Radiation Dosimetry

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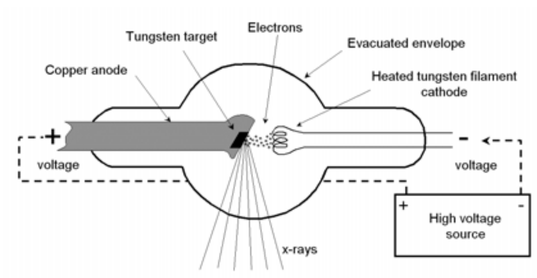
a copy of this lecture may be found at:
http://courses.washington.edu/radxphys/PhysicsCourse.html

Introduction

- Radiation dose is of great importance in diagnostic radiology
- Radiologists need to be the local experts (in absence of a physicist) on the radiation dose received from various imaging exams
- The dose received in x-ray imaging depends on the imaging modality, the equipment, the technique factors used and in case of fluoroscopy, the fluoroscopy time used during the exam
- Radiation dose quantities are used as indicators of the risk of biologic damage to patients from x-rays and thus a good knowledge of the different dose parameters and dose values is essential

X-ray Tube



❖The kVp determines the x-ray beam quality (penetrability) which plays a role in subject contrast

❖The x-ray tube current (mA) determines the x-ray fluence rate (photons/cm2-sec) emitted by the x-ray tube at a given kVp

❖ mAs = mA · sec (exposure time) $\propto$ photons/cm2 (fluence)

c.f.: Bushberg, et al., The Essential Physics of Medical Imaging, 2nd ed., p. 98.

Radiological Quantities

Used to compare assessment of equipment performance etc.

TABLE 3-6. RADIOLOGICAL QUANTITIES, SYSTEM INTERNATIONAL (SI) UNITS, AND TRADITIONAL UNITS

Quantity	Description of Quantity	SI Units (Abbreviations) and Definitions	Traditional Units (Abbreviations) and Definitions	Symbol	Definitions and Conversion Factors
Exposure	Amount of ionization per mass of air due to x- and gamma rays	C kg^{-1}	Roentgen (R)	X	1R = 2.58×10^{-4} C kg^{-1} 1R = 8.708 mGy air kerma @ 30 kVp 1R = 8.767 mGy air kerma @ 60 kVp 1R = 8.883 mGy air kerma @ 100 kVp
Absorbed dose	Amount of energy imparted by radiation per mass	Gray (Gy) 1 Gy = J kg^{-1}	rad 1 rad = 0.01 J kg^{-1}	D	1 rad = 10 mGy 100 rad = 1 Gy
Kerma	Kinetic energy transferred to charged particles per unit mass	Gray (Gy) 1 Gy = J kg^{-1}	—	K	—
Air kerma	Kinetic energy transferred to charged particles per unit mass of air	Gray (Gy) 1 Gy = J kg^{-1}	—	K_{air}	1 mGy = 0.115 R @ 30 kVp 1 mGy = 0.114 R @ 60 kVp 1 mGy = 0.113 R @ 100 kVp

Used to calculate organ dose such as dose to uterus

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.59.

Used to compare rad. dose between different imaging procedures

Radiological Quantities

Imparted energy	Total radiation energy imparted to matter	Joule (J)	—	D_i	1 mGy ≅ 1.4 mGy (dose to skin) Dose (J kg^{-1}) × mass (kg) = J
Equivalent dose (defined by ICRP in 1990 to replace dose equivalent)	A measure of radiation specific biologic damage in humans	Sievert (Sv)	rem	H	$H = w_R D$ 1 rem = 10 mSv 100 rem = 1 Sv
Dose equivalent (defined by ICRP in 1977)	A measure of radiation specific biologic damage in humans	Sievert (Sv)	rem	H	$H = Q D$ 1 rem = 10 mSv 100 rem = 1 Sv
Effective dose (defined by ICRP in 1990 to replace effective dose equivalent)	A measure of radiation and organ system specific damage in humans	Sievert (Sv)	rem	E	$E = \Sigma_T w_T H_T$
Effective dose equivalent (defined by ICRP in 1977)	A measure of radiation and organ system specific damage in humans	Sievert (Sv)	rem	H_E	$H_E = \Sigma_T w_T H_T$
Activity	Amount of radioactive material expressed as the nuclear transformation rate.	Becquerel (Bq) (sec^{-1})	Curie (Ci)	A	1 Ci = 3.7 × 10^{10} Bq 37 kBq = 1 μCi 37 MBq = 1 mCi 37 GBq = 1 Ci

Used to compare risk of stochastic effects, compare different imaging proc.

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.59.

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Radiological Quantities

- Dose-Area Product (DAP)
  - DAP is the product of the entrance skin dose and cross-sectional area of the x-ray beam (exposed area)
  - If entrance skin dose is 0.1 mGy and the exposed area is 1000 cm^2, then DAP = 100 mGy-cm^2
  - Useful in providing relative risks to patients undergoing similar types of radiographic examinations
  - Difficult to use since exposed area difficult to always calculate

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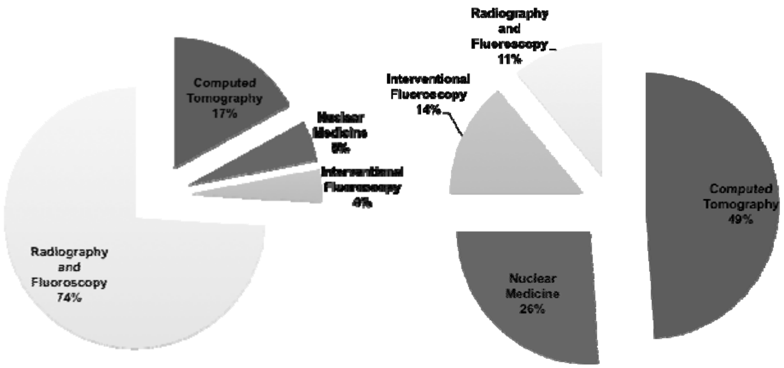
NCRP 160 (2009): Medical Exposure Procedures vs. Effective dose contributions



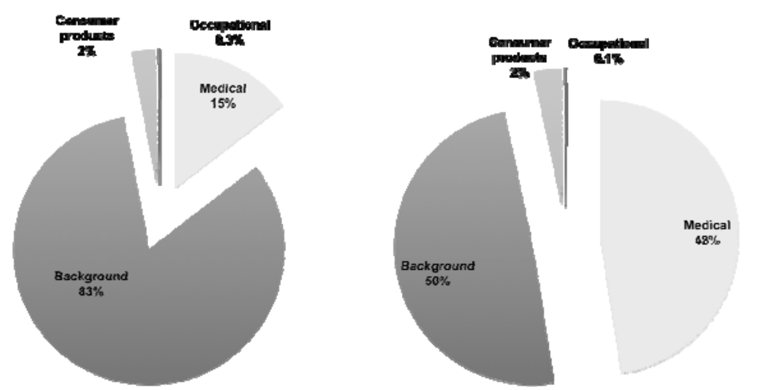
Percent Procedures **Effective Dose Contributions**

Effective dose per capita from medical radiation exposure is ~ 3.0 mSv

Kalpana M. Kanal, Ph.D., DABR *slide courtesy*: Dr M. Mahesh, Johns Hopkins

Radiation exposure to US population from all sources The new pie chart!

US 1982 (NCRP 93) **US 2006**



Medical 0.54 mSv per capita
Total 3.6 mSv per capita

Medical 3.0 mSv per capita
Total 6.2 mSv per capita

Kalpana M. Kanal, Ph.D., DABR *slide courtesy*: Dr M. Mahesh, Johns Hopkins

CT Dose Descriptors

TABLE 1. Radiation Dosimetry Parameters

Variable	Parameter	Physical Equivalent
Radiation exposure	$CTDI_{100}$	No. of ions produced in air by photons
Absorbed radiation dose	CTDI, $CTDI_w$, $CTDI_{vol}$, MSAD	Radiation energy absorbed by patient's body
Cumulative radiation dose	DLP	Total radiation energy absorbed by patient's body
Effective dose	E	Biological effect of radiation dose received

❖ $CTDI_{vol}$ is the approximate average radiation dose over x, y, and z axis of the patient

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$$DLP\ (mGycm) = CTDI_{vol} \times Scan\ length$$

❖ The Dose Length Product is an indicator of the integrated radiation dose of an entire CT examination

❖ It incorporates the number of scans and the scan width

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Morin RL, et al, Circulation 2003;107:917-22

❖A reasonable approximation of E can be obtained by multiplying DLP with a conversion factor, k● which varies dependent on body part imaged and age of patient

E = k * DLP

● *k factors available in AAPM report 96, 2008*

Effective Dose from DLP on console of CT scanner

- For chest, this factor is 0.014 for an adult patient
- For a cardiac protocol, if the DLP is 1000 mGycm, the effective dose can be calculated easily,
  - ✓ 1000 x 0.014 = 14 mSv
- Practical way to determine dose on the fly from the console or for comparison across protocols

● *k factors available in AAPM report 96, 2008*

Average Effective Dose (mSv) for Dx Rad Procedures

Adult Effective Doses for Various Diagnostic Radiology Procedures

Examination	Average Effective Dose (mSv)	Values Reported in Literature (mSv)
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
Hip	0.7	0.18–2.71

cf: Mettler et al. Radiology 2008, 248(1):254-263

Average Effective Dose (mSv) for CT Procedures

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	4.0–18.0
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

cf: Mettler et al. Radiology 2008, 248(1):254-263

Organ Dose

- Organ Doses (from Huda book)
  - 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
  - For AP projections, the embryo dose will be between 1/3rd and 1/4th the ESE (in the direct beam)
  - For PA projections, the embryo dose will be about 1/6th of the ESE (in the direct beam)
  - For LAT projection, the embryo dose will be about 1/20th of the ESE (in the direct beam)

Typical Absorbed and Effective doses

TABLE 24-3. ABSORBED DOSES TO SELECTED TISSUES AND EFFECTIVE DOSES FROM SEVERAL COMMON X-RAY EXAMINATIONS IN THE UNITED KINGDOM

	Active bone marrow		Breasts		Uterus (embryo, fetus)		Thyroid		Gonads[a]		Effective dose	
Examination	(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	*	*	0.1	10
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	*	*	1.0	100
Lumbar spine	1.4	140	0.07	7	3.5	350	*	*	4.3, 0.06	430, 6	2.1	210
Pelvis	0.2	20	*	*	1.7	170	*	*	1.2, 4.6	120, 460	1.1	110
CT pelvis	5.6	560	0.03	3	26	2600	*	*	23, 1.7	2300, 170	7.1	710
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	200	*	*	*	*	*	*	0.1	10

Note: *, less than 0.01 mGy (1 mrad); CT, computed tomography.
[a]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.

Stochastic and Non-Stochastic Effect

- 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

Stochastic Effect

- A stochastic effect is caused by damage to a cell that produces some genetic transformation but cells still capable of reproduction
  - cancer and hereditary effects of radiation
  - probability of a stochastic effect, instead of its severity increases with dose
  - No dose thresholds below which the effects cannot occur

Deterministic (Non-Stochastic) Effect

- Deterministic or non-stochastic effects
  - are believed to be caused by cell killing
  - effects include terratogenic effects to the embryo or fetus, skin damage and cataracts
  - a threshold can be defined below which the effect will not occur
  - for doses greater than the threshold dose, the severity of the effect increases with the dose
  - to assess the likelihood of a deterministic effect on an organ from an imaging procedure, the dose to that organ is estimated

Radiation Dose Occupational Limits

TABLE 23-18. NUCLEAR REGULATORY COMMISSION (NRC) REGULATORY REQUIREMENTS: MAXIMUM PERMISSIBLE DOSE EQUIVALENT LIMITS[a]

	Maximum permissible annual dose limits	
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]

[a]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).
[b]Applies 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).
[c]This 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).

- 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

Expressing Cancer Risk (BEIR VII Report)

- The BEIR VII report addresses the effects of low-dose ionizing radiation to humans
- This report provides the strongest scientific evidence to date regarding potential cancer risks as a result of ionizing radiation from medical imaging
- The BEIR VII lifetime risk model predicts that approximately 1 individual in 1000 would be expected to develop cancer when exposed to a dose of 10 mSv and
- 42 of 100 would be expected to develop solid cancer or leukemia from other causes
- This risk is proportional to dose

BEIR VII report can be obtained at http://www.nap.edu/catalog/11340.html

Effective Dose & Cancer Risk Comparison

Exam	Eff. Dose [mSv]	Additional* LAR of Cancer Incidence %	Equivalent no. of chest x-rays	Approx. period of background radiation
Chest PA & LAT	0.1	0.001	1	12 days
Pelvis	0.6	0.006	6	73 days
Abdomen	0.7	0.007	7	90 days
CT Chest	7	0.07	70	2.3 years
CT Abd or Pelvis	8	0.08	80	2.7 years

Typical Background Radiation ~ 3 mSv per year
***These risks are in addition to the female baseline lifetime risk (in the absence of exposure) of cancer incidence of 36.9% and of death from cancer of 17.5%**

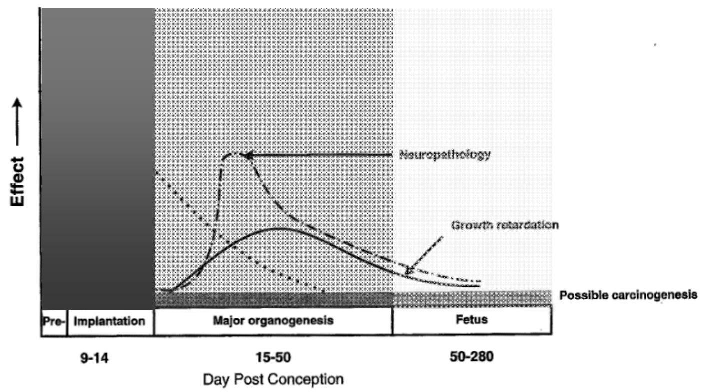
Radiation Dose and the Pregnant Patient?

- Gestational period divided into 3 stages:
  - Relatively short preimplantation stage (day 0-9)
  - Extended period of major organogenesis (day 9-56)
  - Fetal growth stage (day 45 to term)
- Preimplantation: conceptus extremely sensitive and radiation damage can result in prenatal death: “All-or-nothing response”

Radiation Dose and the Pregnant Patient?

- Animal experiments have demonstrated an increase in the spontaneous abortion rate after doses as low as 50 to 100 mGy (5 to 10 rad)
- Fetal doses generally are much less than 100 mGy in most diagnostic and nuclear medicine procedures and thought to carry negligible risk compared with the spontaneous incidence of congenital abnormalities (4%-6%)

Radiation Dose and the Pregnant Patient?



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 860.

Radiation Dose and the Pregnant Patient?

TABLE 25-13. PROBABILITY OF BIRTHING HEALTHY CHILDREN

Dose[a] to Conceptus (mSv [mrem])	Child with No Malformation (Percentage)	Child Will Not Develop Cancer (Percentage)	Child Will Not Develop Cancer or Have a Malformation (Percentage)
0 (0)	96	99.93	95.93
0.5 (50)	95.999	99.927	95.928
1.0 (100)	95.998	99.921	95.922
2.5 (250)	95.995	99.908	95.91
5.0 (500)	95.99	99.89	95.88
10.00 (1,000)	95.98	99.84	95.83

[a]Refers to absorbed dose above natural background. This table assumes conservative risk estimates, and it is possible that there is no added risk.
Source: From Wagner LK, Hayman LA. Pregnancy in women radiologists. *Radiology* 1982;145:559–562.

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 860.

Summary

- There is always a compromise between the image quality and the radiation exposure to the patient
- In the United States, with the exception of mammography, there are no regulatory limits to the amount of radiation received by the patient
- In fluoroscopy, the 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 radiation units and cancer risks