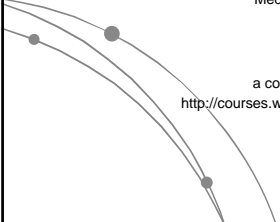


Radiation Dosimetry

Bushberg – Chapter 24
RSNA & AAPM Physics Curriculum: Modules 9 & 11

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a copy of this lecture may be found at:
<http://courses.washington.edu/radphys/PhysicsCourse.html>



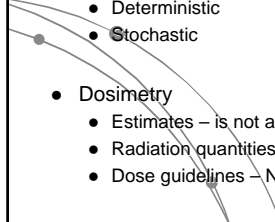
Introduction

- Review – Quantities
 - Important to understand 'the language' when discussing radiation doses

Exposure (R) machine output	Absorbed Dose (Gy) tissue or organ dose	Effective Dose (Sv) biologic effect
---------------------------------------	---------------------------------------------------	-----------------------------------------------

- Other radiological quantities – ESE, ESD, DAP, AK, CTDI, DLP, etc
- Biologic Effects
 - Deterministic
 - Stochastic
- Dosimetry
 - Estimates – is not a science, rather it's an art
 - Radiation quantities are indicators of risk to the patient
 - Dose guidelines – NEXT (US) and NRPB (UK)

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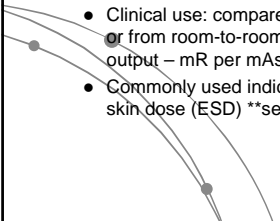
Review – Quantities

- See Table 3-6, page 59 of Bushberg for full review of radiation quantities

Exposure (R) machine output

- Exposure – total ionizations produced by x- and γ-rays per unit mass of air
 - Coulombs per kg (C/kg) = Rontgen (R)
 - Clinical use: compare equipment performance either from year-to-year or from room-to-room in a department (example: measure of equipment output – mR per mAs)
 - Commonly used indices – entrance skin exposure (ESE) and entrance skin dose (ESD) **see next slide for explanation

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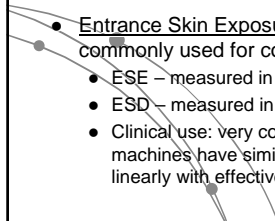
Review – Quantities

- Absorbed dose – total energy imparted per unit mass
 - Gray (Gy) = Joule per kg (J/kg)
 - Clinical use: calculate dose to an organ

Absorbed Dose (Gy) tissue or organ dose

- Imparted Energy – total energy imparted to matter by incident radiation (direct or indirect radiation)
 - Joule (J) = Gy * kg
 - Clinical use: used to compare radiation dose between different imaging procedures
- Entrance Skin Exposure (ESE) or Dose (ESD) – indices more commonly used for comparison within a particular modality
 - ESE – measured in milli-Roentgen (mR)
 - ESD – measured in milli-Gray (mGy)
 - Clinical use: very common in general x-ray and angiography because machines have similar geometry and beam spectra (ESE and ESD track linearly with effective dose)

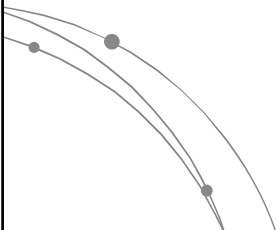
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Review – Quantities

- **Effective Dose** – accounts for tissue sensitivity; measure of radiation and organ specific damage
 - Sievert (Sv)
 - Clinical use: comparison of risks from stochastic effects between different imaging procedures and modalities

Effective Dose (Sv)
 biologic effect



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Radiological Quantities: Dose Indices in Imaging Modalities

- What's the difference between ESE and ESD?
 - Entrance skin exposure (ESE) is a quantity measured in air
 - Entrance skin dose (ESD) is a quantity measuring the energy imparted to the skin; the calculation of ESD takes into account:
 - Back-scatter at the surface of the skin
 - Mass energy absorption coefficient for skin and air (from McPartland, BJR (1998) 71: 1290 – MSACR = 1.05 @ 65 kVp whereas MSACR = 1.06 @ 110 kVp)
 - Inverse square correction factor and/or table attenuation factors

Table 2. Backscatter factors measured with TLD.

HVL (mm Al)	Field size (cm × cm)							
	2×2	4×4	7×7	10×10	15×15	20×20	25×25	30×30
1.0	1.05	1.11	1.16	1.18	1.19	1.20	1.20	1.20
1.5	1.07	1.14	1.20	1.22	1.24	1.25	1.25	1.26
2.0	1.09	1.17	1.23	1.26	1.28	1.29	1.30	1.30
2.5	1.11	1.19	1.25	1.28	1.31	1.32	1.33	1.34
3.0	1.11	1.21	1.27	1.30	1.33	1.35	1.36	1.37
4.0	1.12	1.21	1.27	1.32	1.37	1.39	1.40	1.41

c.f. Harrison, R.M. (1982). Backscatter factors for diagnostic radiology (1-4 mmAl), Phys Med Biol 27(12): 1465-74. © Renée L Dickinson & UW 6

Radiological Quantities: Dose Indices in Imaging Modalities

- Comparing ESE is useful for assessment of equipment performance and calibration, when a comprehensive analysis of effective dose is unnecessary
- ESD is easy to calculate, but does not indicate risk to patient; ESD does not account for area exposed, beam quality or penetrating power of x-rays, nor radiosensitivity of exposed region

TABLE 24-2. ENTRANCE SKIN EXPOSURES (ESEs)*

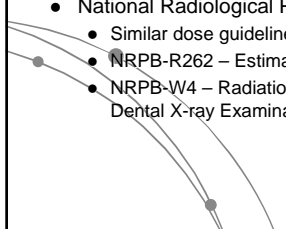
Projection	Patient thickness (cm)	Grid	SID (cm)	ESE, 200 speed (mR)	ESE, 400 speed (mR)
Abdomen (A/P)	23	Yes	100	490	300
Lumbar spine (A/P)	23	Yes	100	570	330
Full spine (A/P)	23	Yes	183	260	145
Cervical spine (A/P)	13	Yes	100	135	95
Skull (lateral)	15	Yes	100	145	70
Chest (P/A)	23	No	183	15	10
Chest (P/A)	23	Yes	183	25	15

Note: A/P, anteroposterior; P/A, posteroanterior; SID, source-to-image distance.
 *ESEs substantially exceeding these values most likely represent excessive patient exposure.
 Sources: Conference of State Radiation Control Program Directors. Average patient exposure/dose guides. Publication 92-4. CRCPD, 1992, Table 1.

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 797. © Renée L Dickinson & UW 7

Radiological Quantities: Dose Indices in Imaging Modalities

- Nationwide Evaluation of X-ray Trends (NEXT) program – US
 - Periodic surveys of x-ray producing devices
 - Jointly conducted by:
 - Conference of State Radiation Control Program Directors (CRCPD)
 - State radiologic health regulatory agencies
 - Center for Devices and Radiologic Health of the U.S. FDA
- National Radiological Protection Board (NRPB) – UK
 - Similar dose guidelines and surveys
 - NRPB-R262 – Estimation of Effective Dose from ESD and DAP
 - NRPB-W4 – Radiation Exposure of the UK Population from Medical and Dental X-ray Examinations



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Radiological Quantities: Dose Indices in Imaging Modalities

- Other common radiological quantities:
 - Gen Rad
 - S-number (Fuji/Philips CR); exposure index = EI (Philips DR) – both unit describe dose at the imaging plane (indirect measure of ESD)
 - S = 200 indicates 1 mR to the IIP
 - EI = 114 indicates 1 mR to the detector
 - Fluoroscopy
 - DAP = dose-area product (Gy-cm²)
 - AK = air kerma (Gy, mGy)
 - Computed tomography
 - DLP = dose-length product (mGy-cm)

Modality	Dose Index	Reference (Chapter no.)
Radiography	Entrance skin exposure (free-in-air)	24
Fluoroscopy	Entrance skin exposure rate (free-in-air)	24
Mammography	Mean glandular dose	8
Nuclear medicine	Activity of radiopharmaceutical injected	2, 18, 19 and 24
Computed tomography	Computed tomographic dose index (CTDI)	13
	Mean scan average dose (MSAD)	

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 797. © Renée L Dickinson & UW

Biologic Effects of Radiation: Stochastic and Deterministic Effects

- Radiation dose quantities serve as indicators of the risk of biologic damage to the patient
- The biologic effects of radiation can be classified as either deterministic (non-stochastic) or stochastic
 - Deterministic or non-stochastic effects** – associated with cell kill; if a sufficient number of cells in an organ or tissue are killed, its function can be impaired
 - Examples: teratogenic effects to embryo/fetus, skin damage, cataracts
 - Threshold dose below which an effect will not occur
 - Severity of effect increases linearly with dose
 - Stochastic effects** – associated with cell damages that produces some genetic transformation; cell(s) still capable of reproduction
 - Examples: cancer and hereditary effects of radiation
 - No dose thresholds
 - Probability of a stochastic effect, instead of its severity, increases with dose

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Biologic Effects of Radiation: NRC Radiation Dose Limits

- The NRC's radiation dose limits defined for occupational personnel and the public are intended to limit the risks of stochastic effects and to prevent the deterministic effects

Limits	Maximum permissible annual dose limits	
	mSv	rem
Occupational limits		
Total effective dose equivalent	50	5
Total dose equivalent to any individual organ (except lens of eye)	500	50
Dose equivalent to the lens of the eye	150	15
Dose equivalent to the skin or any extremity	500	50
Minor (18 years old)	10% of adult limits	10% of adult limits
Dose to an embryo/fetus ^b	5 in 9 months	0.5 in 9 months
Nonoccupational (public limits)		
Individual members of the public	1.0/yr	0.1/yr
Unrestricted area	0.02 in any 1 hr ^c	0.002 in any 1 hr ^c

*These limits are exclusive of natural background and any dose the individual has received for medical purposes; inclusive of internal committed dose equivalent and external effective dose equivalent (i.e., total effective dose equivalent).
^bApplies only to conceptus of a worker who declares her pregnancy. If the limit exceeds 4.5 mSv (450 mrem) at declaration, conceptus dose for remainder of gestation is not to exceed 0.5 mSv (50 mrem).
^cThis means the dose to an area (irrespective of occupancy) shall not exceed 0.02 mSv (2 mrem) in any 1 hour. This is not a restriction of instantaneous dose rate to 0.02 mSv/hr (2 mrem/hr).

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 791. © Renée L Dickinson & UW

Image Quality vs Radiation Dose

- There is always a compromise between the image quality and the radiation exposure to the patient
- In the United States, there are no regulatory limits to the amount of radiation received by the patient for diagnostic procedures
 - Exceptions:
 - Mammo – Mammography Quality Standards Act (MQSA)
 - Fluoro – exposure rate is regulated, but the total fluoroscopic time is not, and therefore the total dose is not
- The physician must decide whether the benefit of the diagnostic procedure justifies the risk to the patient from the radiation exposure
- In order to make informed decisions in this regard, referring physicians as well as radiologists must understand the risks associated with radiation exposure**
- Knowledge of typical dose levels associated with various common radiologic procedures**

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Image Quality vs Radiation Dose Radiation Risk

- The ICRP estimates the risk of fatal cancer to adults of working age to be 4×10^{-2} deaths per Sv (4×10^{-4} deaths per rem)
 - 1 cancer death per 2,500 people receiving an ED of 10 mSv
 - Because of linear, no-threshold assumption used, risk is presumed to be proportional to ED
 - 1 in 25,000 chance from ED of 1 mSv
 - 1 in 500 chance from ED of 50 mSv
- The ICRP estimates the risk to be two or three times higher for infants and children and substantially lower for adults older than 50 years of age

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Image Quality vs Radiation Dose Radiographic Procedures

- Most of the time it is necessary to compute radiation dose after a x-ray procedure has already been performed
 - Most common example: women finds out she is pregnant after she has had a diagnostic procedure and is concerned about radiation dose to the fetus and associated risk of exposure
- Examples for estimating dose from radiographic exams for both manual and AEC techniques are in Bushberg pages 802 – 805

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Radiation Dose Radiographic Procedures

- How do we estimate the dose?
- What information do you think is needed to accurately estimate radiation dose?**
 - What exams were performed?
 - Number of images
 - Radiographic projection of each image
 - Anatomy in direct beam (position of x-ray field)
 - Which room was the procedure(s) performed in? **WHY??**
 - Information regarding the characteristics (HVL) of the x-ray beam... **WHY do you need to know HVL???**
 - Tube output (mR per mAs)**
 - Radiographic technique used for each image (kVp, mAs, AEC, etc)
 - An estimate of the patient's thickness for each radiographic projection

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Radiation Dose Entrance Skin Dose (ESD)

Skin reactions are....
 Stochastic effects?
 Or deterministic effects?

- Recall: ESD are generally poor indicators of patient risk...
- But, when considering skin reactions, estimating ESD is important (i.e. interventional radiology)
 - Transient Erythema – 2 Gy (onset: hours)
 - Temporary Epilation – 3 Gy (onset: about 3 weeks)
 - Main Erythema – 6 Gy (onset: 10 days, peak: 2 weeks)

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Radiation Dose Organ Dose

- It is possible to estimate organ doses from a given entrance skin exposure (ESE)
- Organ doses are substantially lower than skin dose
- Organs not in direct field of view receive only scatter radiation
- Embryo/fetal dose rules of thumb (Huda):
 Note: these are estimates for embryo/fetus in the direct beam
 - AP projections: dose will be between 1/3rd and 1/4th the ESE
 - PA projections: dose will be about 1/6th of the ESE
 - LAT projection: dose will be about 1/20th of the ESE

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Radiation Dose Computed Tomography Doses

- Highest expected doses to any part of the patient (Huda):
 - Typical Head CT (120 kVp, 300 mAs) – about 40 mGy (4 rad)
 - Lens dose – @ 40 mGy (cataracts threshold is 2 Gy)
 - Typical Body CT (120 kVp, 250 mAs) – about 20 mGy (2 rad)
- Skin doses – typically between 20 and 40 mGy (transient skin erythema threshold is 2 Gy)
- Embryo/Fetus (120 kVp, 250 mAs, in direct beam) – about 15 mGy (according to Wagner, doses less than 150 mGy during the 2 and 8th weeks of pregnancy do not necessarily warrant therapeutic abortion)

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Radiation Dose General X-ray Examinations

Examination	Average Effective Dose (mGy)	Values Reported in Literature (mGy)
Skull	0.1	0.03-0.22
Cervical spine	0.2	0.07-0.3
Thoracic spine	1.0	0.6-1.4
Lumbar spine	1.5	0.5-1.8
Posteroanterior and lateral study of chest	0.1	0.05-0.24
Posteroanterior study of chest	0.02	0.007-0.050
Mammography	0.4	0.10-0.60
Abdomen	0.7	0.04-1.1
Pelvis	0.6	0.2-1.2
Rip	0.7	0.18-2.71
Shoulder	0.01	...
Knee	0.005	...
Other extremities	0.001	0.0002-0.1
Dual x-ray absorptiometry (without CT)	0.001	0.001-0.035
Dual x-ray absorptiometry (with CT)	0.04	0.003-0.06
Intravenous urography	3	0.7-3.7
Upper gastrointestinal series	6*	1.5-12
Small bowel series	5	2.0-7.8
Barium enema	8*	2.0-18.0
Endoscopic retrograde cholangiopancreatography	4.0	...

* include fluoroscopy

c.f. Mettler et al. *Effective doses in Radiology and Diagnostic Nuclear Medicine*, Radiology 248(1); July 2008

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Radiation Dose General X-ray Examinations

Examination	Active bone marrow		Breasts		Uterus (embryo, fetus)		Thyroid		Gonads*		Effective dose	
	(mGy)	(mrad)	(mGy)	(mrad)	(mGy)	(mrad)	(mGy)	(mrad)	(mGy)	(mrad)	(mSv)	(mrem)
Chest	0.04	4	0.09	9	*	*	0.02	2	*	*	0.04	4
CT chest	5.9	590	21	2100	0.06	6	2.3	230	0.08	8	7.8	780
Skull	0.2	20	*	*	*	*	0.4	40	*	*	0.3	30
CT head	2.7	270	0.03	3	*	*	1.9	190	*	*	1.8	180
Abdomen	0.4	40	0.03	3	2.9	290	*	*	2.2, 0.4	220, 40	1.2	120
CT abdomen	5.6	560	0.7	70	8.0	800	0.05	5	8.0, 0.7	800, 70	7.6	760
Thoracic spine	0.7	70	1.3	130	*	*	1.5	150	*	*	1.3	130
Lumbar spine	1.4	140	0.07	7	3.5	350	*	*	4.3, 0.06	430, 6	2.3	230
Pelvis	0.2	20	*	*	1.7	170	*	*	1.2, 4.6	120, 460	1.3	130
CT pelvis	5.6	560	0.03	3	26	2600	*	*	23, 1.7	2300, 170	7.3	730
Intravenous urography	1.9	190	3.9	390	3.6	360	0.4	40	3.6, 4.3	360, 430	4.2	420
Barium enema (including fluoro)	8.2	820	0.7	70	16	1600	0.2	20	16, 3.4	1600, 340	8.7	870
Mammography (film-screen)	*	2	2	200	*	*	*	*	*	*	0.3	30

Note: *, less than 0.01 mGy (1 mrad); CT, computed tomography.
 *When two values are given for the gonads, the first is for the ovaries and the second is for the testes.
 Source: Adapted from International Commission on Radiological Protection. Summary of the current ICRP principles for protection of the patient in diagnostic radiology, 1993, and data from two publications of the National Radiological Protection Board of the United Kingdom.

c.f. Bushberg, et al. *The Essential Physics of Medical Imaging*, 2nd ed., p. 798.

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Radiation Dose CT and IR Examinations

Table 2
Adult Effective Doses for Various CT Procedures

Examination	Average Effective Dose (mSv)	Values Reported in Literature (mSv)
Head	2	0.9-4.0
Neck	3	...
Chest	7	4.0-18.9
Chest for pulmonary embolism	15	13-40
Abdomen	8	3.5-25
Pelvis	6	3.3-10
Three-phase liver study	15	...
Spine	6	1.5-10
Coronary angiography	16	5.0-32
Calcium scoring	3	1.0-12
Virtual colonoscopy	10	4.0-13.2

Table 3
Adult Effective Doses for Various Interventional Radiology Procedures

Examination	Average Effective Dose (mSv)	Values Reported in Literature (mSv)
Head and/or neck angiography	5	0.8-19.6
Coronary angiography (diagnostic)	7	2.0-15.8
Coronary percutaneous transluminal angioplasty, stent placement, or radiofrequency ablation	15	6.9-57
Thoracic angiography of pulmonary artery or aorta	5	4.1-9.0
Abdominal angiography or arteriography	12	4.0-48.0
Transjugular intrahepatic portosystemic shunt placement	70	20-180
Pelvic vein embolization	60	44-78

*Values can vary markedly on the basis of the skill of the operator and the difficulty of the procedure.

c.f. Mettler et. al, *Effective doses in Radiology and Diagnostic Nuclear Medicine*, Radiology 248(1); July 2008

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Radiation Dose Interventional Radiology Examinations

TABLE 24-4. RANGE OF FLUOROSCOPY SCREENING TIME, FLUOROSCOPY AND RADIOGRAPHY DOSE-AREA PRODUCT VALUES, AND MEAN EFFECTIVE DOSE FOR SELECTED INTERVENTIONAL PROCEDURES.

Interventional procedures	Fluoroscopy screening time (min)	Dose-area product (Gy-cm ²) ^a		Mean effective dose (mSv) ^b
		Fluoroscopy	Radiography	
Diagnostic				
AV fistula angiography	1.4-3.8	0.3-36.3	0.8-26.2	0.2
Upper extremity angiography	3.6-4.1	2.5-29.8	3.9-40.2	0.3
Lower extremity angiography	1.8-21.7	1.0-80.2	0.2-1.42	0.8
Nephrotomography	0.9-24.7	0.1-72.9	0.0-14.2	2.4
Cerebral angiography	2.6-21.0	2.6-79.8	4.2-63.7	4.9
Transjugular hepatic biopsy	2.8-18.7	5.5-95.3	0.0-25.4	5.5
Renal angiography	2.9-7.8	4.7-31.6	12.3-80.2	6.4
Cerebral angiography	2.9-36.0	7.5-121	10.8-76.6	7.4
Femoral angiography	1.8-17.2	1.9-44.6	0.2-91.8	7.5
Thoracic angiography	0.6-114	2.2-167	9.2-115	11.9
PTC	2.9-44.0	12.0-1.52	0.0-11.3	12.8
CT arterial portography	2.3-25.8	17.1-231	0.0-56.5	12.9
Abdominal angiography	1.8-27.1	13.0-102	5.4-227	18.9
Hepatic angiography	3.6-41.8	22.8-168	16.2-149	21.7
Therapeutic				
AV fistula angioplasty	4.8-57.9	0.2-96.3	0.9-45.1	0.3
Biliary stent insertion/removal	0.6-26.3	3.1-137	0.0-18.7	6.9
Nephrotomography	1.3-20.8	0.6-169	0.0-44.7	6.9
Cerebral embolization	15.2-55.8	28.3-61.9	36.3-162	10.5
Renal angioplasty	11.4-27.2	5.6-190	2.6-77.7	13.6
Thoracic therapeutic procedures	4.2-35.0	4.5-182	10.9-168	16.3
Other abdominal therapeutic procedures (excluding hepatic and renal)	6.6-58.8	16.9-413	1.1-229	25.9
TIPS	21.7-100	212-897	61.4-234	83.9

^a1 Gy = 100 rad; 1 mSv = 100 mrem.
^bsize: AIC, arteriogram; CT, computed tomography; PTC, percutaneous transhepatic cholangiography; TIPS, transjugular intrahepatic portosystemic shunt.
 Adapted from McFarland 83: A study of patient radiation doses in interventional radiological procedures. *Br J Radiol* 1998;71:175-185.

c.f. Bushberg, et al. *The Essential Physics of Medical Imaging*, 2nd ed., p. 798.

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Radiation Dose Communicating with the Patient

- So, we've estimated the dose by...
 - Consulting the literature for average (and/or ranges) of ESDs, effective doses, etc.
 - OR, we used a program that estimate doses based on Monte Carlo techniques (e.g. X-Dose, Impact Scan, etc)
 - OR, someone calculated the dose
- Great! But how do you explain the radiation risk to the patient???
- Literature
 - e.g. Wagner – embryo/fetal risks
 - e.g. BEIR VII; BEIR = Biologic Effects of Ionizing Radiation; reports cancer incidence and cancer mortality per 100 mSv exposure
- BERT = Background Equivalent Radiation Time
 - People in the United States are exposed to an average of 3.6 mSv of annual background radiation

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Radiation Dose Communicating with the Patient

X-ray Study	Effective Dose (mSv)	Eq. # of Chest X-rays	BERT
Chest Radiograph	< 0.1 (0.02)	1	12 days
Thoracic spine	1.0	50	4 months
Lumbar spine	2.1	105	8.5 months
Head CT	1 - 2	50 - 100	4 - 8 months
Chest CT	5 - 7	250 - 350	1.7 - 2.3 years
Abdomen CT	5 - 7	250 - 350	1.7 - 2.3 years
Pelvic CT	3 - 4	150 - 200	1 - 1.3 years
CT Angiography	5 - 12	250 - 600	1.7 - 4 years
Mammography	0.3 - 0.6	15 - 30	37 - 73 days
Barium Enema	3 - 6	150 - 300	1 - 2 years

Table 1. Typical Effective Doses and BERT Values for some common X-ray Studies to an Adult (Sources: JT Bushberg et al. *The Essential Physics of Medical Imaging* and CH McCullough, Mayo Clinic)

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Misc Info

- CT Lifetime Attributable Risk (LAR) Calculator
 - http://depts.washington.edu/diagphys/DPS_Folder/BEIR-VII/BEIR-7-Table-12D-091106e.xls
- Impact scan & fetal dose
- Xdose
- CT Expo – no demo
- RSNA/AAPM Web modules
 - In Huda
 - General info on patient dose – pg 78-80
 - CT dose info – pg 130-132
 - Radiation protection – chapter 10 (some old info, previous to NCRP 160)

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Example Board Question

The following effects are:

- a. Stochastic
- b. Deterministic
- c. Both
- d. Neither

1. Induction of cancer from exposure to radiation.
2. Skin burns from prolonged fluoroscopic exams.

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Example Board Question

The national average ESE for a normal 23 cm thick A/P abdomen film with a 400 speed screen-film system is:

- A. 13 mR
- B. 150 mR
- C. 300 mR
- D. 850 mR
- E. 3000 mR

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Example Board Question

Match the exposure or dose with the appropriate item:

- A. 15 mR
- B. 40 mR
- C. 5 R
- D. 10 R
- E. 50 mrem

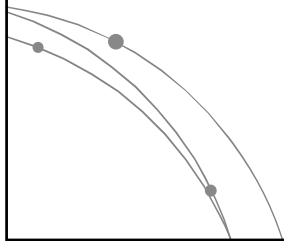
1. CT head scan ESE
2. Lateral chest ESE
3. 10 min fluoro (thin patient)
4. Monthly limit for a pregnant technologist

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Example Board Question

Order the following procedures from highest to lowest effective dose:

- A. Chest CT
- B. Barium enema
- C. Transjugular intrahepatic portosystemic shunt (TIPS) procedure
- D. Head CT
- E. CT Coronary Angiography



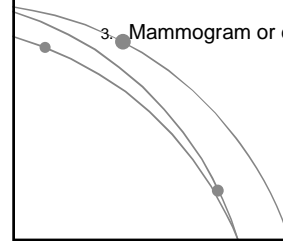
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Example Board Questions

Which has a higher estimated effective dose?

- 1. Cervical spine x-ray or thoracic spine x-ray?
- 2. Pelvic x-ray or upper GI series?
- 3. Mammogram or extremity x-ray?



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