Dosimetry for epidemiologic studies of diagnostic radiation exposures

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DCEG Radiation Epidemiology and Dosimetry Course 2019

Agenda

1. *Diagnostic medical imaging*
2. *Dosimetry concepts*
3. *Dosimetry for:*
   - *Computed tomography*
   - *Nuclear medicine*
   - *Fluoroscopy*

Medical use of radiation in imaging

Based on physics principles; the interaction of **matter** and **radiation**.

We take advantage of the differential attenuation by organs on the beam.

Radiation dose in medical imaging is an **unavoidable side effect** of all procedures and represents a **risk**

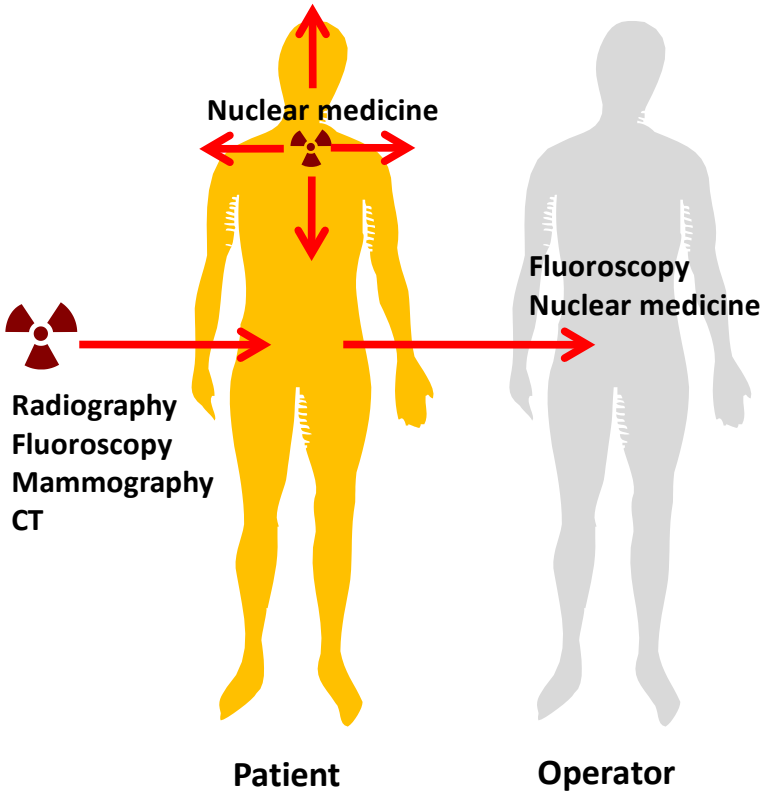
Medical use of radiation in imaging (2)

Obtaining **a clinical image** to provide the relevant diagnostic information **is of paramount importance**.

Justification is achieved by providing clinicians with information on **potential health detriment** from each medical exposure **weighed against the medical benefit**.

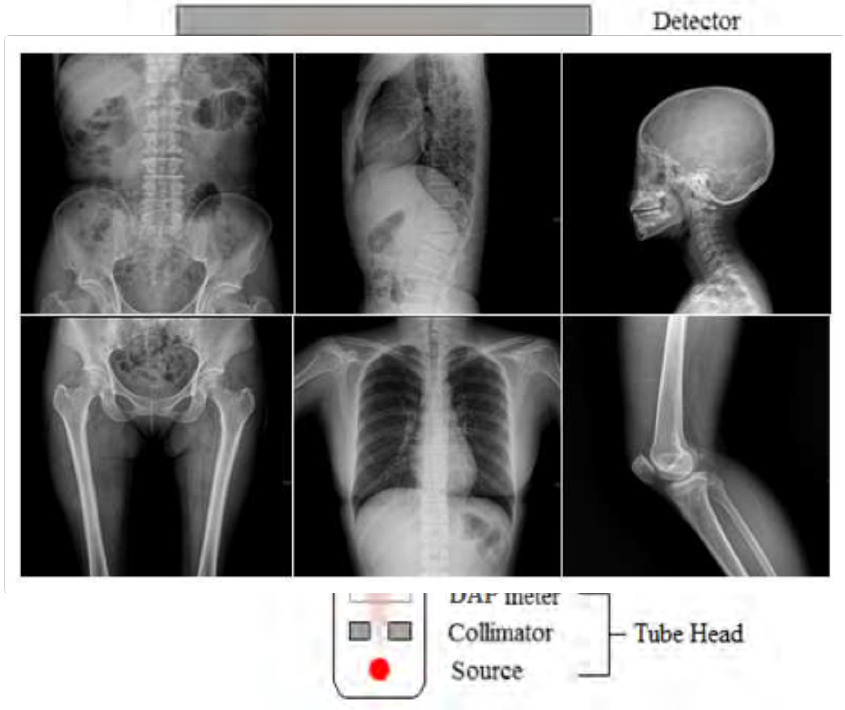
Optimization is accomplished by ensuring that those who carry out the exposure know how the techniques and equipment factors that they select affect the quality of the clinical image and the dose received by the patient.

The two distinct types of medical imaging

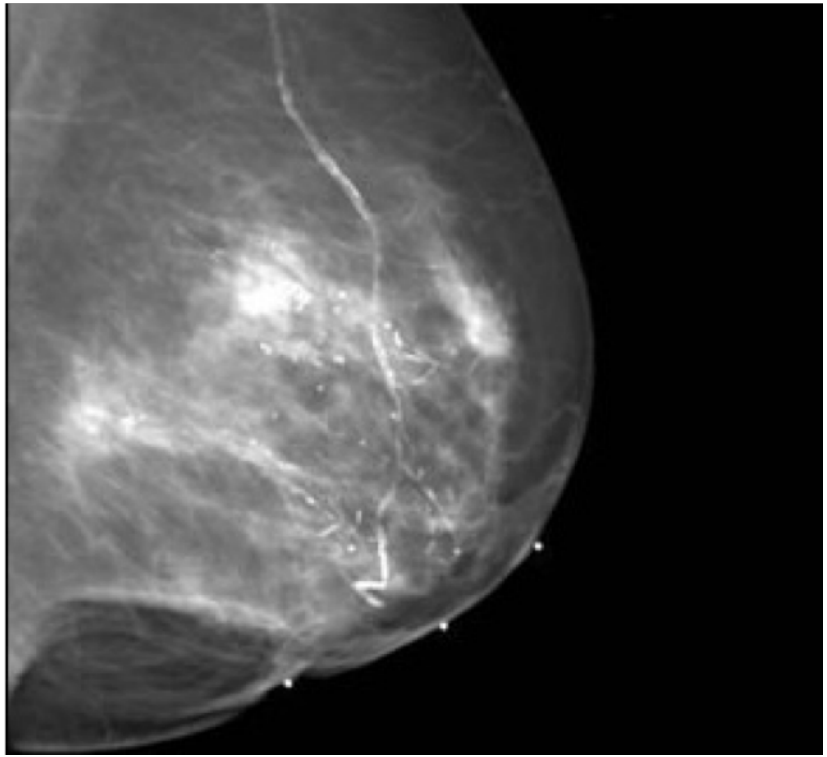


Projection imaging in the healing arts

- Images are obtained from x ray transmission through the body.
- The image produced shows differences in tissue and bone attenuation.
- Less than 1% of the incident x ray beam is transmitted through the body to form the final image.



Mammography



A special application of radiography for examination of the breasts using dedicated equipment.

Lower energy x rays are used in mammography for detecting small abnormalities in the breast.

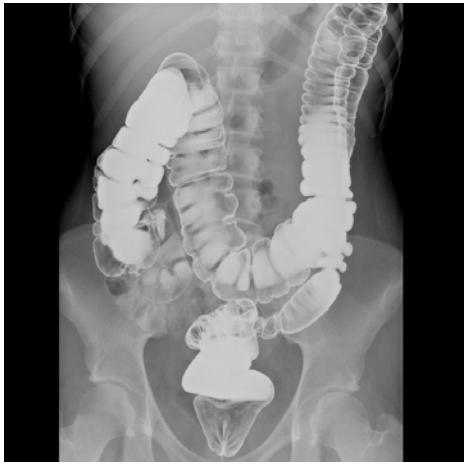
Mammography is important because of the high incidence of breast cancer and the extensive screening programs for early signs of the disease.

Fluoroscopy

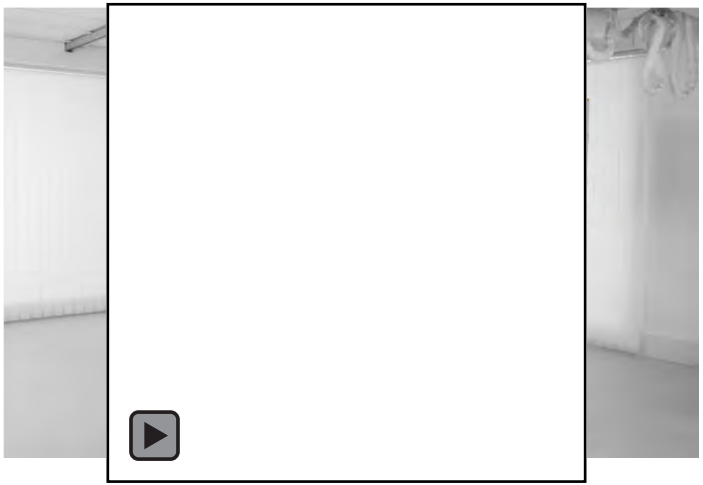
Fluoroscopy is a type of medical imaging that shows a **continuous x ray image** with a high temporal resolution on a monitor, much **like an x ray movie**.

- **Diagnostic**

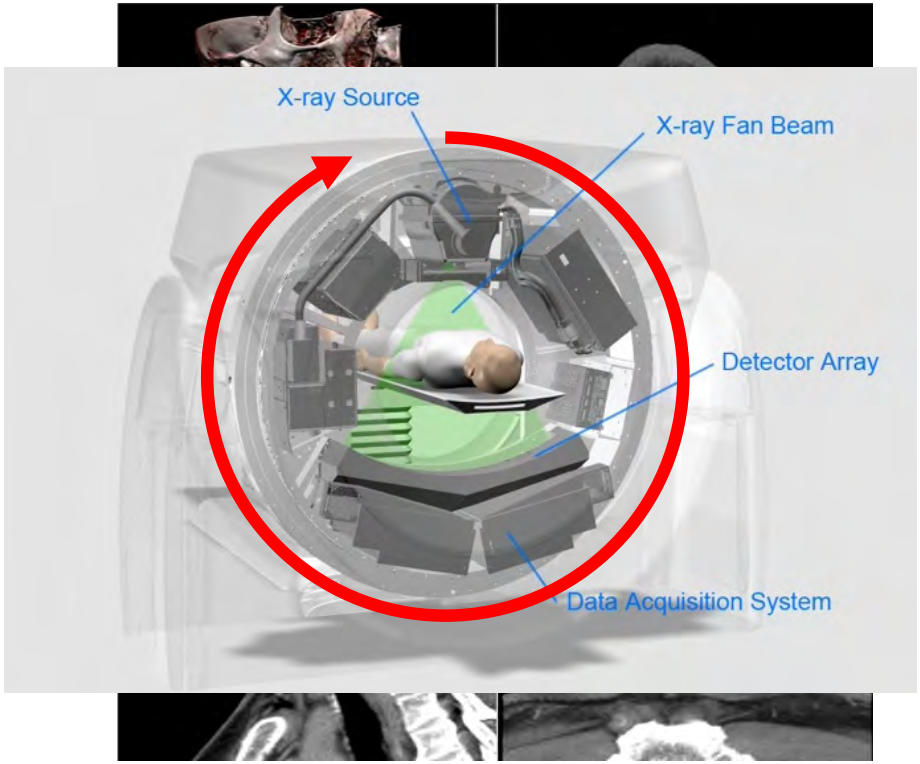
Diagnostic



Interventional



Computed tomography



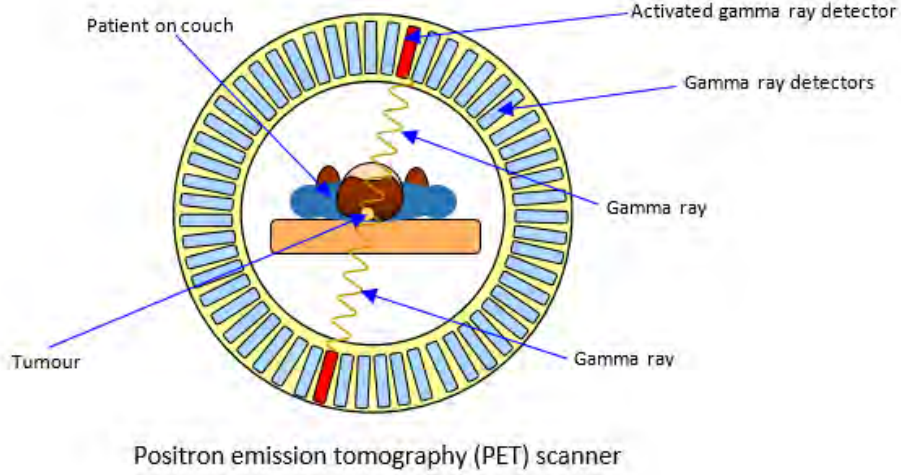
X ray tube and detector array are rotated around the body.

The detector is recording the transmitted radiation at many different angles.

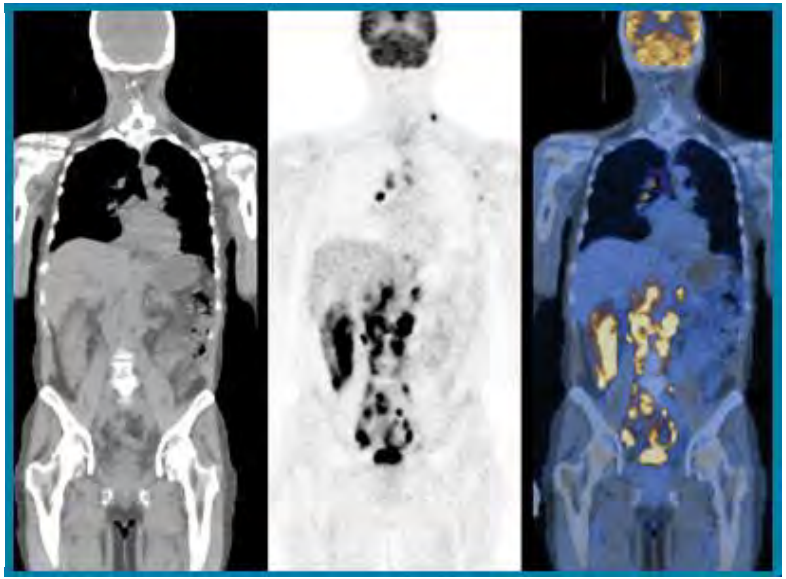
Cross sectional images can then be reconstructed mathematically from the data collected.

Nuclear medicine

The **administration** of **radioactive substances** for **diagnosis** and **treatment** applications.



Positron emission tomography (PET) scanner



Dosimetry concepts

Organ dose estimation for medically-exposed patients

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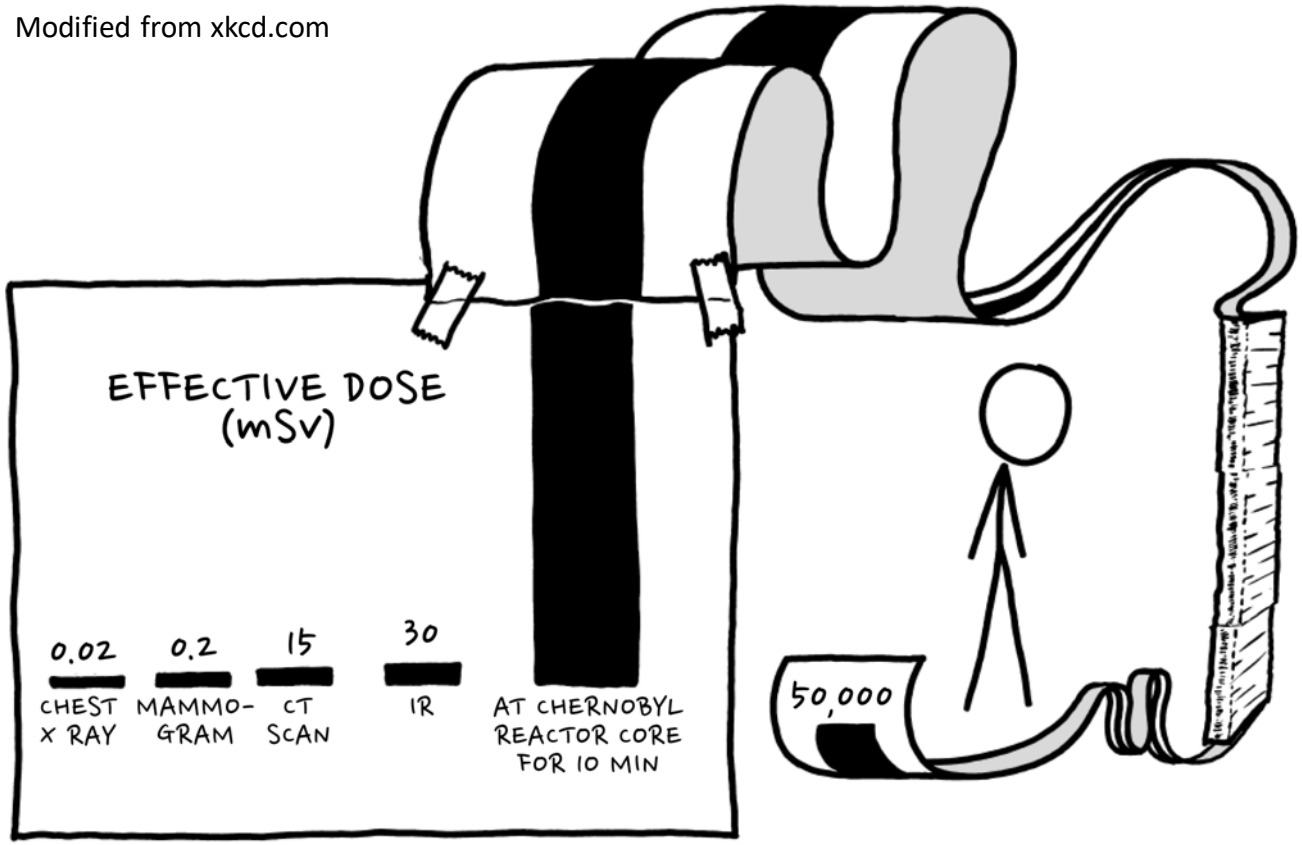
Modified from xkcd.com



SCIENCE TIP: LOG SCALES ARE FOR QUITTERS WHO CAN'T FIND ENOUGH PAPER TO MAKE THEIR POINT PROPERLY.

Examination	Effective Dose (mSv)	No. of Chest X-rays
Conventional Radiology		
PA chest x-ray	0.02	1
Mammography (4 views)		
Screening	0.2	10
64-Slice Computed Tomography		
ECG pulsing	9	450
No ECG pulsing	29	1450
64-CAP	15	750
Diagnostic Nuclear Medicine		
Bone (^{99m}Tc phosphate)	3	150
Tumor-PET (^{18}F FDG)	7	350
Heart (^{201}Tl thallous chloride)	13	650
Interventional Radiology		
Cerebral angiography	1.6-10.6	80-530
Coronary angiography	3.1-10.6	155-555
Coronary angioplasty	6.8-28.9	340-1,445
Cardiac radiofrequency ablation	18-60	900-3,000
Valvuloplasty	29	1,450

Picano *Cardiovascular Ultrasound* (2007); Venneri *American Heart Journal* (2009); Linet *Pediatr Radiol* (2009);

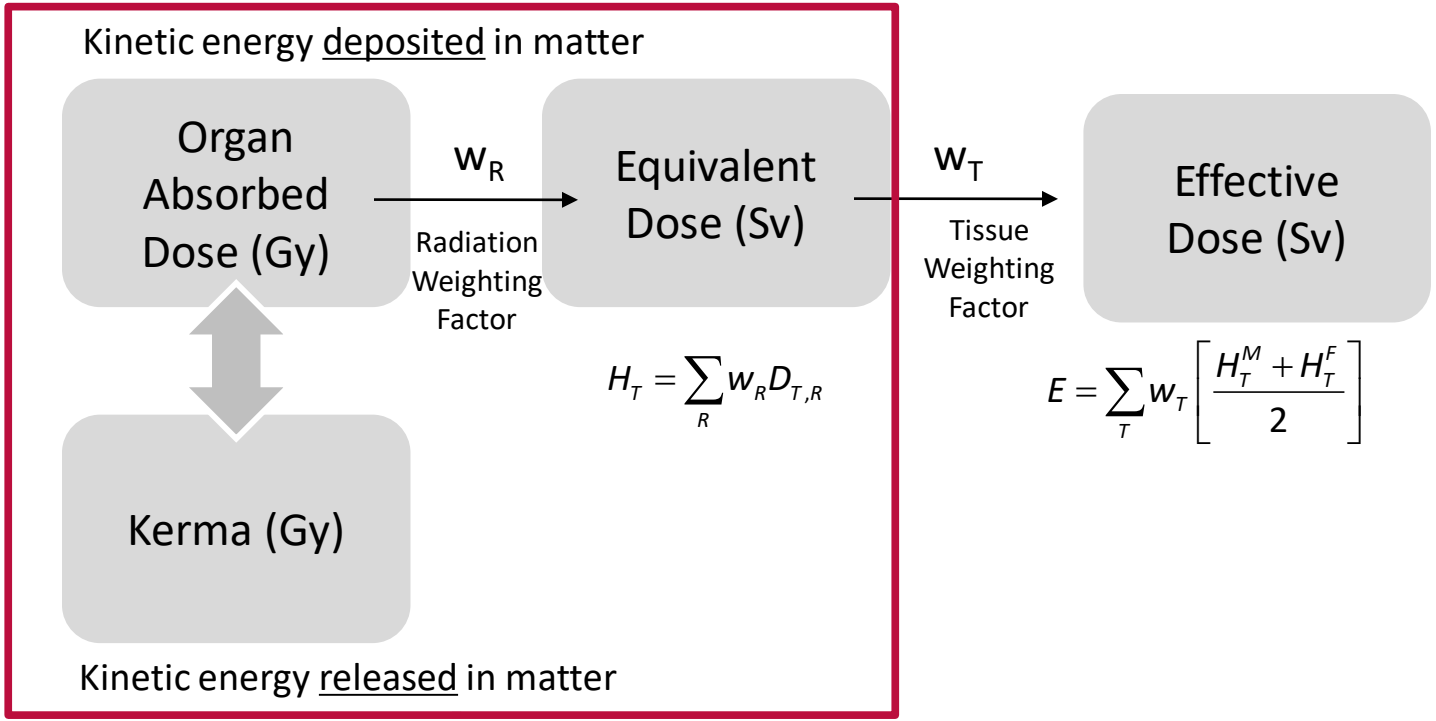
Dosimetry for epidemiologic purposes

Radiation doses received by individuals from occupational and medical exposures in past decades **were not measured and must be reconstructed.**

Radiation **doses** must be **specific to each organ under study.**

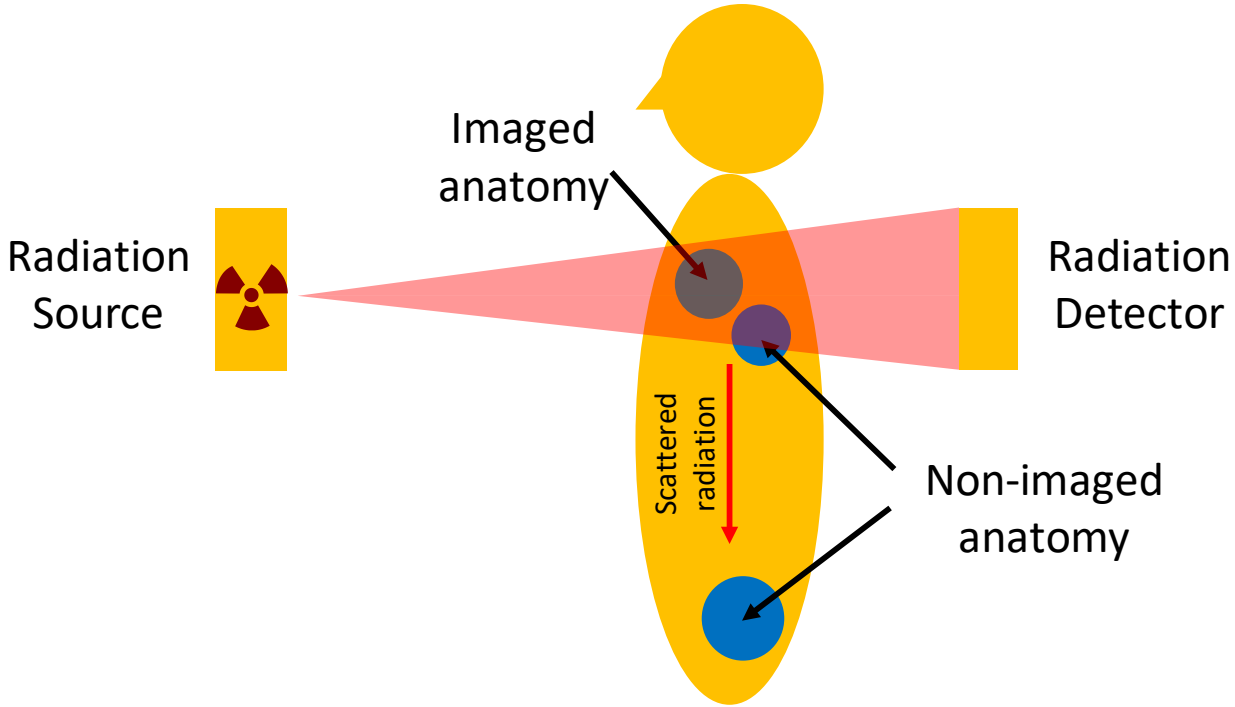
To make realistic estimates of organ doses requires an understanding of radiologic technology and the physics it is based on.

Dosimetric quantities



ICRP *Publication 103* (2007)

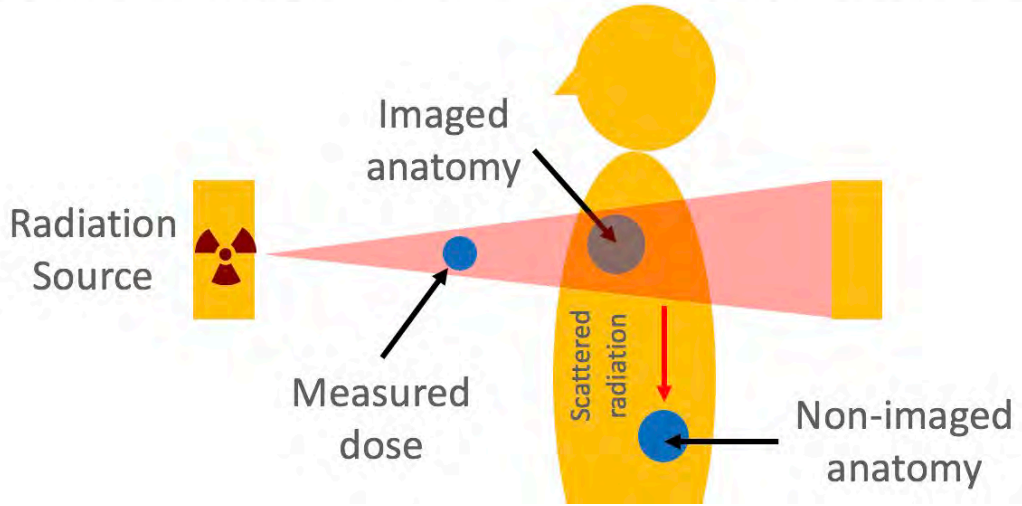
Radiation exposure in imaging procedures



Dose coefficients (DCs)

- Dose coefficients simplify the calculation of organ absorbed dose from external radiation.
- For example, in fluoroscopy we may use:

$$D_{Tissue\ at\ depth} = \mathrm{DC} \times \dot{K}_{a,entrance\ surface} \times T$$



Dose coefficients (DCs) (2)

- Dose coefficients simplify the calculation of organ absorbed dose from external radiation.
- For example, in fluoroscopy we may use:

$$D_{Tissue\ at\ depth} = \mathrm{DC} \times \dot{K}_{a,entrance\ surface} \times T$$

- These DCs are dependent on:
  - Imaging parameters (kVp, filtration, SSD)
  - Imaged anatomy (field size, shuttering)
  - Patient information (age, height, weight)

Dose coefficients (DCs) (3)

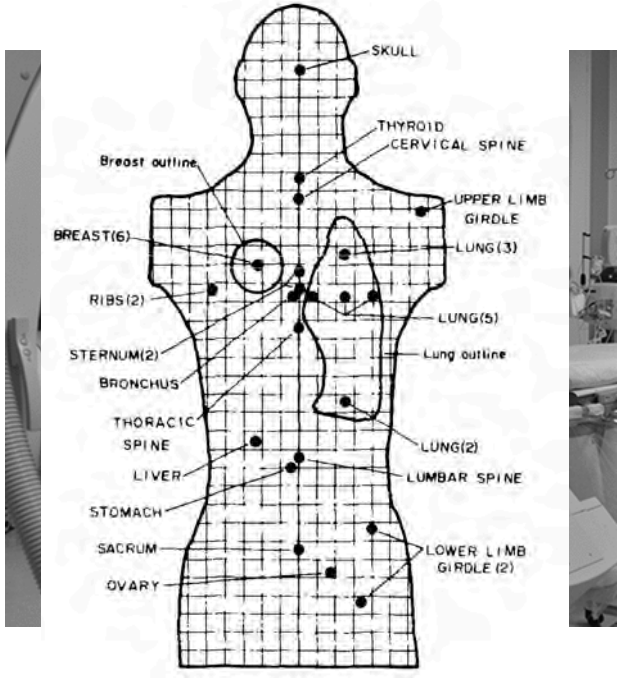
- Dose coefficients simplify the calculation of organ absorbed dose from radiation.
- For example, in [Imaging Procedure] we may use:

$$D_{Tissue\ at\ depth} = \mathrm{DC} \times [Dose\ Index]$$

Imaging Procedure	Dose Index
Radiography	Entrance Skin Dose
Fluoroscopy	Dose Area Product
Computed Tomography	Volumetric CTDI
Nuclear Medicine	Injected Activity

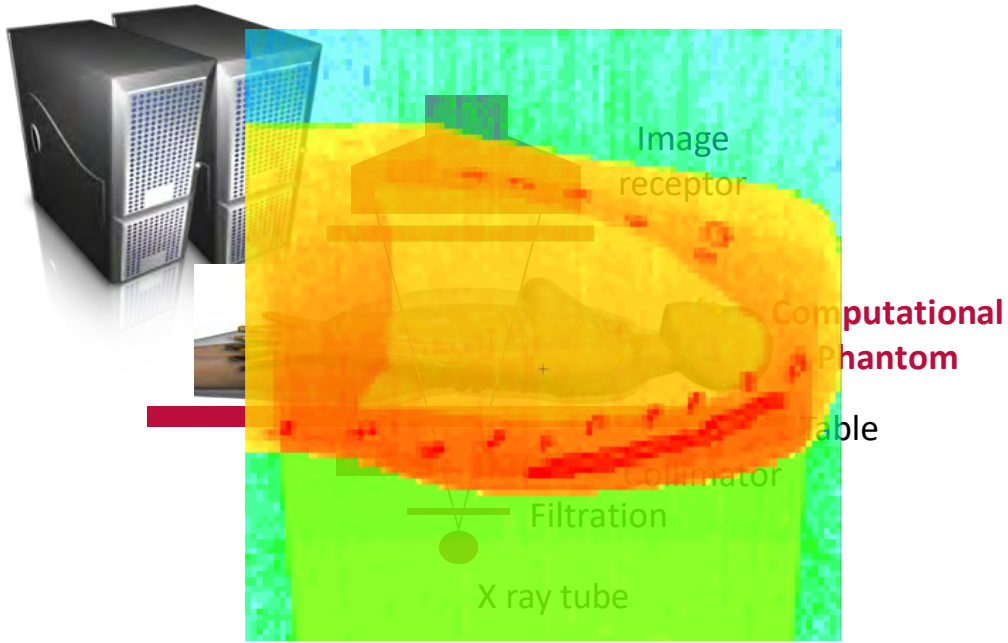
Methods to obtain organ doses:

Measurement



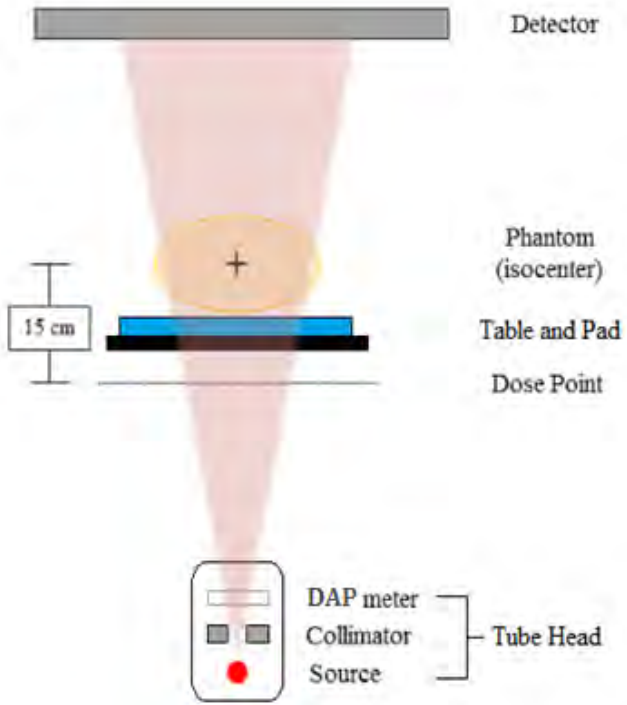
Sherman *Health Physics* (1978)

Computational



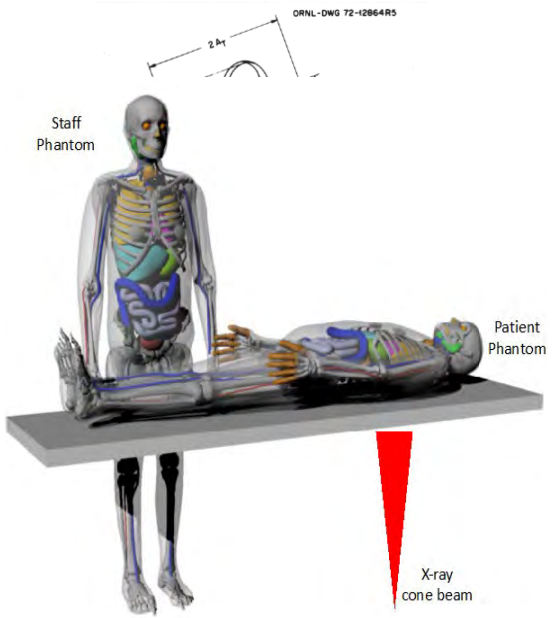
Tailoring dosimetry

- Determination of imaging protocols from literature and medical documents (*e.g.,* energy, filtration, field size, number of images*)*
- Use of relevant clinical measurements (*e.g.*, DAP, HVL, *etc.)*
- Individual subject data including age, gender, body size, number of procedures performed
- Above information is coupled with anatomical models to estimate organ absorbed dose (Gy)



Evolution of computational phantoms

- Stylized mathematical phantom by Cristy and Eckerman.[1]
- Earlier studies of the UF/NCI phantom library have reported accuracy to within 30% by matching the patient to a phantom of equal height and weight.[2]



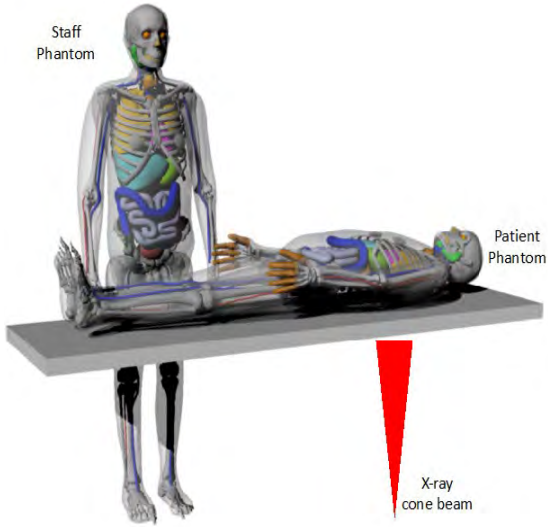
(Figure from Cristy and Eckerman 1987)

[1]Cristy, M., & Eckerman, K. F. (1987). *Specific absorbed fractions of energy at various ages from internal photon source.* (No. ORNL/TM-8381/V1) (pp. 1–100). Oak Ridge: Oak Ridge National Laboratory.

[2]Stepusin E J, Long D J, Marshall E L and Bolch W E 2017 Assessment of different patient-to-phantom matching criteria applied in Monte Carlo-based computed tomography dosimetry. *Medical Physics* **44** 5498–508

Evolution of computational phantoms (2)

- Previous dosimetry using the stylized phantom may significantly overestimate the organ doses of normal to obese patients, particularly for pediatric patients.[1]
- A phantom library facilitates large batch calculations which is often desired for epidemiological investigations of medical exposure to patients.



[1]**D Borrego**, EM Lowe, CM **Kitahara,** and **C Lee.** 2018 Assessment of PCXMC for patients with different body size in chest and abdominal x ray examinations: a Monte Carlo simulation study. *Phys Med Biol* **63** 065015

Wish List

Modality	**Imaged anatomy**	**Patient weight**
Procedure description	**Exposure geometry**	**Clinical dose metrics**
Number of procedures	**Age**	**Tube output measurements**
Technique factors	**Sex**	**Prescribed activity**
Beam quality	**Patient height**	**Biokinetic models**

Reality

Modality

Procedure description

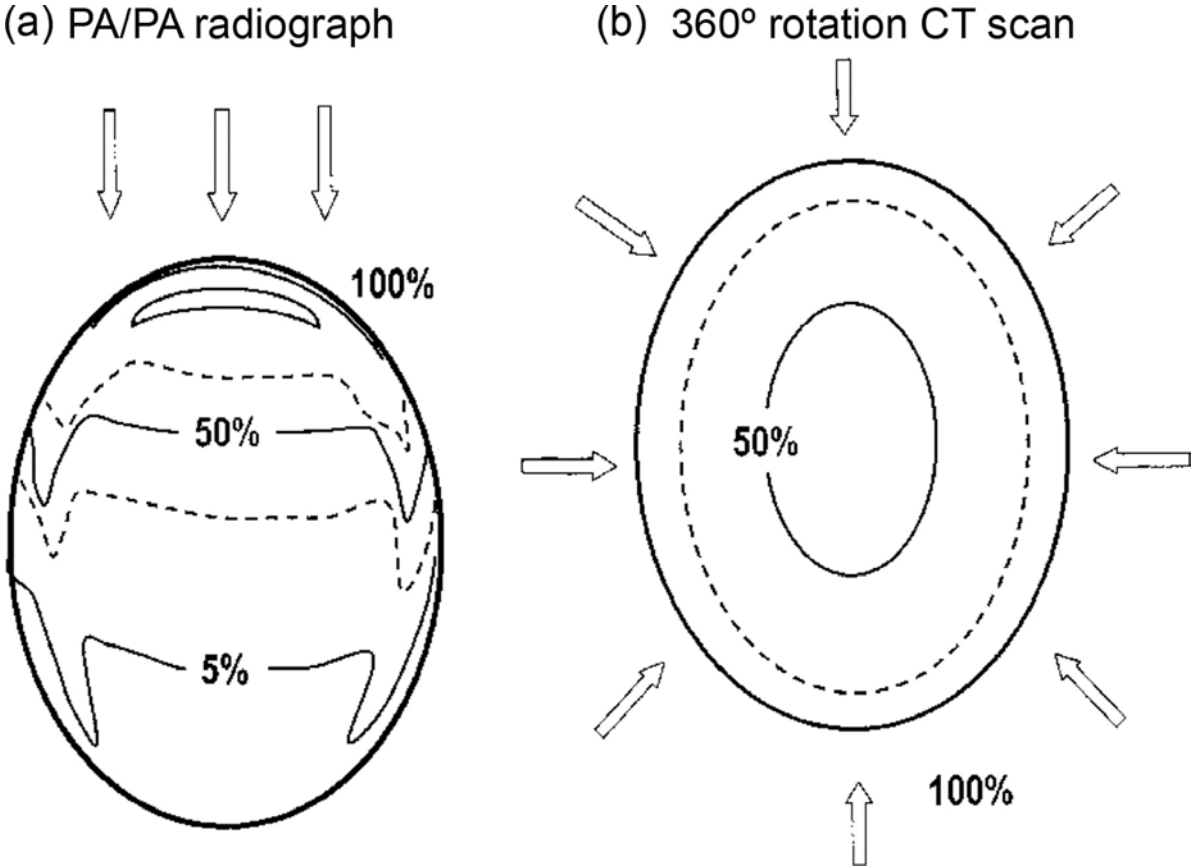
Number of procedures

Age

Sex

Computed tomography (CT)

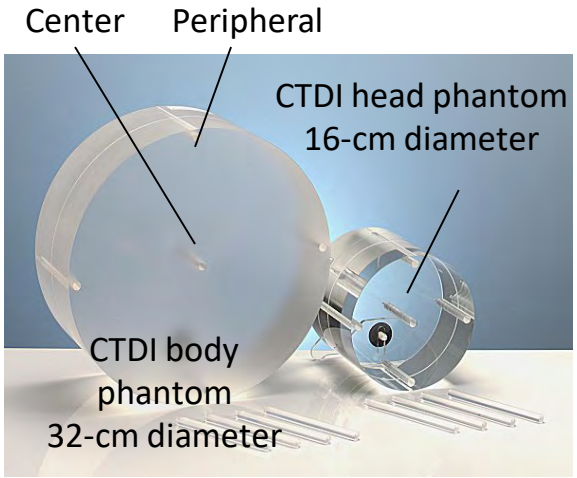
Dose deposition in CT

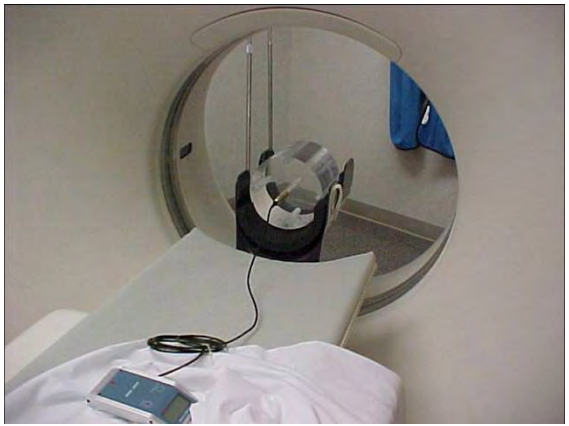


Martin *Radiation Protection Dosimetry* (2008)

Dose descriptors from CT scan

- Computed Tomography Dose Index $(CTDI)_{100}$
  - 100-mm long ion chamber measurement for a single axial rotation
- $CTDI_w = 1/3\ CTDI_{100,center} + 2/3\ CTDI_{100,peripheral}$





Dose descriptors from CT scan (2)

$$DLP = CTDI_{vol} \times l = \frac{CTDI_w}{pitch} \times l = \frac{nCTDI_w \times mAs}{pitch} \times l$$

Patient Name: Exam no: 215
Accession Number: Feb 14 2008
Patient ID: LightSpeed VCT
Exam Description: PRE/POST KIDNEY

Dose Report

Series	Type	Scan Range (mm)	CTDIvol (mGy)	DLP (mGy-cm)	Phantom cm
1	Scout	–	–	–	–
2	Axial	S0.000-I97.500	94.69	946.93	Head 16
2	Helical	I61.650-I101.650	60.81	371.96	Head 16
2	Cine	S12.490-I2.510	121.14	242.29	Head 16
3	Axial	S0.000-I97.500	94.69	946.93	Head 16
3	Helical	I61.650-I101.650	60.81	371.96	Head 16
3	Cine	S12.490-I2.510	121.14	242.29	Head 16

Total Exam DLP: 3122.36

Factors affecting $CTDI_{vol}$ in CT: Pitch

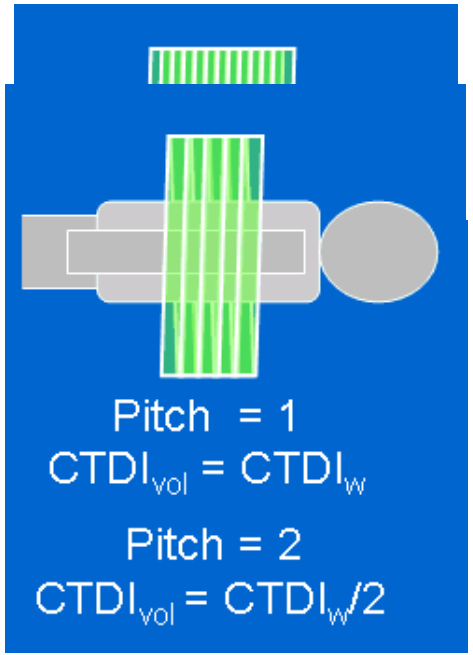


Table 3
Changes in $CTDI_{vol}$ in Head and Body Phantoms as a Function of Pitch

Pitch	$CTDI_{vol}$ in Head Phantom (mGy)	$CTDI_{vol}$ in Body Phantom (mGy)
0.5	80	36
0.75	53	24
1.0	40	18
1.5	27	12
2.0	20	9

Note.—All other factors were held constant at 120 kVp, 300 mA, 1 sec, and 10 mm. Results are from a single-detector CT scanner.

McNitt-Gray Radiographics (2002)

Factors affecting $CTDI_w$ in CT: Energy (kVp)

Table 1
Changes in $CTDI_w$ in Head and Body Phantoms as a Function of Kilovolt Peak

Beam Energy (kVp)	$CTDI_w$ in Head Phantom (mGy)	$CTDI_w$ in Body Phantom (mGy)
80	14	5.8
100	26	11
120	40	18
140	55	25

1.8-fold

3.9-fold

4.3-fold

Note.—All other factors were held constant at 300 mA, 1 sec, and 10 mm. Results are from a single-detector CT scanner.

$$CTDI_{vol} \propto \left(\frac{kVp_2}{kVp_1}\right)^n, n = 2\sim3$$

McNitt-Gray Radiographics (2002)

Factors affecting $CTDI_w$ in CT: Fluence (mAs)

Table 2
Changes in $CTDI_w$ in Head and Body Phantoms as a Function of Milliampere-Seconds Setting

Tube Current–Time Product (mAs)	$CTDI_w$ in Head Phantom (mGy)	$CTDI_w$ in Body Phantom (mGy)
100	13	5.7
200	26	12
300	40	18
400	53	23

Note.—All other factors were held constant at 120 kVp and 10 mm. Results are from a single-detector CT scanner.

McNitt-Gray Radiographics (2002)

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	

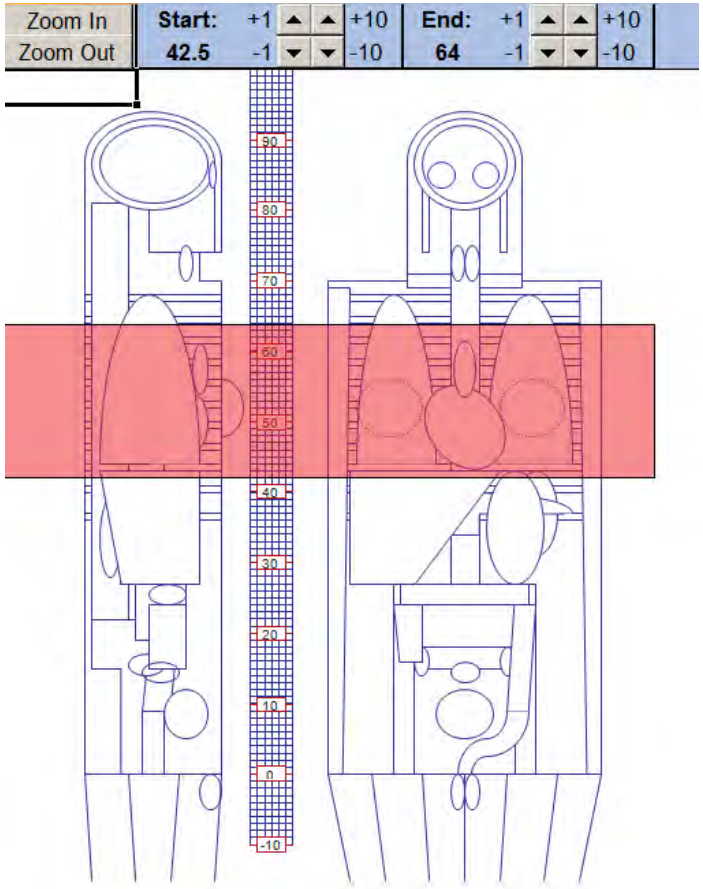
Organ weighting scheme	ICRP 60

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

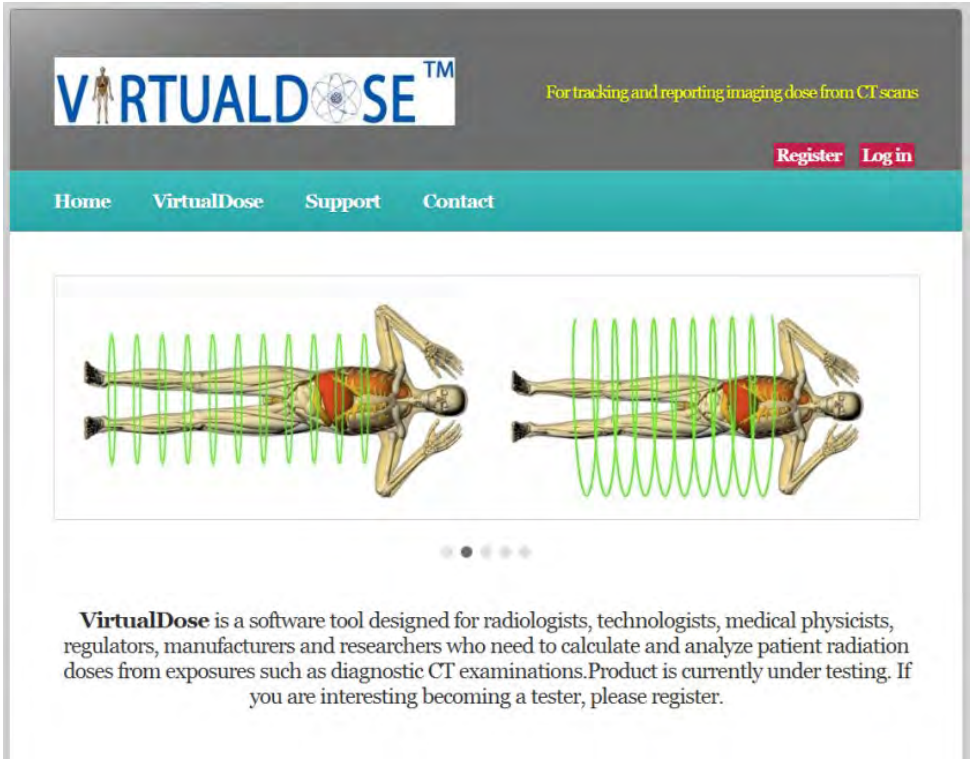
Organ	w_T	H_T (mGy)	$w_T.H_T$
Gonads	0.2	6.5	1.3
Bone Marrow	0.12	4.8	0.57
Colon	0.12	11	1.3
Lung	0.12	1.2	0.15
Stomach	0.12	11	1.3
Bladder	0.05	12	0.61
Breast	0.05	0.35	0.018
Liver	0.05	10	0.5
Oesophagus (Thymus)	0.05	0.26	0.013
Thyroid	0.05	0.031	0.0016
Skin	0.01	3.3	0.033
Bone Surface	0.01	5.8	0.058

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



More recent developments - **VirtualDose™CT** (RPI, USA)

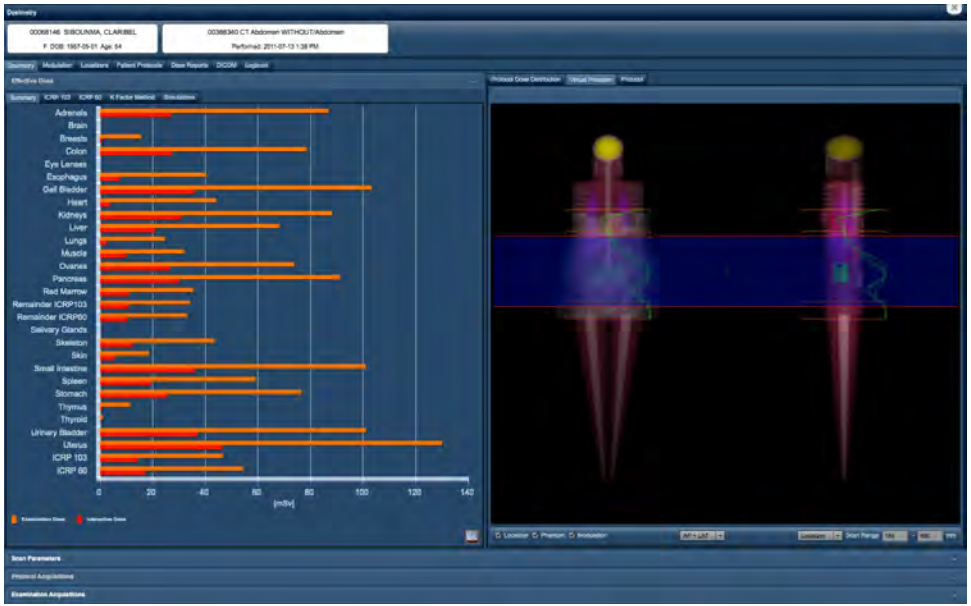
- Commercial solution
- RPI pediatric/adult phantoms
- Limited CT scanner model



Virtual-dose.com

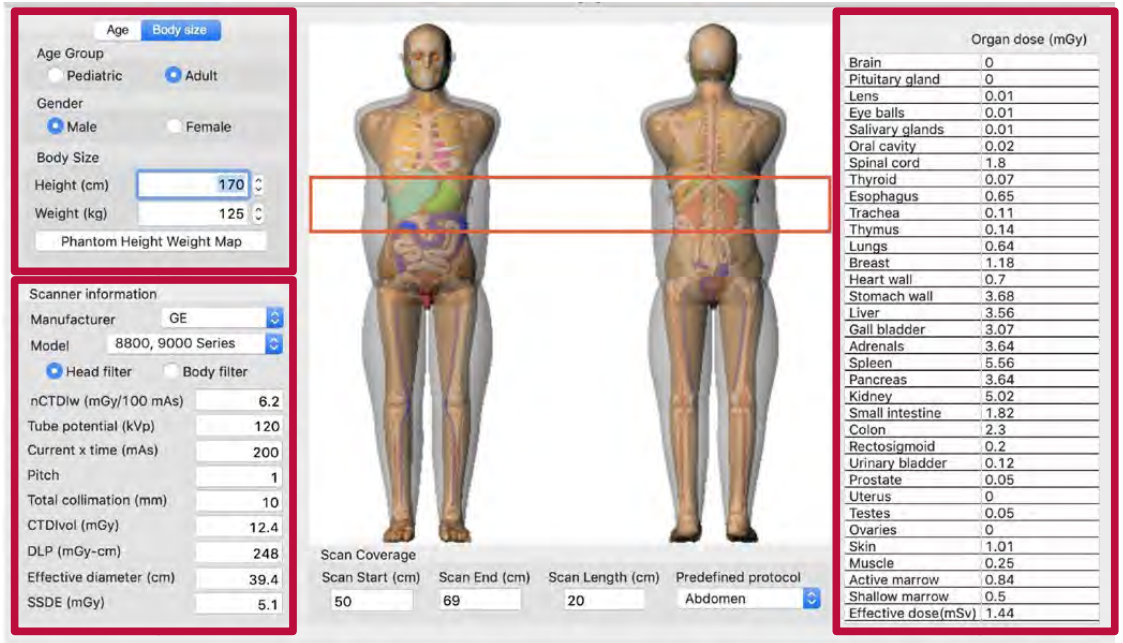
More recent developments - **eXposure™ (Radimetrics, inc)**

- Advanced dosimetry tool that integrates with clinical workflow
- Adopted by a large number of clinical centers worldwide
- Old stylized phantoms



More recent developments - **NCICT**

- Library of computational human phantoms including:
  - ICRP reference pediatric and adult series (NCICT 1.0)
  - 370 pediatric and adult males and females of different height and weight (NCICT 2.0)
  - Pregnant phantoms containing detailed fetus models at 8 gestational stages (NCICT 3.0)
- Graphical User Interface (GUI) mode OR
- Batch Calculation mode



Nuclear Medicine

Complexities of nuclear medicine

Specific Radionuclide

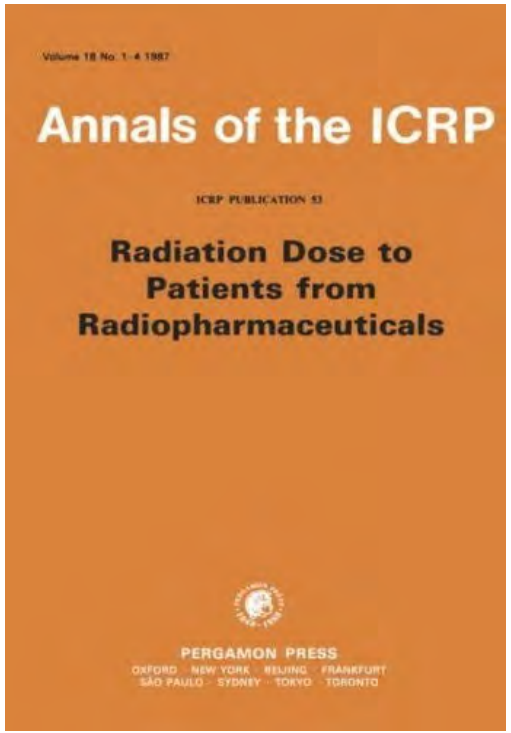
- Type of radiation emitted
- Half-life
- Energy of radiation

Chemical form of radionuclide

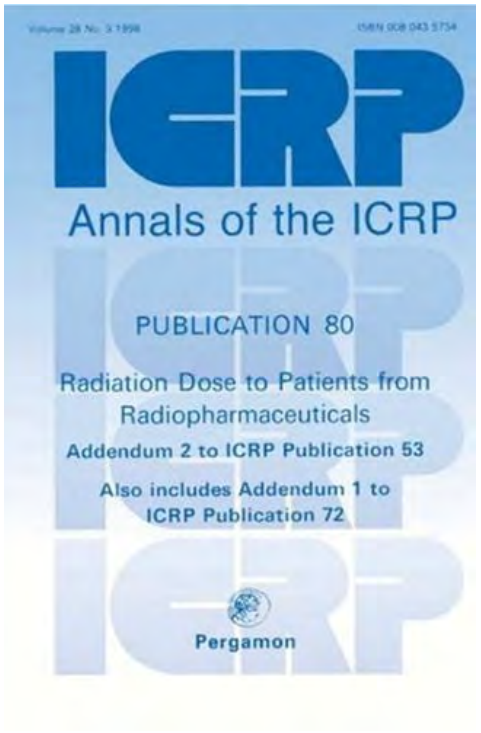
Chemical and temporal behavior of nuclide in body (residence time in the body and accumulation in organs)

Specifics about the exposed individual (age, health status)

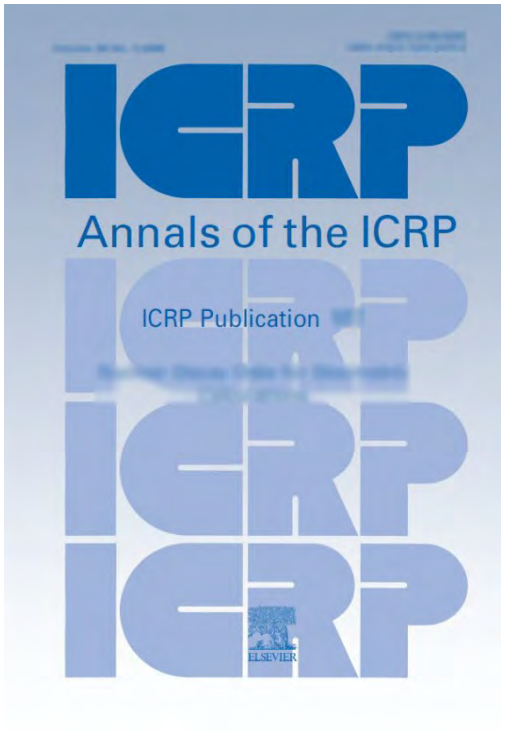
Dose Coefficients from ICRP



ICRP Publication 53 (1988)

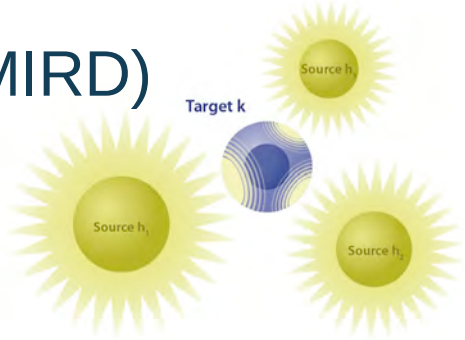


ICRP Publication 80 (1998)



ICRP Publication 106 (2008)

Medical Internal Radiation Dose Committee (MIRD)



Cumulated activity
Number of radioactive disintegrations in source volume *h*

Absorbed dose
in target volume *k*

$$D(k) = \sum_h \tilde{A}_h \cdot S(k \leftarrow h)$$

S value
Absorbed dose in target *k* by disintegration in source *h*

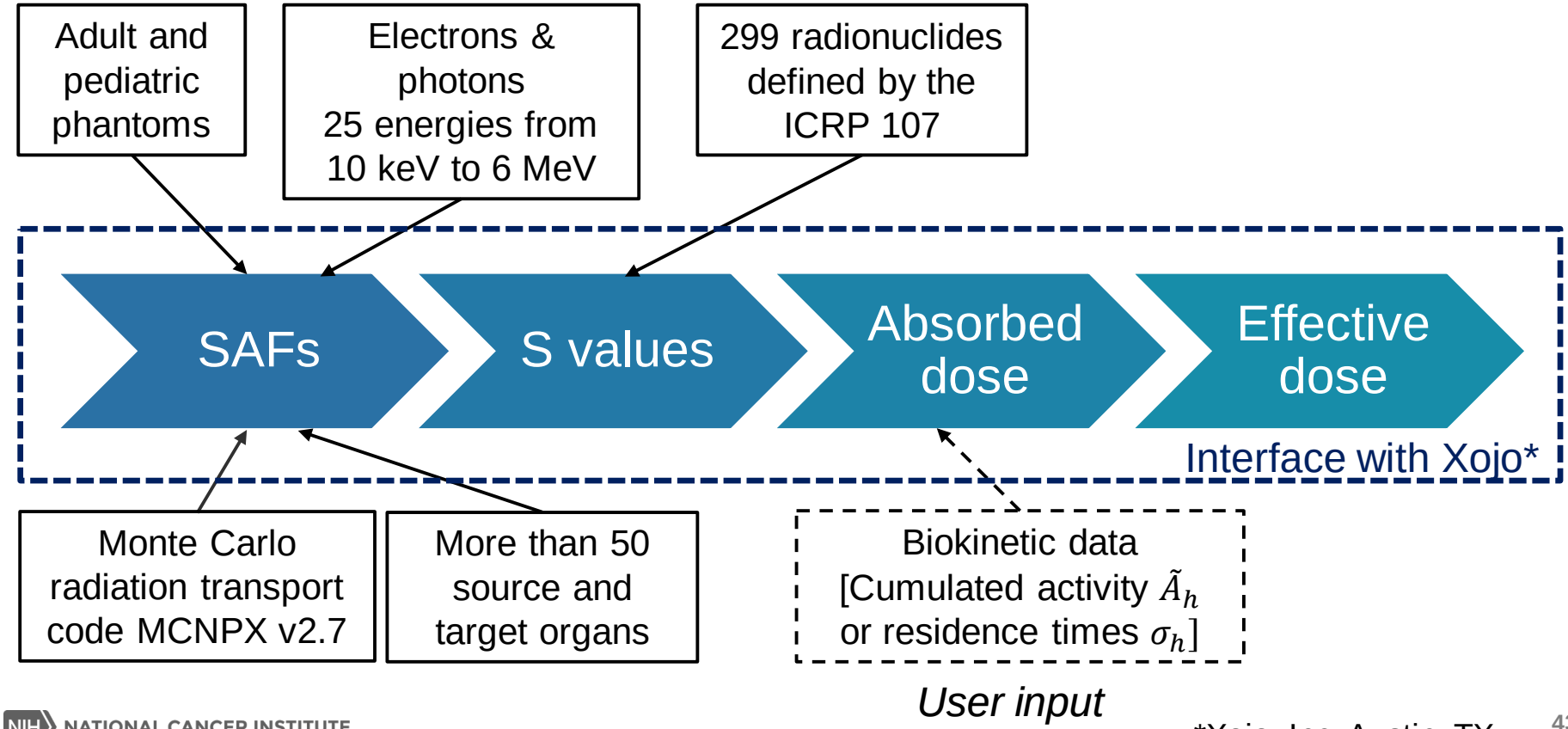
Specific Absorbed Fraction (SAF) (in kg^{-1})

$$S(k \leftarrow h) = \sum_i \Delta_i \cdot \Phi(k \leftarrow h)$$

MIRD Schema

 Biokinetic parameters	Identification of source organs The time dependent cumulated activity activity organs
 Physics parameters	Energies and yields of all radiation particles emitted by the radionuclide
 Anatomic parameters	Masses of all target organs Values of absorbed fraction

NCINM - flowchart



*Xojo, Inc. Austin, TX

NCINM

INPUT PANEL

NCI data | ICRP data

NCI Phantom Gender

Male | Female

NCI Phantom Age

0-year | 1-year | 5-year | 10-year | 15-year | Adult

Radionuclide

In-111

Administered activity (MBq)

18.5

Administered activity (mCi)

0.5

Source region	S value export?	Residence Time (h)	Cumulated Activity (MBq-s)
Kidney R Pelvis	☐		
Kidney RL	☑	2.76	1.838e+5
Lenses of Eye	☐		
Liver	☑	2.59	1.725e+5
Lung L	☐		
Lung R	☐		
Lung RL	☐		
Lymph Nodes ET	☐		
Lymph Nodes but ET/Th	☐		
Lymph Nodes Thoracic	☐		
Muscle	☐		
Nasal Anterior	☐		
Nasal Posterior	☐		
Oral Cavity	☐		
Pancreas	☐		
Pituitary Gland	☐		
Prostate or Uterus	☐		
Salivary Glands	☐		
Skin	☐		
Small Intestine C	☐		
Small Intestine W	☐		
Spinal Cord	☐		
Spleen	☑	2.30	1.532e+5
Stomach C	☐		
Stomach W	☐		
Teeth	☐		
Thymus	☐		
Thyroid	☑	0.05	3.33e+3
Tongue	☐		
Tonsils	☐		
Trabecular Bone Marrow	☐		
Trabecular Bone Mineral	☐		
Ureters	☐		
Urinary Bladder C	☑	1.65	1.099e+5

Export S values (mGy/MBq-s) | Initialize parameters

OUTPUT PANEL

Target region	Organ Mass	Organ Dose	Dose per administered activity (mGy/MBq)
Adrenal	8.84	2.568e+0	1.388e-1
Adrenal L	4.42	3.019e+0	1.632e-1
Adrenal R	4.42	2.117e+0	1.144e-1
Bronchi	6.34	1.589e+0	8.587e-2
Brain	1244.64	2.41e-1	1.303e-2
Breast adipose	66.51	3.173e-1	1.715e-2
Breast glandular	203.51	2.944e-1	1.591e-2
Colon	299.29	5.594e-1	3.024e-2
Colon W L	122.	4.711e-1	2.547e-2
Colon W R	121.56	4.967e-1	2.685e-2
ET	9.31	5.951e+0	3.217e-1
Gall bladder W	7.59	2.936e+0	1.587e-1
Gonads	6.	2.044e-1	1.105e-2
Heart W	217.92	7.083e-1	3.828e-2
Kidney	252.41	8.752e+0	4.731e-1
Kidney R	126.19	8.549e+0	4.621e-1
Kidney L	126.22	8.955e+0	4.84e-1
Kidney cortex L	88.34	8.644e+0	4.672e-1
Kidney cortex R	88.31	8.17e+0	4.416e-1
Kidney medulla L	31.57	9.628e+0	5.204e-1
Kidney medulla R	31.57	9.365e+0	5.062e-1
Kidney pelvis L	6.32	9.919e+0	5.362e-1
Kidney pelvis R	6.32	9.756e+0	5.273e-1
Lenses of eye	0.39	1.016e+0	5.494e-2
Liver	1301.27	2.692e+0	1.455e-1
Lung	773.53	6.031e-1	3.26e-2
Lung L	340.15	6.42e-1	3.471e-2
Lung R	433.37	5.725e-1	3.094e-2
Lymph nodes ET	10.69	3.854e-1	2.083e-2
Lymph nodes but ET&Th	108.8	4.921e-1	2.66e-2
Lymph nodes thoracic	10.19	1.657e+0	8.957e-2
Muscle	16749.77	2.4e-1	1.297e-2
Nasal passage Ant	0.5	8.391e-1	4.536e-2
Nasal passage Post+pharynx	9.31	5.951e+0	3.217e-1

Effective dose ICRP60 (mSv) 1.602e+0

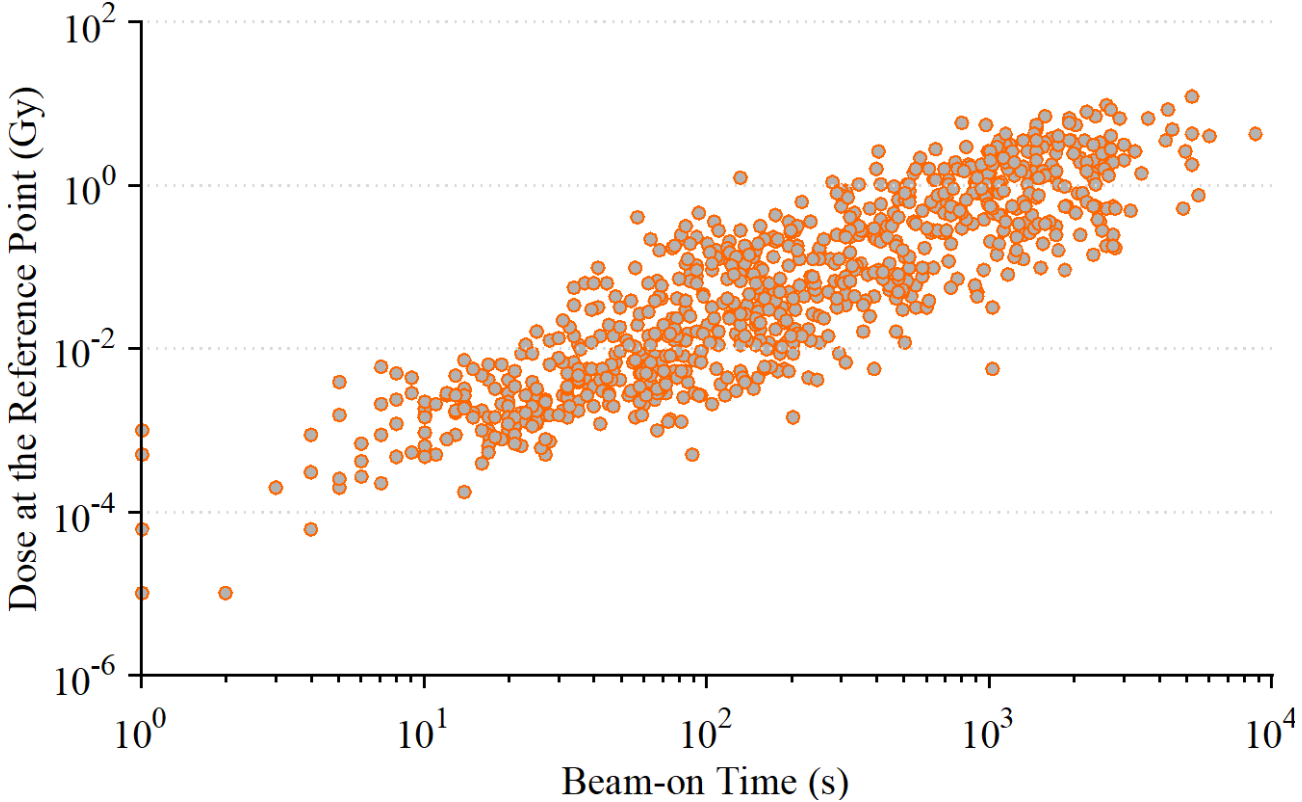
Effective dose ICRP103 (mSv) 1.602e+0

NCINM - dataset

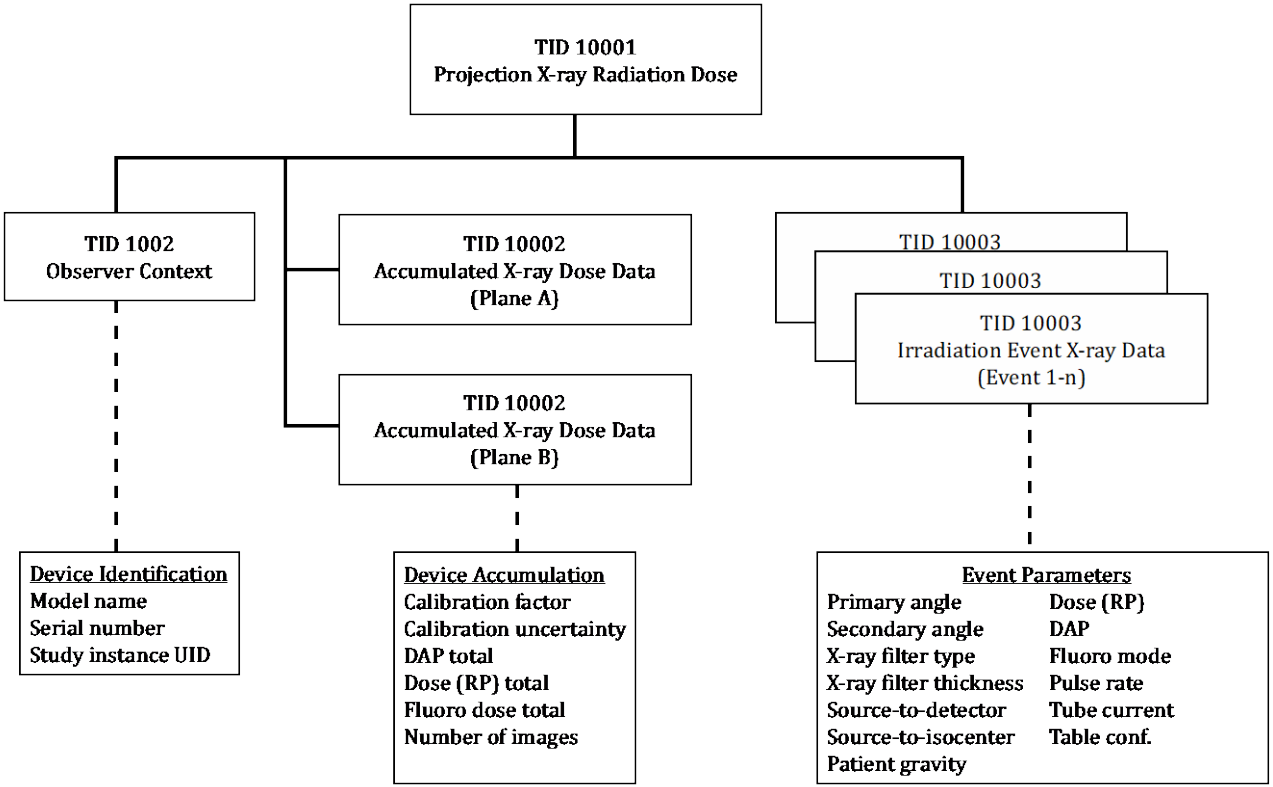
- SAFs generated for 2 particle types (γ, e^-), 25 energies, 12 phantoms, 70 source regions, 55 target regions.
  - ➢ 2.3 million SAFs
- S values generated for 299 radionuclides, 12 phantoms, 70 source regions, 55 target regions.
  - ➢ 13.8 million pre-calculated S values
- Absorbed doses to 55 organs of interest and effective doses (ICRP 60 &103) can be obtained for **all photon and electron emitters, for adult and pediatric patients.**

Radiography/Fluoroscopy

Fluoroscopy time as a scaling factor

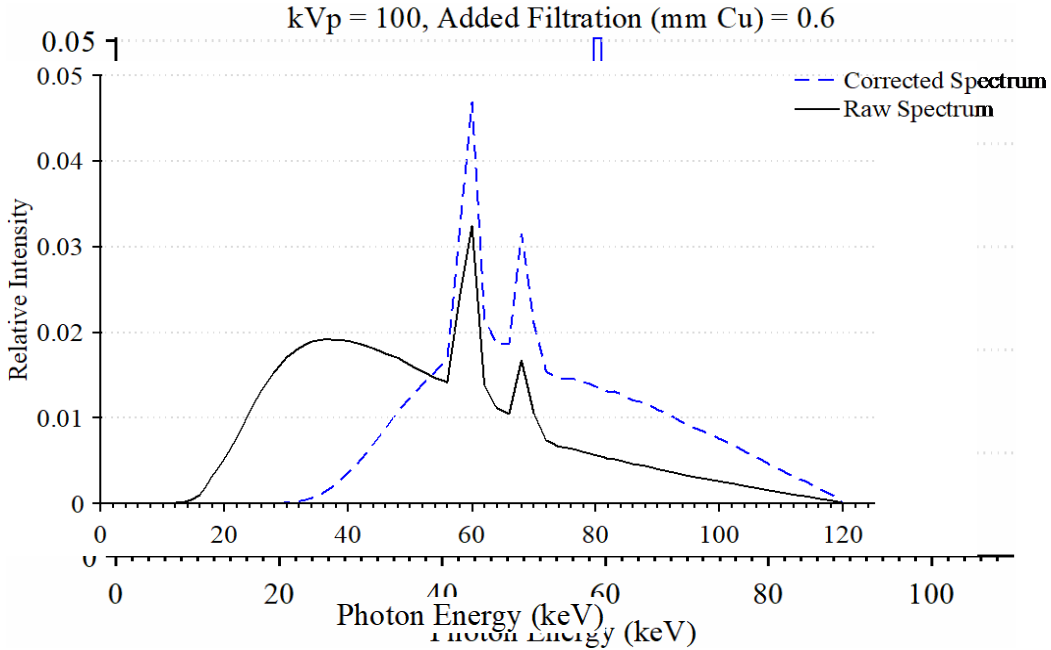


Patient dosimetry with the RDSR



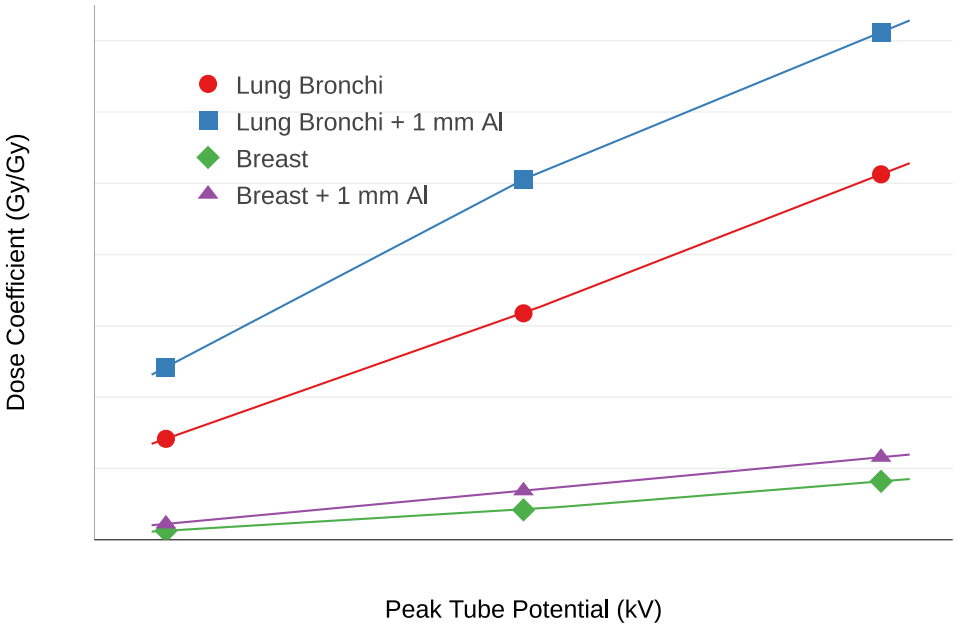
Modeling beam quality

- Filtered to eliminate low energy photons
- Beam qualities for mammography, radiography, fluoroscopy, and computed tomography (soft → hard)
- Beam qualities have changed over time
- Spectra are fitted to match measured beam quality



Dose coefficients for different beam qualities

Dose coefficients are sensitive to beam quality (*i.e.,* applied tube potential and amount of added filtration).

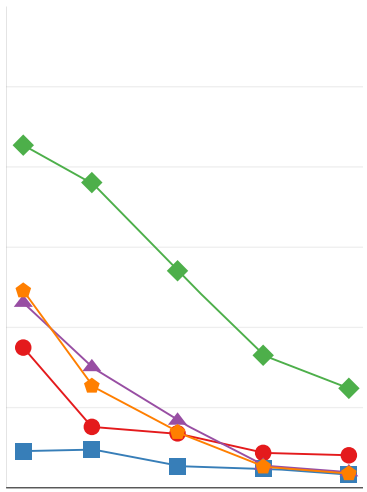


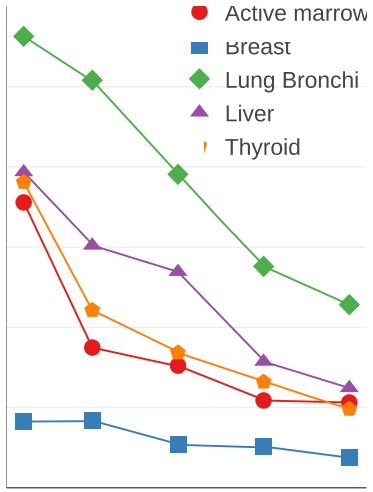
Borrego *Journal of Radiological Protection* (2019)

Dose coefficients for different ages

Dose coefficients are sensitive to beam quality (*i.e.,* applied tube potential and amount of added filtration).

Consider the effects of age on dose coefficients. If no adjustment in the technique factors is performed for pediatric patients their organ doses will be greater than adult patients.





ears)

Pneumothorax

Chest radiography

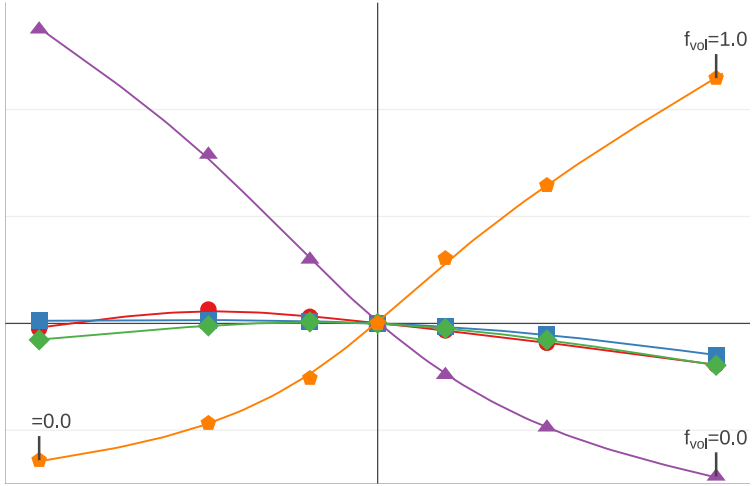
Borrego *Journal of Radiological Protection* (2019)

Dose coefficients for different displacements

Dose coefficients are sensitive to beam quality (*i.e.,* applied tube potential and amount of added filtration).

Consider the effects of age on dose coefficients. If no adjustment in the technique factors is performed for pediatric patients their organ doses will be greater than adult patients.

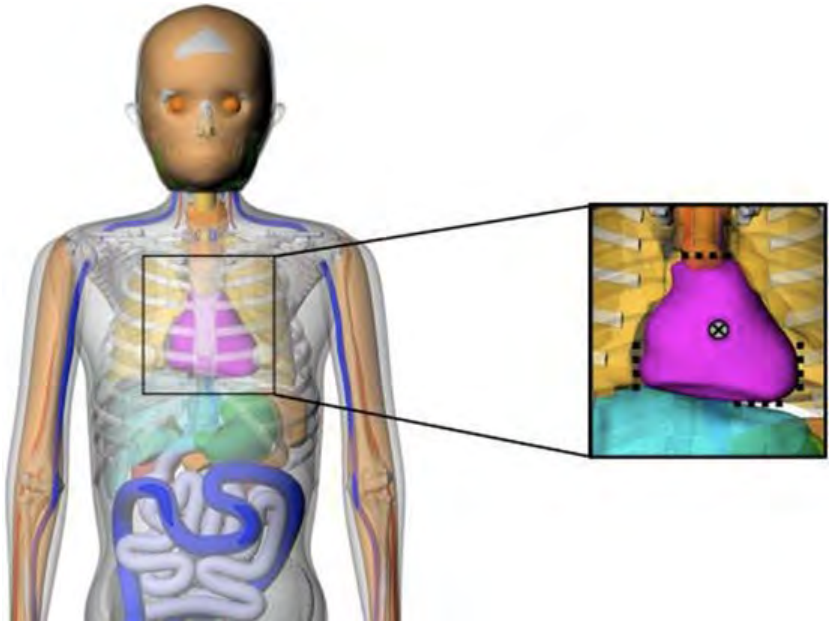
In-field organs are rather insensitive to small changes in displacements of central ray. Whereas, near-field organs are very sensitive to changes in the central ray location.



Borrego *Journal of Radiological Protection* (2019)

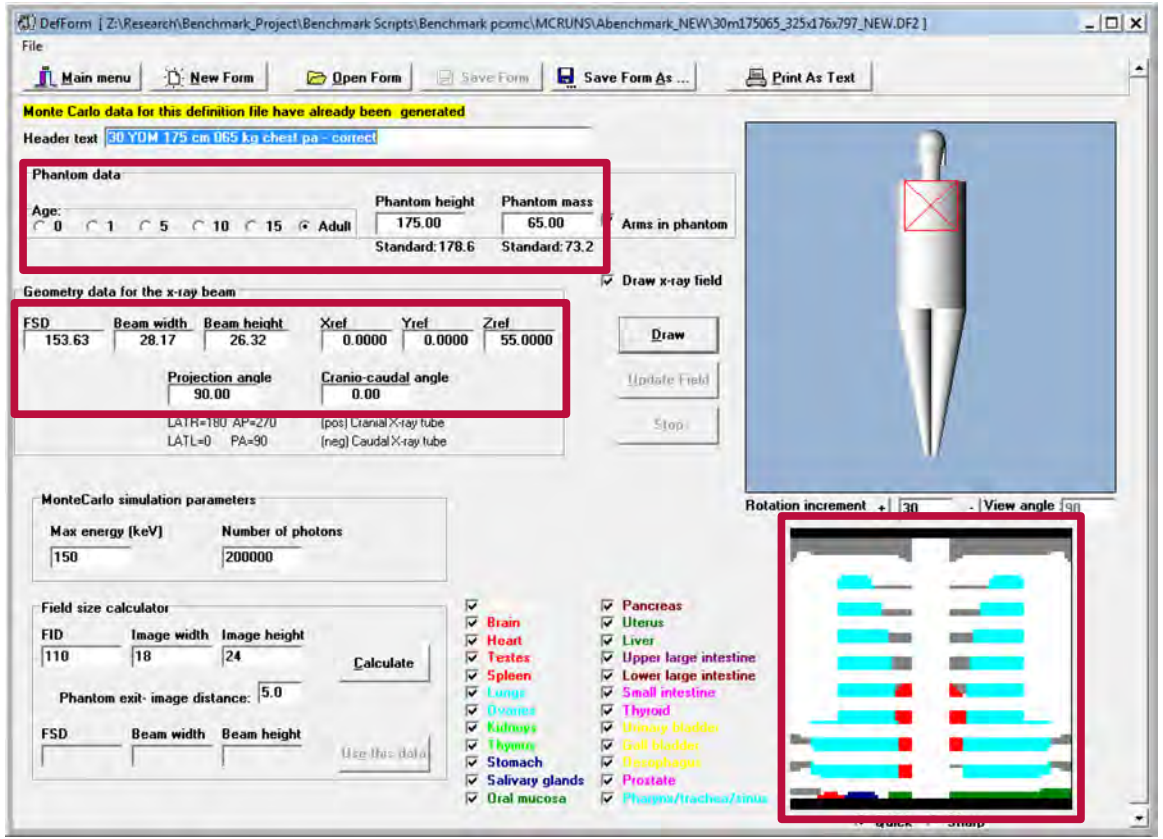
Patient positioning in interventional cardiology

- Lack of patient positioning information in structured reports.
- Without a priori knowledge of patient positioning it is possible to model the exposure geometry with limited information on procedure type.



Marshall *Physics in Medicine and Biology* (2019)

Methods to compute doses – PCXMC

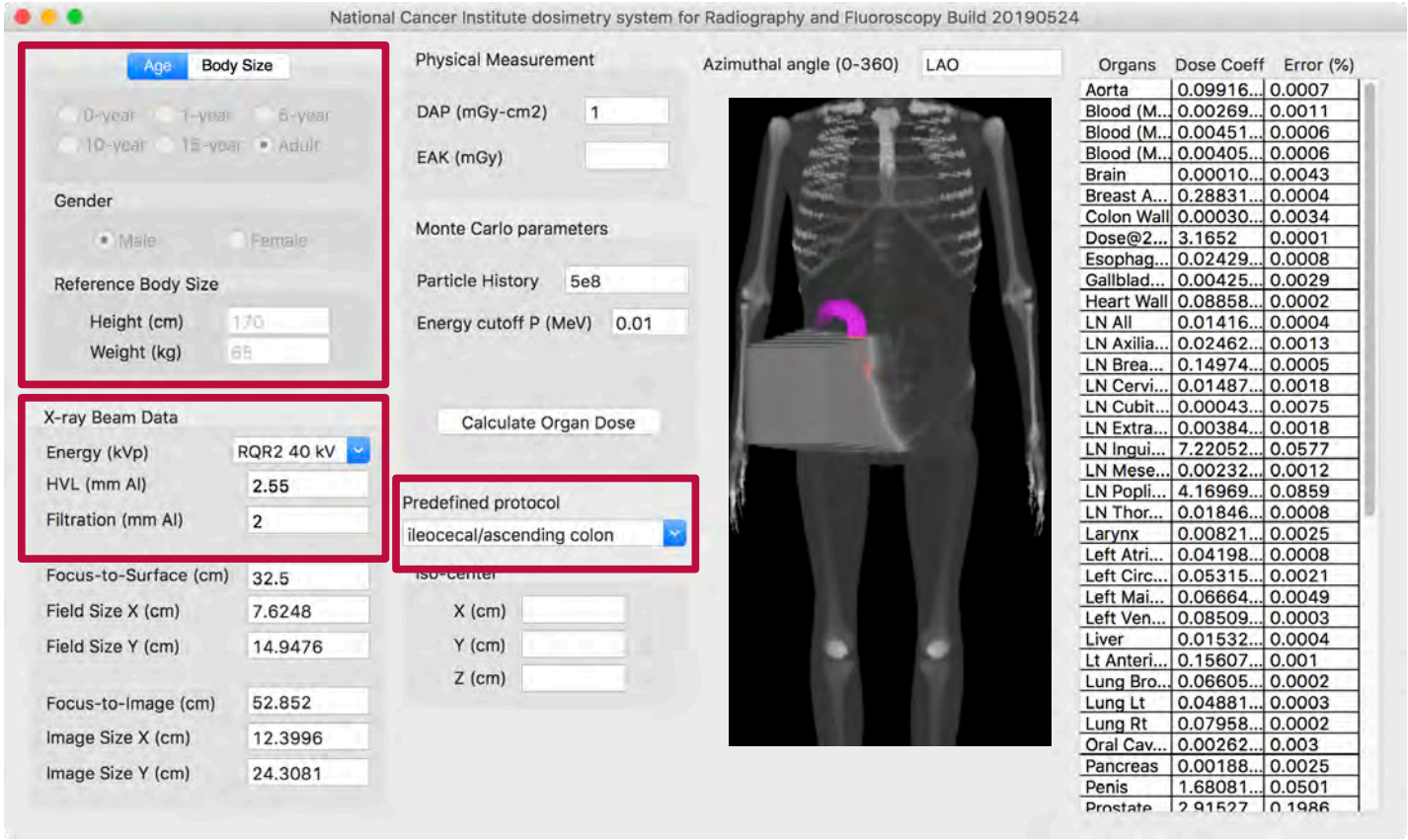


M. Tapiovaara and T. Siiskonen, PCXMC, 2nd ed. (2008).

Summary PCXMC in epidemiology

- H. Baysson, B. Nkoumazok, N. Journy, S. Dreuil, C. Etard, and M.O. Bernier, “Cardiologie interventionnelle dans l'enfance et risque de cancer,” Congrès National de Radioprotection (2015).
- R.W. Harbron et al., “Radiation doses from fluoroscopically guided cardiac catheterization procedures in children and young adults in the United Kingdom: a multicentre study,” BJR 88(1048), (2015).
- H. Baysson et al., “Follow-up of children exposed to ionising radiation from cardiac catheterisation: the Coccinelle study,” Radiation Protection Dosimetry 165(1-4), 13–16 (2015).
- R.W. Harbron, C.-L. Chapple, J.J. O'Sullivan, K.E. Best, A. Berrington de Gonzalez, and M.S. Pearce, “Survival adjusted cancer risks attributable to radiation exposure from cardiac catheterisations in children.,” Heart heartjnl–2016–309773 (2016).

NEXT STEPS in patient dosimetry: NCIRF



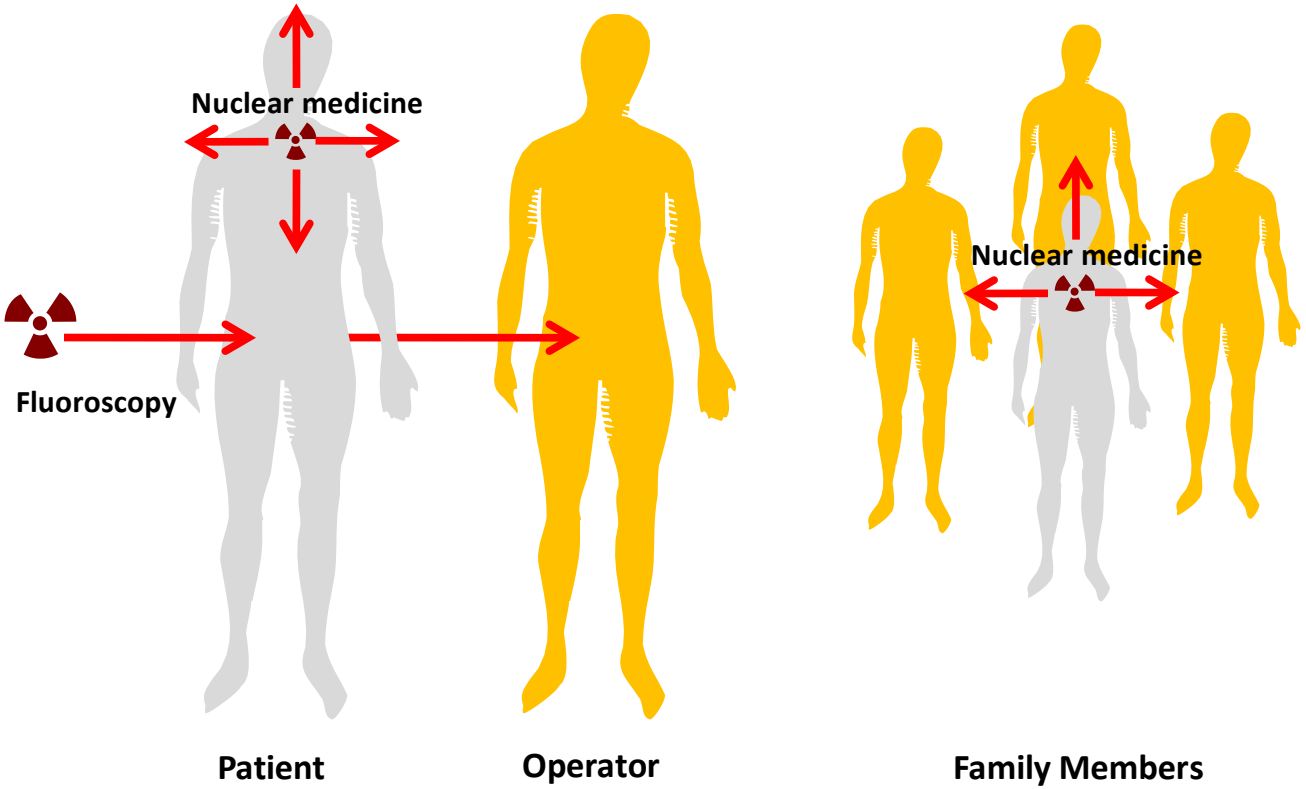
Some final thoughts

The challenge of dosimetry for epidemiologic purposes is not in applying the physics, but rather in determining how the exposure was received and how much radiation a person was exposed to.

Most of the difficulties are associated with determining the specifics of past exposure conditions.

All uncertainties, including uncertainties in exposure scenarios and uncertainties in data and models used to estimate organ dose, should be considered and taken into account in an appropriate manner.

What about non-patient doses? – Stay tuned!



Quiz question #1:

Your study team has collected all the information needed to perform an exposure scenario-specific calculation. Which of the following pieces of information can you disregard when calculating the organ doses?

1. Imaging parameters
2. Imaged anatomy
3. Patient information
4. All of the above would be useful

Quiz question #2:

Which of these modalities does not emit ionizing radiation?

1. Computed tomography
2. Magnetic resonance imaging
3. Fluoroscopy
4. Dental x ray

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Quiz question #3:

In fluoroscopically guided interventional procedures the patient dose is limited to no more than:

1. 10 mGy
2. 100 mGy
3. 1000 mGy
4. It is never appropriate to apply dose limits when the procedure is medically justified

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1-800-4-CANCER

Produced September 2019