Tracking Doses in the Pediatric Population

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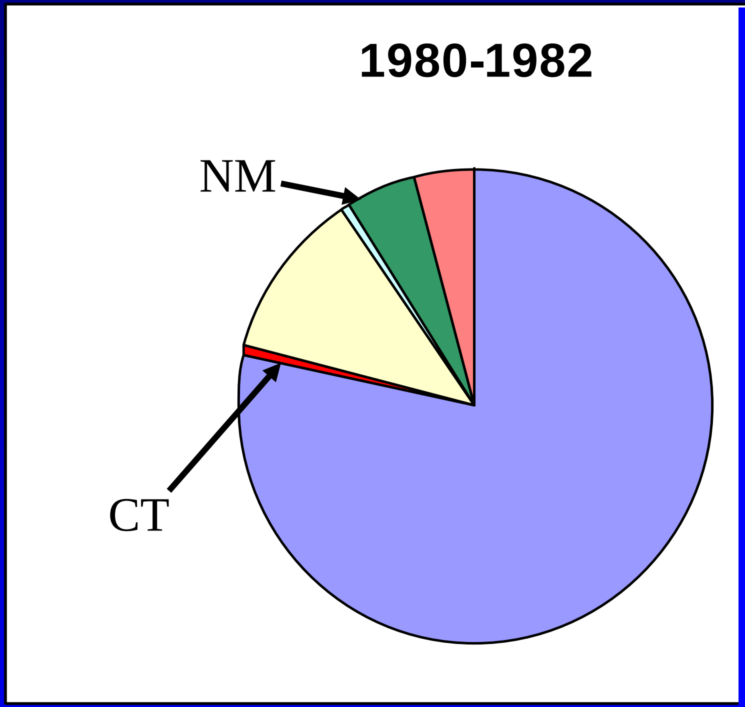
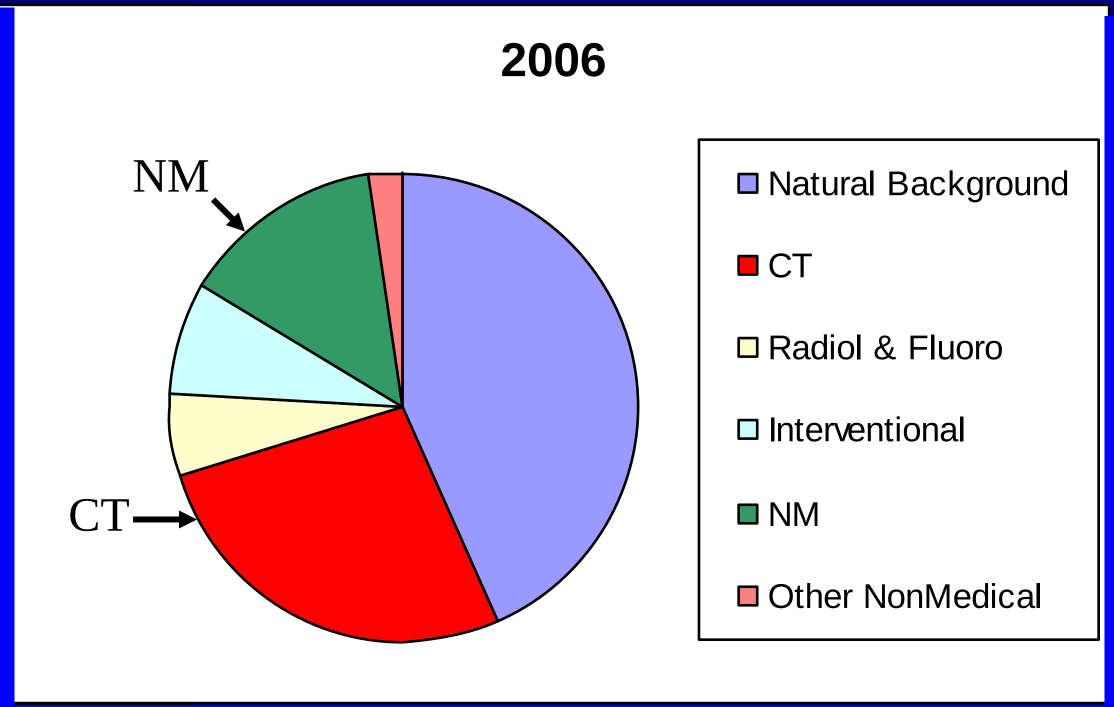
Disclosures

- Sadly, none that pay me any money! ☹
- SNMMI Dose Estimation Task Force
- Image Gently
- Image Wisely
- MITA Dose Reduction Task Force Advisory Board

Estimated Annual Per Capita Adult Effective Dose in US



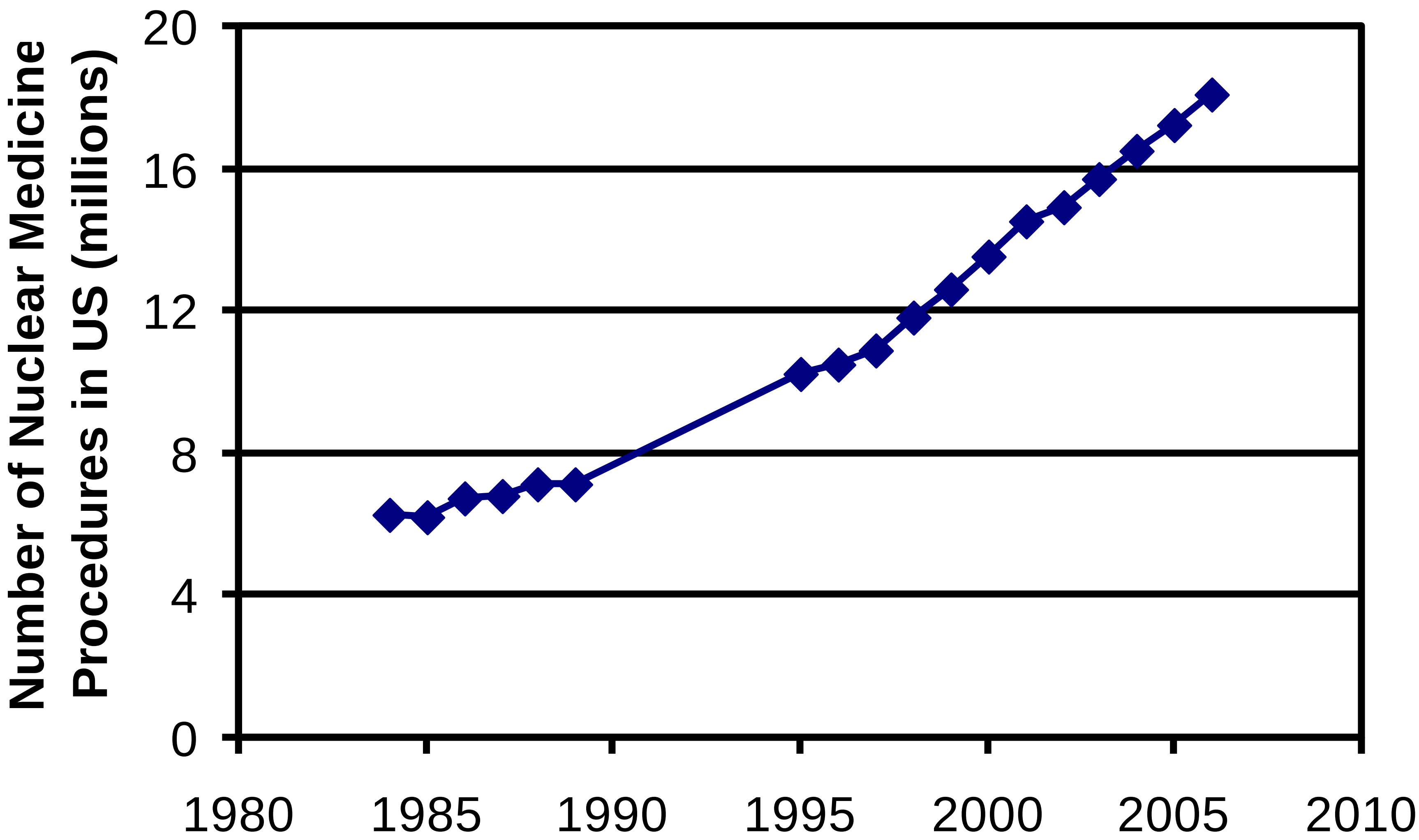


Medical 0.5 mSv
Total 3.1 mSv

Medical 3.0 mSv
Total 5.5 mSv

from NCRP 160

Nuclear Medicine Procedures in the US



NCRP 160

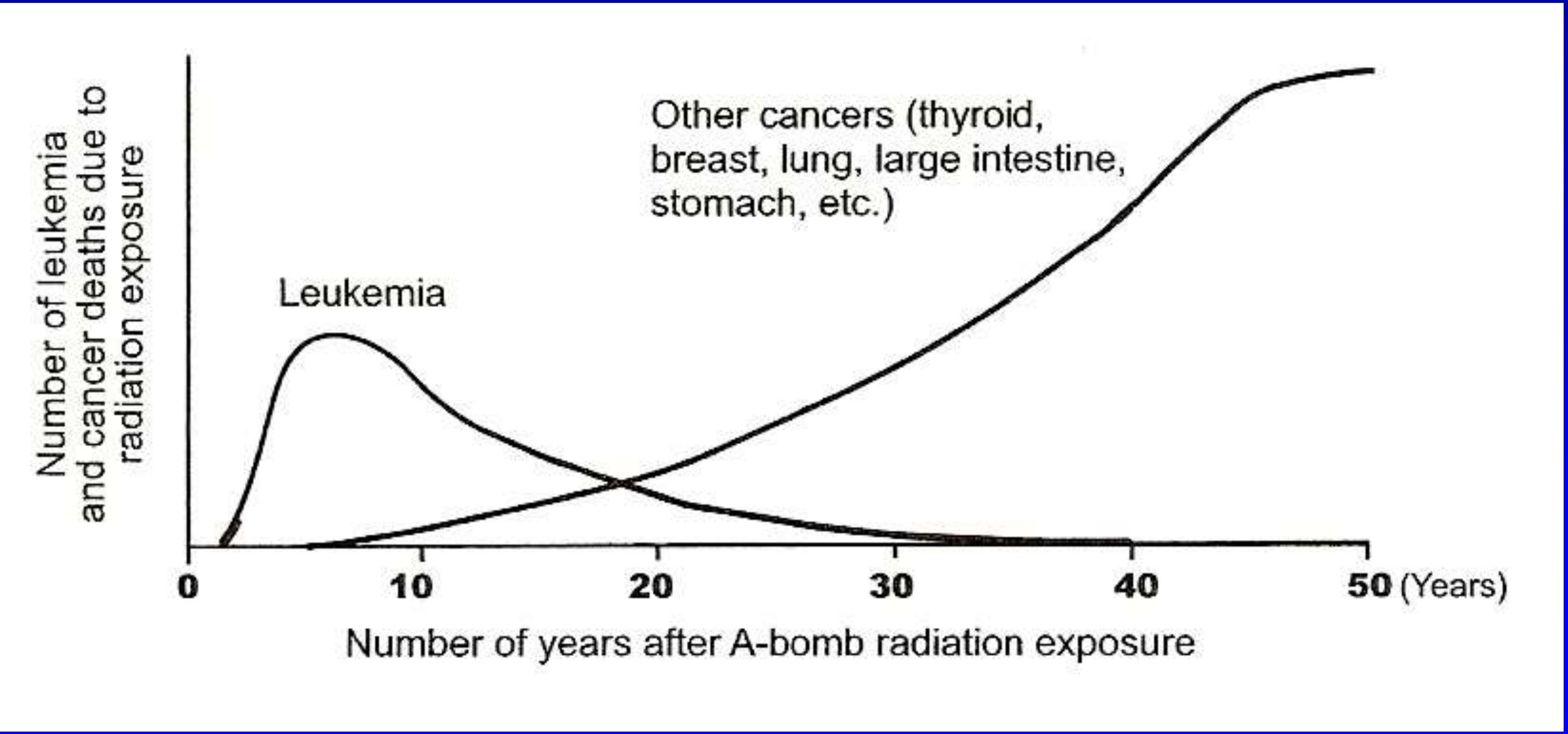
R. Fazel et al., Exposure to Low-Dose Ionizing Radiation from Medical Imaging Procedures. NEJM 2009; 361:841-843

- Studied insurance records of over 900,000 patients (18-65 YO) over 3 years
- 69% had at least 1 radiologic exam
- Annual effective dose
  - Mean 2.4 ± 6.0 mSv
  - Median 0.1 mSv (inter-quartile range 0.1-1.7 mSv)
  - 78.6% < 3 mSv; 19.4% 3-20 mSv
  - 1.9% 30-50 mSv; 0.2% >50 mSv

A. Dorfman et al., Use of Medical Imaging Procedures with Ionizing Radiation in Children. Arch Pediatr Adolesc Med. 2011;165:458-464.

- Insurance records of 355,000 children (under 18 YO) over 3 years
- Number and type of exams, not dose
- 42.5% of children had a radiologic procedure
- Ave of 7 radiologic exams by 18 YO
- 84.7% radiography, 11.9% CT, 2.5% fluoro, 0.9% NM
- 4 NM studies per yr per 1000 children (bone, thyroid)

From the Life Span Study (LSS) of the Radiation Effects Research Foundation atom bomb survivors we have learned about the time course of cancer appearance after a single acute dose of radiation – in the next decade we will learn more from those exposed in early childhood.



Cancer Mortality (Solid Tumors) from Lifespan Study (1950-2003)

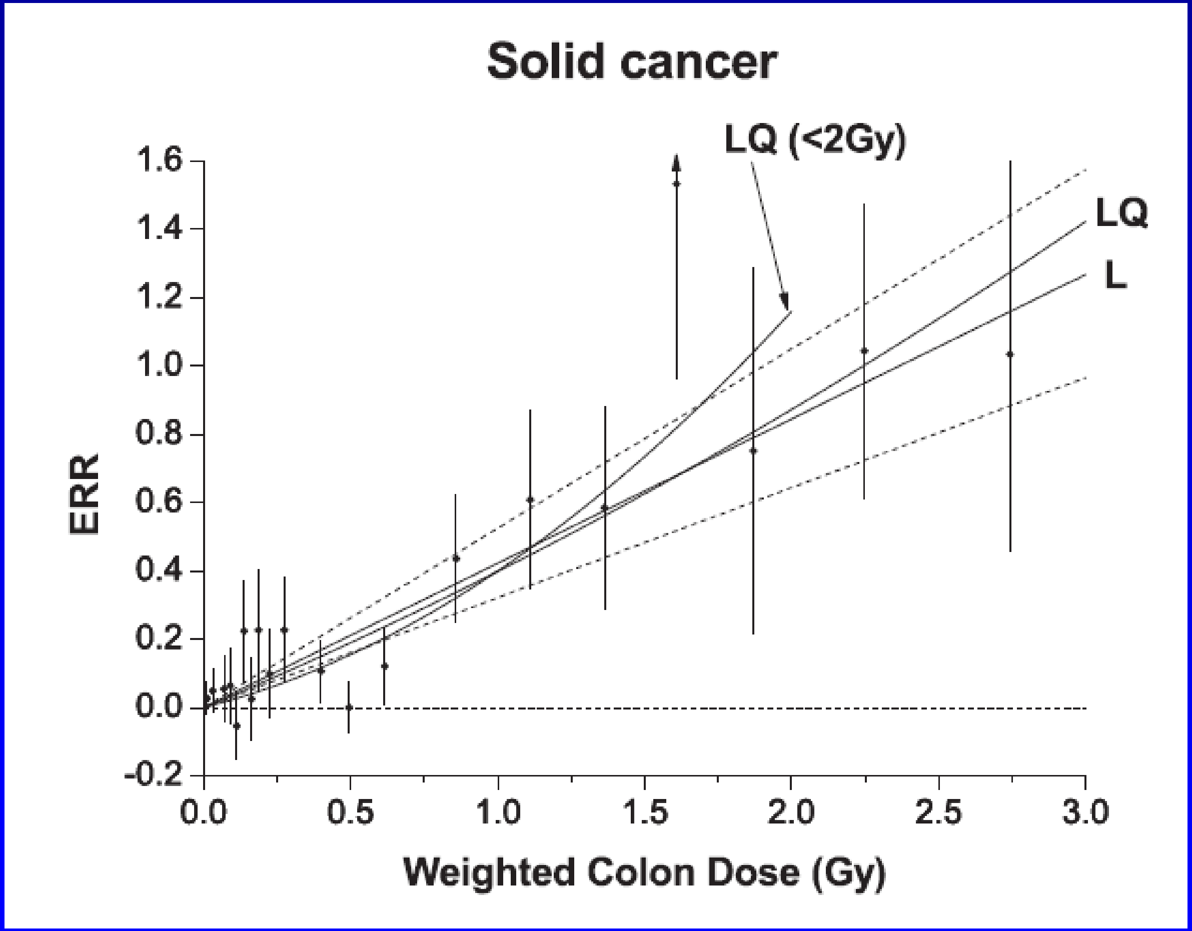
TABLE 9
Observed and Excess Deaths from Solid Cancer and Noncancer Diseases

			Solid cancer			Noncancer diseases[c]		
Colon dose (Gy)	Number of subjects	Person-years	Number of deaths	Number of excess cases[a]	Attributable fraction (%)	Number of deaths	Number of excess cases[b]	Attributable fraction (%)
<0.005	38,509	1,465,240	4,621	2	0	15,906	1	0
0.005–	29,961	1,143,900	3,653	49	1.3	12,304	36	0.3
0.1–	5,974	226,914	789	46	5.8	2,504	36	1.4
0.2–	6,356	239,273	870	109	12.5	2,736	82	3.0
0.5–	3,424	129,333	519	128	24.7	1,357	86	6.3
1–	1,763	66,602	353	123	34.8	657	76	11.6
2+	624	22,947	124	70	56.5	221	36	16.3
Total	86,611	3,294,210	10,929	527	4.8	35,685	353	1.0

[a] Based on the ERR model was defined as the linear model with effect modification: $\lambda_0(c,s,b,a)[1 + \beta_1 d \cdot \exp(\tau\, e + \upsilon \ln(a)) \cdot (1 + \sigma\, s)]$.
[b] Non-neoplastic blood diseases were excluded from noncancer diseases.

Ozasa et al., Rad Research 2012;177:229-243.

Most national and international bodies (ICRP,NCRP) have based their low dose (<100 mSv) risk estimates on linear extrapolation of the higher dose data. This report states that there is a significant trend in this range, consistent with that observed for the full dose range.



Ozasa et al., Rad Research 2012;177:229-243.

This, in turn, has led to the battle of the national academies:

<u>From BEIR VII – National Academies of the USA</u>

…current scientific evidence is consistent with the hypothesis that there is a linear, no-threshold dose-response relationship between exposure to ionizing radiation and the development of cancer in humans

<u>From Académie des Science – Institut de France</u>

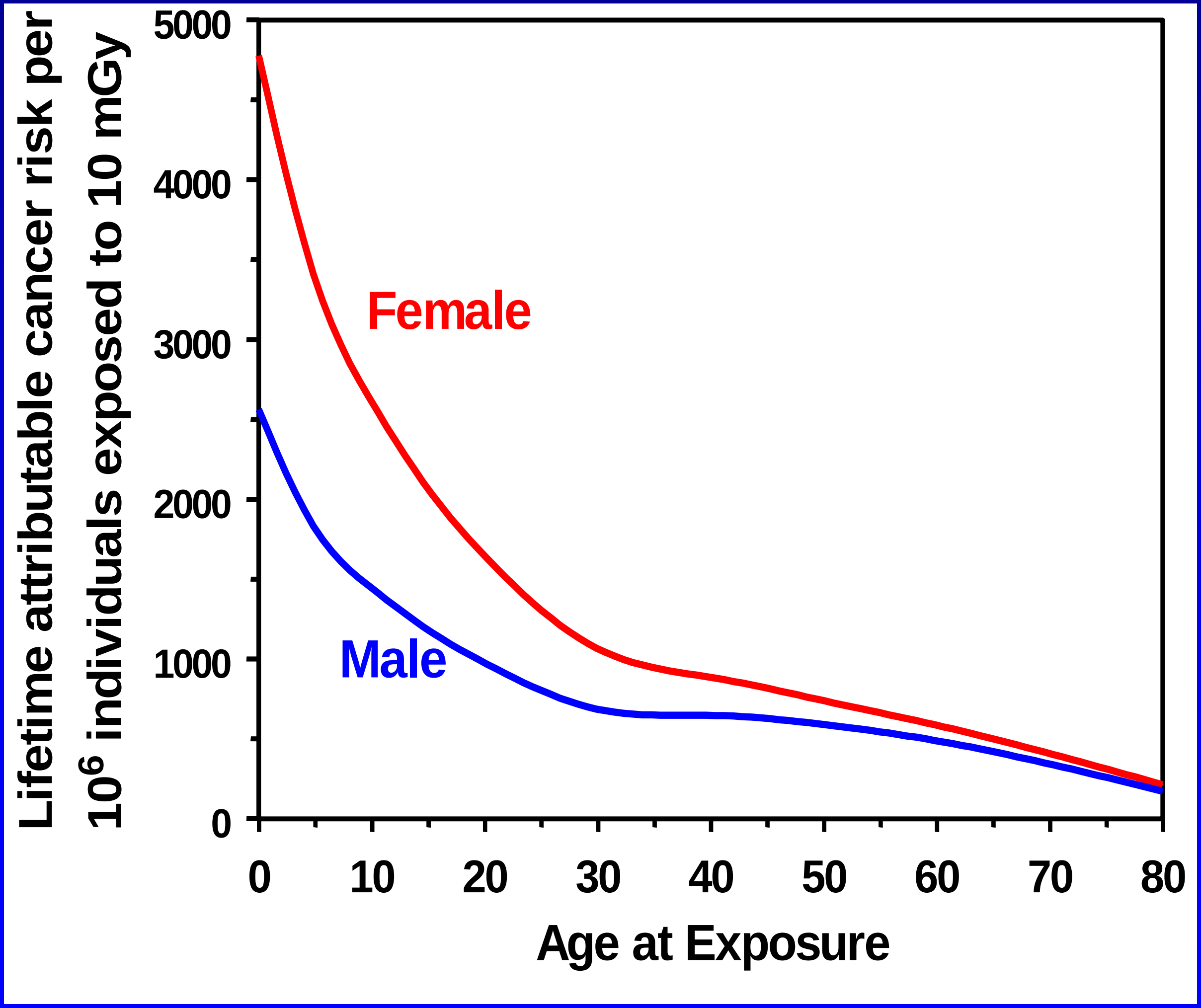
While LNT may be useful for the administrative organization of radioprotection, its use for assessing carcinogenic risks, induced by low doses, such as those delivered by diagnostic radiology or the nuclear industry, is not based on valid scientific data.

Lifetime Attributable Risk
10 mGy in 100,000 exposed persons
(BEIR VII Phase 2, 2006)

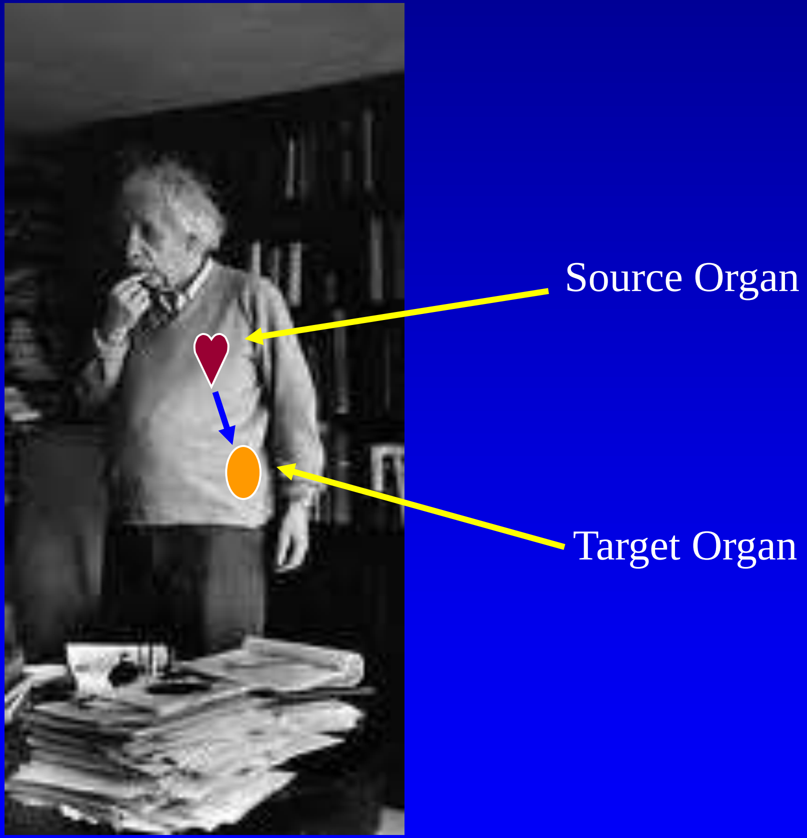
	All Solid Tumors		Leukemia	
	Male	Female	Male	Female
Excess Cases	80	130	10	7
Excess Deaths	41	61	7	5

Note: About 45% will contract cancer and 22% will die.

Lifetime Attributable Risk
10 mGy in 1,000,000 exposed persons
(Based on BEIR VII Phase 2, 2006)



MIRD Equation



Medical Internal Radiation Dosimetry Committee of the SNMMI

MIRD Equation

MIRD Pamphlet 21. J Nucl Med 2009;50:477

$$D(r_T) = \sum_S \tilde{A}(r_S)\, S(r_T \leftarrow r_S)$$

- $D(r_T)$ is radiation dose to the target organ
- $\tilde{A}(r_S)$ is time integrated activity for the source organ
- "S" value is a radionuclide specific quantity which is the mean dose to the target organ per integrated activity in the source organ
- $\sum_S$ indicates that this is summed over all source organs

Time Integrated Activity (Ã)

- Units of activity-time (e.g. Bq-hr) & is total # of decays
- Depends on
  - Administered activity (A_o in Bq)
  - Fraction of activity that goes to source organ (F)
  - How long the activity stays there (T_{eff})

$$\tilde{A}(r_S) = A_o \, F \, T_{eff}$$

F depend on the particular radionuclide administered, and the specific uptake of the patient.

S Factor

$$S(r_T \leftarrow r_S) = \sum_i \Delta_i \varphi_i / M_T$$

- Δ_i is mean energy per nuclear transformation for the i^{th} radiation emitted by the radiopharmaceutical
- M_T is the mass of the target organ
- φ_i is the fraction of energy emitted by the source organ that is absorbed by the target organ of the i^{th} radiation which depends on the radiation and the size and anatomy of the patient. φ_i/M_T is the specific absorbed fraction (SAF).
- $\sum_i$ Indicates that this is summed over all radiations
- Determined by physical parameters such as radionuclide's decay scheme and orientation, size and spacing of patient's organs

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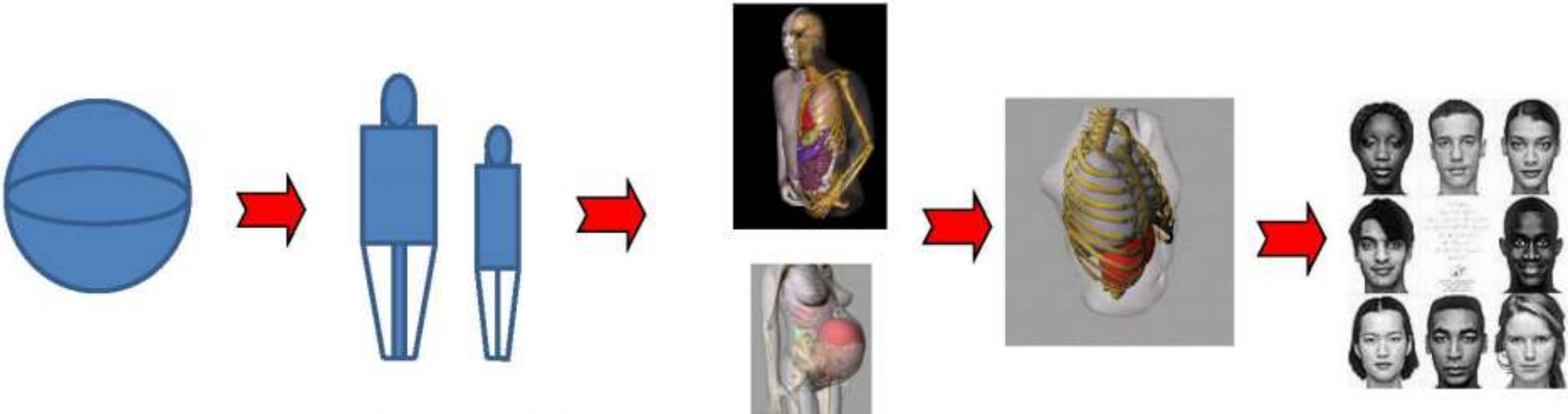
Evolution of Computational Phantoms

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



ICRU sphere 1960s

MIRD anthropomorphic models in 1980s

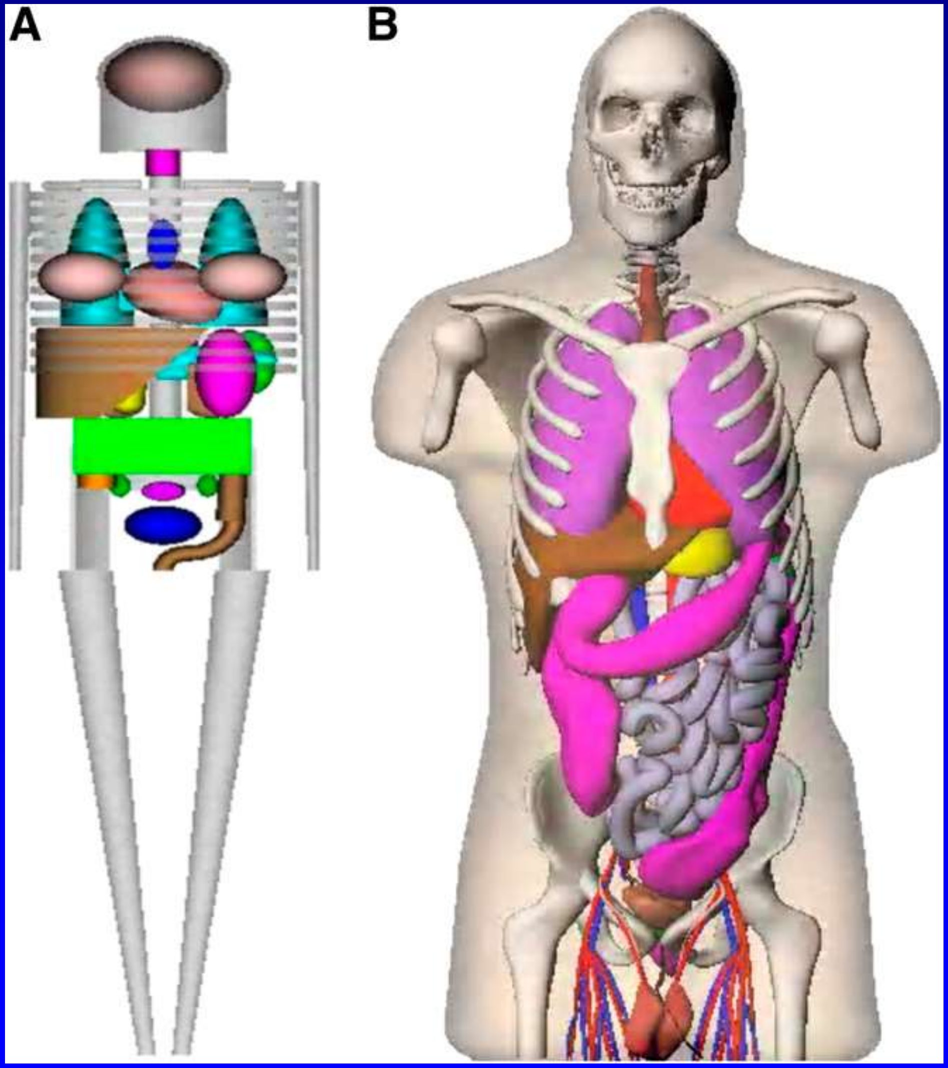
Image-based rigid, 3D model in 1990-2000s

Currently Deformable and moving 4D models 2008-2010

Future?

Courtesy of George Xu, RPI

Traditional vs Realistic Phantom



- Use of non-uniform rational B-splines or "NURBS"
- Easier to compute and more scalable than voxel based approaches

Marine et al. J Nucl Med 2010;51:806-811

Uncertainties

Uncertainties in Internal Dose Calculations for Radiopharmaceuticals

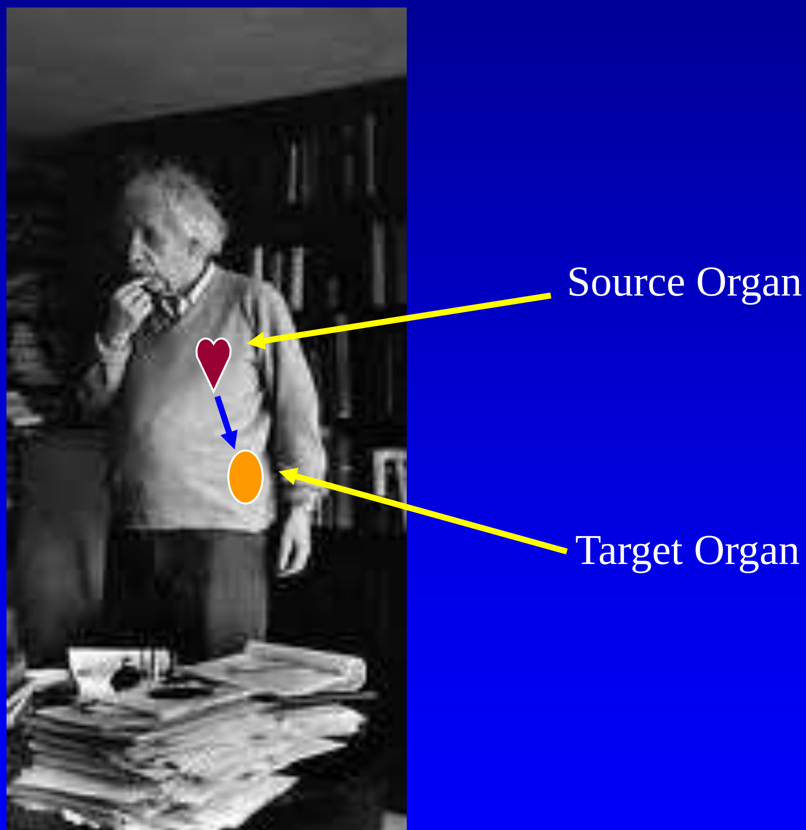
Michael G. Stabin

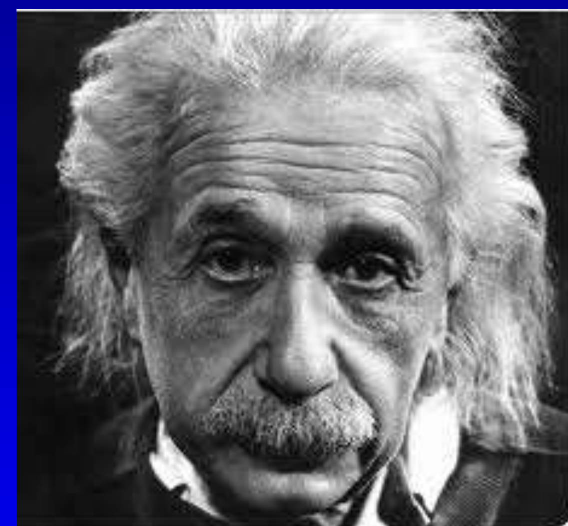
The combined uncertainties in most radiopharmaceutical dose estimates will be typically at least a factor of 2 and may be considerably greater.

J Nucl Med. 2008;49:853-860

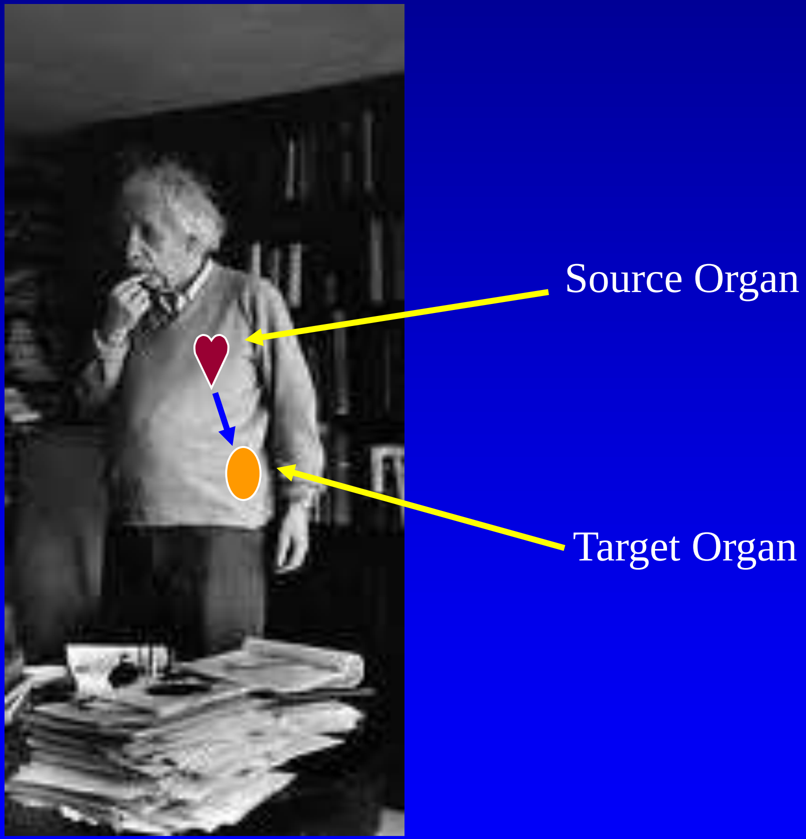
Most of uncertainty in physiologic factors.

MIRD Equation





MIRD Equation

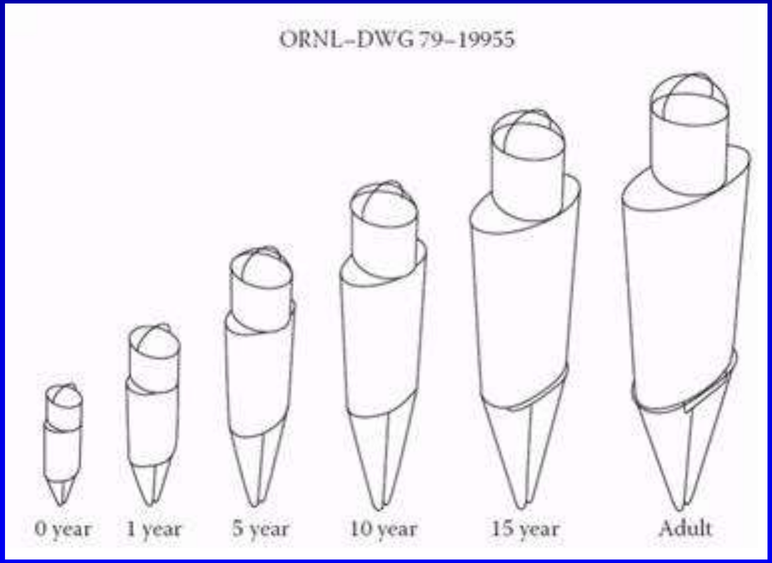


What aspects of the MIRD formalism may vary for pediatric patients?

- S Factor
  - Patient size
  - Relative size and location of organs


ISLAND STORE
MY
IS #1

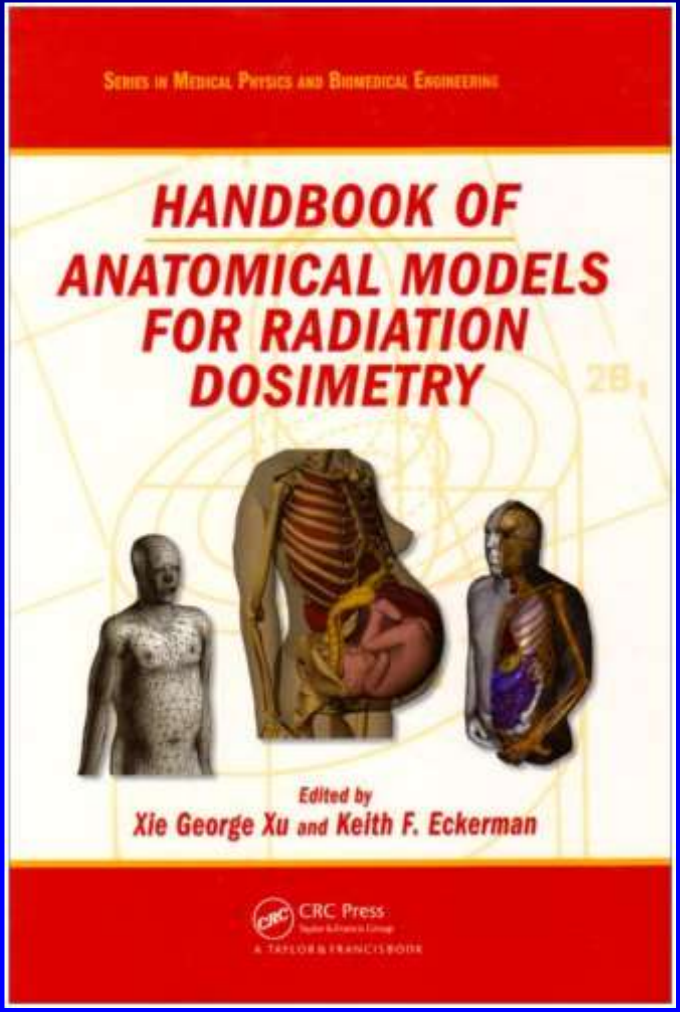
Pediatric Dosimetry Phantoms



M. Cristy and K. Eckerman
1987 ORNL report

Lee *et al*. Med Phys 2007;
34:1858-1873

Anatomical Models for Radiation Dosimetry



- Xu G, Eckerman KF, eds. Handbook of Anatomical Models for Radiation Dosimetry. CRC Press, 2009.
- Whalen S, Lee C, Williams J, Bolch WE. Phys Med Biol. 2008;53:453.
- Nosske D, Blanchardon E, Bolch WE, et al. Radiat Prot Dosimetry. 2011;144:314.
- Stabin M et al. RADAR reference phantom series. J Nucl Med 2012;53:1807.

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What aspects of the MIRD formalism may vary for pediatric patients?

- S Factor
  - Patient size
  - Relative size and location of organs
- Integrated Activity
  - Relative uptake of radionuclide in organs
  - Clearance rate

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Children are NOT small adults!

Effective Dose

Effective Dose is equivalent to the absorbed dose given to the whole body of the patient that would result in the same biological effect as the actual clinical dose given to a fraction of the patient's whole body. It is calculated by taking a weighted sum of the absorbed doses delivered to individual organs where each organ is weighted by its radiation sensitivity.

$$ED = \Sigma H_T \times W_T$$

Where H_T is dose to organ, T, and W_T is the radiosensitivity weight assigned to that organ.

Effective Dose

TABLE 1: Tissue-Weighting Factors for International Commission on Radiological Protection (ICRP) Publications 26, 60, and 103

Tissue or Organ	Publication		
	ICRP 26	ICRP 60	ICRP 103
Gonads	0.25	0.20	0.08
Red bone marrow	0.12	0.12	0.12
Lung	0.12	0.12	0.12
Colon		0.12	0.12
Stomach		0.12	0.12
Breast	0.15	0.05	0.12
Bladder		0.05	0.04
Liver		0.05	0.04
Esophagus		0.05	0.04
Thyroid	0.03	0.05	0.04
Skin		0.01	0.01
Bone surface	0.03	0.01	0.01
Brain			0.01
Salivary glands			0.01
Remainder	0.30	0.05	0.12
Total	1.00	1.00	1.00

From Christner et al. AJR 2010;194:881-889

Effective Dose

Note: Effective dose is based on a population-based estimate of radiation risk and dose NOT apply to a specific patient. In particular, the risk estimates do NOT apply to children.

Lifetime Excess Attributable Risk of Mortality per 100,000 for 10 mSv Whole Body Exposure

		Newborn	10 Years	40 Years
Breast	Female	27.4	16.7	3.5
Lung	Female	64.3	44.2	21.2
	Male	31.8	21.9	10.7
Colon	Female	10.2	7.3	3.7
	Male	16.3	11.7	6.0
All Solid	Female	172	105	45.5
	Male	103	64.1	31.0
Leukemia	Female	5.3	5.3	5.2
	Male	7.1	7.1	6.7

Based on BEIR VII Ph 2

Factors Affecting Dose in NM and SPECT

- **Administered activity**
  - **Total counts and imaging time**
- Choice of camera
  - Detector thickness and material
  - Number of detectors
- Choice of collimator
  - Hi Sens, Gen Purpose, Hi Res, Pinhole
- Image processing and reconstruction

Patient Effective Dose (mSv)

Summary	**1 Year**	**5 Year**	**10 Year**	**15 Year**	**Adult**
Mass (kg)	9.7	19.8	33.2	56.8	70
Tc-MDP (20 mCi*)	2.8	2.9	3.9	4.2	4.2
Tc-ECD (20 mCi*)	4.1	4.6	5.3	5.9	5.7
Tc-MAG3 (10 mCi*)	1.2	1.3	2.2	2.8	2.7

*max admin activ

ICRP 80 and 106

Factors Affecting Dose in PET

- **Administered activity**
  - **Total counts and imaging time**
- Choice of scanner
  - Crystal material and thickness
  - 2D vs 3D
  - Axial field of view
- Image processing

Patient Dose from FDG (mSv)

Summary	**1 Year**	**5 Year**	**10 Year**	**15 Year**	**Adult**
Mass (kg)	9.7	19.8	33.2	56.8	70
Act (mCi)	*1.46*	*2.97*	*4.98*	*8.52*	*10.5*
Bladder*	25.6	35.9	44.4	48.8	50.5
Eff Dose*	5.2	5.9	6.6	7.3	7.4

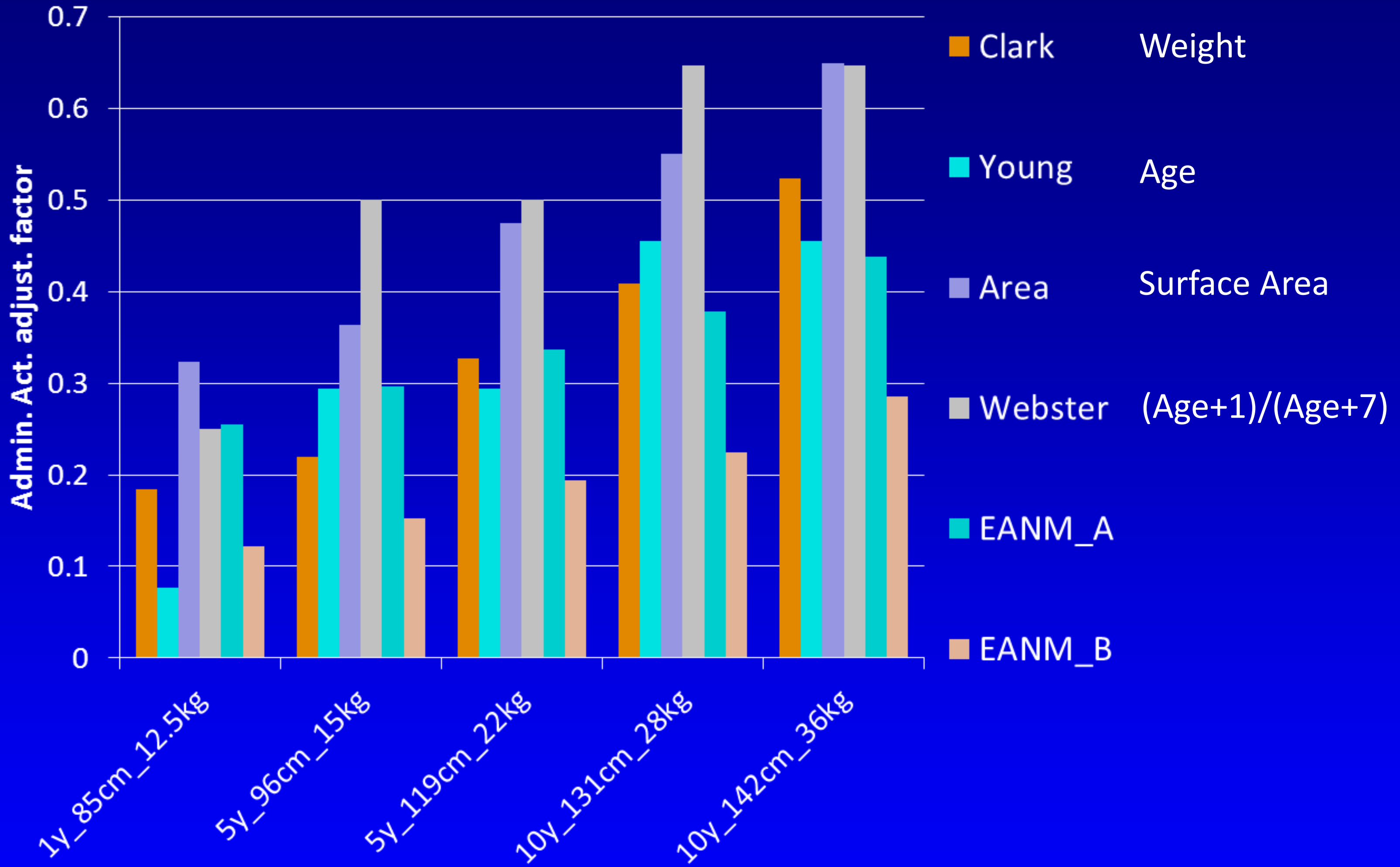
ICRP 106

Pediatric NM/PET Dose Tracking

- **Administered activity**
- **Patient size (height, weight)**

- Route of administration
- Physiologic parameters (age, disease)
- Image data

These data may not be available from DICOM header without double entry.



Adjustment factor from the adult dose

Gelfand MJ, Parisi MT, Treves ST *Pediatric radiopharmaceutical administered doses: 2010 North American consensus guidelines*. J Nucl Med. 2011;52:318-22.

In 2013, Image Gently and EANM worked successfully to harmonize the pediatric guidelines of both organizations. EANM has recently approved their harmonized guidelines.

Thirteen international NM organizations involved in NM Global Initiative considering Pediatric NM administered activities.

Pediatric NM in Clinical Practice

- In 2007, surveyed 13 dedicated pediatric hospitals in North America.* Follow-up survey in 2013
- Survey in 2013 of 200 general hospitals with over 300 beds in the US. Email survey survey to NM chief technologist or supervisor

*Treves ST, Davis RT, Fahey FH. *J Nucl Med*, 2008;49:1024-1027.

Pediatric NM in Clinical Practice (Dedicated Pediatric Hospitals)

- **2007:** For dose/kg and Maximum Dose the range factor varied, on average, by a factor of 3, and by as much as a factor of 10. Minimum Dose ranged , on average, by a factor of 10 and as much as a factor of 20
- **2013:** Dose parameters reduced or same in all cases. Range reduced in dose/kg and min dose but raised in max dose due to dose reduction (some stayed the same/ some lowered). All familiar with Image Gently and North American Guidelines. 10/13 modified their administered activities based on North American Guidelines

Pediatric NM in Clinical Practice (General Hospitals)

- 121/294 hospitals responded. 80% perform pediatric NM studies. Essentially all scaled administered activity in smaller patients (90% by weight).
- Of 5 procedures considered, the median of the surveyed group was consistent with the North American Guidelines in all cases of dose/kg and Min Dose.
- 83% familiar with Image Gently, 58% familiar with North American Guidelines, 55% modified their administered activities based on North American Guidelines

Factors Affecting Radiation Dose in Multi-Detector CT

- Tube current or time (α mAs)
- Reduce tube voltage (α kVp^2)
- Beam collimation
- Pitch (table speed) (α 1/pitch)
- Patient size
- Region of patient imaged

Median Effective Dose Values

Review of Published Results

Head CT	1.9 mSv (0.3-8.2)
Chest CT	7.5 mSv (0.3-26.0)
Abdomen CT	7.9 mSv (1.4-31.2)
Pelvis CT	7.6 mSv (2.5-36.5)
Abd & pelvis CT	9.3 mSv (3.7-31.5)

Pantos et al., Brit J Radiol 2011;84:293-303

CIRS Tissue Equivalent Phantoms

- Dosimetric CT phantoms
- Simulated spine
- Five 1.3 cm holes
- Five different sizes

Phantom	AP x Lat (cm)	Circum (cm)
Newborn	9 x 10.5	32
1 Year Old	11.5 x 14	42
5 Year Old	14 x 18	53
10 Year Old	16 x 20.5	61
Med Adult	25 x 32.5	96

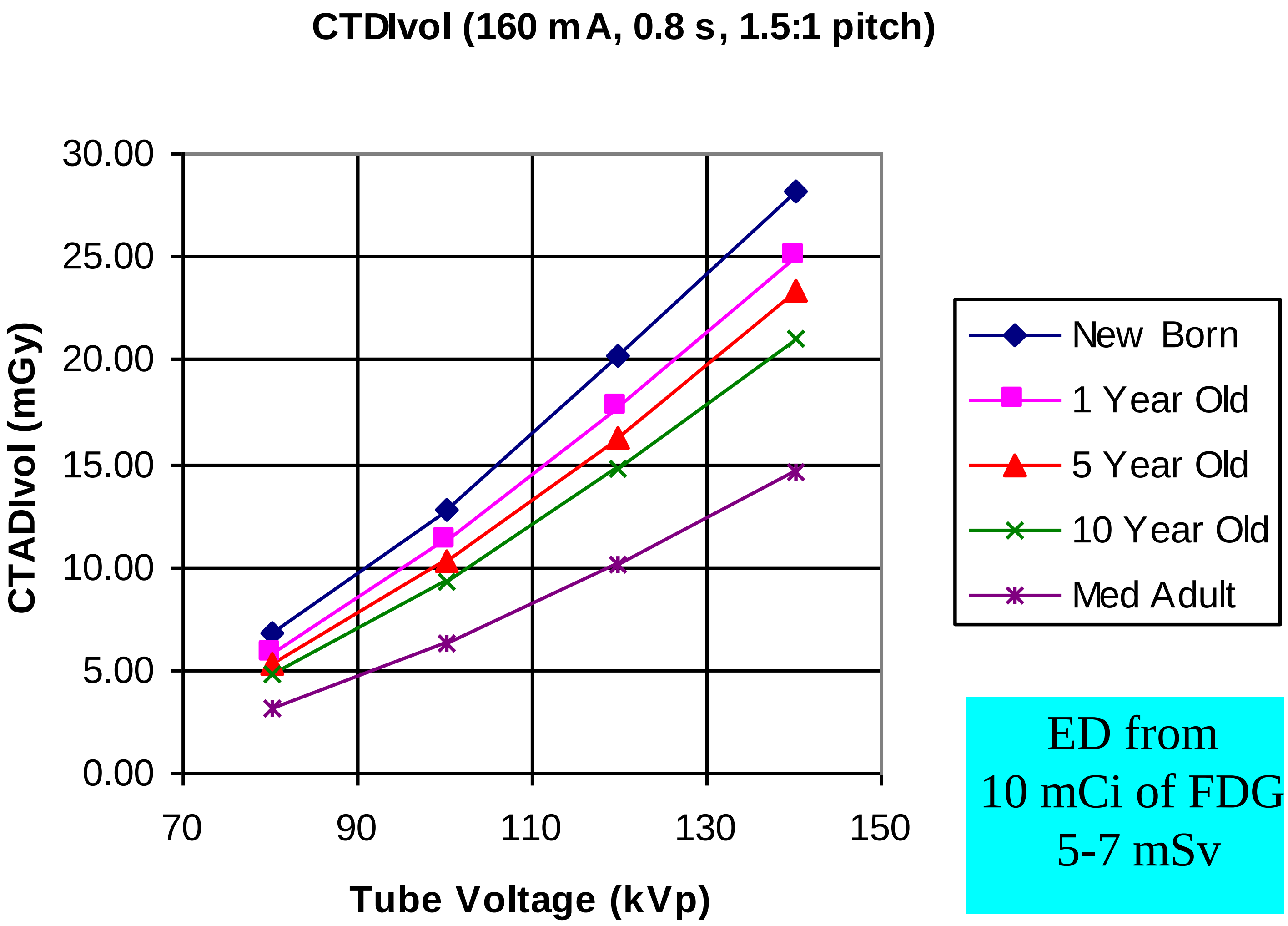
Fahey et al. *Radiology* 2007;243:96-104

Dosimetry of PET-CT and SPECT-CT

- PET/CT
  - –GE Discovery LS

- SPECT/CT
  - –Philips Precedent

Dose from CT of PET-CT
GE Discovery LS (4-slice)



ED from
10 mCi of FDG
5-7 mSv

Organ and effective doses in pediatric patients undergoing helical multislice computed tomography examination

Lee *et al*. Med Phys 2007;34:1858-1873

Estimated organ and effective doses from helical CT for 5 phantoms and the MCNPX Monte Carlo photon transport code

CAP CT exam, 120 kVp, 100 mAs
12 mm beam thickness, 1:1 Pitch
(Dose in mGy)

Organ	9 MO (M)	4 YO (F)	11 YO (M)	14 YO (M)
Bone marrow	6.02	6.64	7.33	7.62
Lungs	15.95	14.75	12.74	13.04
Stomach	15.62	14.13	12.71	10.73
Muscle	8.20	7.68	5.93	5.40
Breast		10.67		
Gonads	12.66	14.39	8.15	7.83

Lee *et al*. Med Phys 2007;34:1858-1873

Output of IMPACT Spreadsheet

ImPACT CT Patient Dosimetry Calculator
Version 1.0 28/08/2009

Scanner Model:		
Manufacturer:	GE	
Scanner:	GE LightSpeed VCT	
kV:	120	
Scan Region:	Body	
Data Set	MCSET20	Update Data Set
Current Data	MCSET20	

Scan range			
Start Position	-10	cm	Get From Phantom Diagram
End Position	85	cm	

Organ weighting scheme	ICRP 103

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	35.0	mGy/100mAs
CTDI (soft tissue)		37.4	mGy/100mAs
$_nCTDI_w$	Look up	11.1	mGy/100mAs

$CTDI_w$	11.1	mGy
$CTDI_{vol}$	11.1	mGy
DLP	1053	mGy.cm

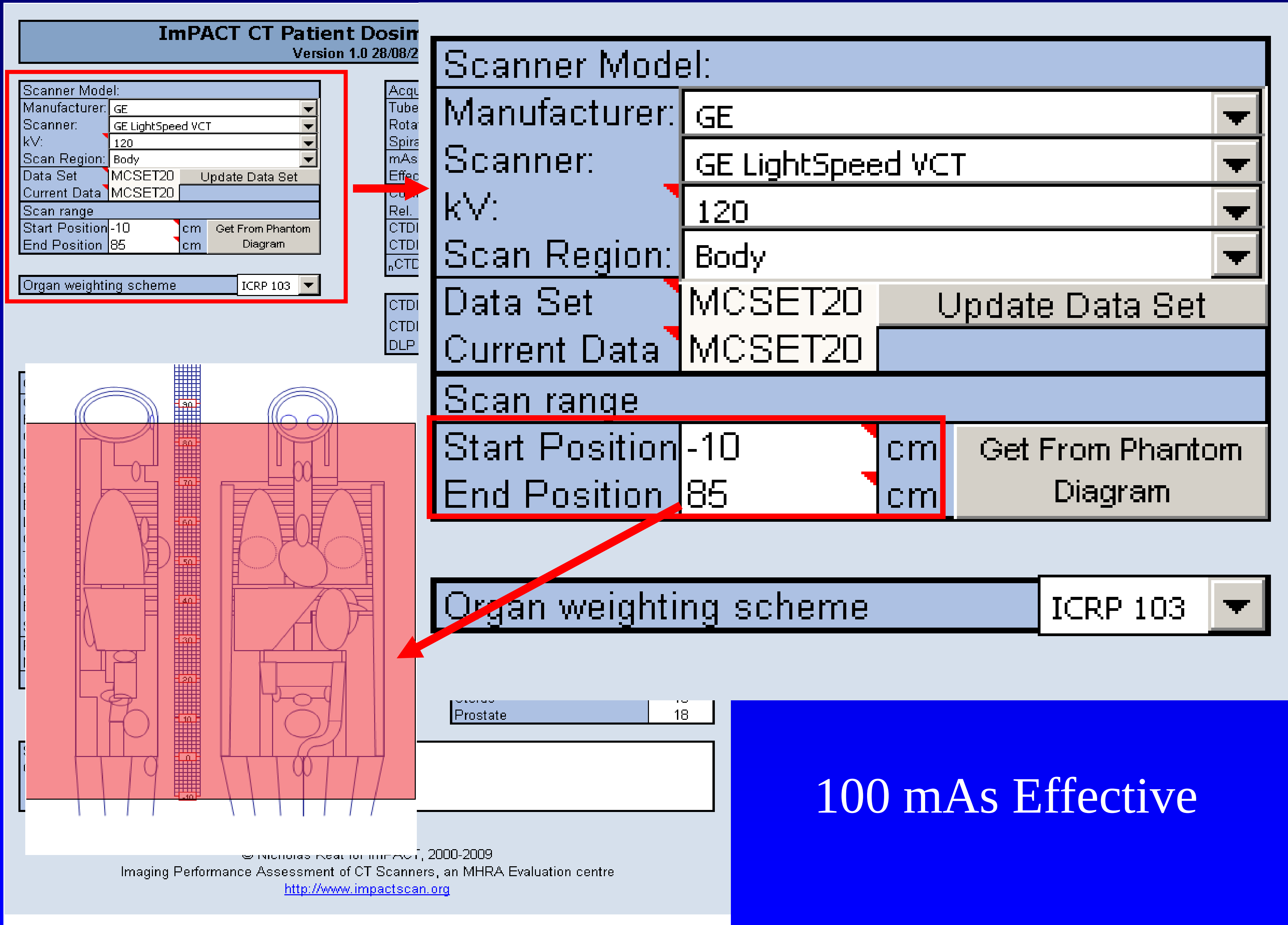
Organ	w_T	H_T (mGy)	$w_T.H_T$
Gonads	0.08	17	1.4
Bone Marrow	0.12	12	1.4
Colon	0.12	15	1.8
Lung	0.12	18	2.2
Stomach	0.12	17	2
Bladder	0.04	18	0.72
Breast	0.12	14	1.6
Liver	0.04	16	0.64
Oesophagus (Thymus)	0.04	21	0.82
Thyroid	0.04	27	1.1
Skin	0.01	11	0.11
Bone Surface	0.01	25	0.25
Brain	0.01	5.7	0.057
Salivary Glands (Brain)	0.01	5.7	0.057
Remainder	0.12	16	1.9
Not Applicable	0	0	0
Total Effective Dose (mSv)			**16**

Remainder Organs	H_T (mGy)
Adrenals	16
Small Intestine	15
Kidney	18
Pancreas	15
Spleen	15
Thymus	21
Uterus / Prostate (Bladder)	17
Muscle	13
Gall Bladder	17
Heart	18
ET region (Thyroid)	27
Lymph nodes (Muscle)	13
Oral mucosa (Brain)	5.7

Other organs of interest	H_T (mGy)
Eye lenses	21
Testes	20
Ovaries	14
Uterus	16
Prostate	18

Scan Description / Comments	

Imaging Performance Assessment of CT Scanners, an MHRA Evaluation centre
http://www.impactscan.org



100 mAs Effective

ImPACT CT Patient Dosimetry Cal

Version 1.0 28/08/2009

Scanner Model:	
Manufacturer:	GE
Scanner:	GE LightSpeed VCT
kV:	120
Scan Region:	Body
Data Set	MCSET20 (Update Data Set)
Current Data	MCSET20
Scan range	
Start Position	-10 cm
End Position	85 cm

Get From Phantom Diagram

Organ weighting scheme: ICRP 103

Acquisition Param

Tube current

Rotation time

Spiral pitch

mAs / Rotation

Effective mAs

Collimation

Rel. CTDI

CTDI (air)

CTDI (soft tissue)

$_{n}CTDI_{w}$

$CTDI_{w}$

$CTDI_{vol}$

DLP

Organ	w_T	H_T (mGy)	$w_T.H_T$
Gonads	0.08	17	1.4
Bone Marrow	0.12	12	1.4
Colon	0.12	15	1.8
Lung	0.12	18	2.2
Stomach	0.12	17	2
Bladder	0.04	18	0.72
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Remainder	0.12	16	1.9
Not Applicable	0	0	0
Total Effective Dose (mSv)			**16**

Remain...	
Adrena...	
Small I...	
Kidney	
Pancrea...	
Spleen	
Thymus	
Uterus /...	
Muscle	
Gall Bla...	
Heart	
ET regi...	
Lymph ...	
Oral mu...	
Other o...	
Eye len...	
Testes	20
Ovaries	14
Uterus	16
Prostate	18

Scan Description / Comments

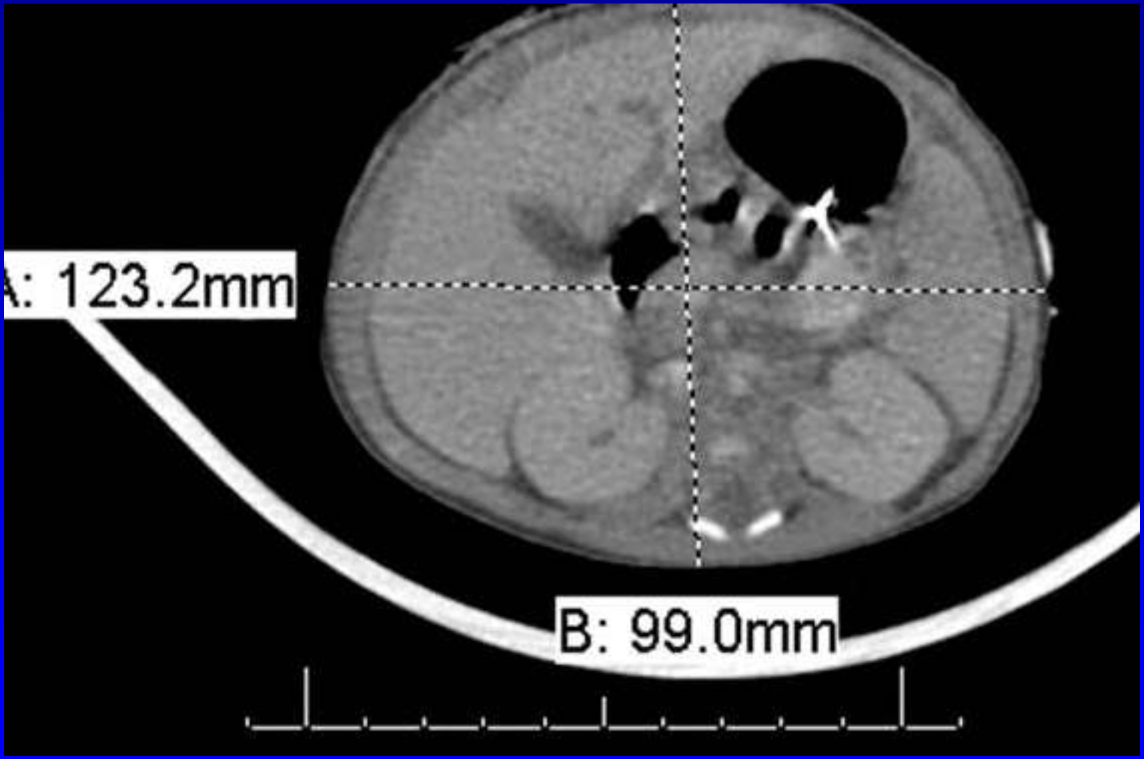
© Nicholas Keat for ImPACT, 2000-2009

Imaging Performance Assessment of CT Scanners, an MHRA Evaluation centre

http://www.impactscan.org

In adults

Size Specific Dose Estimation
AAPM Report 204



Consider
AP and LAT
dimensions

SUM = AP+LAT
=22 cm

Effective Diam =
SQRT(AP * LAT)

Size Specific Dose Estimation

Table 1A

Lat+AP Dim (cm)	Effective Dia (cm)	Conversion Factor
16	7.7	2.79
18	8.7	2.69
20	9.7	2.59
22	10.7	2.50
24	11.7	2.41
26	12.7	2.32
28	13.7	2.24
30	14.7	2.16
32	15.7	2.08
34	16.7	2.01
36	17.6	1.94
38	18.6	1.87
40	19.6	1.80
42	20.6	1.74
44	21.6	1.67
46	22.6	1.62
48	23.6	1.56
50	24.6	1.50
52	25.6	1.45
54	26.6	1.40
56	27.6	1.35
58	28.6	1.30
60	29.6	1.25
62	30.5	1.21
64	31.5	1.16
66	32.5	1.12
68	33.5	1.08

Table 1B

Lateral Dim (cm)	Effective Dia (cm)	Conversion Factor
8	9.2	2.65
9	9.7	2.60
10	10.2	2.55
11	10.7	2.50
12	11.3	2.45
13	11.8	2.40
14	12.4	2.35
15	13.1	2.29
16	13.7	2.24
17	14.3	2.19
18	15.0	2.13
19	15.7	2.08
20	16.4	2.03
21	17.2	1.97
22	17.9	1.92
23	18.7	1.86
24	19.5	1.81
25	20.3	1.76
26	21.1	1.70
27	22.0	1.65
28	22.9	1.60
29	23.8	1.55
30	24.7	1.50
31	25.6	1.45
32	26.6	1.40
33	27.6	1.35
34	28.6	1.30

Table 1C

AP Dim (cm)	Effective Dia (cm)	Conversion Factor
8	8.8	2.68
9	10.2	2.55
10	11.6	2.42
11	13.0	2.30
12	14.4	2.18
13	15.7	2.08
14	17.0	1.98
15	18.3	1.89
16	19.6	1.81
17	20.8	1.73
18	22.0	1.65
19	23.2	1.58
20	24.3	1.52
21	25.5	1.45
22	26.6	1.40
23	27.6	1.34
24	28.7	1.29
25	29.7	1.25
26	30.7	1.20
27	31.6	1.16
28	32.6	1.12
29	33.5	1.08
30	34.4	1.05
31	35.2	1.02
32	36.0	0.99
33	36.8	0.96
34	37.6	0.93

Table 1D

Effective Dia (cm)	Conversion Factor
8	2.76
9	2.66
10	2.57
11	2.47
12	2.38
13	2.30
14	2.22
15	2.14
16	2.06
17	1.98
18	1.91
19	1.84
20	1.78
21	1.71
22	1.65
23	1.59
24	1.53
25	1.48
26	1.43
27	1.37
28	1.32
29	1.28
30	1.23
31	1.19
32	1.14
33	1.10
34	1.06

32 cm phantom

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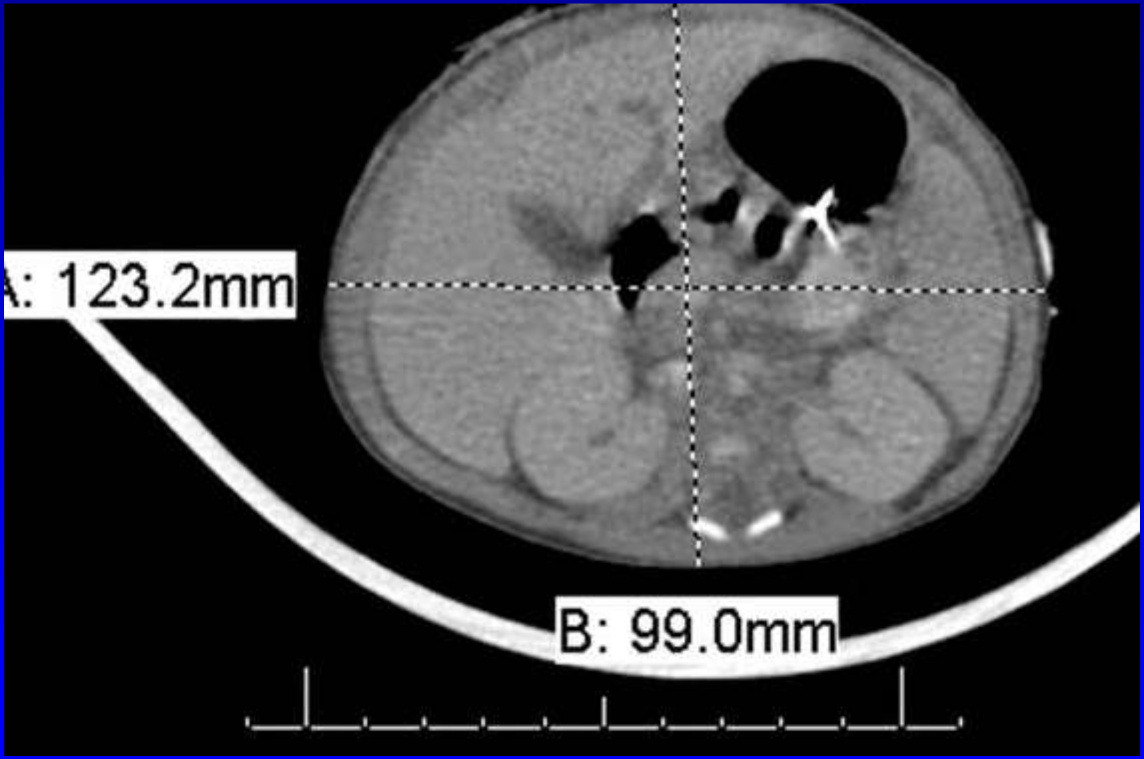

Example
CTDI (32) = 5.4mGy

Peds patient

SUM = AP+LAT
=22.2 cm

⇒ 2.5 Factor

SSDE = 5.4 * 2.5
= 13mGy

Hybrid Imaging Dose Tracking

- CT dose from hybrid imaging should be tracked within ACR Dose Index Registry
- Size Specific $CTDI_{vol}$ and DLP corrected

IMHO, imaging and patient parameters should be reported that will allow the most sophisticated dose estimates in the future. In NM, this is the administered activity to the patient and the patient size.