Radiation Units and Dosimetry

Kalpana Kanal, Ph.D., DABR
Associate Professor
Director of Resident Physics Education
Dept. of Radiology
UW Medicine

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

Introduction

- 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

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
  - 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
  - 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]

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]

[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

Radiological Quantities

Used to compare assessment of equipment performance etc.

Resource: http://www.sprawls.org/resources/RADQU/

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.

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

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

Examination	Active bone marrow		Breasts		Uterus (embryo, fetus)		Thyroid		Gonads[a]		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	*	*	0.1	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.

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%**

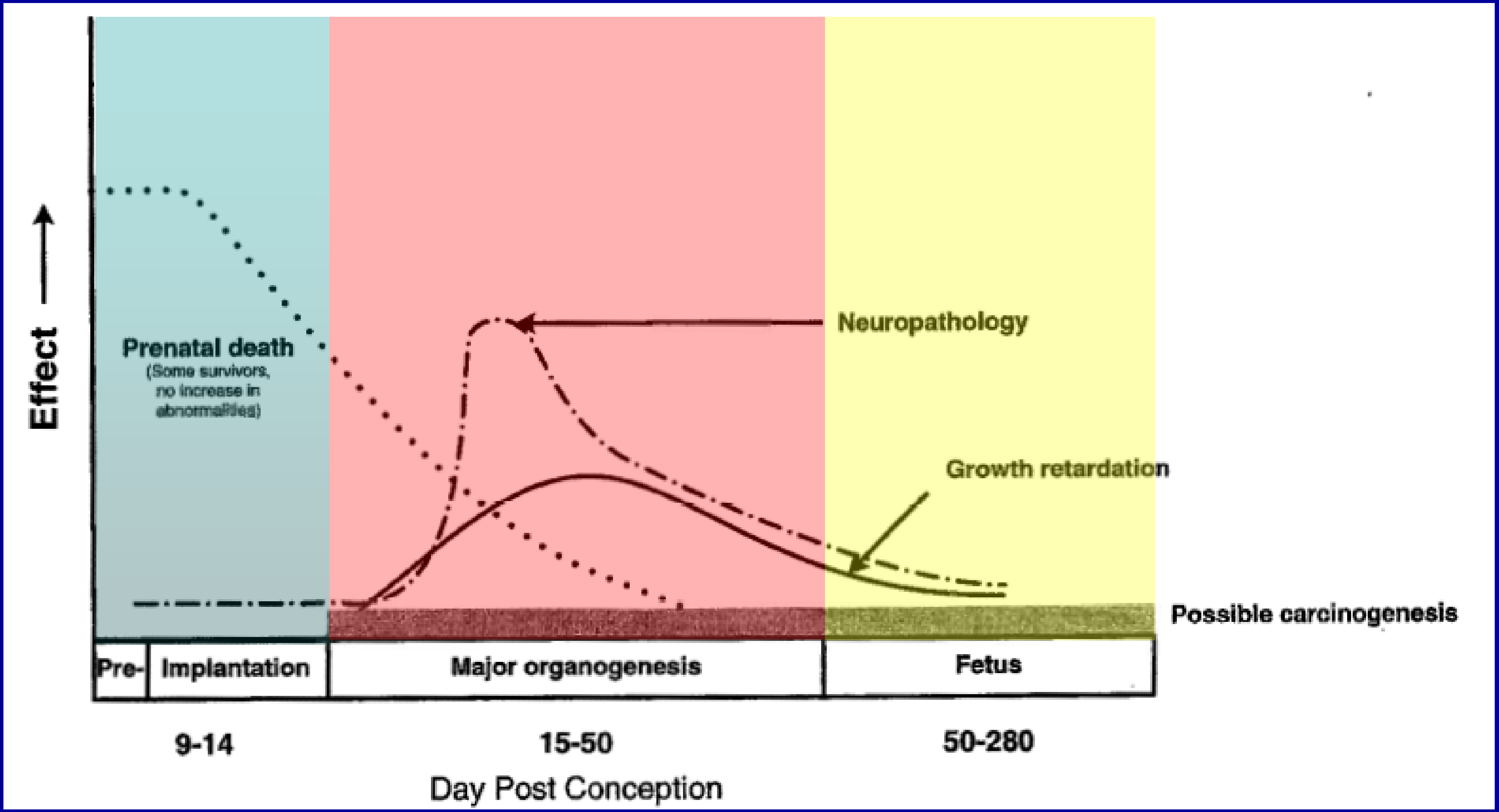
Radiation Dose and the Pregnant Patient?

- 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?

- 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.