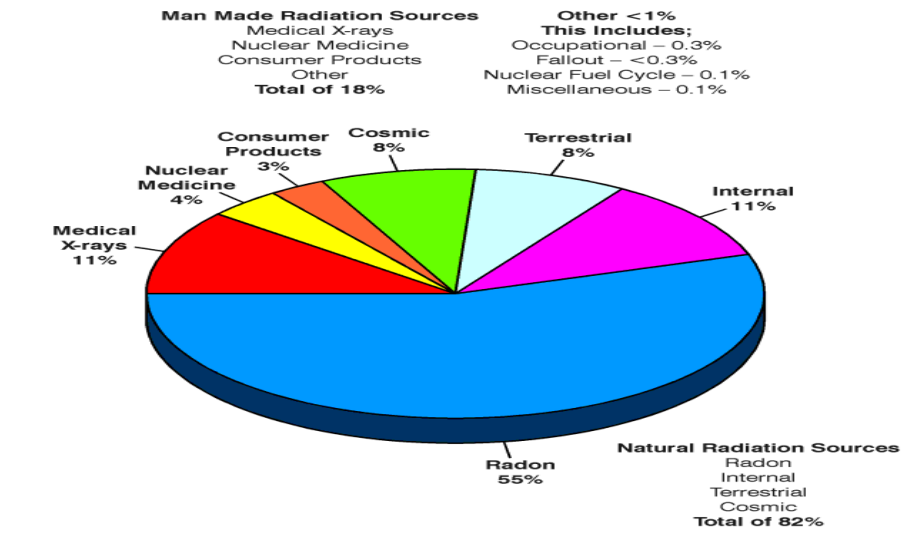
Diagnostic Imaging, Nuclear Medicine, Radiation Risks vs. Benefit & Radiation Protection

(Chapter 15, 16, & 17)

Outline

- Background perspective
- Diagnostic radiology
- Interventional radiology
- Nuclear medicine
- Fetal & childhood dose

Ionizing Radiation Exposure to the Public

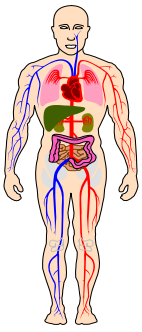


The above chart is taken from the National Council on Radiation Protection and Measurements (NCRP) Report No. 93, "Ionizing Radiation Exposure of the Population of the United States," 1987.

This chart shows that natural sources of radiation account for about 82% of all public exposure while man made sources account for the remaining 18%.

Internal Radiation

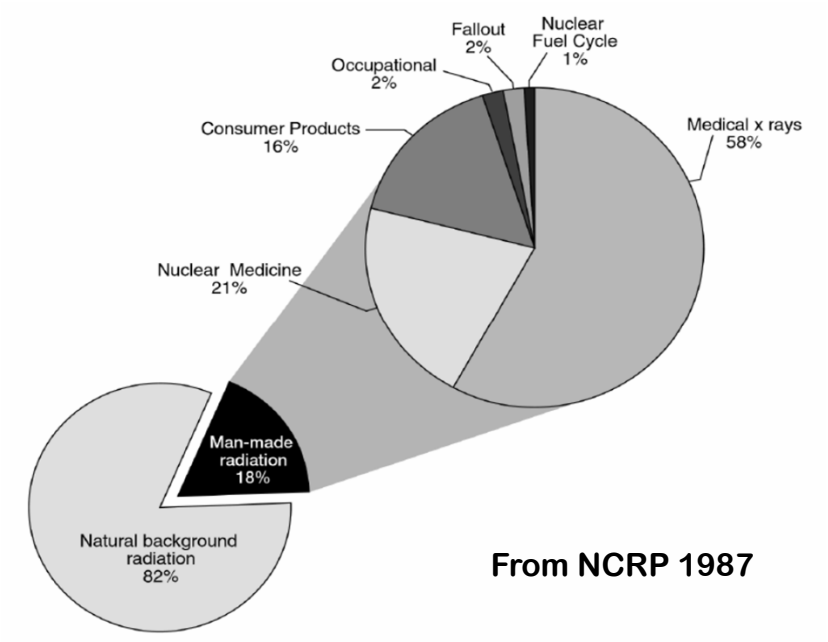
- People are exposed to radiation from radioactive material inside their bodies. Besides **radon,** the most important internal radioactive element is naturally occurring **K-40**, but uranium and thorium are also present as well as **H-3 and C-14.**
- The amount of radiation from potassium-40 does not vary much from one person to another. However, **exposure from radon varies** significantly from place to place depending on the amount of uranium in the soil.
- On average, in the United States **radon** contributes **55%** of all radiation exposure from natural and man-made sources. Another 11% comes from the other radioactive materials inside the body.



Average Annual Effective Dose in US population (1982)

	mSv
Natural Background	
Radon	2.0
other	1.0
Occupational	0.009
Medical	
diagnostic X-rays	0.39
nuclear medicine	0.14
Total (rounded)	**3.6 mSv (360 mrem)/year**

From: Mettler et al., Ionizing Radiation



From NCRP 1987

The annual outdoor effective dose (μSv) from cosmic radiation for Canada and the U.S.

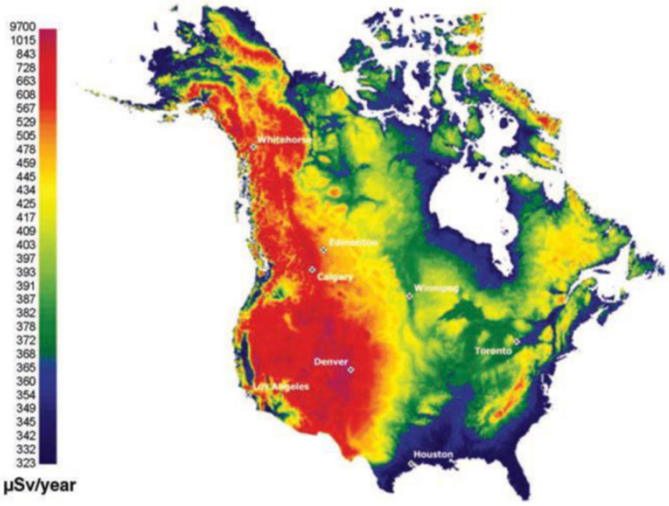


FIGURE 16.3 Color plot of the annual cosmic radiation doses (in microsievert) in North America. The variation with altitude is very clear, with the highest doses in the Rocky Mountains.

Looking at Medical Exposures

- Patients
- Professionals
- Classes of Exposure in Medicine
  - Diagnostic
  - Interventional Radiology
  - Nuclear Medicine
  - Irradiation of Children and Pregnant Women

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Diagnostic Radiology

- Surveys of dose from diagnostic exposures conducted with:
- NCRP 100 (1989) which contains a compilation of limited surveys,
- UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) 2000
- Various other surveys and sources of dose info
- Diagnostic dose is certainly a potential for stochastic effects, deterministic effects very unlikely.

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TABLE 16.1 Overview of the Practice of Radiology

	Population $\times 10^6$	Mammography Units (per 10^6 Population)	CT Scanners—Total (per 10^6 Population)	Medical X-rays—Number of Annual Radiation Exams and Treatments $\times 10^6$ (per 10^6 Population)	Physicians Conducting Radiology (per 10^6 Population)
Canada	27.9	20.2	223 (8.0)	24.9 (0.89)	74
France	57.7	42.2	561 (9.7)	92.0 (1.59)	119
Germany	81.5	43.6	1,400 (17.2)	102.2 (1.25)	405
Japan	125.0	11.7	7,959 (63.7)	184.7 (1.48)	94
Sweden	8.8	19.3	115 (13.1)	5.0 (0.57)	125
United Kingdom	58.2	4.4	350 (6.0)	28.9 (0.50)	41
United States	260.0	38.6	6,800 (26.2)	250.0 (0.96)	92

Based on UNSCEAR 2000, which in turn is based on UNSCEAR surveys 1991–1996.

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Table 1 of 2

TABLE 14.3

Entrance Skin Exposure and Absorbed Doses to Various Organs from Radiographic Studies in Adults[a]

Examination and View	Free-in-Air Exposure at Skin Entrance, mR	Dose, mGy (mrad) Active Bone Marrow	Thyroid	Breast	Lungs	Ovaries	Testes
Chest							
PA	20	0.02 (2)	0.01 (1)	0.01 (1)	0.07 (7)	N	N
Lateral	65	0.02 (2)	0.07 (7)	0.15 (15)	0.12 (12)	N	N
Series	—	0.04 (4)	0.07 (7)	0.16 (16)	0.19 (19)	N	N
Skull							
AP	330	0.08 (8)	0.06 (6)	—	N	N	N
Lateral	190	0.05 (5)	0.21 (21)	—	N	N	N
Series	—	0.24 (24)	0.34 (34)	—	0.01 (1)	N	N
Cervical spine							
AP	150	0.02 (2)	1.00 (100)	—	0.02 (2)	N	N
Lateral	100	0.02 (2)	0.06 (6)	—	0.02 (2)	N	N
Series	—	0.09 (9)	2.60 (260)	—	0.11 (11)	N	N
Thoracic spine							
AP	280	0.05 (5)	0.25 (25)	0.95 (95)	0.35 (35)	N	N
Lateral	630	0.12 (12)	0.05 (5)	0.05 (5)	0.75 (75)	N	N
Series	—	0.17 (17)	0.30 (30)	1.00 (100)	1.10 (110)	N	N
Lumbar spine							
AP	640	0.18 (18)	N	—	0.40 (40)	1.10 (110)	0.02 (2)
Lateral	2,300	0.44 (44)	N	—	0.30 (30)	0.90 (90)	0.02 (2)
Series	—	1.10 (110)	N	—	1.70 (170)	3.70 (370)	0.06 (6)

The unit used to measure the quantity of air kerma is the Gray (Gy). For X-rays with energies less than 300 keV, 1 Gy = 100 rad. In air, 1 Gy of absorbed dose is delivered by 114 roentgens (R) of exposure. (f=0.876).

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Table 2 of 2

TABLE 14.3

Entrance Skin Exposure and Absorbed Doses to Various Organs from Radiographic Studies in Adults[a]

Examination and View	Free-in-Air Exposure at Skin Entrance, mR	Dose, mGy (mrad) Active Bone Marrow	Thyroid	Breast	Lungs	Ovaries	Testes
Urography							
KUB (AP)	600	0.20 (20)	N	—	0.07 (7)	1.30 (130)	0.10 (10)
Series	—	0.90 (90)	N	—	0.27 (27)	5.50 (550)	0.40 (40)
Series + 4 tomograms	—	1.70 (170)	N	—	0.54 (54)	6.50 (650)	0.50 (50)
Mammography[b]	—	—	—	2.40 (240)	—	—	—
Upper gastrointestinal series	—	3.00 (300)	0.03 (3)	0.50 (50)	1.00 (100)	12.00 (1,200)	0.80 (80)
Barium enemia series	—	5.20 (520)	N	—	—	—	—

[a] Values given are exposures and doses received by some patients at some facilities. Values can be much higher or lower depending on patient size, the technology employed, and the examination protocols established by the radiologist. Key: —, no estimate is made; N, negligible dose (<0.01 mGy [<1 mrad]).
[b] Two-view screening with film-screen grid.
Adapted from Wagner LK: *Radiation Bioeffects and Management Test and Syllabus*. Reston, VA, American College of Radiology, 1991, with permission.

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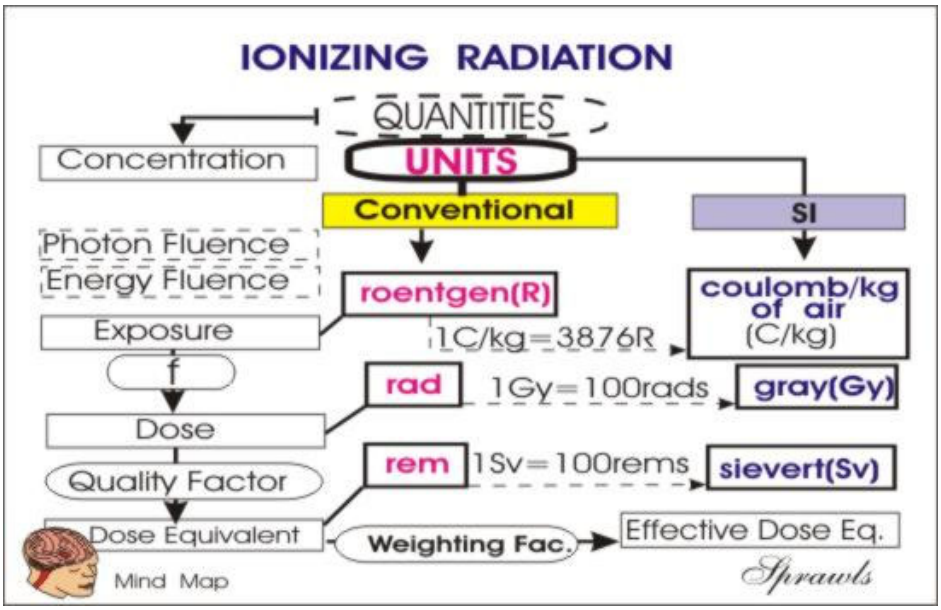

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Mammography Mean Glandular Dose

- The Mean Glandular Dose (MGD) is the special dose quantity used in mammography.
- It is defined as the mean, or average dose to the glandular tissue within the breast.
- The assumption is that the glandular tissue, and not the fat, is the tissue at risk from radiation exposure.
- It is unrealistic to determine the actual dose to the glandular tissue during a specific mammographic procedure because of variations in breast size and distribution of glandular tissue within the breast.
- The MGD is based on some standard breast parameters.

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Calculation of Mammography Mean Glandular Dose

- MGD values are determined by following a standard two-step protocol.
  - The first step is to determine the entrance surface exposure, or air kerma, to the breast. This can be measured directly with small dosimeters placed on the breast or calculated from the known calibration factors for the mammography equipment.
  - MGD is then determined by multiplying the surface exposure value by published dose factors.
  - The dose factor values are tabulated according to breast size and composition and the penetrating characteristics of the x-ray beam as determined by the anode material, filtration, and KV.

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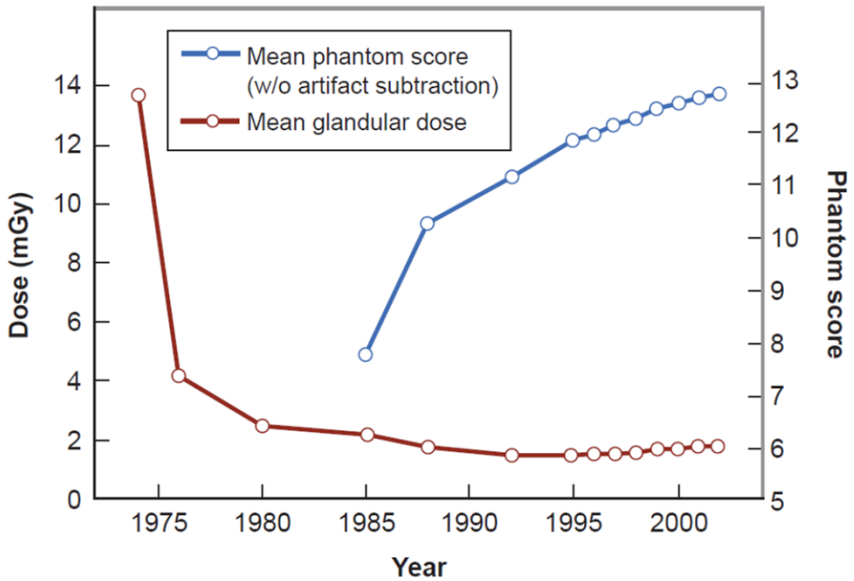

Table 16.2 is a summary of entrance skin exposures, as well as absorbed doses to various organs, characteristic of a representative sample of standard diagnostic procedures.

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TABLE 14.4

Abdomen and Lumbosacral Spine (NEXT 1995)

	1995 Abdomen	1995 LS Spine
Entrance air kerma (mGy)	2.8	3.2
Clinical kVp	76	78
Exposure time (ms)	145	247
Percent using grids	97	96
Phantom film optical density	1.74	1.32

From the NEXT 1995 Abdomen and LS Spine X-Ray Data Survey.

NEXT = Nationwide Evaluation of X-ray Trends

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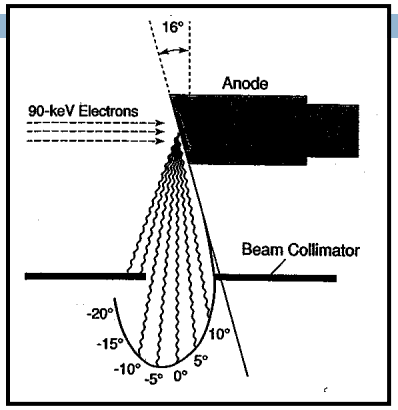
X-ray Production

- Accelerated electrons bombard the anode
- X-rays emerge with a scattering angle profile
- Beam collimation is inserted to reduce angle of divergence



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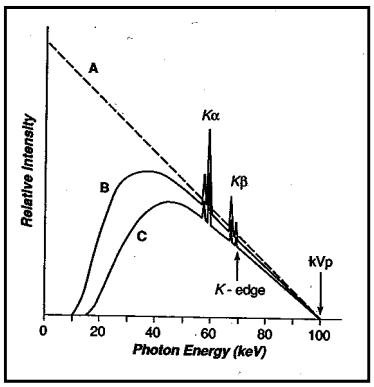
X-Ray Beam Spectrum - 100 kVp

A. Hypothetical total Bremsstrahlung beam

B. Spectrum from tungsten target without filtration

C. Spectrum with filtration equivalent to 2.4 mm Al (inherent + added)



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X-ray Terms

- mAs (milli-amp second)
  - governs the *quantity* (e.g. intensity) of X-rays produced.
  - directly proportional to patient dose. Double mAs, double dose.
- kVp (kilovolt peak)
  - governs "quality" of the X-ray beam
  - Relates to energy of the beam
  - influences image quality.
  - effects image contrast (ability to distinguish regions).
  - higher kVp radiographs show greater density and longer scale of contrast.
- For radiographs, setting the kVp as high as possible, without a loss of contrast will give the lowest patient dose because a greater fraction will penetrate through the body to the imaging medium.

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Surface Integral Exposure

- Given a uniform exposure over some area of a body,
- SIE is the product of the exposure value (mR) and the size of the exposed area (cm^2).
- The unit for SIE is the R-cm^2.
  - It is not R/cm^2, it is the product.
- An alternate name is Exposure Area Product

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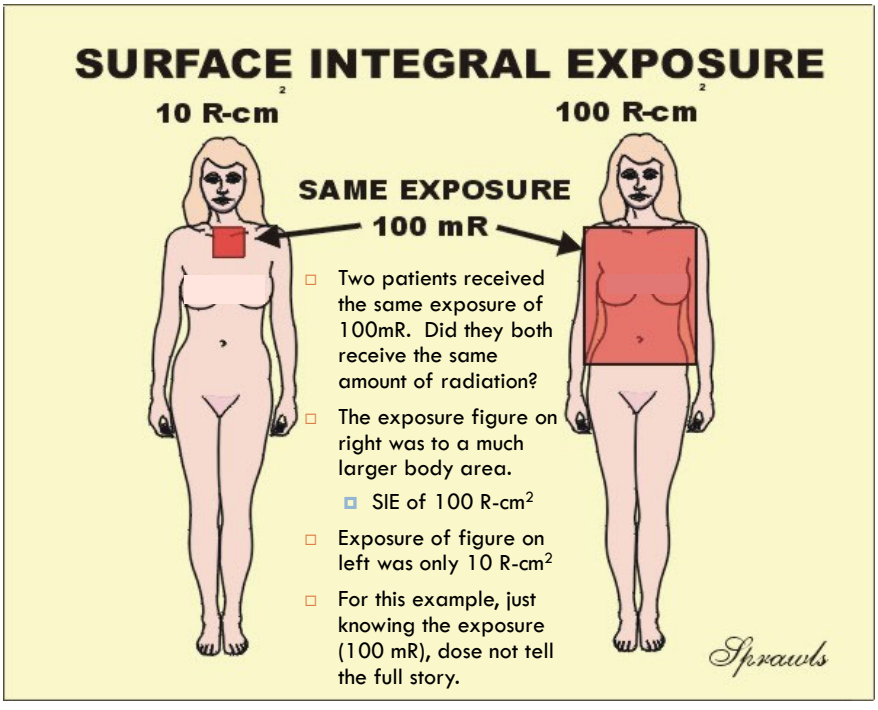

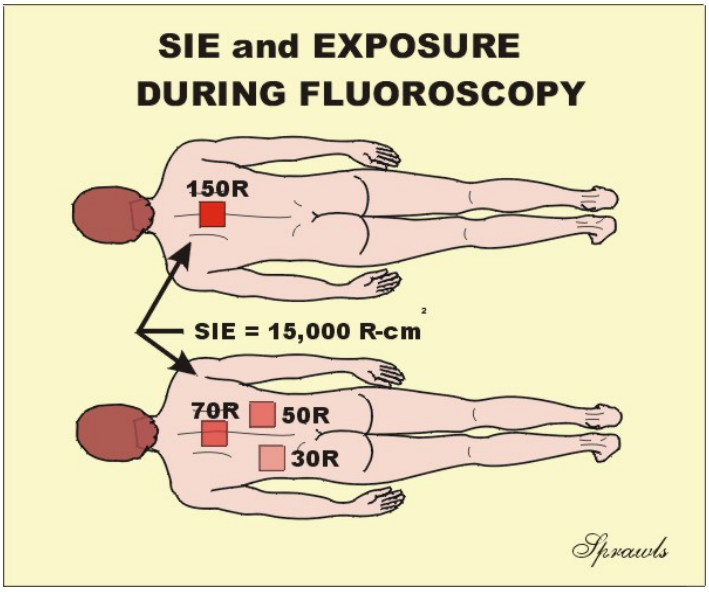

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Analysis of Previous Image

- Both individuals received the same SIE, 15,000 R-cm^2 because exposure time was the same
- Did they receive the same surface exposure?
- For the upper patient, the x-ray beam was not moved during the procedure and all of the radiation was concentrated in one area.
  - A relatively high exposure of 150 R to that area.
- During the procedure for the lower patient, the beam was moved to several different areas.
  - This distributed the radiation so it was not all concentrated in one area.
- So, which quantity, exposure or SIE, would provide the most information?
- It depends on what type of risk is being considered.
  - The stochastic risk of cancer is probably more related to the SIE.
  - The risk of skin burning is more related to exposure, that is the concentration of the radiation

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Dose-Area Product

- Dose Area Product (DAP) is similar to SIE (surface Integral Exposure) and EAP – (Exposure Area Product)
  - They all express total radiation delivered to a patient.
  - Principle difference is in the units used.
  - DAP is in dose units, such as Gy-cm^2.
- For a uniformly exposed area, the DAP is the product of the air kerma in Gy, cGy, or mGy, and the exposed area in cm^2.
- DAP provides a good estimation of the total radiation energy delivered to a patient during a procedure.
- Both radiographic and fluoroscopic machines can be equipped with devices (DAP meters) or computer programs that measure or calculate the DAP for each procedure.
- It is the most practical quantity for monitoring the radiation delivered to patients.

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TABLE 14.5

Dose Rates from Fluoroscopy (NEXT 1996)

	1996 Upper GI	1996 Cardiac Cath Labs	1996 C-Arm Units
Entrance air kerma (mGy/min)[a]	45	38	22
Clinical kVp	99	82	78
Fluoroscope tube current (mA)	2.3	5.1	3.0
Air kerma rate w/contrast[b] (mGy/min)[a]	67	71	41
Maximum air kerma rate[a]	70	74	44

[a] Determined at 1 cm of the table top and does not include contributions from over-table units.
[b] Copper is used to simulate the presence of barium contrast medium.
From the NEXT 1996 Upper G.I. Fluoroscopy Survey.

•Entrance air kerma (free-in-air, without backscatter) is taken at the point where the central axis of the x-ray beam enters the patient.
•It refers to the amount of radiation at a location before adjustment for any external shielding

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TABLE 14.6

Global Activity in Computed Tomography for 1995

Region	Scanners per Million Population	Annual Procedures per Thousand Population
World	3.5	11
United States	26.4	91
European Union	10.1	33
France	7.7	33
Germany	16.6	53
Italy	9.6	30
Spain	5.7	15
United Kingdom	6.2	21

Adapted from Bahador B: *Trends in Diagnostic Imaging to 2000*. London, FT Pharmaceutical and Health Care Publishing, 1996, with permission.

TABLE 14.7. *Effective Doses for Common Diagnostic Procedures (United States)*

			EFFECTIVE DOSE, mSv (mrem)	
	ESAK, mGy	Entrance Skin Exposure, mR	Male	Female
Chest (PA)	0.18	20	0.03 (3)	0.03 (3)
Chest (lateral)	0.57	65	0.05 (5)	0.08 (8)
Skull (AP)	2.9	330	0.04 (4)	0.04 (4)
Skull (lateral)	1.5	166	0.02 (2),	0.02 (2)
C-spine (AP)	1.3	150	0.05 (5)	0.05 (5)
C-spine (lateral)	0.88	100	0.02 (2)	0.02 (2)
T-spine (AP)	2.5	280	0.27 (27)	0.54 (54)
T-spine (lateral)	6.0	680	0.25 (25)	0.27 (27)
L-spine (AP)	5.6	640	0.40 (40)	0.78 (78)
L-spine (lateral)	20	2300	0.53 (53)	0.84(84)
Abdomen (AP)	5.3	600	0.37 (37)	0.73 (73)

Entrance skin exposure values taken from Wagner LK: Radiation Bioeffects and Management Test and Syllabus. Reston, VA, American College of Radiology, 1991.

Effective doses calculated by Dr. Beth A. Schueler using Rosenstein M: Handbook of Selected Tissue Doses for Projections Common in Diagnostic Radiology. HEW (FDA) Publication 89-8031 for organ doses (HVL assumed to be 3.0 mm Ae at 80 kVp, our kVp used for exam kVp settings) and ICRP: Recommendations of the ICRP. Publication 26. 1977 for risk weighting factors.

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TABLE 14.10. *Mean Values of Patient Dose and Effective Dose from Computed Tomographic Examinations in the United Kingdom for 1989*

Examination	Organ Dose, mGy				Effective Dose, mSv
	Eyes	Uterus	Ovaries	Testes	
Routine head	50	—	0	0	1.8
Posterior fossa	53	—	—	0	0.72
Pituitary	60	—	—	0	0.57
Internal auditory meatus	2.6	—	0	0	0.35
Orbits	50	—	—	0	0.64
Facial bones	9.0	—	—	0	0.68
Cervical spine	0.62	—	—	0	2.6
Thoracic spine	0.04	0.02	0.02	—	4.9
Routine chest	0.14	0.06	0.08	—	7.8
Mediastinum	0.11	0.03	0.04	—	7.6
Routine abdomen	—	8.0	8.0	0.70	7.6
Liver	—	1.0	1.2	0.03	7.2
Pancreas	—	0.35	0.41	0.01	4.8
Kidneys	—	1.1	1.3	0.03	6.3
Adrenals	—	0.10	0.12	—	3.4
Lumbar spine	—	2.4	2.7	0.06	3.3
Routine pelvis	—	26	23	1.7	7.1

Multiply by 100 to convert mGy to mrad and mSv to mrem.

Adapted from NRPB 1992: Protection of the patient in x-ray computed tomography. Documents of the NRPB 3(4), 1992, with permission.

TABLE 14.9

Effective Doses to Patients from Computed Tomography, 1991–1995

Country/Area	Mean Effective Dose per Procedure, mSv						
	Head	Chest	Abdomen	Liver	Kidneys	Pelvis	Lumbar Spine
Australia	2.6	10.4	16.7	12.7	—	11.0	5.2
Finland	1.3	5.1	11.6	—	—	—	5.0
Germany	2.6	20.5	27.4	—	—	—	9
Japan	—	4.6–10.8	6.7–13.3	—	—	—	—
Netherlands	0.8–5.0	6–18	6–24	—	—	—	2–12
New Zealand	1.8	8.9	9.7	6.5	7.6	6.9	4.7
Norway	2.0	11.5	12.8	11.9	9.9	9.8	4.5
Sweden	2.1	10	10	10	10	10	6
United Kingdom (Wales)	1.6	9.7	12	10.3	9.1	9.8	3.3

Based on the United Nations Scientific Committee on the Effects of Atomic Radiation: *Annex C Medical Radiation Exposures*. New York, UNSCEAR, 2000.

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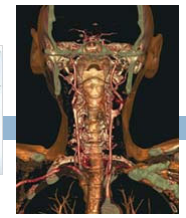
CT



- A computed tomography (CT) scan uses X-rays to produce detailed pictures of structures inside the body.
- A CT scan is also called a computerized axial tomography (CAT) scan.
- A CT scanner directs a series of X-ray pulses through the body. Each X-ray pulse lasts only a fraction of a second and represents a "slice" of the organ or area being studied.
- The slices or pictures are recorded on a computer and can be saved for further study or printed out as photographs

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TABLE 14.10

Effective Doses Characteristic of CT Scans in the United States in the Year 2000

	Head	Chest	Abdomen	Pelvis
mAs	355	—	—	—
kVp	127	—	—	—
MSAD, mGy	50.3	—	—	—
Effective dose, mSv	2	7	7	6

Based on the NEXT 2000 Computed Tomography Protocol Survey.

MSAD: multiple scan, average dose

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Computed Tomography Dose Index

- In CT the x-ray beam is rotated around the patient and passes through from all sides.
- This gives a relatively uniform distribution of absorbed dose within each slice.
- A dose value determined at the center of the slice is considered a good indicator of tissue dose and can be used to compare imaging techniques and for dose management purposes.
- One of the complicating factors in determining CT dose is that the tissue in a slice is exposed to two sources of x-radiation.
- One is the direct beam and the other is the scattered radiation from adjacent slices in the typical multiple slice imaging procedure.
- It is the contribution from the scattered radiation that is very difficult to measure.

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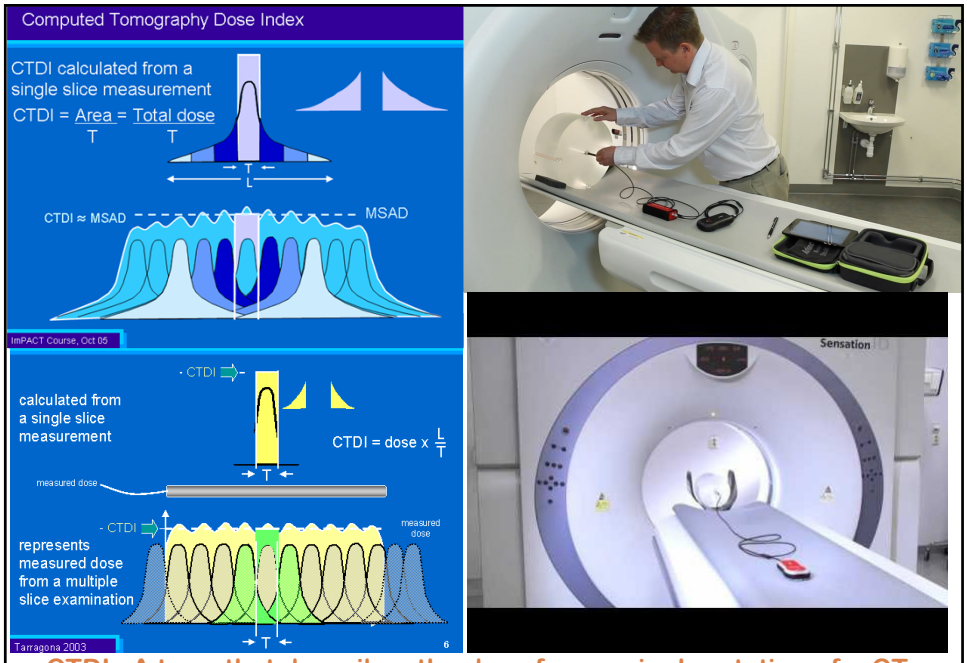

CTDI: A term that describes the dose from a single rotation of a CT scanner. There are a number of definitions of CTDI commonly used

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CTDI, continued

- Values for the CTDI are determined by a measuring protocol that makes a reasonable estimate of the dose contribution from scatter.
- A pencil shaped dosimeter (ionization chamber) is placed in a phantom. It is then scanned for only one complete slice and the dose value is read.
- The dosimeter will read the radiation from the direct x-ray beam within the slice plus the scattered radiation coming out of the sides of the slice and reaching the dosimeter.
- The CTDI is based on the assumption that the scatter measured from a single slice is a good estimate of the scatter into a slice from adjacent slices in a multiple-slice scan.
- Since it is not completely precise, it is called a dose index.
- The CTDI can be measured at points other than the center of a slice, if needed

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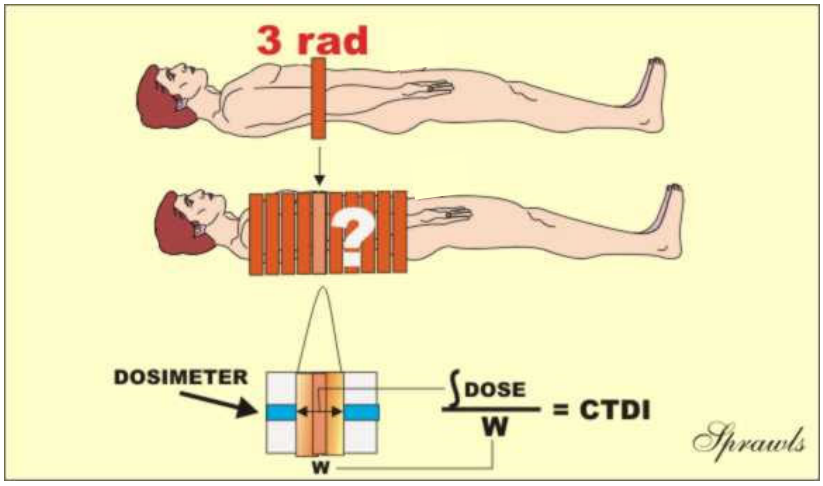

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TABLE 14.11

Effective Doses from Computed Tomography in the United Kingdom

Examination	Mean Effective Dose, mSv[a]	
	United Kingdom, 1989	Wales, 1994
Routine head	1.8	1.6
Posterior fossa	0.7	1.2
Pituitary	0.6	0.9
Internal auditory meatus	0.4	1.0
Facial bones	0.7	0.3
Orbits	0.6	0.8
Cervical spine	2.6	1.5
Thoracic spine	4.9	2.4
Lumbar spine	3.3	3.3
Chest	7.8	9.7
High-resolution lung	—	1.9
Abdomen	7.6	12.0
Liver	7.2	10.3
Pancreas	4.8	7.4
Kidneys	6.3	9.1
Pelvis	7.1	9.8

[a] Multiply by 100 to convert mSv to mrem.

Adapted from Shrimpton PC, Wall BF, Hart D: Diagnostic medical exposures in the UK. *Appl Radiat Isot* 50:261–269, 1999, with permission.

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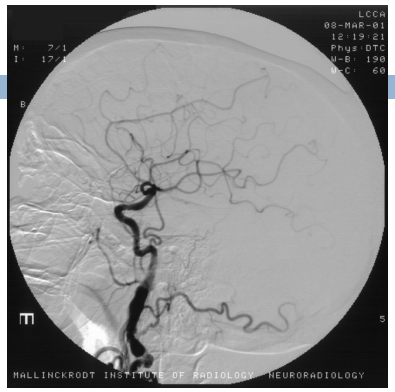
TABLE 14.12

Effective Doses from Cerebral Angiography

Procedure	Effective Dose, mSv
Cerebral angiography	10.6
Nuclear medicine: brain imaging	About 10
Computed tomography	2
Skull x-ray	0.15

Adapted from Feygelman VM, Huda W, Peters K: Effective dose equivalents to patients undergoing cerebral angiography. *AJNR* 13:845–849, 1992, with permission.



- Images blood vessels of the brain and blood flowing through them.
- Involves entering a catheter into the body to inject a dye (a contrast medium) into the carotid arteries, the vessels of the neck that lead to the brain.
- Regular x-ray is used to image the dye that is flowing through the blood vessels.

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TABLE 14.13

Representative Effective Doses from Bone Mineral Densitometry

Type of Measurement	Effective Dose, μSv	Comments
Dual-energy x-ray absorptiometry	~2.5	Representative value for single PA scan
Single-energy quantitative CT[a]	~300	SPR + 3 CT slices @ 80 kVp
Dual-energy quantitative CT	~1,000	SPR + 3 CT slices @ 80 kVp + 3 CT slices @120 kVp
Radiographs	~100	Single (collimated) view (AP or lateral)

[a] CT, computed tomography.
Adapted from Huda W, Morin RL: Patient doses in bone mineral densitometry. *Brit J Radiol* 69:422–425, 1996, with permission.

- Bone mineral densitometry is an x-ray technique used in the diagnosis and prevention of osteoporosis.
- By comparing x-ray images taken at different intensities, or of different materials, physicians can calculate a patient's bone mass (or lack thereof).
- Weak, brittle, osteoporotic bones contain a lower concentration of minerals like calcium

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TABLE 14.14

Collective Effective Dose from Diagnostic Medical X-Rays: United States, 1980

Examination Type	Effective Dose, mSv[a]	Thousands of Examinations	Collective Effectiv Dose, person-Sv[b]
Computed tomography (head and body)	1.11	3,300	3,660
Chest	0.08	64,000	5,120
Skull	0.22	8,200	1,800
Cervical spine	0.20	5,100	1,020
Biliary	1.89	3,400	6,430
Lumbar spine	1.27	12,900	16,400
Upper gastrointestinal	2.44	7,600	18,500
Abdomen (kidneys, ureters, bladder)	0.56	7,900	4,420
Barium enema	4.06	4,900	19,900
Intravenous pyelogram	1.58	4,200	6,640
Pelvis	0.44		
Hip	0.83	0.64 4,700	3,010
Extremities	0.01	45,000	450
Other	0.50	(8,400)	4,200
Rounded total			92,000

[a] 1 mSv = 100 mrem.
[b] 1 person-Sv = 100 man-rem.
Adapted from National Council on Radiation Protection and Measurements: *Exposure of the US Population from Diagnostic Medical Radiation*. Report 100. Bethesda, MD, NCRP, 1989, with permission.

Diagnostics

- Dose
  - maximum during fluoroscopy
    - spine;
    - GI series
- Effective Dose Equivalent
  - necessary for risk comparisons
  - X-rays (few mrem to tens of mrem)
  - CT exams (tens of mrem to hundreds of mrem)

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Diagnostics

- Population dose
  - meaningful risk measure
  - 9.2 million per-rem/yr (1980) over ~100 million persons exposed medically
  - ~4600 cancer deaths (5%/Sv)
  - ~ 920 genetic effects (1%/Sv)
  - impact on 5.5×10^{-5} of the exposed population
  - natural cancer fatalities …. 17 million
  - late 90's; thought that CT scans contribute ~40% of population dose from medical procedures

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Occupational Exposures

- How do nuclear plant workers compare with individuals in the medical profession?

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TABLE 14.15

Collective Effective Doses to Radiation Workers

Occupational Category	Annual Collective Effective Dose, person-Sv[a]
Industrial personnel (other than nuclear fuel cycle)	390
Nuclear power plant personnel	551
Department of Energy personnel	224
Uranium miners	112
Uranium mill and fuel fabrication personnel	6
Well loggers	30
U.S. Public Health Service personnel	0.3
U.S. Navy	51
Flight crews and attendants	165
Medical staff (non-Federal)	410
Government	120
Other workers	145
Education and transportation personnel	50
Rounded total	2,200

[a] 1 person-Sv = 100 man-rem.

Adapted from National Council on Radiation Protection and Measurements: *Exposures of the US Population from Occupational Radiation.* Report 101. Bethesda, MD, NCRP, 1989, with permission.

TABLE 14.16

Summary of Mean Collective Equivalent Doses to Monitored Medical Workers

Sources of Occupational Exposures	Thousands of Workers	Collective Equivalent Dose,[a] person-Sv
Dentistry	259	60
Private medical practice	155	160
Hospital	126	170
Other[b]	44	20
Total	584	410

[a]Collective equivalent doses are reported in the source of these data, but because the data were obtained from personnel monitors worn at waist level, the readings are assumed to represent total-body exposures; hence, collective equivalent dose is identical to collective effective dose.
[b]"Other" includes chiropractic medicine with 15,000, podiatry with 8,000, and veterinary medicine with 21,000 potentially exposed workers.
Adapted from National Council on Radiation Protection and Measurements: *Exposures of the US Population from Occupational Radiation*. Report 101. Bethesda, MD, NCRP, 1989, with permission.

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Interventional Radiology

- Fluoroscopically-guided procedures
- High doses to patient AND workers
- Deterministic effects are possible
- Due to patient age and prognosis, stochastic risk is generally ignored

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Interventional Radiography

- Dose
  - some fluoroscopy entrance doses are from tens to hundreds of rads
  - epilation and erythema are the most frequently reported effects
    - > 200 rad … erythema
    - > 300 rad … temporary epilation
    - > 700 rad … permanent epiliation
    - > 1200 rad … delayed necrosis
    - > 1400 rad … dry desquamation
    - > 1500 rad … late erythema
    - > 1800 rad … moist desquamation
    - > 2400 rad … ulceration

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Interventional Radiography

- Patient EDE (Effective Dose Equivalent)
  - typical fluoroscopy doses: tens to thousands of millirem
  - typical interventional fatal cancer risk ~ 0.001
- Dose to Radiologist
  - tens of millirad to head or extremities per procedure

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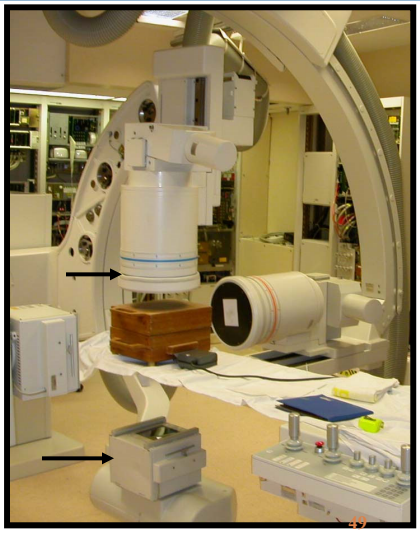
The Interventional Fluoroscopic Suite

- C-arm fluoroscopic unit
- Arrows point to the X-ray tube beneath the table and the Image Intensifier above the table



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Interventional Fluoroscopic Suite

- Note the low level of the X-ray tube beneath the table and the close proximity of the Image Intensifier above the table.
- Monitors as seen by the clinical team are in the background.

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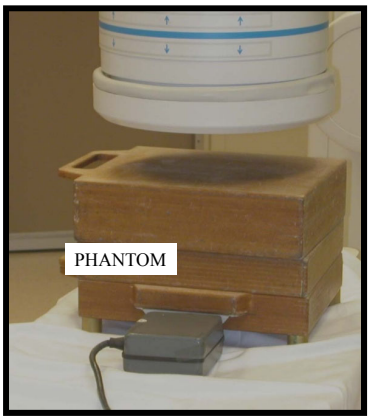
Interventional Fluoroscopic Suite

- A 23 cm. Phantom is positioned beneath the Image Intensifier.
- An ion chamber is located at the base of the phantom to measure Entrance Skin Dose



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Fluoroscopic X-ray Imaging

- **Tube as far below the table as practical**
- **Image Intensifier above patient, at convenient height, but minimized air gap**
- **Automatic exposure control provides kVp and mA change for constant monitor image intensity**

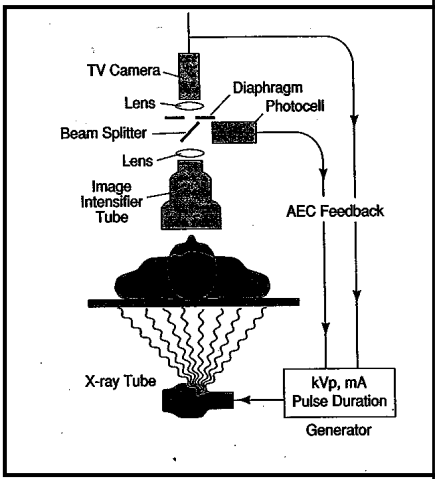

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TABLE 14.17

Fluoroscopy Times, Cine Times, and Area–Exposure Products for Diagnostic, Interventional, and Combined Procedures

	Diagnostic (n = 173)	Interventional (n = 225)	Combined (n = 112)
Time, min			
Fluoroscopy	6.8 ± 6.4	19.9 ± 13.6	20.4 ± 10.5
Cine	0.78 ± 0.32	0.91 ± 0.6	1.18 ± 0.55
Area–exposure product, Gy cm^2			
Fluoroscopy	39 ± 46	101 ± 76	107 ± 65
Cine	70 ± 36	62 ± 33	92 ± 38
Total	108 ± 74	163 ± 95	198 ± 87
Cine runs	95 ± 33	136 ± 58	172 ± 59
Fluoroscopy[a]	32 ± 15	58 ± 14	52 ± 12

[a]Fluoroscopy expressed as a percentage of total area–exposure product.

Adapted from Bakalyar DM, Castellani MD, Safian RD: Radiation exposure to patients undergoing diagnostic and interventional cardiac catheterization procedures. *Cathet Cardiovasc Diagn* 42:121–125, 1997, with permission.

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Table 1 of 2

TABLE 14.18

Mean Fluoroscopy Screening Times, Dose–Area Product Values

Interventional Procedure	Fluoroscopy Screening Time, min	Dose–Area Product, Gy cm^2			Effective Dose, mSv
		Fluoroscopy	Radiography	Total	
Diagnostic					
Cerebral angiography	12.1	28.2	45.8	74.1	7.4
Carotid angiography	10.3	22.9	26.4	49.3	4.9
Upper extremity angiography	4.6	10.5	16.8	27.3	0.3
AV fistula angiography	2.3	4.6	12.6	17.2	0.2
Thoracic angiography	22.1	49.0	36.2	85.2	11.9
Nephrostography	4.0	12.4	2.2	14.7	2.4
Renal angiography	5.1	17.7	22.1	39.8	6.4
PTC	14.6	76.9	3.3	80.2	12.8
CT arterial portography	10.0	69.0	11.6	80.6	12.9
Hepatic angiography	12.1	74.9	61.0	136	21.7
Transjugular hepatic biopsy	6.8	30.8	3.4	34.1	5.5
Abdominal angiography	8.0	46.1	72.1	118	18.9
Femoral angiography	7.2	17.2	29.6	46.7	7.5
Lower extremity angiography	7.5	28.0	51.9	79.8	0.8

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Table 2 of 2

TABLE 14.18

Mean Fluoroscopy Screening Times, Dose–Area Product Values

Interventional Procedure	Fluoroscopy Screening Time, min	Dose–Area Product, Gy cm^2			Effective Dose, mSv
		Fluoroscopy	Radiography	Total	
Therapeutic					
Cerebral embolization	34.1	43.1	61.4	105	10.5
AV fistula angioplasty	14.6	16.4	8.7	25.1	0.3
Thoracic therapeutic procedures	14.9	59.5	56.9	116	16.3
Biliary stent insertion/removal	7.1	40.5	2.6	43.1	6.9
TIPS	48.4	400	125	524	83.9
Nephrostomy	7.0	39.8	3.2	43.0	6.9
Renal angioplasty	14.0	57.0	28.1	85.2	13.6
Other abdominal therapeutic procedures (excluding hepatic and renal)	18.4	114	54.1	168	26.9

Adapted from McParland BJ: A study of patient radiation doses in interventional radiological procedures. *Br J Radiol* 71:175–185, 1998, with permission.

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TABLE 14.19

Potential Effects of Fluoroscopic Exposures on the Reaction of the Skin

Effect	Approximate Threshold Dose, Gy	Time of Onset
Early transient erythema	2	2–24 h
Main erythema reaction	6	~1.5 wk
Temporary epilation	3	~3 wk
Permanent epilation	7	~3 wk
Dry desquamation	14	~4 wk
Moist desquamation	18	~4 wk
Secondary ulceration	24	>6 wk
Late erythema	15	8–10 wk
Ischemic dermal necrosis	18	>10 wk
Dermal atrophy (1st phase)	10	>12 wk
Dermal atrophy (2nd phase)	10	>52 wk
Telangiectasis	10	>52 wk
Delayed necrosis	12?	>52 wk (related to trauma)
Skin cancer	Not known	>15 y

Adapted from Wagner LK, Archer BR: *Minimizing Risks from Fluoroscopic X-rays*, 2nd ed. Houston, TX, Partners in Radiation Management, 1998, with permission, and modified by Hopewell (personal communication).

TABLE 14.20

Effective Doses to Patients from Radiologic and Nuclear Medicine Procedures

Procedure	Effective Dose, mSv
Arrhythmia ablation	17
Coronary angiography	12
Coronary angioplasty	22
Thallium-201 scan	21
Technetium-99 radionuclide ventriculogram	8

Adapted from Lindsay BD, Eichlin JO, Ambos HD, Cain ME: Radiation exposure to patients and medical personnel during radiofrequency catheter ablation for supraventricular tachycardia. *Am J Cardiol* 70:218–223, 1992, with permission.

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Doses to Radiologist & Cardiologist

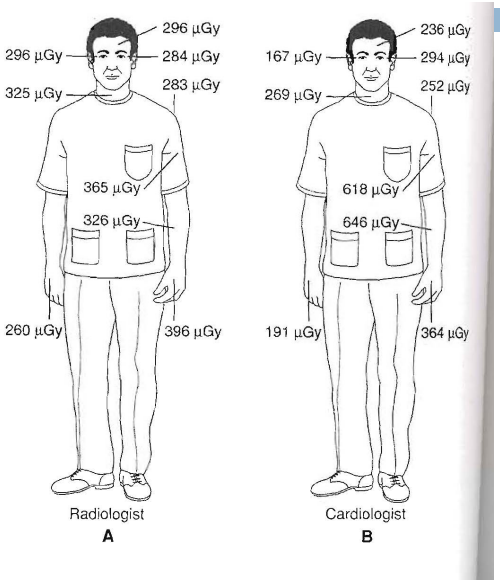

FIGURE 14.7 Graphic representation of the mean values of doses per procedure for a radiologist (**A**) and a cardiologist (**B**) engaged in an interventional procedure. The figures are the mean of measurements taken during more than 80 procedures. (Adapted from Vano E, Gonzalez L, Guibelalde E, Fernandez JM, Ten JI: Radiation exposure to medical staff in interventional and cardiac radiology. *Br J Radiol* 71:954–960, 1998, with permission.)

TABLE 14.21

Estimated Dose to Staff during Typical Cardiac Studies

	One Catheterization, mSv				One Angioplasty, mSv				One Pacemaker Implant (No Cine), mSv			
Category of Staff	Weighted Surface Dose, No Apron	Weighted Surface Dose with Apron	Hands	Eyes	Weighted Surface Dose, No Apron	Weighted Surface Dose with Apron	Hands	Eyes	Weighted Surface Dose, No Apron	Weighted Surface Dose with Apron	Hands	Eyes
Cardiologist	1.6	0.09	2.1	0.6	3.1	0.2	4.2	1.0	0.14	0.01	0.2	0.05
Cardiologist who stands back during cine	0.3	0.01	0.3	0.2	1.5	0.1	1.9	0.7				
Technologist	0.08	<0.01	0.09	0.02	0.2	0.01	0.2	0.05	0.01	<0.01	0.01	<0.01
Technologist who stands back during cine	0.04	<0.01		0.04	0.01	0.1	0.01	0.1	0.03			
Nurse or anesthetist	0.3	0.02	0.4	0.2	0.8	0.06	0.9	0.5	0.04	<0.01	0.04	0.03

Adapted from National Council on Radiation Protection and Measurements: *Implementation of the Principle of As Low As Reasonably Achievable (ALARA) for Medical and Dental Personnel* Report 107. Bethesda, MD, NRCP, 1990, with permission.

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Nuclear Medicine

- Use of radiopharmaceuticals
  - therapy (primarily thyroid, ^{131}INa)
  - diagnosis (^{67}Ga , ^{99m}Tc, ^{131}I, ^{133}Xe, ^{201}Tl)
- Doses on the order of tens to hundreds of millirad
- Pharmaceutical takes radioactive label to a particular biological site
- Dosage limited by critical-organ dose

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Example - PET Scan

- Pharmaceutical labeled with positron emitter (^{15}O, ^{11}C, ^{18}F)
- Positron travels short range then annihilates
- Two 511 keV photons emitted in opposite directions
- Time-of-flight measurements to pin-point origin
- Typically 0.01 Ci dosage - ~ 1 rem/treatment

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PET Scan Equipment

Pet/CT Scanner

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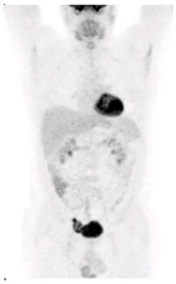
PET Scan Image



- Many cancers use more glucose (sugar) than most normal tissues.
- Glucose with a small amount of radiotracer is injected to obtain images of the distribution of glucose metabolism throughout the body.
- If an area of abnormally increased glucose concentration is observed it can be further investigated

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TABLE 14.22

Relative Frequency of Nuclear-Medicine Procedures (1991), Typical Activities Administered, and Typical Dose

Procedure	Relative Frequency of Procedure, %	Radiopharmaceutical	Activity Administered per Procedure, MBq	Typical Dose to Patient, mGy
Diagnostic				
Bone	20.6	^{99m}Tc medronate or oxidronate	740	1.3
Gastric emptying	4.6	^{99m}Tc sulfur colloid	40	0.2
Heart Equilibrium radiocardiography	11.8	^{99m}Tc red cells	110	4.5
Heart Myocardial perfusion	17.9	^{201}Tl thallous chloride	110	6.3
		^{99m}Tc sestamibi	1,110	5.0
		^{99m}Tc teboroxime	1,850	8.3
Hepatobiliary	2.9	^{99m}Tc disofenin	300	1.3
Kidney	9.6	^{131}I iodohippurate	15	0.4
		^{99m}Tc penetate	370	0.6
		^{99m}Tc mertiatide	370	0.7
Lung				
Perfusion	8.2	^{99m}Tc macro-aggregated albumin	110	0.5
Ventilation	7.3	^{133}Xe gas	370	0.14
		^{99m}Tc penetate aerosol	740	1.6
Thyroid (25% uptake of iodine)	5.6	^{123}I Na iodide	15	0.4
		^{131}I Na iodide	4	0.7
		^{99m}Tc pertechnetate	185	0.7
Tumor/Infection	3.8	^{67}Ga citrate	190	13.0
Other	5.7			
Therapeutic				
Hyperthyroidism	1.8	^{131}I Na iodide	740	—
Thyroid cancer	0.2	^{131}I Na iodide	3,700	—

Based on National Council on Radiation Protection and Measurements. *Sources and Magnitude of Occupational and Public Exposures from Nuclear Medicine Procedures.* Report 124. Bethesda, MD, NCRP, 1996.

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TABLE 14.25. *Administered Activity and Gonadal Doses*

Examination Type	Estimated Administered Activity per Examination[a,1]	Gonadal Dose for Each Radiopharmaceutical, mGy[b]		Gonadal Dose, Weighted Average, mGy[b]	
		Male	Female	Male	Female
Brain	740 MBq ^{99m}Tc DTPA (50)	2.2	4.4	1.9	4.4
	740 MBq ^{99m}Tc O_4 (50)	1.5	4.4		
Hepatobiliary	185 MBq ^{99m}Tc iminodiacetic acid (IDA)(10)	0.2	1.7	0.2	0.5
	185 MBq ^{99m}Tc sulfur colloid (90)	0.2	0.4		
Bone	740 MBq ^{99m}Tc phosphate	3.7	4.4	3.7	4.4
Respiratory				0.3	0.3
Perfusion	185 MBq ^{99m}Tc macroaggregated albumin (MAA) (66)	0.4	0.4		
Ventilation	370 MBq ^{133}Xe gas (34)	0.1	0.1		
Thyroid	185 MBq ^{99m}TcO_4 (80)	0.4	1.1		
	3.7MBq ^{131}I (10)	<0.1	0.1	0.3	0.9
	11.1 MBq ^{123}I (10)	<0.1	0.1		
Renal	740 MBq ^{99m}Tc DTPA (60)	2.2	4.4	1.3	2.7
	9.25 MBq ^{131}I hippuran (40)	<0.1	<0.1		
Abscess/tumor	111 MBq ^{67}Ga citrate	7.2	8.4	7.2	8.4
Cardiovascular	740 MBq ^{99m}Tc labeled red blood cells (40)	0.2	0.8		
	111 MBq ^{201}T1 chloride (40)	45.5	11.1	18.9	5.7
	740 MBq ^{99m}Tc phosphate (20)	3.2	4.4		

[a]Number in parentheses is the estimated percent of examination type with a particular radiopharmaceutical.
[b]1 mGy = 100 mrad.
Adapted from National Council on Radiation Protection and Measurements: Exposure of the US Population From Diagnostic Medical Radiation Report No. 100. Bethesda, MD, NCRP, 1984, with permission.

TABLE 14.24

Maximum Usual Activity per Test Recommended in the United Kingdom and Corresponding Effective Dose for Some Common Diagnostic Nuclear-Medicine Procedures

Procedure	Radiopharmaceutical	Maximum Usual Activity per Test, MBq	Effective Dose, mSv
Bone scan	^{99m}Tc phosphate compounds	600	3.5
Renal scan	^{99m}Tc DMSA	80	0.7
Renal scan	^{99m}Tc DTPA	300	1.6
Dynamic cardiac scan	^{99m}Tc erythrocytes	800	5.3
Biliary scan	^{99m}Tc IDA	150	2.3
Brain scan	^{99m}Tc HMPAO	500	4.7
Abscess imaging	^{99m}Tc leukocytes	200	2.2
Lung perfusion scan	^{99m}Tc MAA	100	1.1
Renal scan	^{99m}Tc MAG3	100	0.7
Myocardial imaging	^{99m}Tc MIBI	400	3.4
Thyroid scan	^{99m}Tc pertechnetate	80	1.0
Tumor/Abscess imaging	^{67}Ga citrate	150	16.5
Thrombus imaging	^{111}In leukocytes	20	7.2
Thyroid scan (35% uptake)	^{123}I iodide	20	4.4
Tumor imaging	^{123}I MIBG	400	5.6
Thyroid metastase (0% uptake)	^{131}I iodide	400	24
Myocardial imaging	^{201}Tl chloride	80	18

Adapted from Shrimpton PC, Wall BF, Hart D: Diagnostic medical exposures in the UK. *Appl Radiat Isot* 50:261–269, 1999, with permission.

TABLE 14.25

Comparison of Collective Effective Dose versus Age-Weighted Collective Dose for U.S. Nuclear-Medicine Procedures in 1982

Examination	Effective Dose, mSv[a]	Examinations, $\times 10^3$	Collective Effective Dose, person-Sv[b]	Age-Weighted Collective Dose, person-Sv[b]
Brain	6.5	813	5,300	2,200
Hepatobiliary	3.7	180	700	300
Liver	2.4	1,424	3,400	1,300
Bone	4.4	1,811	8,000	2,900
Pulmonary	1.5	1,203	1,800	800
Thyroid	7.5	530	4,000	2,400
Renal	3.1	236	700	400
Tumor	12.2	121	1,500	600
Cardiovascular	7.1	961	6,800	2,600
Total			32,100	13,500
Per caput			140 μSv (14 mrem)	59 μSv (5.9 mrem)

[a] 1 mSv = 100 mrem.
[b] 1 person-Sv = 100 man-rem.
Adapted from National Council on Radiation Protection and Measurements: *Exposure of the US Population from Diagnostic Radiation*. Report 100. Bethesda, MD, NCRP, 1989, with permission.

TABLE 14.26

Some Reported Annual Individual and Collective Effective Doses from Diagnostic Nuclear-Medicine Procedures

Country/Area	Effective Dose, mSv		Collective Effective Dose, person-Sv[a]
	Per Examination	Per Caput	
Australia	5.3	0.064	1,110
Canada	4	0.16	4,500
Finland	4.0	0.04	207
Germany	3	0.1	5,000
Netherlands	4.2	0.067	1,000
New Zealand	3.1	0.026	90
Romania	16.2	0.049	1,124
Russian Federation	5.4	0.075	10,000
Switzerland	4.2	0.04	300
United Kingdom	4.2	0.036	2,000
United States	4.4	0.14	35,400

[a] 1 person-Sv = 100 man-rem.
Based on the United Nations Scientific Committee on the Effects of Atomic Radiation: *Annex C Medical Radiation Exposures*. New York, UNSCEAR, 2000.

TABLE 14.27

Organ Doses and Effective Doses for Position Emission Tomography Compounds

	F-18 FDG		0-15 H_2O	
	mGy/MBq $\times 10^{-2}$	rad/mCi $\times 10^{-2}$	mGy/MBq $\times 10^{-3}$	rad/mCi $\times 10^{-3}$
Brain	1.9	7.0	1.3	4.9
Heart wall	6.0	22.0	2.2	8.2
Kidneys	2.0	7.4	1.9	7.2
Ovaries	1.7	6.3	0.36	1.3
Red marrow	1.3	4.8	0.90	3.3
Spleen	3.7	14.0	1.6	5.8
Testes	1.3	4.8	0.67	2.5
Thyroid	1.0	3.9	1.7	6.3
Bladder wall	19.0	70	0.22	0.81
	mSv/MBq $\times 10^{-2}$	rem/mCi $\times 10^{-2}$	mSv/MBq $\times 10^{-3}$	rem/mCi $\times 10^{-3}$
Effective dose	3.0	11.0	1.1	4.2

Data from the Oak Ridge Institute for Science and Education (ORISE).

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TABLE 14.28

Typical Effective Doses to Patients from Diagnostic PET Imaging

Radionuclide	Chemical Form	Investigation	Administered Activity, MBq	Effective Dose, mSv	Dose to Uterus, mSv
^{11}C	L-methyl-methionine	Brain tumor imaging	400	2	1
^{11}C	L-methyl-methionine	Parathyroid imaging	400	2	1
^{13}N	Ammonia	Myocardial blood flow imaging	550	2	1
^{15}O	Water (bolus)	Cerebral blood flow imaging	2,000	2	1
^{15}O	Water (bolus)	Myocardial blood flow imaging	2,000	2	1
^{18}F	FDG	Tumor imaging	400	10	7
^{18}F	FDG	Myocardial imaging	400	10	7
^{18}F	Fluoride	Bone imaging	250	7	5

Based on UNSCEAR 2000.

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Nuclear Medicine

- Dosimetry/Risk
  - Common diagnostic procedures (hundreds to thousands of millirem)
  - Calculated using MIRDOSE (MIRD* method)
  - NCRP: population dose from nuclear medicine procedures in 1982 was about 3.2 million person-rem (from dose to 7.3 million persons)
  - ~ 1,600 cancer fatalities and ~ 190 genetic effects

*MIRD = Medical Internal Radiation Dose

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Therapeutic Radiopharmaceuticals

- Primarily thyroid (^{131}I) related
  - hyperthyoidism
  - thyroid cancer
- Thousands of rads to the thyroid
- 5-15 rads to body from iodine in the blood
- 7-15 rads to bone marrow
- Secondary leukemia studied, but not significant

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Childhood Exposures

- ABS data shows that the radiosensitivity of certain organs decreases with age
  - breast cancer; thyroid cancer (3x greater risk in childhood)
- General thinking in diagnosis is that children should receive as little dose as possible
- Pediatric CT scans, however, are becoming more popular

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Fetal Exposures

- Risks involve:
  - <2 weeks - embyronic death (preimplantation)
  - 2-8 weeks - congenital malformation/reduced head size
  - 8-15 weeks - mental retardation/reduced head size
  - 15-25 weeks - same, but to a lesser extent
  - >25 weeks - carcinogenesis
    - risk of carcinogenesis is always present
- Threshold of about 10-20 rad for serious deterministic effects
- Risk/benefit assessment is a necessity!

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TABLE 14.29

Typical Effective Doses to Pediatric Patients from Diagnostic Nuclear Medicine Procedures

Radiopharmaceutical	Activity for Adult Patient, MBq	Effective Dose per Procedure by Patient Age[a] (mSv)				
		Adult 70 kg [1.0]	15-Year-Old 55 kg [0.9]	10-Year-Old 3.3 kg [0.69]	5-Year-Old 18 kg [0.44]	1-Year-Old 10 kg [0.27]
^{99m}Tc MAG3 (normal renal function)	100	0.7	0.8	0.7	0.6	6.0
^{99m}Tc MAG3 (abnormal renal function)	100	0.6	0.7	0.7	0.5	0.5
^{99m}Tc DTPA (normal renal function)	300	1.6	1.8	2.1	1.8	2.2
^{99m}Tc DTPA (abnormal renal function)	300	1.4	1.6	1.9	1.8	2.0
^{99m}Tc DMSA (normal renal function)	80	0.7	0.7	0.8	0.8	0.8
^{99m}Tc pertechnetate (no thyroid block)	80	1.0	1.2	1.3	1.4	1.4
^{99m}Tc IDA (normal biliary function)	150	2.3	2.4	2.9	3.0	3.7
^{99m}Tc HMPAO	500	4.7	5.0	5.9	5.7	6.5
^{99m}Tc leukocytes	200	2.2	2.7	3.0	2.9	3.4
^{99m}Tc erythrocytes	800	5.3	6.0	6.6	6.7	7.6
^{99m}Tc phosphates	600	3.6	3.7	4.1	4.2	4.9
^{99m}Tc MIBI (resting)	400	3.3	4.0	4.4	4.8	5.4
^{201}Tl chloride	80	20	30	129	95	86
^{123}I iodide (55% thyroid uptake)	20	7.2	10.2	12.1	16.3	18.8
^{123}I iodide (total thyroid block)	20	0.2	0.3	0.3	0.3	0.3
^{123}I MIBG (no impurity)	400	5.6	6.5	9.1	8.8	10.1
^{67}Ga citrate	150	15	18.9	22.8	23.1	27.9

[a] Figures in brackets are scaling factors for activity based on body weights shown. Doses are calculated using age-specific coefficients. Based on UNSCEAR 2000.

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TABLE 14.30

Thyroidal Radioiodine Dose to the Fetus

Gestation Period	Fetal/Maternal Ratio (Thyroid Gland)	Dose to Fetal Thyroid, rad/μCi[a]
10–12 weeks	—	0.001 (precursors)
12–13 weeks	1.2	0.7
Second trimester	1.8	6
Third trimester	7.5	—
Birth imminent	—	8

[a] Rad/μCi of ^{131}I ingested by mother.
Courtesy of Dr. J. Keriakes, unpublished data.

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TABLE 14.31

Dose Estimate to Embryo from Radiopharmaceuticals

Radiopharmaceutical	Embryo Dose, rad/mCi Administered
^{67}Ga citrate	0.25
^{5}Se methionine	3.8
^{99m}Tc DTPA	0.035
^{99m}Tc human serum albumin	0.018
^{99m}Tc lungaggregate	0.035
^{99m}Tc polyphosphate	0.036
^{99m}Tc sodium pertechnetate	0.037
^{99m}Tc stannous glucoheptonate	0.04
^{99m}Tc sulfur colloid	0.032
^{123}I sodium iodide (15% uptake)	0.032
^{131}I sodium iodide (15% uptake)	0.1
^{123}I rose bengal	0.13
^{131}I rose bengal	0.68

Courtesy of Dr. J. Kereiakes, unpublished data.

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TABLE 15.2

Radiation Weighting Factors

Type and Energy Range	Radiation Weighting Factor, W_R
Photons	1
Electrons	1
Protons	2
α-Particles, fission fragments, heavy nuclei	20
Neutrons	A continuous curve is recommended with a maximum of 20 for the most effective neutrons of about 1 MeV

Based on International Commission on Radiological Protection: Relative biological effectiveness (RBE), quality factor (Q), and radiation weighting factor (W_R). ICRP Publication 92, Oxford, UK, Elsevier Science Ltd, 2004.

e.g., if a tissue or organ were exposed to 0.15 Gy of cobalt-60 -rays plus 0.02 Gy of 1-MeV neutrons, the equivalent dose would be:
(0.15 x1) + (0.02 x 20) = 0.55 Sv

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TABLE 17.2 **Tissue Weighting Factors**

Organ/Tissue	Number of tissues	w_T	Total contribution
Lung, stomach, colon, bone marrow, breast, and remainder	6	0.12	0.72
Gonads	1	0.08	0.08
Thyroid, esophagus, bladder, and liver	4	0.04	0.16
Bone surface, skin, brain, and salivary glands	4	0.01	0.04

The specified remainder tissues (14 in total, 13 in each sex) are adrenals, extrathoracic tissue (ET), gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (m), small intestine (SI), spleen, thymus, uterus/cervix (f).

From ICRP 2007.

Tissue weighting factor (**WT**), represents the relative contribution of each tissue or organ to the total detriment resulting from uniform irradiation of the whole body. The sum of all of the weighted equivalent doses in all the tissues or organs irradiated is called the **effective dose**, which is expressed by the formula Effective dose = Σ absorbed dose x WR x WT for all tissues or organs exposed.

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TABLE 15.4

Quantities and Units Used in Radiation Protection

Quantity	Definition	Unit	
		New	Old
Absorbed dose	Energy per unit mass	Gray	Rad
For individuals			
Equivalent dose (Radiation weighted dose)	Average dose × radiation weighting factor	Sievert	Rem
Effective dose	Sum of equivalent doses to organs and tissues exposed, each multiplied by the appropriate tissue weighting factor	Sievert	Rem
Committed equivalent dose	Equivalent dose integrated over 50 years (relevant to incorporaated radionuclides)	Sievert	Rem
Committed effective dose	Effective dose integrated over 50 years (relevant to incorporated radionuclides)	Sievert	Rem
For populations			
Collective effective dose	Product of the average effective dose and the number of individuals exposed	Person-sievert	Man-rem
Collective committed effective dose	integration of the collective dose over 50 years (relevant to incorporated radionuclides)	Person-sievert	Man-rem

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FIGURE 15.1 The basic differences in the shape of the dose–response relationship for stochastic as opposed to deterministic effects. Deterministic effects (e.g., cataracts or mental retardation) show no threshold in dose; the severity of the effect increases with dose above this threshold, and the proportion of individuals rises rapidly with dose to 100%. The dose–response relationship is therefore sigmoid after a threshold. Stochastic effects are all-or-nothing effects (e.g., cancer and hereditary effects). The severity of the effect is not dose related, though the probability of it occurring is. The increase with dose may be linear or linear-quadratic. There is no threshold, that is, no dose below which the probability of an effect is zero. The dose–response relationship is therefore linear, or linear-quadratic, with no threshold.

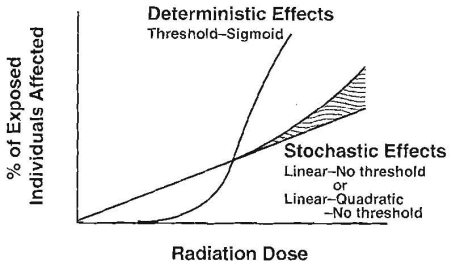

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TABLE 15.6

Summary of Recommended Dose Limits

	NCRP	ICRP (If Different)
Occupational Exposure:		
Stochastic effects: effective dose limits		
Cumulative	10 mSv × age	20 mSv/y averaged over 5 years
Annual	50 mSv/y	—
Deterministic effects: dose equivalent limits for tissues and organs (annual):		
Lens of eye	150 mSv/y	—
Skin, hands, and feet	500 mSv/y	—
Embryo/Fetus Exposure:		
Effective dose limit after pregnancy declared	0.5 mSv/month	Total of 2 mSv to abdomen surface
Public Exposure (annual):		
Effective dose limit, continuous or frequent exposure	1 mSv/y	No distinction between frequent and infrequent—1 mSv/y
Effective dose limit, infrequent exposure	5 mSv/y	
Dose equivalent limits of lens of eye, skin, and extremities	50 mSv/y	—
Education and Training Exposure (annual):		
Effective dose limit	1 mSv/y	No statement
Dose equivalent limit for lens of eye	15 mSv/y	No statement
Skin and extremities	50 mSv/y	No statement
Negligible Individual Dose (annual):	0.01 mSv/y	No statement

Based on National Council on Radiation Protection and Measurements: *Recommendations on Limits for Exposure to Ionizing Radiation.* NCRP Report No. 116. Bethesda, MD, 1993; and International Commission on Radiation Protection. *Recommendations of the ICRP.* ICRP Publication 60. New York, Pergamon Press, 1991.

TABLE 15.5

Deleterious Effects of Radiation that Highlight the Need for Protection

End Point	Risk Estimate
Severe mental retardation:	
Exposure of embryo/fetus (8–15 weeks)	40%/Sv
Carcinogenesis:	
General population (low dose, low dose rate)	5%/Sv
Hereditary effects:	
General population	0.2%/Sv

Based on ICRP, BEIR, and UNSCEAR.

TABLE 15.8

Trends in Fatal Accident Rates (1976, 1989) for Workers in the United States

	Mean Rate 1976 $10^{-6}y^{-1}$	Mean Rate 1989 $10^{-6}y^{-1}$
All groups	142	90
Trade	64	40
Manufacture	89	60
Service	86	40
Government	111	90
Transport/public utilities	313	240
Construction	568	320
Mines and quarries	625	430
Agriculture (1973–1980)	541	400

Based on National Safety Council: Accident Facts 1976, Chicago, National Safety Council, 1977; and National Safety Council: Accident Facts 1989, Chicago, National Safety Council, 1990.

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TABLE 15.7

Detriment Due to Cancer and Hereditary Effects

	Detriment 10^{-2} Sv^{-1}		
	Fatal and Non-Fatal Cancers	Hereditary Effects	Total
Adult radiation workers	4.6	0.1	4.7
Whole population	5.9	0.2	6.1

Data from International Commission on Radiation Protection: Relative biological effectiveness (RBE), quality factor (Q), and radiation weighting factor (W_R). ICRP Publication 92, Oxford, UK, Elsevier Science Ltd, 2004.

TABLE 17.6 **Cancer Risks for a Radiation Worker Receiving the Maximum Permissible Dose from Age 18 to 65 years**

Rule	Total Dose	Cancer Incidence	Cancer Mortality
NRC 50 mSv/y	2.35 Sv	19.0	10.8
NCRP 10 mSv × age	0.65 Sv	6.1	3.3

US-NRC: Total effective dose equivalent = 50 mSv. Consequently, if a radiation worker starts at age18 years and works at the dose limit until retiring at age 65, he or she would face a radiation induced cancer incidence risk of 19% and a cancer mortality of 10.8%. NCRP: limitations were followed, when the radiation-induced cancer incidence would be 6%, and mortality would be 3%. (data from BEIR VII report).

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