X-Ray Interactions (1)

- X-ray interactions with matter via Rayleigh (classical or coherent) scattering, Compton scattering, Photoelectric effect, Pair production

- ***Compton***
  - Dominant interaction of x-rays with soft tissue in the Dx energy
  - Photon interacts with a “free” outer shell electron
  - Probability of Compton interaction proportional to material density (ρ)
- ***Photoelectric***
  - Interaction of incident photon, E_0 with inner shell electron
  - $E_e = E_0 – E_b$
  - Photon totally absorbed
  - Characteristic x-rays and/or auger electrons
  - Negative ion (photoelectron) and positive ion (atom)
  - Probability of photoelectric absorption $\propto Z^3/E^3$
  - Maximum subject contrast arises with a photoelectric effect interaction
  - Explains why contrast ↓ as higher energy x-rays are used in the imaging process
  - Increased probability of photoelectric absorption just above the E_b of the inner shells cause discontinuities in the attenuation profiles (e.g., K-edge)

X-Ray Interactions (2)

- ***Pair Production***
  - Not important in Dx radiology
  - Need at least 1.02 MeV incident energy for interaction, produces two 511 keV photons

- ***Attenuation*** - removal of photons from a beam of x- or gamma rays as it passes through matter
- ***Linear Attenuation Coefficient (μ)***
  - *Fraction of photons removed from a monoenergetic beam of x- and gamma rays per unit thickness of material* (cm^{-1})
  - $N = N_0 e^{-\mu \cdot x}$
  - Energy dependent, $\mu(E)$ ↓ as E ↑
- The linear attenuation coefficient, normalized to unit density is called the ***mass attenuation coefficient***
- ***Half value layer (HVL)*** - Thickness of material required to reduce the intensity of the incident beam by ½
  - $½ = e^{-\mu(E) \cdot HVL}$ or $HVL = 0.693/\mu(E)$
  - Reduction in beam intensity can be expressed as $(½)^n$

Radiation Units (1)

- ***Fluence*** *(Φ)* [cm^{-2}] – # photons per area (i.e. total # photons directed at a target)
  - ***Energy fluence (Ψ)*** [J per m^2] = fluence · energy = $\Phi \cdot E$
- ***Flux*** [$cm^{-2} \cdot sec^{-1}$] – # photons per area per time = fluence per unit time (e.g. useful in describing quantity of photons in fluoroscopy)
- ***Exposure*** [R]
  - Measurement that describes an x-ray machine output intensity
  - Only a measure of photon intensity IN AIR
  - Formal definition: the amount of electrical charge (ΔQ) produced by ionizing radiation per mass of air (Δm) [C per kg]
  - Traditional units: Roentgen (R) = 2.58×10^{-4} C/kg (note: R is still a commonly used unit)
- ***Kerma (K)*** [J/kg = Gray (Gy)] – fraction of *photons* absorbed
  - only defined for *indirect radiation* absorbed (i.e. photons absorbed in matter, does not account for direct radiation interactions)
  - μ_{tr} = mass energy transfer coefficient
  - Formal definition: the kinetic energy transferred to charged particles by indirectly ionizing radiation per mass matter.

$$\Psi \cdot \left(\mu_{tr} / \rho_o \right)$$

- ***Absorbed Dose*** [J/kg = Gray (Gy)] – fraction of radiation (*direct or indirect*) absorbed
  - defined for *all radiation types*
  - μ_{en} = mass energy absorption coefficient
  - Formal definition: the amount of energy (ΔE) deposited by ionizing radiation per unit mass (Δm) [J/kg] (note: traditional unit is rad; where 100 rad = 1 Gy)

$$\Psi \cdot \left(\mu_{en} / \rho_o \right)$$

Radiation Units (2)

$$\mu_{tr} / \rho_o \geq \mu_{en} / \rho_o$$

- Comparing Kerma to Absorbed Dose
  - Energetic electrons may subsequently produce bremsstrahlung radiation
    - If energy imparted is deposited locally and the bremsstrahlung losses are negligible, then absorbed dose = kerma
    - If the bremsstrahlung radiation escapes the volume of interest, then dose is less than kerma
- ***Imparted Energy*** [J]– total amount energy deposited in a mass
  - Imparted Energy [J] = dose [Gy = J/kg] · mass [kg]
- ***Equivalent Dose*** (H) [Sv = 100 rem] – accounts for different types of radiation
  - ‘High LET’ radiation (e.g., alpha particles, protons) are much more damaging than ‘low LET’ radiation (e.g. electrons and ionizing radiation such as x-rays and gamma rays)
  - Different radiation weighting factors (w_R) – established by ICRP in publication 60
  - Traditional unit – rem (acronym for Roentgen equivalent man)
- ***Effective Dose*** (E) [Sv] – accounts for different tissue sensitivities
  - Different tissue weighting factors (w_T) – established by ICRP in publication 60 (1991) & 103

$$E = \sum w_T \cdot H_T$$

Radiation Units (3)

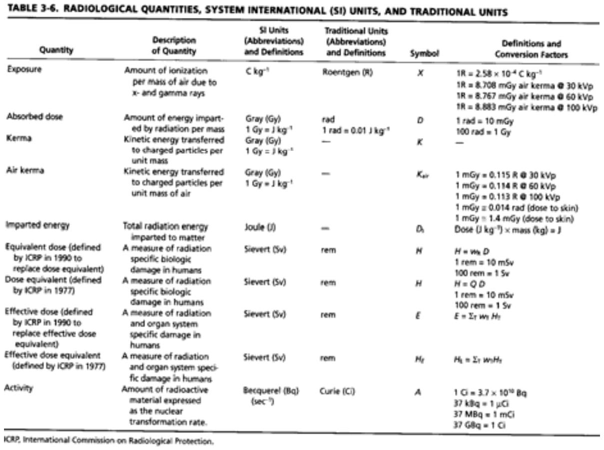


TABLE 3-6. RADIOLOGICAL QUANTITIES, SYSTEM INTERNATIONAL (SI) UNITS, AND TRADITIONAL UNITS

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 1 mGy ≅ 0.014 rad (dose to skin) 1 mGy ≅ 1.4 mGy (dose to skin)
Imparted energy	Total radiation energy imparted to matter	Joule (J)	—	D_i	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

ICRP, International Commission on Radiological Protection.

X-ray Production, Tubes, & Generators

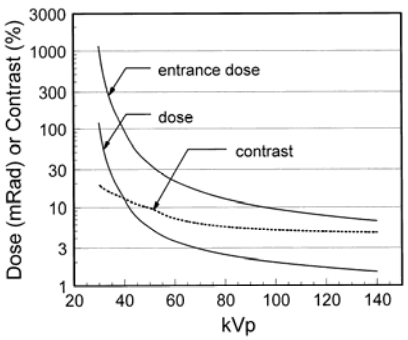
- ***X-ray Production***
  - Electron interactions with target
    - 99% heat production – angled, rotating anode; oil bath and bellows
    - ~1% x-ray production: bremsstrahlung (coulomb interactions, continuous energy spectrum) and characteristic x-rays (electron collisions w/orbital electrons, discrete energies determined by the target material)
    - X-ray spectrum: kVp determines max x-ray energy (E_{max}) ; average energy (E_{Avg}) is ~1/3 to 1/2 E_{max}; natural (insert window) and added filtration
- ***X-ray Tubes***
  - Components: cathode (electron source), anode (target; usually tungsten [W], Molybdenum [Mo], or Rhodium [Rh]), tube insert (evacuated path), generator (external kilo voltage energy source to accelerate electrons)
  - Focal spot (FS) size: typical sizes are 0.6 mm and 1.2 mm (power loading); smaller FS improved spatial resolution
    - Focusing cup – determines FS width
    - Filament length – determines FS length; anode angle affects FS length, power loading, and field coverage; anode angle also cause heel effect
- ***X-ray Generators***
  - Multi-phase input power supply (constant input voltage) or constant-potential generators; transformers (ramp V to kV using EM induction); rectifier circuits (utilize both positive/negative of alternating current)

Screen-Film Radiography (1)

- ***Magnification (M)*** = I/O = SID/SOD
- ***Penumbra or blur (f)***
  - edge gradient blurring due to finite size of focal spot (F)
  - f = F(M-1)
  - f or blur increases with F and M
- ***Inverse Square law:*** $I_2 = I_1 \cdot \left(\frac{D_1}{D_2}\right)^2$
- Film Emulsion: silver halide (AgBr and AgI)
- ***Optical density (OD)*** = $-\log_{10}(T) = \log_{10}(1/T) = \log_{10}(I_0/I)$, inverse relationship is $T = 10^{-OD}$
  - As OD increases, transmittance decreases
  - The OD of superimposed films is additive
- ***H&D (characteristic) curve*** describes how film responds to x-ray exposure

Screen-Film Radiography (2)

- As the speed of SF system increases, the amount of x-ray exposure required to achieve same OD decreases
- ***Latitude*** is the range of x-ray exposures that deliver ODs in the usable range
- kVp as a function of dose and contrast



Screen-Film Radiography (3)

- ***Scatter radiation***
  - Scattered photons are the result of Compton interactions within the body
  - Scatter radiation causes loss of contrast
  - As FOV is reduced, scatter is reduced
  - Larger patients create more scatter
  - The antiscatter grid is used to clean up scatter
    - ↑ GR → ↓ S/P and↑ GR → ↑ dose
  - Air gap can also be used to clean up scatter (e.g. mammography)

- ***Bucky factor*** is the ratio of dose with a grid to the dose without the grid
  - Range from 2 to 3

$$\frac{Dose_{w/\,grid}}{Dose_{w/\,out\,grid}}$$

Digital Radiography

- Computed Radiography and Direct or Indirect Digital Radiography systems
- Wide dynamic range (synonymous with S/F latitude) – a wider range of x-ray exposures are acceptable than S/F
- CR – photostimulable phosphor systems
- DR – indirect CCD or TFT systems
- DR – direct - Selenium systems
- ***Benefits of CR***
  - Same exam process and equipment as screen-film radiography
  - Many exam rooms serviced by one reader, lower initial cost
- ***Benefits of DR***
  - Throughput ↑: radiographs available immediately for QC & read
  - Reduced radiation dose: 2-3x compared with CR
  - Greater spatial resolution possible
- Image processing plays an important role in digital radiography

Image Properties (1)

- Imaging technique affects both image quality and radiation dose
  - ***kVp*** (penetrability) – increasing the penetrating power (to account for patient thicknesses, bone vs tissue vs air in lungs, etc), decreases contrast; exposure is proportional to the kVp^2
  - ***mAs*** is the tube current (which is influenced by filament current, mA is usually 5-10x less than the filament current) and exposure time –exposure increases linearly with mAs, improves SNR because less image noise
  - Also affected by focal spot size, automatic exposure control (AEC, gen rad or fluoro) or automatic tube current modulation (CT), and collimation
- Factors affecting X-ray emission: ***quantity*** (proportional to Z_{target}* kVp^2 * mAs) and ***quality*** (determined by kVp, generator waveform, and tube filtration)
  - Electrons have higher probability of radiative interactions w/higher Z-material targets
  - Tube voltage determines maximum energy in bremsstrahlung spectrum & affects the quality of the output spectrum
  - Beam filtration modifies the quantity and quality of the spectrum by selectively removing low-energy photons

$$kVp_1^5 \cdot mAs_1 = kVp_2^5 \cdot mAs_2$$

  - Exposure is proportional to kVp^2; the exposure for a given kVp and filtration is directly proportional to the mAs
  - HOWEVER, adjustments in the kVp affect the attenuation characteristics of the x-rays as they traverse the patient, so the mAs varies with the fifth power of the kVp!

Image Properties (2)

- ***Contrast*** – result of image acquisition, processing, and display
  - ***Subject contrast*** – difference between two adjacent objects BEFORE the signal is recorded; different interactions b/w type of energy used in the modality (x-ray, MR signal) and the patient's anatomy/physiology); contrast agents include air, barium, and iodine
  - ***Detector contrast*** – detector characteristics affect the small changes of input energy striking the detector, resulting in the final image (contrast is either amplified or washed out); depends on detector efficiency, processing, & display
    - Screen-film contrast = $OD_A – OD_B$ (optical density)
    - Digital systems – better described by contrast-to-noise ratio (CNR) = (A-B)/σ
- ***Contrast resolution (LCR)*** – decreasing the noise improves LCR; LCR is related to SNR and is affected by structural noise (e.g. normal anatomy)
- ***Contrast-detail curves*** – DQE(f) is a good quantitative method of measuring spatial resolution (MTF(f)) and contrast resolution (SNR), C-D curves are a qualitative method measure of the same concepts

Image Properties (3)

- ***Spatial resolution (HCR)*** – LSF/PSF/ESF, FWHM, blurring (result of detector blur, motion, or tomographic partial volume averaging), image magnification (geometry), matrix size, field of view (FOV)
- ***To improve spatial resolution*** – increase matrix, decrease FOV, decrease slice thickness (tomographic imaging), decrease motion artifact (including sample rate for temporal imaging), decrease air gap (obj-to-detector distance), use smaller focal spot
- ***To improve contrast*** – decrease kVp, increase mAs (which decreases quantum noise)
- ***Image representations***
  - Spatial domain: Fourier transform of the LSF (x) = MTF(f)
  - Frequency domain: line pairs per mm, modulation transfer function as a function of frequency (***MTF(f)***) and describes how well the system processes signal
  - Temporal domain: ultrasound, cardiac imaging, digital subtraction angio (DSA)
- ***Nyquist criterion***: signal needs to be sampled such that each cycle is sample at least twice; under sampling results in aliasing, oversampling results in time loss (i.e. sampling in MRI is a time consuming process)

$$lp/mm = \frac{1}{2\Delta}$$
$$\text{where } \Delta = \text{object size}$$

Image Properties (4)

- ***Noise*** – random (stochastic) component in the image
  - ***Quantum noise*** (countable, discrete measures): Poisson statistics; as the signal (N) increases, the noise (σ) also increases but at a slower rate therefore the relative noise (described by the coefficient of variation = COV) decreases with increasing signal
  - ***Electronic noise***
  - ***Structured noise***: appears to be random, but has non-random components (high frequency, low amplitude component); frequency analysis of an image; noise power spectrum (***NSF(f)***) describes how well the system processes noise
- ***Signal-to-noise ratio (SNR)***: if the signal is doubled, the dose will also double, but the SNR (or the image quality) only increases by sqrt(2)
- ***Quantum Detector Efficiency (QDE)***: in the real world, not all the incident photons to a detector are absorbed and counted as signal (SNR_{meas} = sqrt (QDE * $N_{incident}$)
- ***Detector Quantum Efficiency (DQE) or detection efficiency***: describes the SNR performance of the system; descriptor for dose efficiency; only measure that considers both noise and signal simultaneously

Radiation Biology (1)

- Biologic effects of radiation exposure can be classified as either stochastic or deterministic (non-stochastic)
- ***Stochastic Effect***
  - The probability of the effect, rather than its severity, ↑ with dose
  - Radiation-induced cancer and genetic effects
  - Basic assumption: risk ↑ with dose and no threshold
- ***Deterministic or Non-stochastic Effect***
  - Severity of the effect, rather than its probability, ↑ with dose
  - Threshold dose below which the effect is not seen
  - Cataracts, erythyma, fibrosis, and hematopoietic damage are some deterministic effects
- Interactions producing biologic changes classified as either direct or indirect

Radiation Biology (2)

- Vast majority of interactions are indirect
- Free radicals are primary cause of biologic damage
- ***Linear Energy Transfer (LET)***
  - Amount of energy deposited per unit length (eV/cm)
  - LET $\propto Q^2/KE$
  - High LET >> damaging than low LET radiation
- ***Relative Biological Effectiveness (RBE)***
  - Compare dose required to produce the same specific biologic response as a reference radiation dose (typically 250 kVp x-rays):
- Target theory
  - Considerable evidence that damage to DNA is the primary cause of radiation-induced cell death
- Cellular inability to form colonies as a function of radiation exposure → ***cell survival curves***
- Three parameters defining response to radiation: n, D_q and D_o

Radiation Biology (3)

- ***Radiosensitivity*** greatest for cells with: High mitotic rate, Long mitotic future and Undifferentiated cells
  - Cells most sensitive to radiation during mitosis (M phase) and RNA synthesis (G2 phase)
  - Least sensitive during DNA synthesis (S phase)

- Skin erythema dose threshold 2 Gy

- The most conservative approach for radiation protection and risk analysis is to use the ***linear no-threshold* model**
- Latency periods: Leukemia 5-15 average and Solid tumors 10-60 yrs average
- Relative risk and absolute risk models
- On average, the BEIR VII lifetime risk model predicts that approximately **1 person in 100 would be expected to develop cancer from a dose of 0.1 Sv above background**, while approximately 42 of the 100 individuals would be expected to develop solid cancer or leukemia from other causes

Radiation Biology (4)

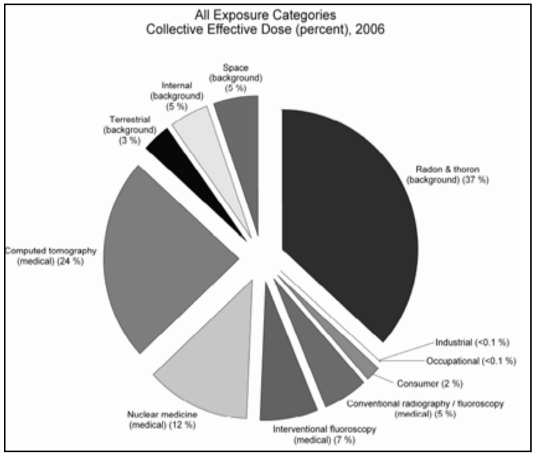
- Fetal doses generally << 100 mGy for most diagnostic and nuclear medicine procedures and thought to carry negligible risk compared with the spontaneous incidence of congenital abnormalities (4%-6%)
- Fetal dose estimates for a singlepass abdominal and pelvic acquisition are below the consensus levels for negligible risk (50–150 mGy) and well below the actionable level of 150 mGy.

Menstrual or Gestational age	Conception age	<0.05 Gy	0.05-0.1 Gy	>0.1 Gy
0 - 2 weeks	Prior to conception	None	None	None
3rd and 4th weeks	1st - 2nd weeks	None	Probably none	Possible spontaneous abortion.
5th - 10th weeks	3rd - 8th weeks	None	Potential effects are scientifically uncertain and probably too subtle to be clinically detectable.	Possible malformations increasing in likelihood as dose increases.
11th - 17th weeks	9th - 15th weeks	None	Potential effects are scientifically uncertain and probably too subtle to be clinically detectable.	Increased risk of deficits in IQ or mental retardation that increase in frequency and severity with increasing dose.
18th - 27th weeks	16th - 25th weeks	None	None	IQ deficits not detectable at diagnostic doses.
>27 weeks	>25 weeks	None	None	None applicable to diagnostic medicine.

*Taken from "ACR Practice Guideline for Imaging Pregnant of Potentially Pregnant Adolescents and Women with Ionizing Radiation", derived from ICRP Publications 84 (2001) and 90 (2004).

Sources of Exposure to Ionizing Radiation

NCRP Report 160 (published in 2009)



Radiation Protection (1)

Bushberg Table 23-18. Nuclear Regulatory Commission (NRC) Regulatory Requirements: Maximum Permissible Dose Equivalent Limits[a]

Limits	Maximum Possible Annual Dose Limit mSv	Maximum Possible Annual Dose Limit rem
Occupational Limits		
Total effective dose equivalent (ED)	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 limit	10% of adult limit
Dose to an embryo/fetus[b]	5 in 9 months	0.5 in 9 months
Non-occupational (Public) Limits		
Individual members of the public	1.0 per yr	0.1 per yr
Unrestricted area	0.02 in any 1 hr[c]	0.002 in any 1 hr[c]

Radiation Protection (2)

- As low as reasonably achievable (ALARA)
- ***<u>Exposure control: time, distance, shielding</u>***
- Shielding: primary barrier or secondary (leakage and scatter radiation) barriers
  - NRPB report 147 *Structural Shielding Design for Medical X-ray Imaging Facitilies*
    - ***Workload*** (W) – total mGy per week (or mA-min per week for fluoro)
    - ***Distance*** (d) – from focal spot to wall of interest (inverse square)
    - ***Use factor*** (U) – fraction of time the radiation workload (W) is directed at a particular barrier; note: secondary barriers have U = 1 ALWAYS
    - ***Occupancy factor*** (T) – fraction of time during the week an individual occupies the room of interest adjacent to the x-ray room
  - ***Design goals: <0.02 mSv per week for areas accessible to the public (non-occupational exposure); <0.1 mSv per week for controlled areas (rad workers only)***
    - Typical mammo – gypsum wallboard;
    - Typical gen rad/fluoro – 1/32”-1/16” lead;
    - Typical CT – walls 1/16”-1/8” lead, floor/ceiling standard thickness concrete w/lead as needed

Radiation Dosimetry

- Comparing entrance skin exposure (ESE) for assessment of equipment performance
- ***Entrance skin dose (ESD)*** – multiplying ESE by backscatter factor, mean energy absorption coefficient, inverse square correction (if necessary), table attenuation factor
- Radiation dose quantities can be used to estimate biologic risk to the patient
  - ***Deterministic*** – threshold dose, severity increases w/dose; examples: teratogenic effects to embryo/fetus, skin damage, cataracts
  - ***Stochastic*** – cell damage causes genetic transformation; no threshold dose, probability of effect increase with dose; examples: cancer and hereditary effects
- In the US, there is no regulatory limit to the amount of radiation received by a patient for a diagnostic procedure
  - Exception – mammography MQSA regulated glandular breast dose
- Dose metrics:
  - General radiography – DR is exposure index (EI); CR is S-number (fuji)
  - Fluoroscopy – dose-area product (DAP) or air kerma (AK)
  - Computed tomography (CT) – dose-length product (DLP)
- ***BEIR VII*** estimates increased incidence/mortality in cancer to adults
- ***BERT*** = background equivalent radiation time (relative to annual background exposure)