1-90 keV (1 year), 1-100 keV (5 year), 1-110 keV (10 year), 1-120 keV (15 year) with 1-keV step
- Number of primary photons: 10^8
- Particles transported: photons and secondary electrons

Skeletal Dosimetry (RBM and Bone Surface)





Adult male

Derived based on micron-CT skeletal images

$$D(AM\ or\ TM_{50}, x) = \int_E DRF(E, AM\ or\ TM_{50}, x)\ \Phi(E, x)\ dE$$

Computed by MC simulation using the phantom

AM	:	Active bone marrow (i.e., red bone marrow)
TM_{50}	:	Bone surface (endosteum)
x	:	Bone site (e.g., upper humeri spongiosa)
$D(AM\ or\ TM_{50}, x)$	:	Bone-site-specific absorbed dose to AM or TM_{50}
$\Phi(E, x)$	:	Bone-site-specific energy-dependent fluence at bone site x
$\mathrm{DRF}(\mathrm{E}, AM\ or\ TM_{50}, x)$	:	Bone-site-specific energy-dependent **photon fluence-to-skeletal dose response functions (DRFs)** at bone site x

- **ICRP P116 (2010) – skeletal dosimetry method using DRFs**
- **Annex C in the report – practical implementation method in Monte Carlo codes (MCNP, Geant4, PHITS, EGSnrc)**
- **ICRP P155 (in press) – tabulation of the DRF values for both adult and pediatric phantoms**

Examples of Monoenergetic Dose Coefficients

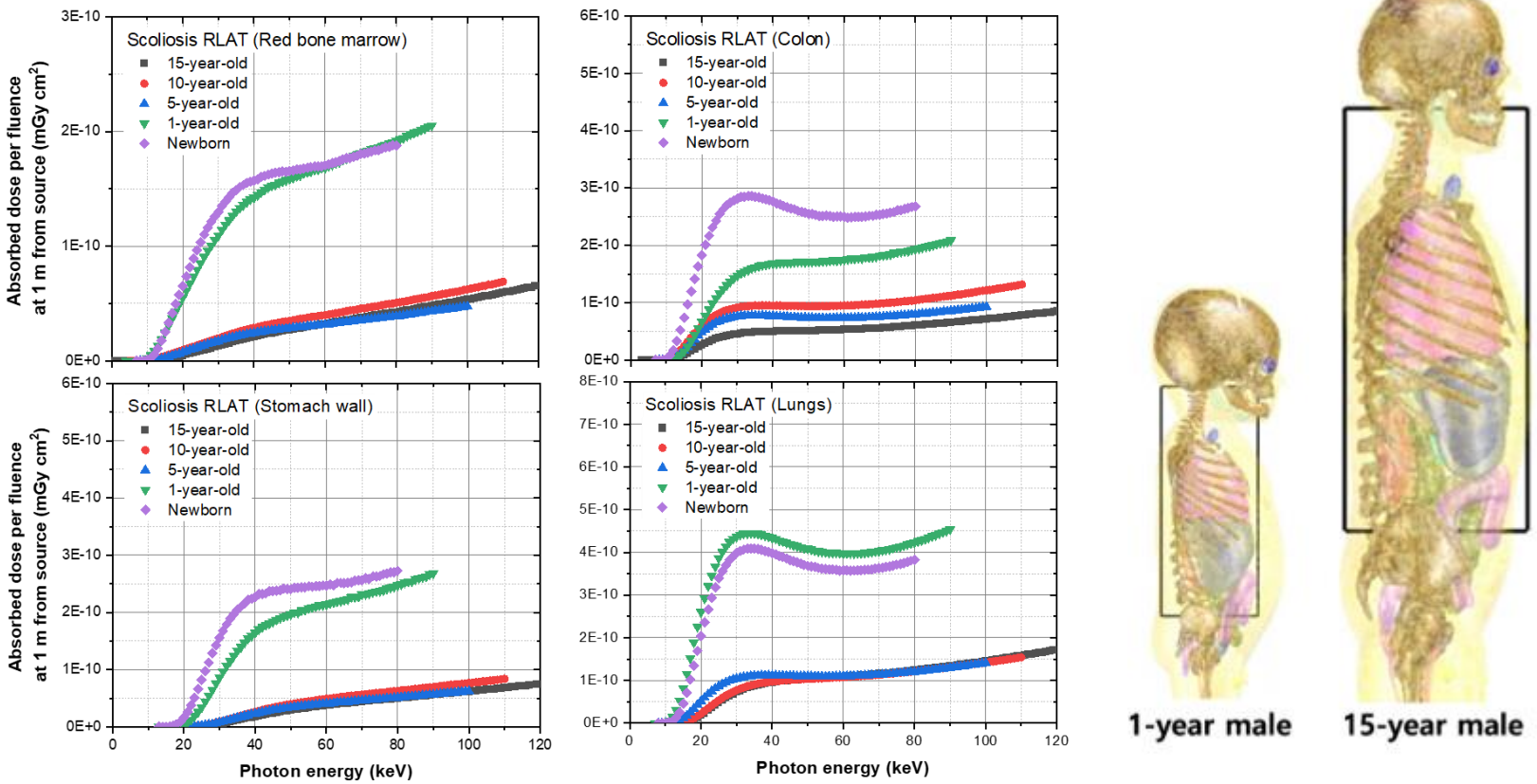


Fig. 4.2. Left: Absorbed dose per fluence at 1 m from the source, for red bone marrow, colon, stomach, and lungs, as a function of photon energy for scoliosis right lateral projection and male paediatric reference phantoms. Right: schematic representation of the irradiation fields showing anatomical landmarks on the 1- and 15-year-old male phantoms.

All DCs will be provided in the electronic supplement!!!

Spot-check Calculations for Quality Assurance

- **For quality assurance, the dose coefficients from the primary calculations compared with those from additional calculations for some selected examinations (spot-check calculations)**

✓ **Adult dose coefficients:** Primary (EGSnrc) vs Spot-check (Geant4)

✓ **Paediatric dose coefficients:** Primary (Geant4) vs Spot-check (EGSnrc / Geant4)

Examples of Quality Assurance Results

Adult female
(Pelvic AP, 100 keV)

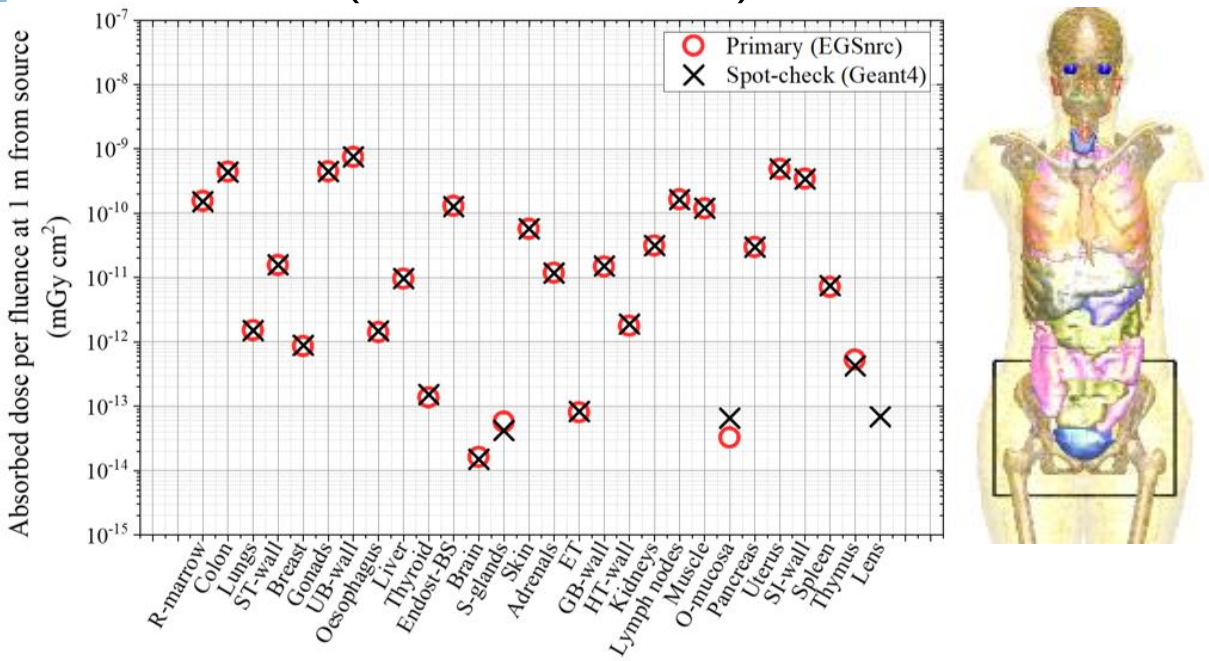


Fig. 4.3. Organ absorbed dose coefficients for a pelvis anterior-posterior examination on the adult female reference phantom for 100 keV photons, as calculated with EGSnrc and GEANT4 codes. The red circles show the data of the primary calculations and the black crosses those of the spot checks (in most cases the two are superimposed).

Primary (EGSnrc) vs Spot-check (Geant4)

Newborn male
(Chest AP, 50 keV)

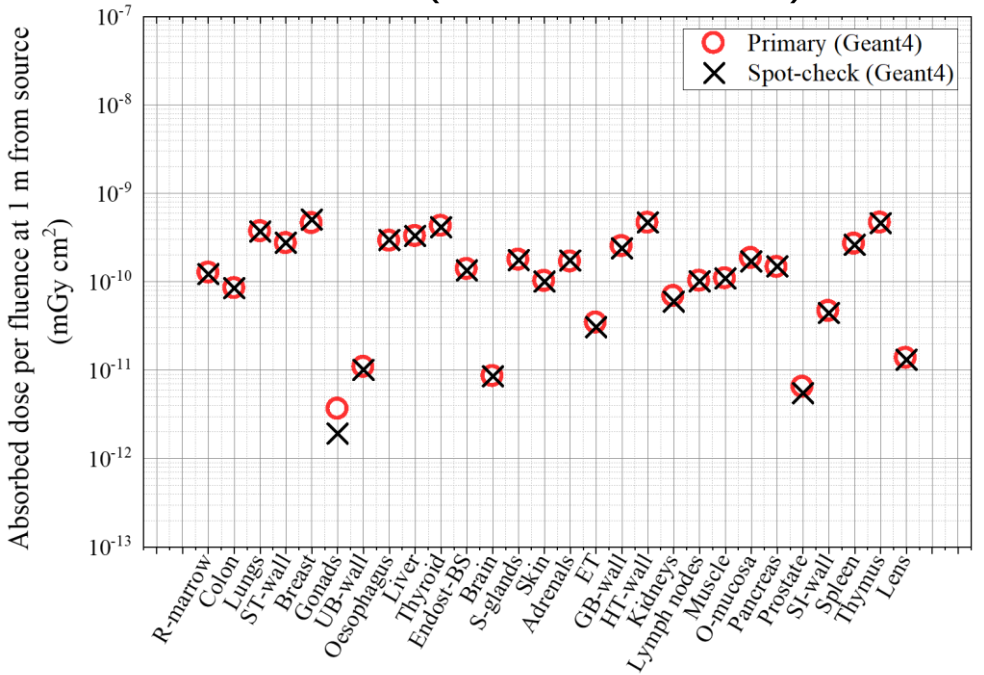


Fig. 4.4. Organ absorbed dose coefficients for a chest anterior-posterior examination on the newborn male reference phantom and 50 keV photons, calculated with the GEANT4 code by two different calculators. The red circles show the data of the primary calculations and the black crosses those of the spot checks (in most cases the two are superimposed).

Primary (Geant4) vs Spot-check (Geant4)

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Dose Coefficients for X-ray Spectra

- Air kerma per fluence at 1 m from source (Gy cm^2)

- Organ absorbed dose per fluence at 1 m from source (Gy cm^2)
- Organ absorbed dose per air kerma at 1 m from source (Gy Gy^{-1})
- Organ absorbed dose per kerma area product (KAP) (Gy Gy^{-1} cm^{-2})

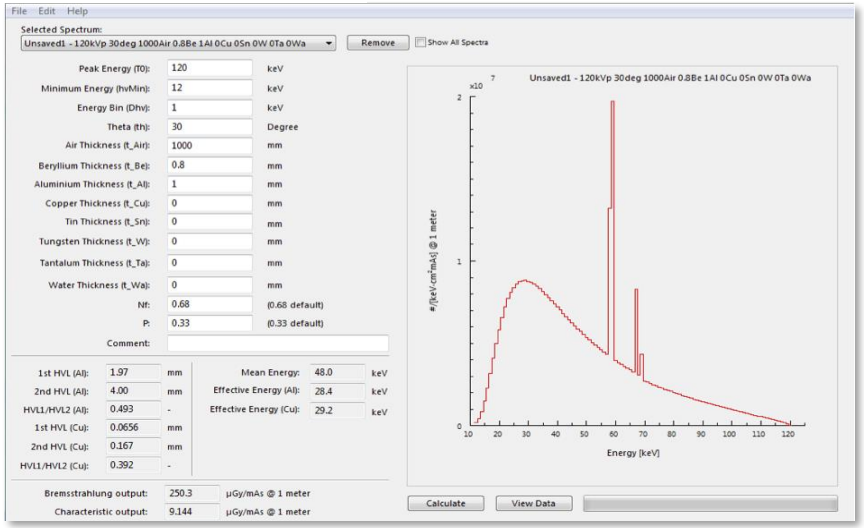
- $\sum w_T \times H_T^{xxM}(E_{103,\,xxM})$ or $\sum w_T \times H_T^{xxF}(E_{103,\,xxF})$ per fluence at 1 m from source (Sv cm^2)
- $\sum w_T \times H_T^{xxM}(E_{103,\,xxM})$ or $\sum w_T \times H_T^{xxF}(E_{103,\,xxF})$ per air kerma at 1 m from source (Sv Gy^{-1})
- $\sum w_T \times H_T^{xxM}(E_{103,\,xxM})$ or $\sum w_T \times H_T^{xxF}(E_{103,\,xxF})$ per kerma area product (KAP) (Sv Gy^{-1} cm^{-2})

- Effective dose per fluence at 1 m from source (Sv cm^2)
- Effective dose per air kerma at 1 m from source (Sv Gy^{-1})
- Effective dose per kerma area product (KAP) (Sv Gy^{-1} cm^{-2})

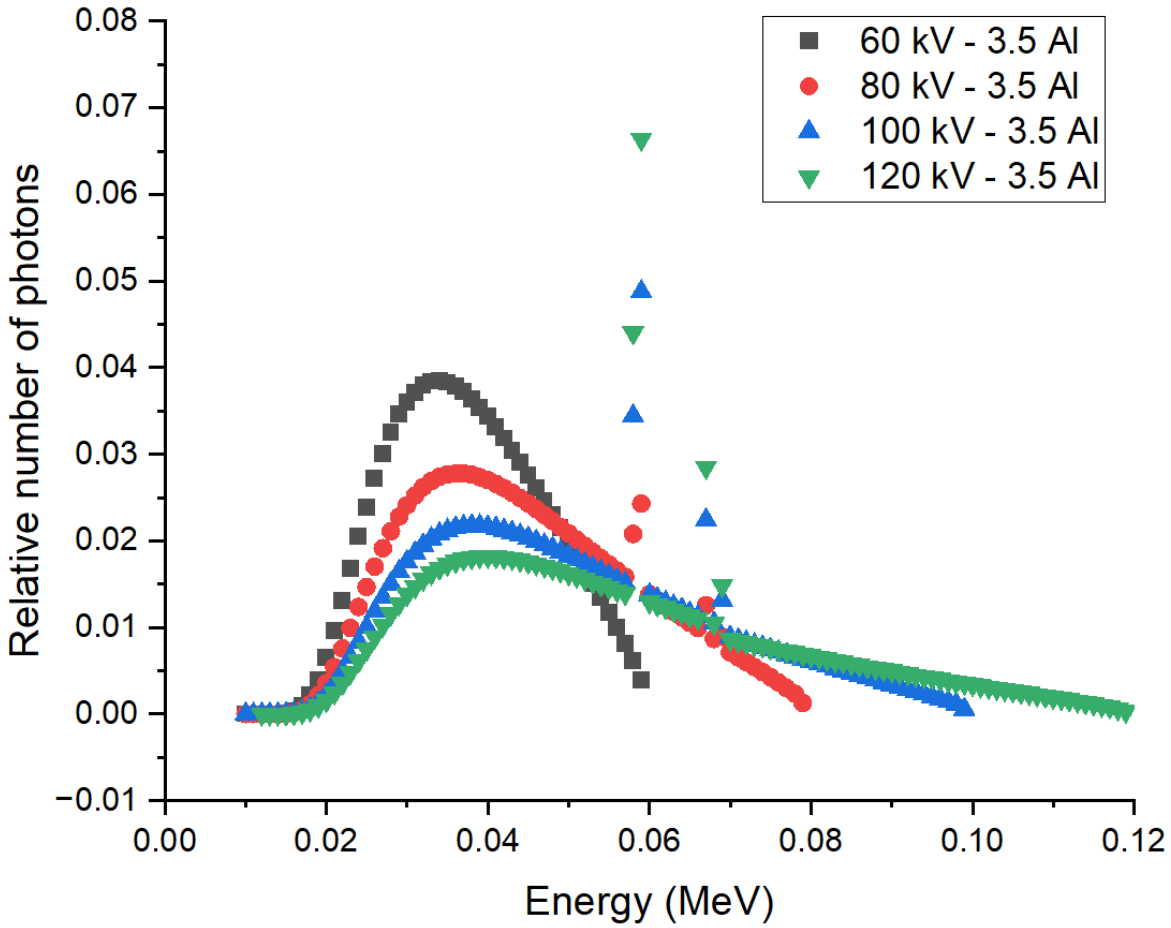
Selected X-ray Spectra – Adult Examinations

- Tube potential (kV): 60, 80, 100, 120
- Filter: 2.5-mm Al, 3-mm Al, 3.5-mm Al

SpekCalc



http://spekcalc.weebly.com/



Selected X-ray Spectra – Pediatric Examinations

Table 5.1. Details of beam qualities considered for paediatric examinations, for which dose coefficients are provided.

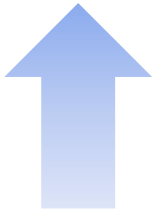
	Tube Potential(kV)					Filtration	
Examination	00MF	01MF	05MF	10MF	15MF	mm Al	mm Al+Cu
Chest PA	N/A	N/A	70	70	100	2.5, 3.0, 3.5	3.00 Al +0.1Cu
Chest AP	65	65	70	70	100	2.5, 3.0, 3.5	3.00 Al +0.1Cu
Chest Lat	65	65	75	75	100	2.5, 3.0, 3.5	3.00 Al +0.1Cu
Pelvis AP	65	65	70	75	80	2.5, 3.0, 3.5	3.00 Al +0.1Cu
Abdomen AP	65	65	70	75	75	2.5, 3.0, 3.5	3.00 Al +0.1Cu
Lumbar Spine AP	65	70	70	75	80	2.5, 3.0, 3.5	3.00 Al +0.1Cu
Lumbar Spine Lat	65	70	70	75	80	2.5, 3.0, 3.5	3.00 Al +0.1Cu
Thoraco-lumbar spine Lat	60	60	65	70	70	2.5, 3.0, 3.5	3.00 Al +0.1Cu
Scoliosis AP	65	70	N/A	N/A	N/A	2.5, 3.0, 3.5	3.00 Al +0.1Cu
Scoliosis PA	N/A	N/A	75	75	80	2.5, 3.0, 3.5	3.00 Al +0.1Cu
Scoliosis Lat	65	70	76	80	85	2.5, 3.0, 3.5	3.00 Al +0.1Cu
Skull AP	70	70	75	75	75	2.5, 3.0, 3.5	3.00 Al +0.1Cu
Skull PA	70	70	75	75	75	2.5, 3.0, 3.5	3.00 Al +0.1Cu
Skull Lat	70	70	75	75	75	2.5, 3.0, 3.5	3.00 Al +0.1Cu

00MF, newborn male and female; 01MF, 1-year-old male and female; 05MF. 5-year-old male and female; 10MF, 10-year-old male and female; 15MF, 15-year-old male and female; PA, posterior-anterior; AP, anterior-posterior; Lat, lateral; N/A, not applicable.

Calculation of Dose Coefficients for X-ray Spectra

Dose coefficient for X-ray spectra =

$$\sum \text{Relative number of photons (E)} \times \text{monoenergetic dose coefficient (E)}$$



X-ray spectral data obtained from SpekCalc

Example of Spectral Dose Coefficients (Chest AP – 5-year male)

Organ absorbed dose per fluence at 1 m from source

Tube Potential	Filtration - Al	Filtration - Cu	1st HVL - Al	E_{mean}	R-marrow	Colon	Lungs	ST-wall	Breast
[kV]	[mm]	[mm]	[mm]	[keV]	[mGy*cm^2]	[mGy*cm^2]	[mGy*cm^2]	[mGy*cm^2]	[mGy*cm^2]
70	2.50	0.00	2.31	39.31	4.70E-11	6.99E-11	3.05E-10	2.97E-10	5.17E-10
70	3.00	0.00	2.57	40.24	4.82E-11	7.09E-11	3.08E-10	3.02E-10	5.01E-10
70	3.00	0.10	3.96	44.63	5.33E-11	7.42E-11	3.17E-10	3.20E-10	4.42E-10
70	3.50	0.00	2.81	41.05	4.93E-11	7.17E-11	3.11E-10	3.07E-10	4.88E-10

Organ absorbed dose per Ka at 1 m from source

Tube Potential	Filtration - Al	Filtration - Cu	1st HVL - Al	E_{mean}	R-marrow	Colon	Lungs	ST-wall	Breast
[kV]	[mm]	[mm]	[mm]	[keV]	[mGy/Gy]	[mGy/Gy]	[mGy/Gy]	[mGy/Gy]	[mGy/Gy]
70	2.50	0.00	2.31	39.31	7.76E+01	1.15E+02	5.03E+02	4.90E+02	8.54E+02
70	3.00	0.00	2.57	40.24	8.46E+01	1.24E+02	5.41E+02	5.31E+02	8.79E+02
70	3.00	0.10	3.96	44.63	1.19E+02	1.65E+02	7.08E+02	7.15E+02	9.87E+02
70	3.50	0.00	2.81	41.05	9.09E+01	1.32E+02	5.73E+02	5.66E+02	9.00E+02

Organ absorbed dose per KAP

Tube Potential	Filtration - Al	Filtration - Cu	1st HVL - Al	E_{mean}	R-marrow	Colon	Lungs	ST-wall	Breast
[kV]	[mm]	[mm]	[mm]	[keV]	[mGy/(Gy*cm^2)]	[mGy/(Gy*cm^2)]	[mGy/(Gy*cm^2)]	[mGy/(Gy*cm^2)]	[mGy/(Gy*cm^2)]
70	2.50	0.00	2.31	39.31	1.47E-01	2.18E-01	9.50E-01	9.26E-01	1.61E+00
70	3.00	0.00	2.57	40.24	1.60E-01	2.35E-01	1.02E+00	1.00E+00	1.66E+00
70	3.00	0.10	3.96	44.63	2.25E-01	3.13E-01	1.34E+00	1.35E+00	1.86E+00
70	3.50	0.00	2.81	41.05	1.72E-01	2.50E-01	1.08E+00	1.07E+00	1.70E+00

All DCs will be provided in the electronic supplement!!!

Spot-check Calculations for Quality Assurance

Convolution vs Direct Monte Carlo Calculation (with spectra)

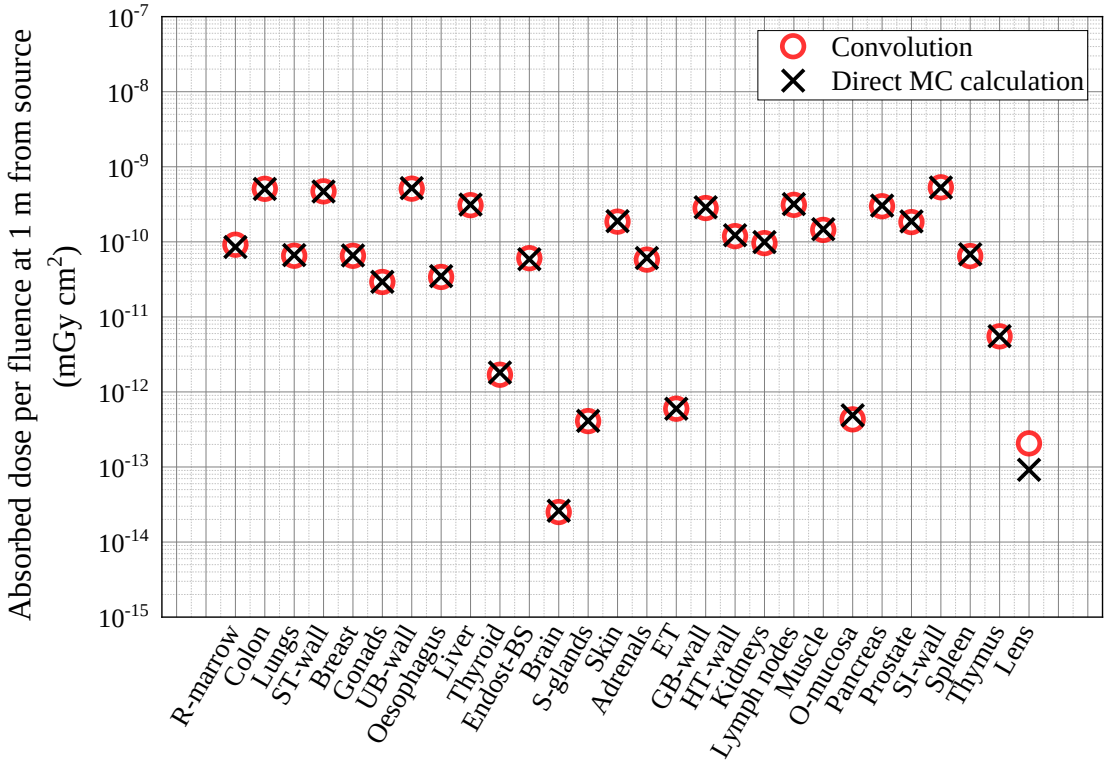


Fig. 5.1. Comparison of organ absorbed dose coefficients for abdomen anterior-posterior examination of the adult male reference phantom, for 60 kV tube potential and additional filtration of 3.5 mm Al, evaluated using the monoenergetic data and convolution method and direct Monte Carlo (MC) calculation employing spectral input data.

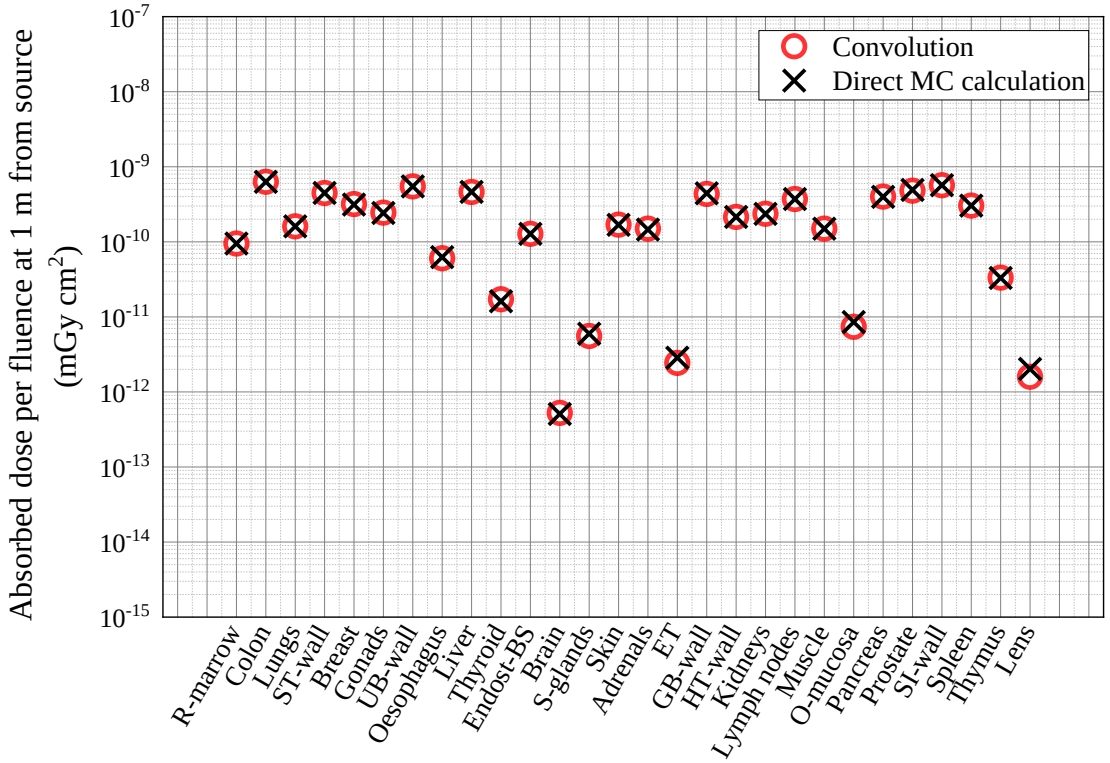


Fig. 5.2. Comparison of organ absorbed dose coefficients for abdomen anterior-posterior examination of the one-year-old reference phantom (01M), for 65 kV tube potential and additional filtration of 3.0 mm Al +0.1 mm Cu, evaluated using the monoenergetic data and convolution method and direct Monte Carlo (MC) calculation employing spectral input data.

Summary

- **Reference phantoms – Chapter 2**
  - Adult reference voxel phantoms – ICRP Publication 110
  - Pediatric reference voxel phantoms (15-yr, 10-yr, 5-yr, 1-yr, newborn) – ICRP Publication 143

- **Dose coefficients for monoenergetic photons – Chapter 4**
  - Adults: 3-150 keV with 1-keV step (EGSnrc)
  - Children: 1-80 (0-yr), -90 (1-yr), -100 (5-yr), -110 (10-yr), -120 (15-yr) keV with 1-keV step (Geant4)
  - Quality assurance: Primary vs Spot-check (additional calculations)

- **Dose coefficients for example X-ray spectra – Chapter 5**
  - 12 spectra for adults and 28 spectra for children (obtained from SpekCalc)
  - Convolution of monoenergetic dose coefficients with the spectra (relative number of photons)
  - Quality assurance: Convolution vs Direct Monte Carlo calculation

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