Introduction to Medical Imaging

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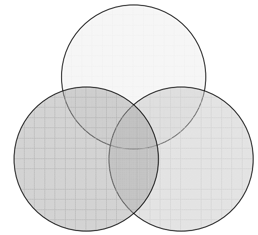
a copy of this lecture may be found at:
http://depts.washington.edu/diagphys/

PATIENT CARE IN RADIOLOGY

CLINICAL



PHYSICS BIOLOGY

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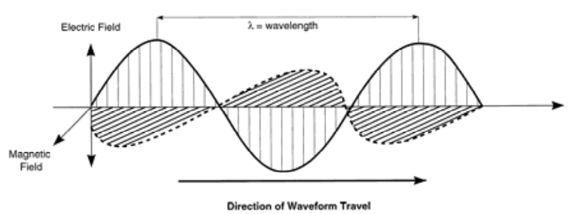
Introduction to Medical Imaging

- Radiation is energy that travels through space or matter
- Two types of radiation used in Dx Imaging: electromagnetic (EM) and particulate
- ĒM radiation - combination of an electric (Ē) and magnetic (M) field, both of which vary sinusoidally as a function of space and time
- Wave characteristics – c [m/sec] = λ [m] · ν [1/sec]
  - As c is essentially constant, then $\nu \leftarrow 1/\lambda$ (inversely proportional)



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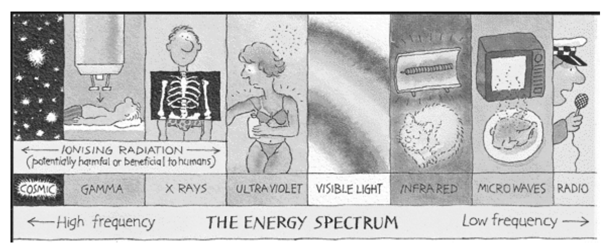
Introduction to Medical Imaging

- Physical manifestations are classified in the ĒM spectrum based on energy (E) and wavelength (λ) and comprise the following general categories:



Ionizing radiation (UV, x-rays, gamma rays)

Non-ionizing radiation (MRI, Ultrasound)

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Introduction to Medical Imaging

- Except for nuclear medicine, the EM radiation required also interacts (via absorption, scatter) with tissues it penetrates
- In NM, radioactive agents are injected or ingested, and the metabolic or physiologic interactions of the agent give rise to the information in the images

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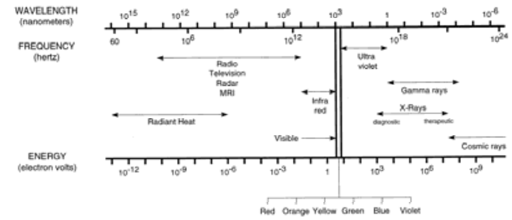
Particulate Radiation

- When interacting with matter, EM radiation can exhibit particle-like behavior with bundles of energy known as photons, $E=h\nu = hc/\lambda$
- $E = 1.24/\lambda$
- The most significant particulate radiations of interest are:
- Alpha particles, Electron, Positron, Negatrons, Protons, Neutrons



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The Modalities

- Different types of medical images can be made by varying the types of energies used and the acquisition technology
- The different modes of making images are referred to as modalities

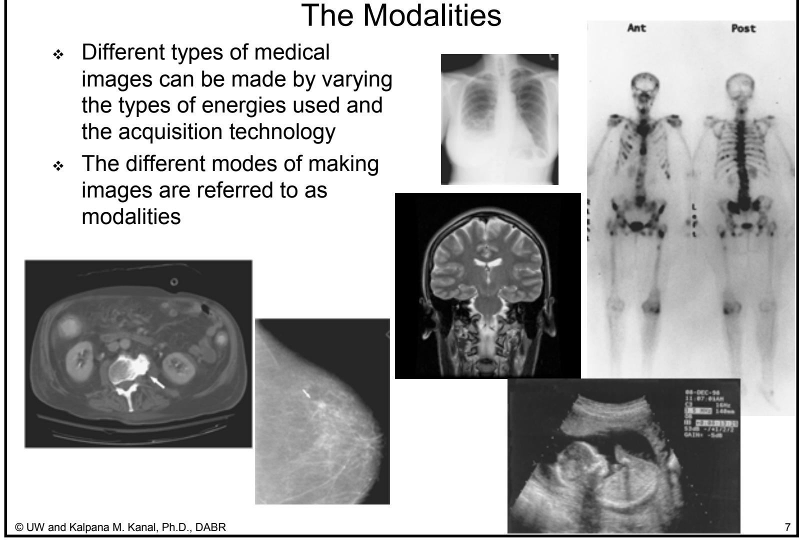

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Image Properties

- EM radiation must interact with the body's tissues in some differential manner to provide *contrast*
- The diagnostic utility of a medical image relates to both technical *image quality* and acquisition conditions
- Image quality requires many trade-offs
  - Patient safety – levels of radiation utilized or DOSE (ALARA)
  - Spatial resolution
  - Contrast resolution
  - Detail (Blur)
  - Noise properties
  - Artifacts

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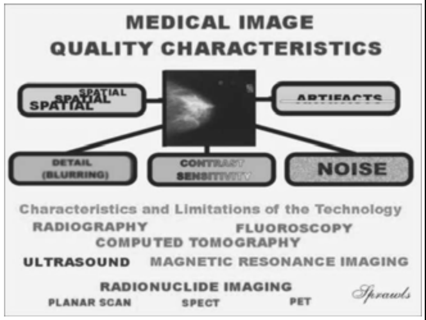
Image Properties



c.f. http://www.sprawls.org/resources/IMGCHAR/module/#1

Patient Safety - ALARA Principle

- As Low As Reasonably Achievable
  - Dose should be kept ALARA
  - The ALARA doctrine is the driving force for many of the policies, procedures and practices
- An optimized clinical protocol for a specific modality produces a balance among the image characteristics (for example, blurring and noise) and uses the radiation dose that is necessary to produce the required image quality

Spatial Resolution

- Spatial resolution is a property that describes the ability of an imaging system to accurately depict objects in the two spatial dimensions of the image (x,y)
- Classic notion: ability of an imaging system to distinctly depict objects as they become smaller and closer together (resolve fine detail)
- Each modality has different abilities to resolve fine detail in the patient

Spatial Resolution – What are the limits?

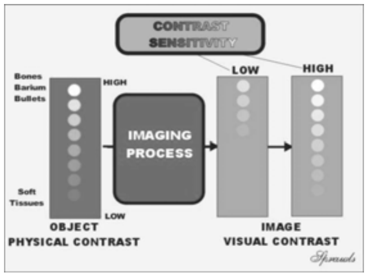
TABLE 1-1. THE LIMITING SPATIAL RESOLUTIONS OF VARIOUS MEDICAL IMAGING MODALITIES: THE RESOLUTION LEVELS ACHIEVED IN *TYPICAL* CLINICAL USAGE OF THE MODALITY

Modality	Δ (mm)	Comments
Screen film radiography	0.08	Limited by focal spot and detector resolution
Digital radiography	0.17	Limited by size of detector elements
Fluoroscopy	0.125	Limited by detector and focal spot
Screen film mammography	0.03	Highest resolution modality in radiology
Digital mammography	0.05–0.10	Limited by size of detector elements
Computed tomography	0.4	About ½-mm pixels
Nuclear medicine planar imaging	7	Spatial resolution degrades substantially with distance from detector
Single photon emission computed tomography	7	Spatial resolution worst toward the center of cross-sectional image slice
Positron emission tomography	5	Better spatial resolution than with the other nuclear imaging modalities
Magnetic resonance imaging	1.0	Resolution can improve at higher magnetic fields
Ultrasound imaging (5 MHz)	0.3	Limited by wavelength of sound

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 15.

Contrast

- Radiation must interact with the body's tissues in some *differential* manner to provide *contrast*
- Contrast in an image is the difference in the gray scale of the image



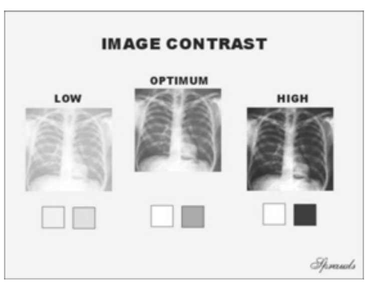
c.f. http://www.sprawls.org/resources/IMGCHAR/classroom.htm

Contrast – What does it depend on?

- X-ray/CT: differences in e^- density ($e^-/cm^3 = \rho \cdot e^-/gr$)
- Ultrasound: differences in acoustic impedance ($Z = \rho \cdot c$)
- MRI: proton density and relaxation phenomena
- NM: tissue's ability to concentrate the radioactive materials
- Contrast agents exaggerate natural contrast levels
  - Iodinated (x-ray/CT)
  - Paramagnetic (MRI)
  - Microspheres (US)

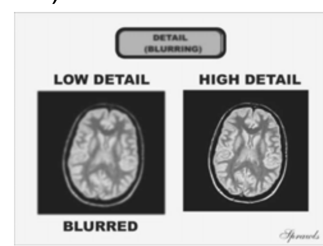
Contrast Resolution

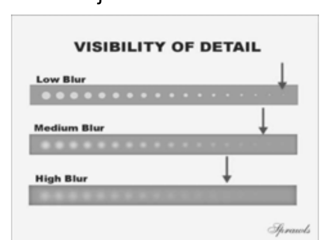
- The ability to visualize low-contrast objects in the image is the essence of contrast resolution
- Better contrast resolution implies that more subtle objects can be routinely seen on the image

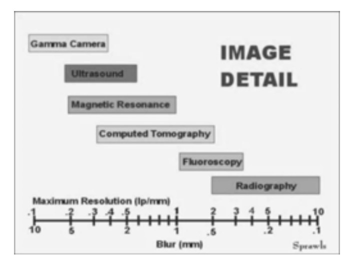


Detail (blur)

- Different mechanisms in radiologic imaging cause blurring (different principles and methods of image formation and the design characteristics of the equipment, patient motion etc.)
- Blurring reduces the visibility of small objects and detail



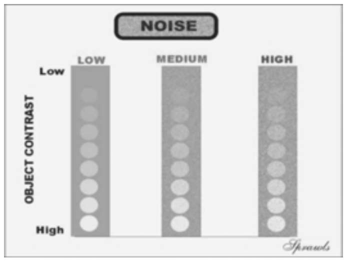


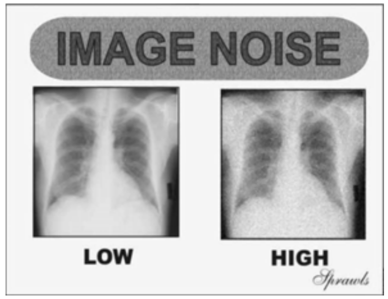


c.f. http://www.sprawls.org/resources/IMGCHAR/module/#20

Image Noise

- Noise (electronic noise, quantum noise etc.) is an undesirable image characteristic that reduces the visibility of certain objects and structures





 c.f. http://www.sprawls.org/resources/IMGCHAR/module/#20 17

Image Noise – Quantum Noise

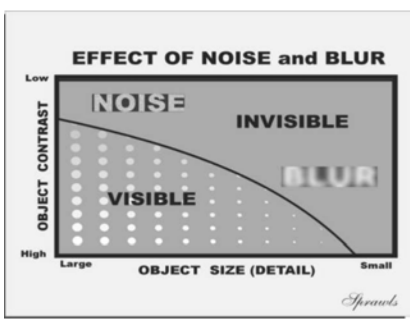
- Noise as perceived by a human observer in an image is the relative noise
- As number of photons or x-rays increase, relative noise decreases, signal to noise ratio (SNR) increases improving image quality

Photons/Pixel (N)		Noise (σ) ($\sigma = \sqrt{N}$)	Relative Noise (σ/N) (%)	SNR (N/σ)
10	Increasing dose ↓	3.2	32	3.2
100		10	10	10
1,000		31.6	3.2	32
10,000		100	1.0	100
100,000		316.2	0.3	316

 c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 278. 18

Effect of Noise and Blur

- Noise reduces visibility of low-contrast objects
- Blur reduces visibility of small objects
- Typically, most small anatomic objects also have low contrast and their visibility is reduced by both blur and noise



 c.f. http://www.sprawls.org/resources/IMGCHAR/module/#20 19

Artifacts

- **Artifacts** are misrepresentations of tissue structures seen in medical images
- These artifacts are caused by a variety of mechanisms, such as:
  - The underlying physics of the energy-tissue interaction (i.e.: Ultrasound-air)
  - Data acquisition errors (mostly from patient motion)
  - A reconstruction algorithm's inability to represent the anatomy
- Physicians learn to recognize these artifacts to avoid confusing them with real pathology

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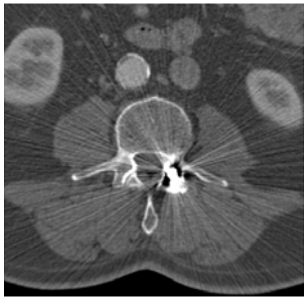
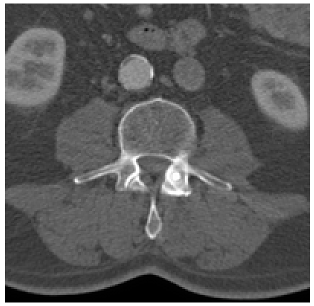
Artifacts

(a) **(b)**





CT images of a patient with metal spine implants, reconstructed without any correction **(a)** and with metal artifact reduction **(b)**

RadioGraphics 2004;24:1679-1691

Radiation Units

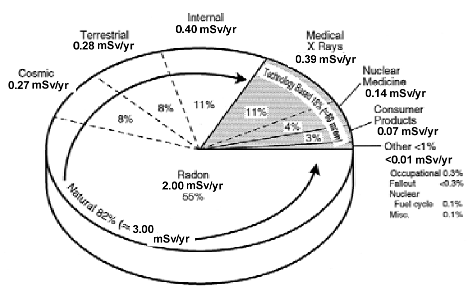
TABLE 3-6. RADIOLOGICAL QUANTITIES, SYSTEM INTERNATIONAL (SI) UNITS, AND TRADITIONAL UNITS

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

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

Sources of Exposure to Ionizing Radiation

- Annual average total effective dose from exposure to ionizing radiation in USA is approximately 3.6 mSv (National Council on Radiation Protection and Measurement - NCRP)



TOTAL ≈ 3.60 mSv/yr

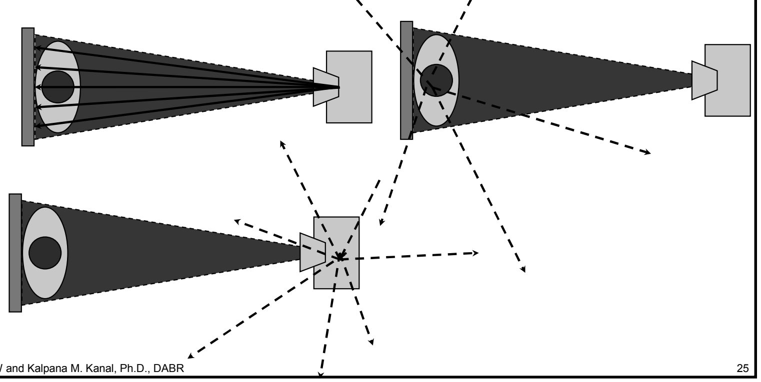
c.f. Bushberg, et al. The Essential Physics of Medical Imaging 2nd ed.

Radiation Protection and Exposure Control

- There are three principal methods by which radiation exposures to persons can be minimized: time, distance, shielding
- Time
  - reducing time spend near a radiation source
- Distance
  - inverse square law
  - For diagnostic x-rays, a good rule of thumb is that at 1 m from a patient at 90 degrees to the incident beam, the radiation intensity is 0.1% of the intensity of the beam incident upon the patient

Radiation Protection and Exposure Control

- Shielding is used to reduce exposure to patients, staff and the public
- Shielding against primary (focal spot), scattered (patient) and leakage radiation



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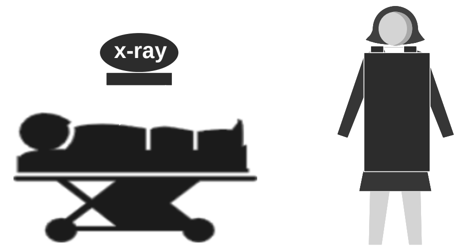

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Dose Limits

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).

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 791.

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Typical Patient 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 (mGy)	(mrad)	Breasts (mGy)	(mrad)	Uterus (embryo, fetus) (mGy)	(mrad)	Thyroid (mGy)	(mrad)	Gonads[a] (mGy)	(mrad)	Effective dose (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.

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Effective Dose Comparison with Chest PA Exam

Procedures	Eff. Dose [mSv]	Equivalent no. of chest x-rays	Approx. period of background radiation
Chest PA	0.02	1	3 days
Pelvis	0.7	35	4 months
Abdomen	1.0	50	6 months
CT Chest	8	400	3.6 years
CT Abdomen or Pelvis	10-20	500	4.5 years

Typical Background Radiation - 3 mSv per year

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Organ Doses in CT

- Head CT
  - ✓ Thyroid - 1.9 mGy
  - ✓ Eye lens - 40 mGy
- Chest CT
  - ✓ Breast - 21 mGy
- Abdomen CT
  - ✓ Uterus – 8 mGy
  - ✓ Gonads - 8 mGy
- Pelvis CT
  - ✓ Uterus – 26 mGy
  - ✓ Gonads - 23 mGy
- Patient skin doses are typically between 20 (body) and 40 mGy (head) or 2 to 4 rad
- Induction of erythema is typically 2 Gy

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Summary

- In diagnostic radiology, the electromagnetic spectrum outside the visible light region is used for almost all x-ray imaging except ultrasound where sound waves are used and MRI where radio waves are used
- Image quality requires many trade-offs
  - Spatial resolution ,Contrast resolution, Detail (Blur), Noise properties, Artifacts
- Radiation Protection and ALARA very important
- Radiation Dose for different modalities
- CT and fluoroscopy are high dose modalities

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