GET1024 / GEC1036 Lecture 15

Applications of Radiation – Medical Imaging

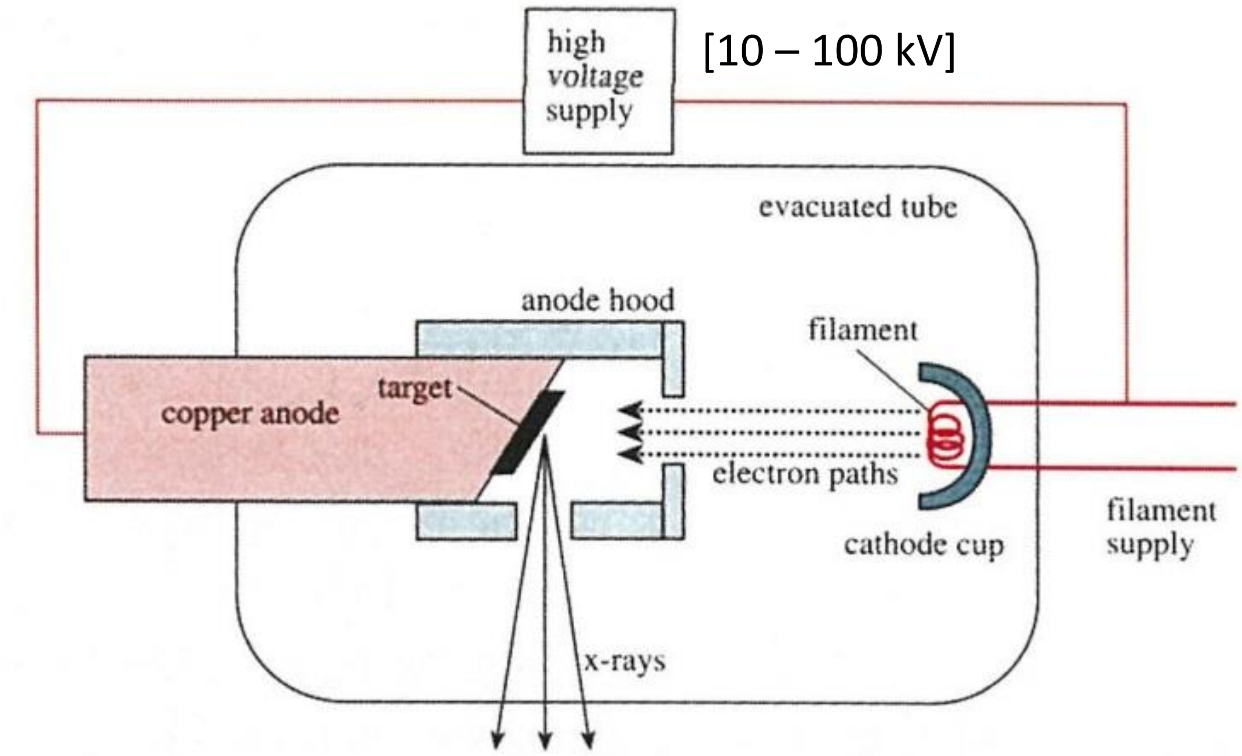
- X-Ray
  - Principle & Spectra
  - Interaction with Matter
  - Attenuation
  - Contrast & Improvement
- Computed Tomography
  - Typical Doses
- Radioactive Tracers
- Gamma Camera, SPECT & PET

Different Modes of Medical Imaging

- Medical imaging usually refers to techniques to present the interior of a body for the purpose of diagnosis or treatment of disease.
- Some techniques are good for mapping the anatomical structures while some others are good for revealing the function and performance of the organs.
- Medical imaging is most commonly performed with
  - Ultrasound (will not discuss this, as it does not involve electromagnetic radiation)
  - **X-ray**
  - **Radioactive materials**
  - Nuclear magnetic resonance (brief mention at the end of lecture)
- The quality of an image is measured by
  - Resolution
  - Contrast
  - “Noise” level

X-ray Production

- X-ray is produced by beaming high-energy electrons at metal targets, usually tungsten, lead or molybdenum.
- A schematic diagram of an X-ray machine is shown below:



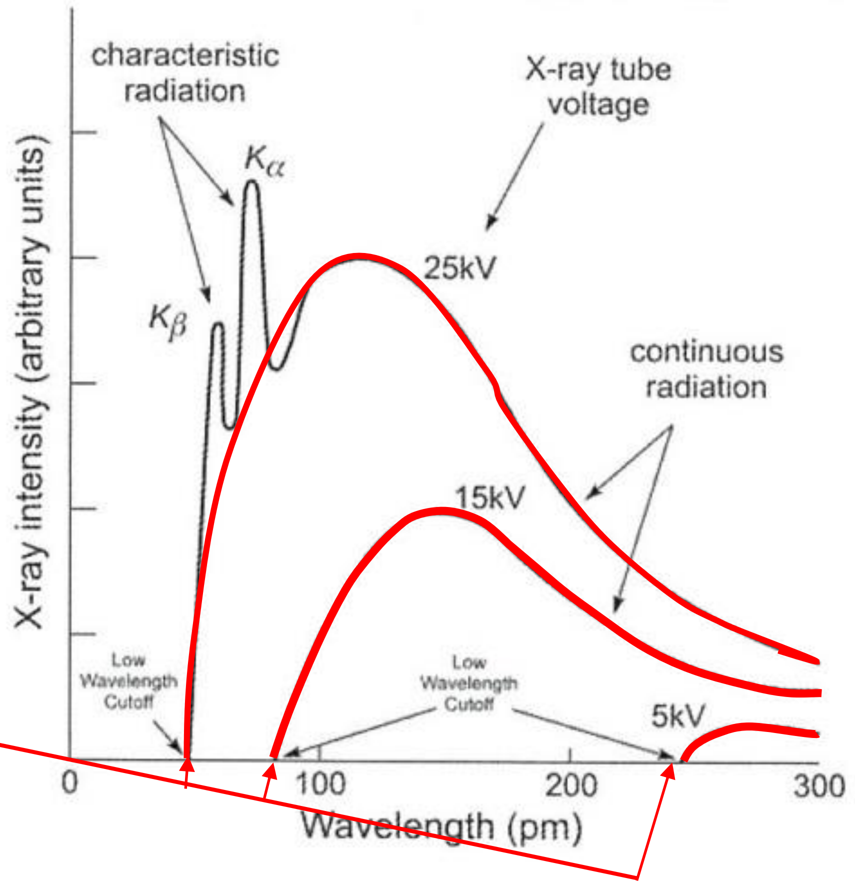
From: Nuclear and Radiation Physics in Medicine, by Tony Key

Typically < 1% of the electron energy is converted to X-rays. The anode has to be able to dissipate heat efficiently. In the schematic diagram, the anode is embedded in copper to conduct heat. In some design, a rotating anode is used to spread out the heat.

X-ray Spectrum

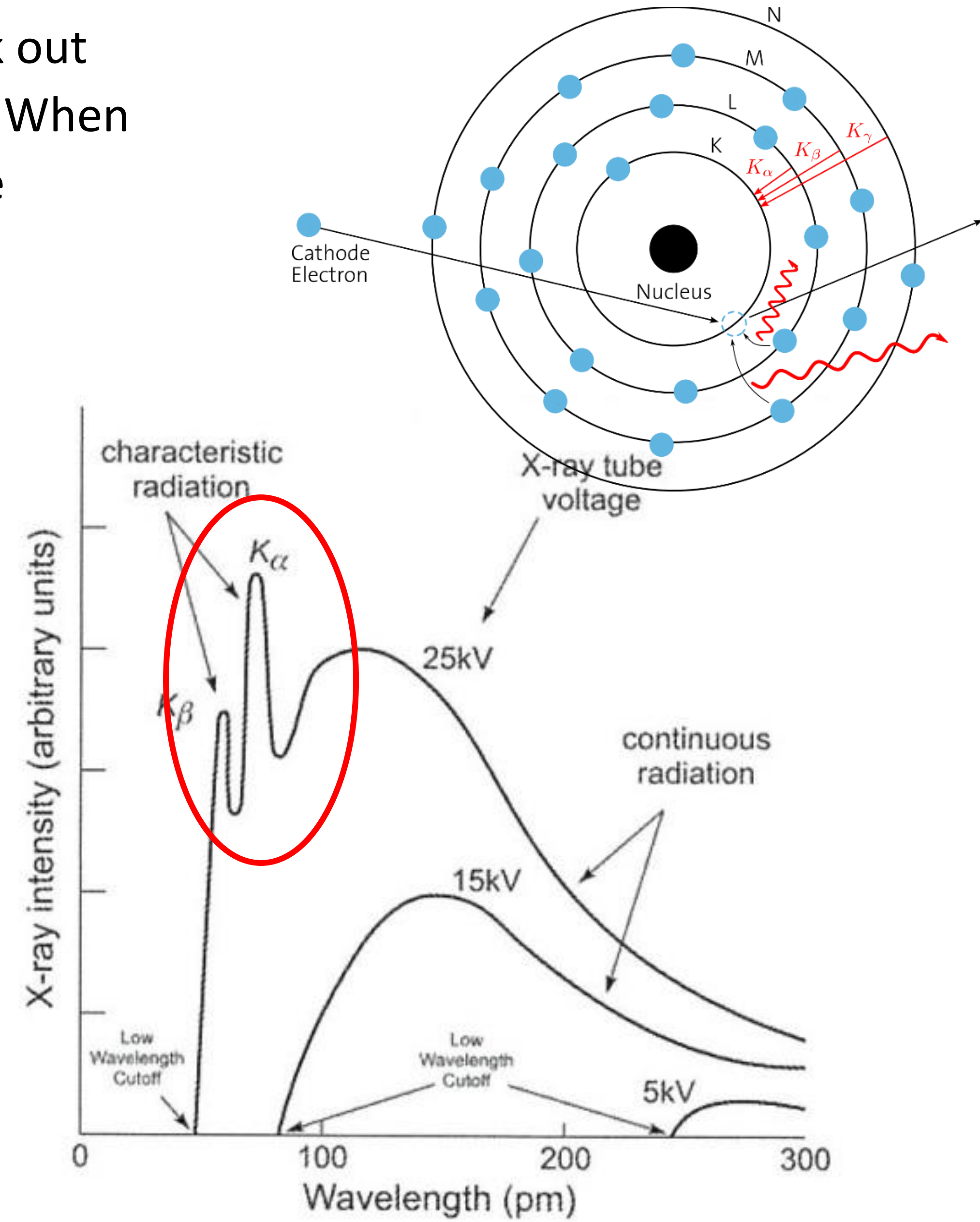
- X-ray is generated by two mechanisms.
- When the high-speed electrons hit the metal anode, they are stopped quickly. Electrons in rapid deceleration radiate X-rays. These X-rays are called Bremsstrahlung radiation (literally braking radiation).
- The energy of the photons emitted in Bremsstrahlung radiation varies smoothly from low values to a maximum, which correspond to the case when the electrons losing all its energy on hitting the target. Electrons which lose part of its energy generate lower energy X-ray photons.
- The spectrum (intensity versus wavelength) of X-rays generated with a Molybdenum anode is shown on the right.
- At lower anode voltage (5 kV and 15 kV), the spectrum is smooth. Note the sharp short wavelength cut-off.

$$eV = \frac{hc}{\lambda_L} \Rightarrow \boxed{\lambda_L = \frac{hc}{eV}}$$



X-ray Spectrum

- At higher energy, the electron hitting the target is able to knock out some electrons in the lower energy levels of the anode atoms. When electrons from the higher energy levels cascade down to fill the vacated lower energy levels, X-ray photons of characteristic wavelengths are emitted.
- These characteristic X-rays show up as sharp spikes superimposed on the smooth spectrum of the Bremsstrahlung radiation.
- The figure shows two spikes in the spectrum for electron energy at 25 kV.
- The characteristic X-ray spikes are labelled “K” if it is associated with the lowest electronic energy level of the anode atoms, and labelled “L”, “M”, etc., if associated with successively higher electronic energy levels.
- The label subscript “α” indicates that the electron that cascade down came from one energy level above; “β” from two energy levels above, etc.

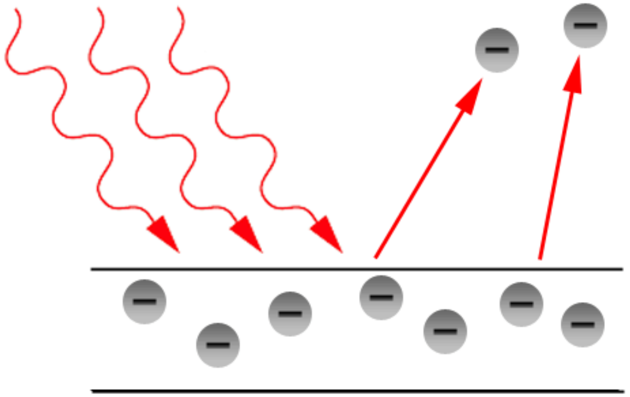


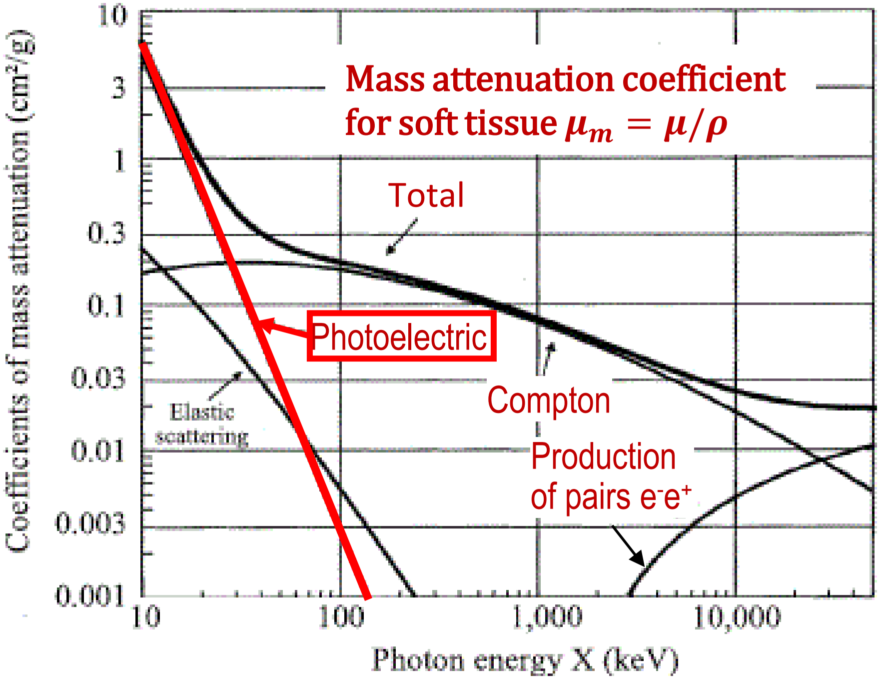
Interaction of X-ray Photons with Matter – Photoelectric Effect

- **Photoelectric Effect** — For energy less than a few keV, photon interacts with matter mostly by the photoelectric effect. The photon is **absorbed** by an atom, which then gives up the energy by emitting an electron.

- The attenuation coefficient μ due to photoelectric effect is proportional to $Z^3E^{-3}\rho$, where E is the energy of the photon, while Z and ρ are the atomic number and the density of the matter.

- The attenuation coefficient shows that for shielding of X-ray, the materials should have high density and large atomic number, such as lead ($Z = 82$).

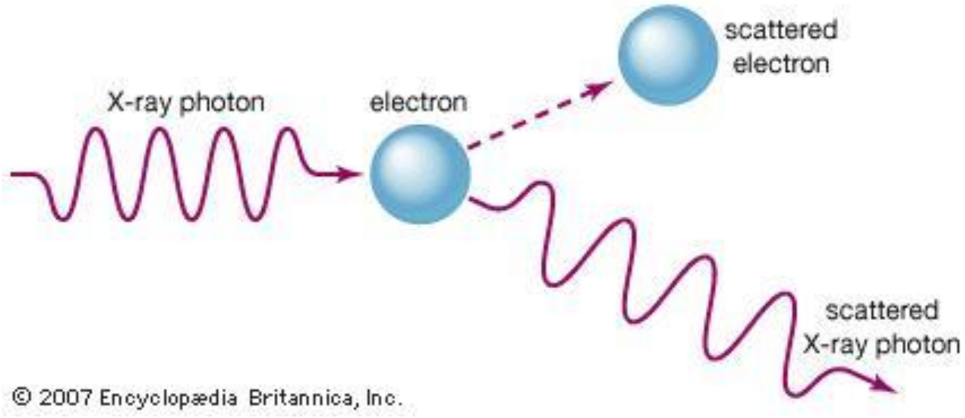


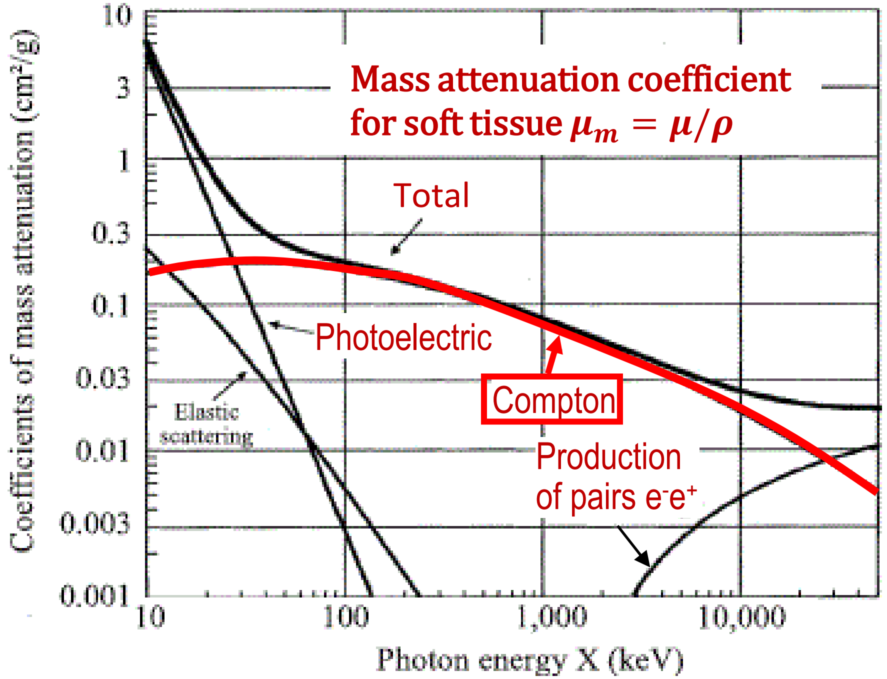


http://wiley-vch.e-bookshelf.de/products/reading-epub/product-id/754443/title/Photon-based%2BMedical%2BImagery.html

Interaction of X-ray Photons with Matter – Compton Effect

- **Compton Effect** — At higher energy, the photon tend to knock orbital electrons out of the target atoms. The photon still exists after the interaction but has become a lower energy photon and is **deflected** from its original path.
- The deflected photon can still be of X-ray energy and remain highly penetrative. Shielding is therefore required around an X-ray machine to block off these deflected photons.
- The attenuation coefficient due to Compton effect is approximately proportional to $E^{-1}\rho$ but does not depend much on the atomic number Z.





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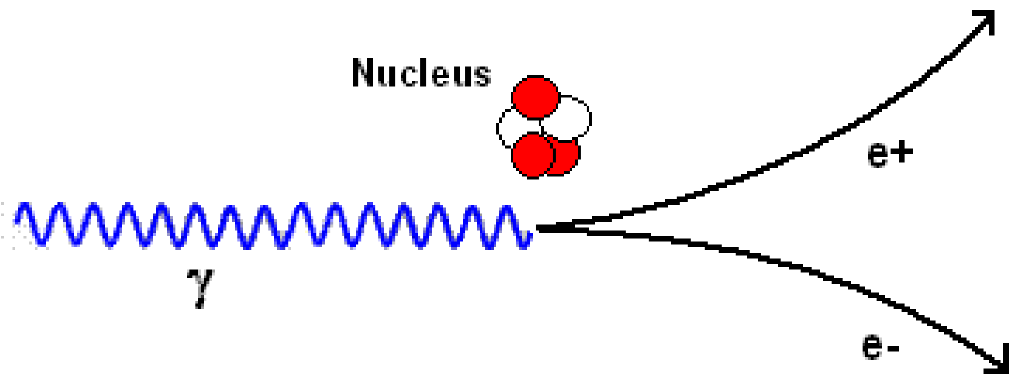
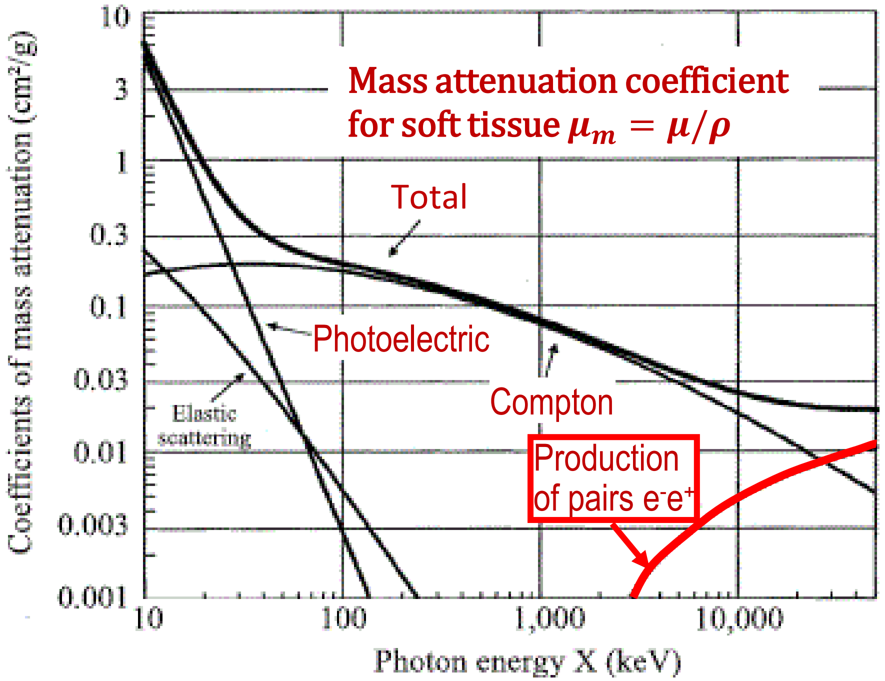
Interaction of X-ray Photons with Matter – Pair Production

- **Pair Production Effect** — For photons with energy higher than 1.022 MeV, interactions with the nuclei can convert the photon into a pair of electron and positron.
- The attenuation coefficient for pair production is proportional to $ZE\rho$.
- Pair production effect in fact does not become the dominant process until the photon energy reaches 30 MeV for water and soft tissues. It is therefore not an important process for medical imaging.



$(m_e c^2 = 0.511 \text{ MeV})$



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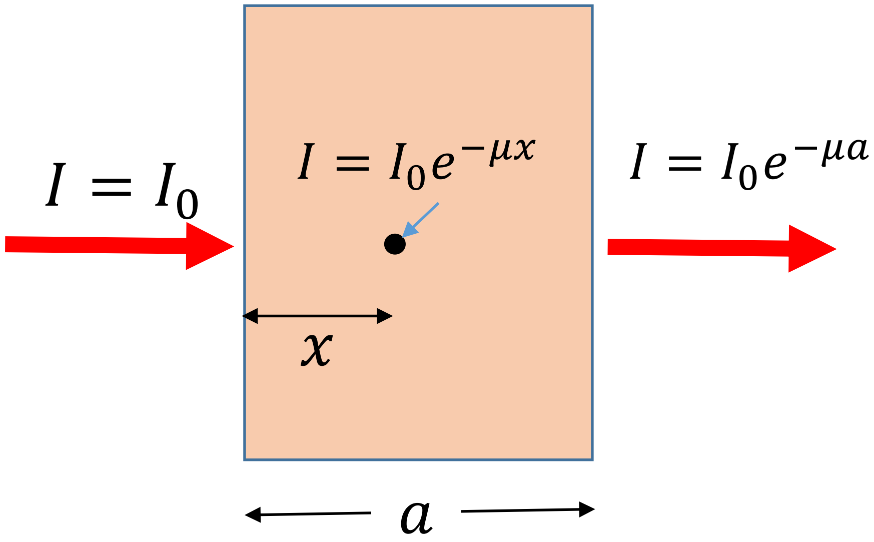
Interaction of X-ray Photons with Matter – Attenuation Coefficient

- When a beam of X-ray passes through matter, the photons will interact with the atoms they encounter. Some photons will be absorbed. Some will be deflected. Some of high enough energy may be converted into electron-positron pairs. The beam will therefore be attenuated as it continuously loses photons along its path.

- The intensity decreases exponentially with penetration depth: $I(x) = I_0 e^{-\mu x}$, where μ is called the **<u>attenuation coefficient</u>**. The X-ray beam loses half its energy in a distance of $x_{1/2} = 0.693/\mu$.

- For some applications, the mass attenuation coefficient μ_m is more convenient. It is defined as $\mu_m = \mu/\rho$, where ρ is the density of the matter.



$$I = \frac{1}{2} I_0 = I_0 e^{-\mu x_{1/2}}$$

$$e^{-\mu x_{1/2}} = 0.5$$

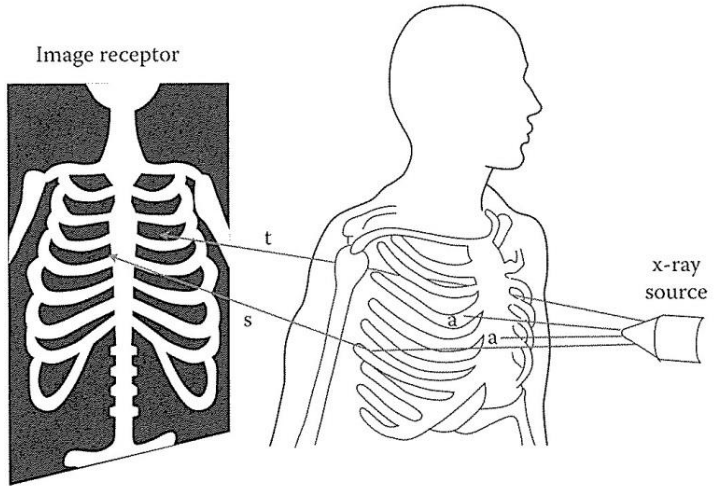
$$\mu x_{1/2} = \ln 2$$

$$x_{1/2} = 0.693/\mu$$

X-ray Imaging

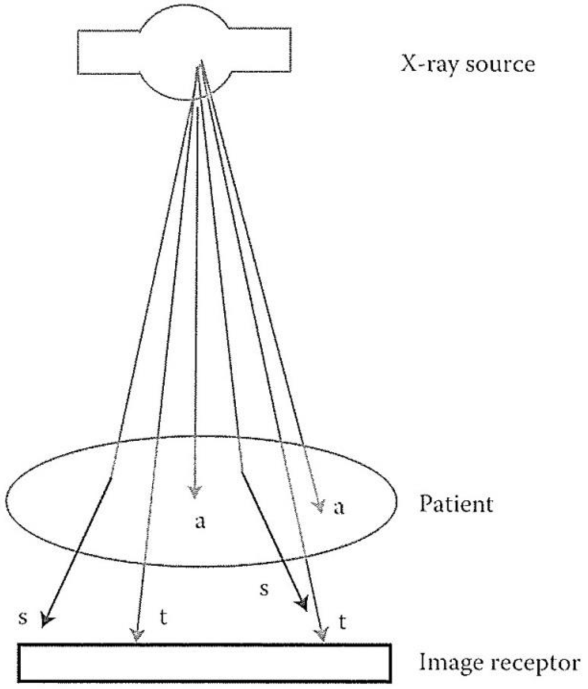
- X-ray images are called radiographs. They are basically shadows cast by the parts of the body which absorb partially an X-ray beam passing through them. A schematic of the imaging set-up is shown in the figure on the right. A typical radiograph is shown below it.

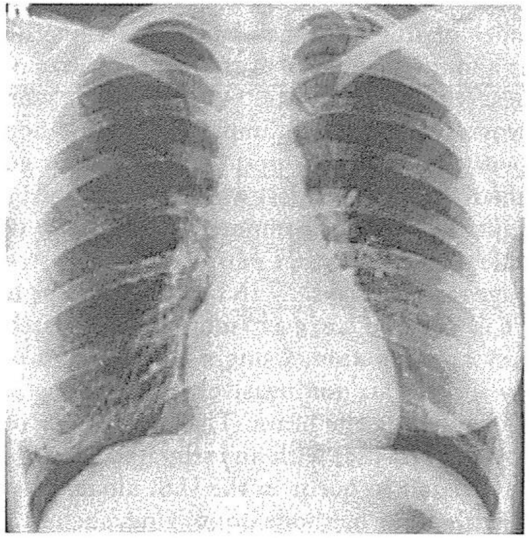
- The image formed is a projection of all the radiopaque objects in the path of the X-ray beam. Depth information is lost as there is no way to tell if one object is above or below another



- The figure next to this point shows the set-up in cross section view. Some of the photons are absorbed (a). The radiograph is a map of the number of the transmitted photons (t) which varies with the opaqueness of the body parts traversed.

- Some photons are scattered (s). They are deflected from their path and have the effect of giving a general fogging, reducing the contrast of the image.





Energy Range of X-ray Suitable for Imaging

- The table give the mass attenuation coefficients and densities of body tissues, muscle, and bone.
- From the table, it appears that low energy X-ray at 10 keV might be good for imaging, as the attenuation coefficients of tissue, muscle and bone are quite well differentiated, giving rise to good contrast in the image.
- Unfortunately, little low energy photons can pass through body tissues for imaging.

Photon Energy (keV)	Tissue $(\rho = 0.95\ g\ cm^{-3})$	Muscle $(\rho = 1.00\ g\ cm^{-3})$	Bone $(\rho = 1.85\ g\ cm^{-3})$
10	3.268	5.356	28.51
20	0.568	0.821	4.000
40	0.239	0.269	0.666
60	0.197	0.205	0.315
80	0.180	0.182	0.223
100	0.169	0.169	0.186

Mass attenuation coefficients of body parts

Energy Range of X-ray Suitable for Imaging

- At photon energy of 20 keV, the tissue attenuation coefficient is $0.568 \times 0.95 = 0.54\ \mathrm{cm}^{-1}$. For 20 cm of tissue (upper chest), the fraction of photon energy that can pass through is $e^{-0.54\times 20} = 2.04 \times 10^{-5}$.
- This means that nearly all the X-ray is absorbed by the body. No meaningful imaging can be done.
- At 60 keV, the fraction that can pass through is $e^{(-0.197\times 0.95\times 20)} = 0.024$, or 2.4%
- We see that lower energy X-rays may give images of better contrast. But for imaging of thick body section, we need to use higher energy photons.
- The usual energy range of radiography is **17 to 150 keV**.

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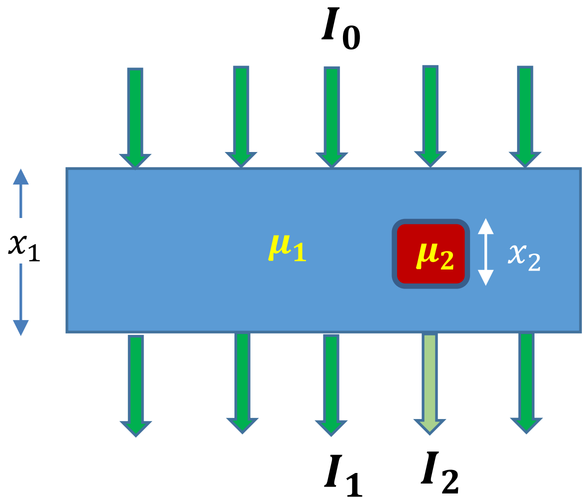
Mass attenuation coefficients of body parts

X-ray Imaging Considerations

- The quality of a radiograph is measured by its spatial resolution, contrast, and noise.
- The absorption or scattering of X-ray photons also give rise to radiation dose to the patient.
- The arts and science of radiography entails achieving the optimal compromise between **enhancing image quality** and **minimizing radiation dose to the patient**.
- **Contrast** — The figure shows a slab of tissue with attenuation coefficient μ_1 and a growth embedded in it with attenuation coefficient μ_2. The intensity of X-rays going through the normal tissue is I_1 and that through the growth is I_2. Contrast is defined to be $C = (I_1 - I_2)/I_1$.
- If the thickness of the normal tissue and the growth be x_1 and x_2 respectively, then

$$C = \frac{I_0 e^{-\mu_1 x_1} - I_0 e^{-\mu_1 (x_1 - x_2)} e^{-\mu_2 x_2}}{I_0 e^{-\mu_1 x_1}} = 1 - e_2^{-(\mu_2 - \mu_1) x_2}.$$



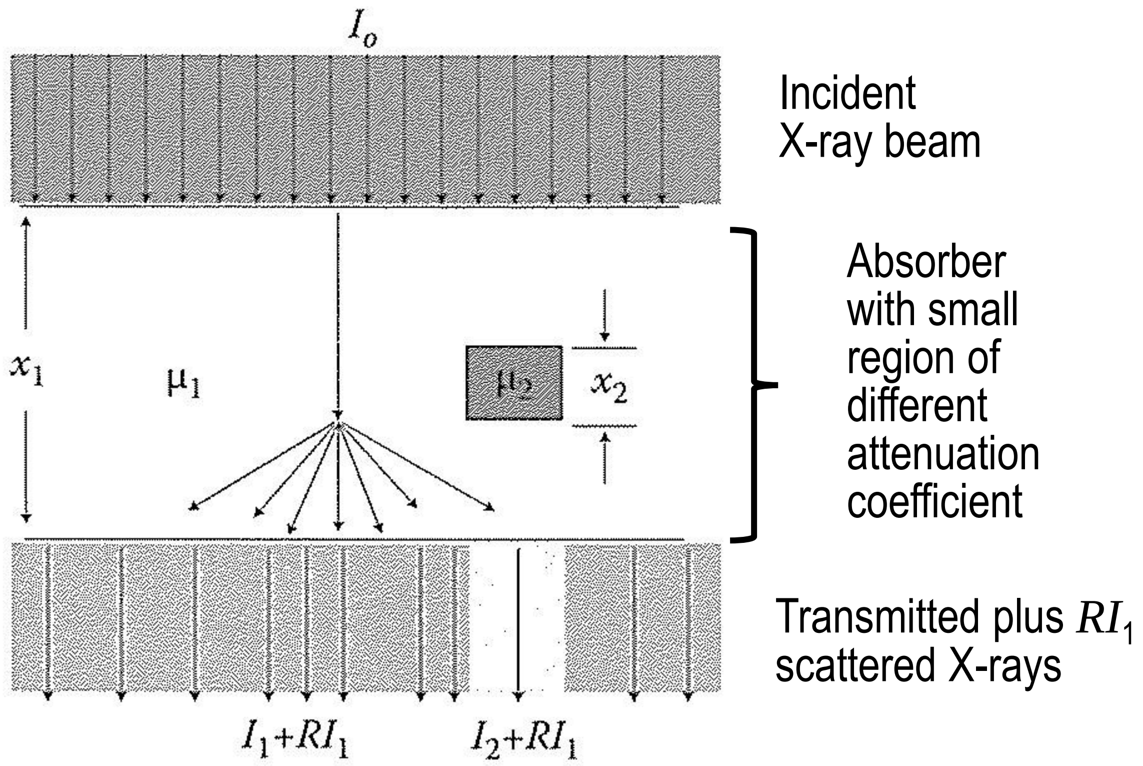
- We see that contrast is determined by the **difference in attenuation coefficients** and the **size of growth**.

X-ray Imaging Considerations

- The photons that are scattered by body tissue are deflected from their path, and on average give rise to a uniform intensity on the image receptor.
- Let the uniform intensity be RI_1, where I_1 is the transmitted intensity. Then the total intensity below normal tissue will be $(I_1 + RI_1)$, while the intensity below the growth will be $(I_2 + RI_1)$.
- The contrast is now

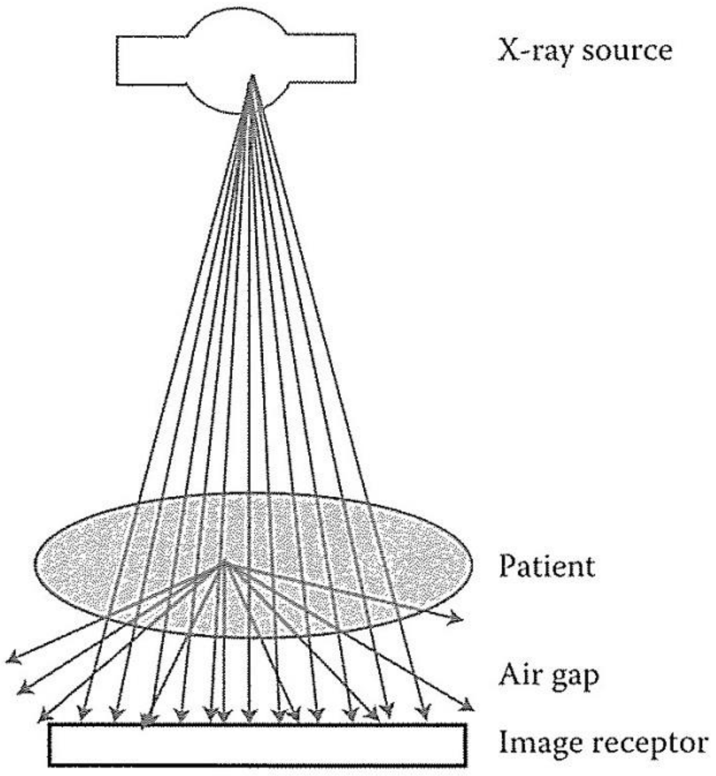
$$C = \frac{(I_1 + RI_1) - (I_2 + RI_1)}{I_1 + RI_1} = \frac{1}{1+R}\,\frac{I_1 - I_2}{I_1}$$

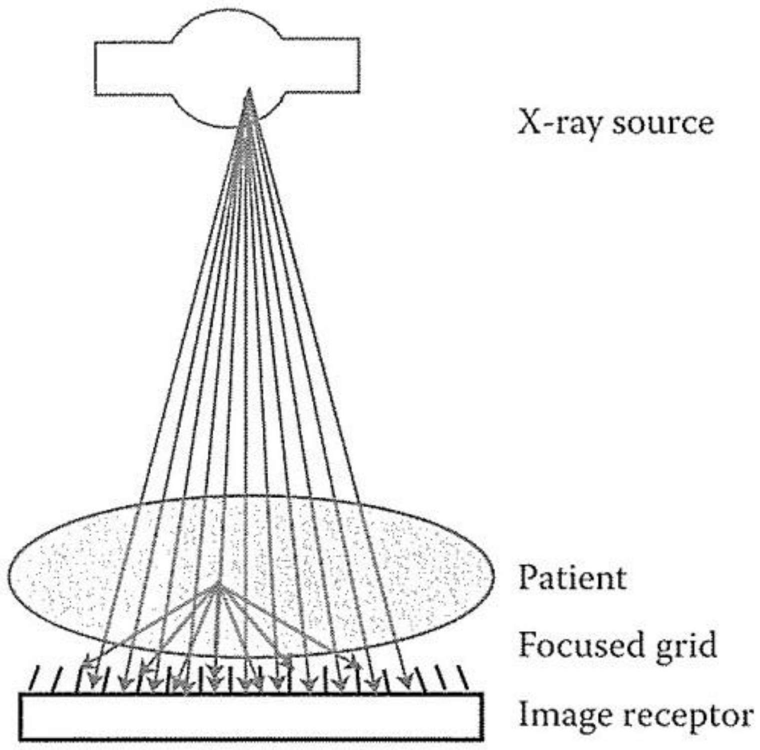
- The contrast is degraded by the factor 1/(1+R).



X-ray Imaging Considerations

- The effect of scattering can be reduced. The first figure to the right shows that by leaving an air gap between the patient and the image receptor, some of the scattered photons will miss the image receptor.
- The second figure to the right shows the image receptor with a "focused grid" made of thin lead strips separated by radiolucent spacers. Scattered photons coming at random directions are mostly absorbed by the grid.



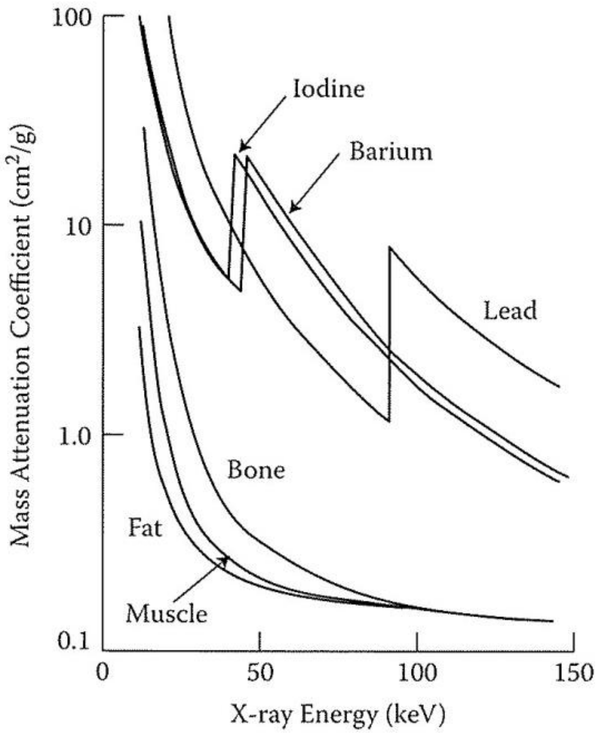


Contrast Media

- One difficulty in X-ray imaging is that body tissues tend to have similar attenuation coefficient. For example, when imaging the heart or the digestive tract, water, blood, and muscle have very similar density and effective atomic number. The contrast is low and it is difficult to identify the organs in radiographs.
- One solution is to introduce radiopaque materials, called contrast media, into the soft tissue.
- Barium (Z=56) and Iodine (Z=53) are commonly used contrast media.

- The figure on the left shows the skeleton clearly. The figure on the right uses contrast media to show the organ of interest.

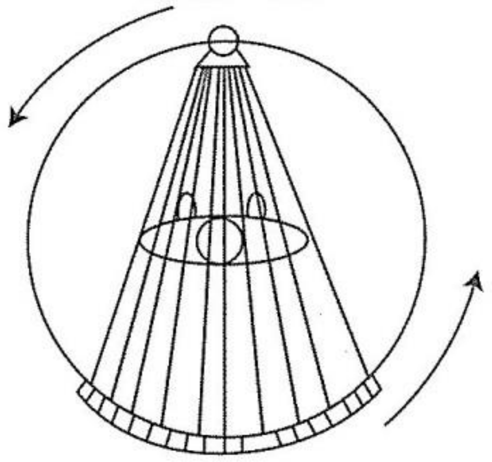
- Barium and Iodine are chosen because their high atomic number makes them absorb X-ray much stronger than body tissues.



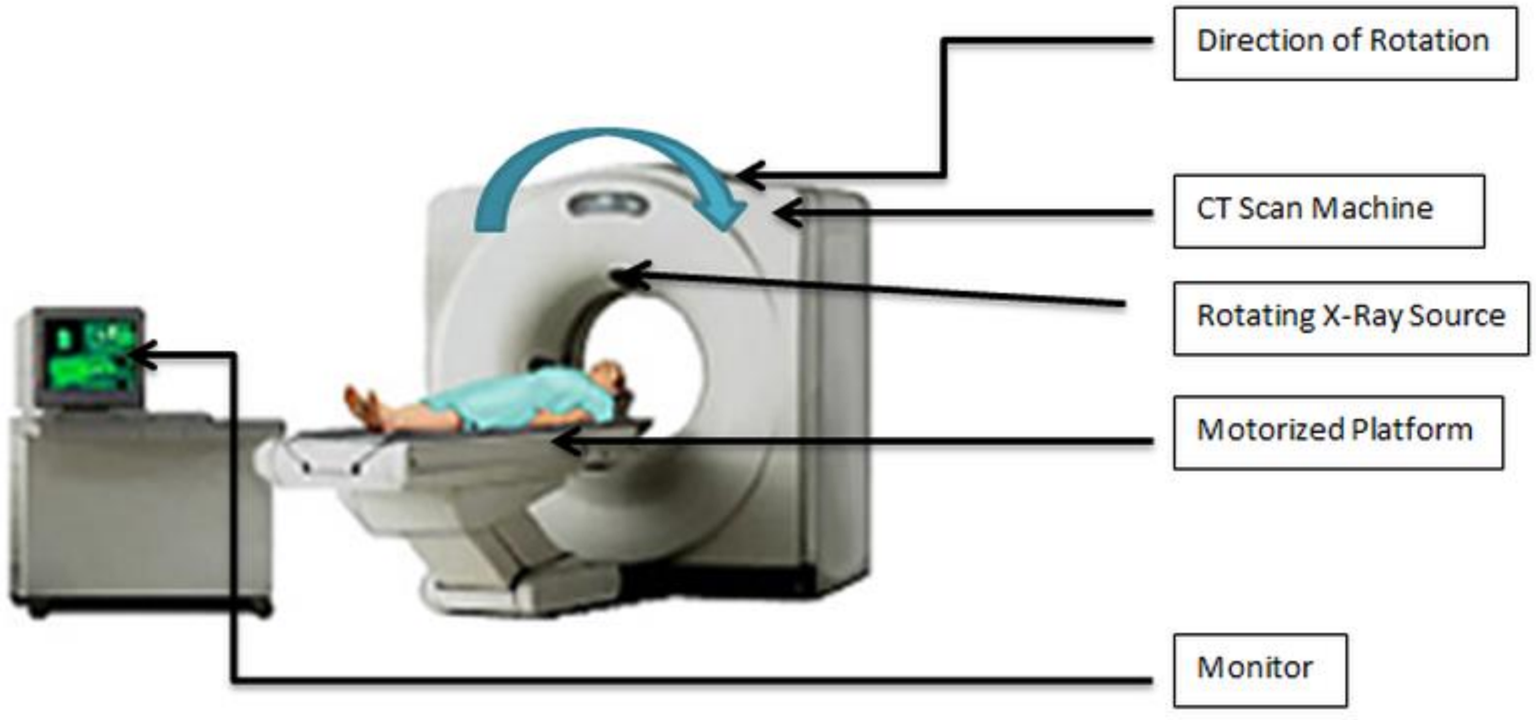
https://www.slideshare.net/mr_koky/contrast-media

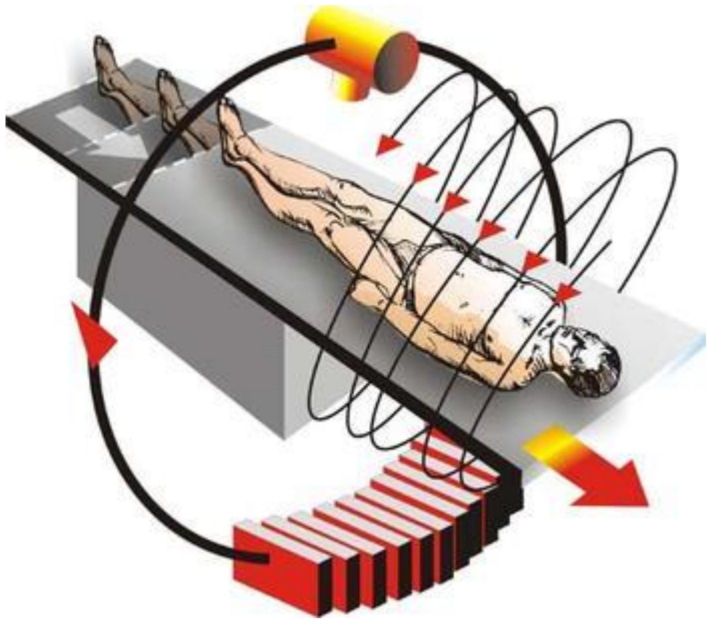
Computed Tomography (CT)

- The CT scanner has an X-ray source and an array of X-ray detectors housed in a doughnut shape gantry. The patient lies on a bed that slides through the opening.
- The X-ray source and detector array rotate round the patient, taking a series of X-ray "images" through a section of the body at various angles. A 3-D model of the patient's internal can be computed from the data collected.



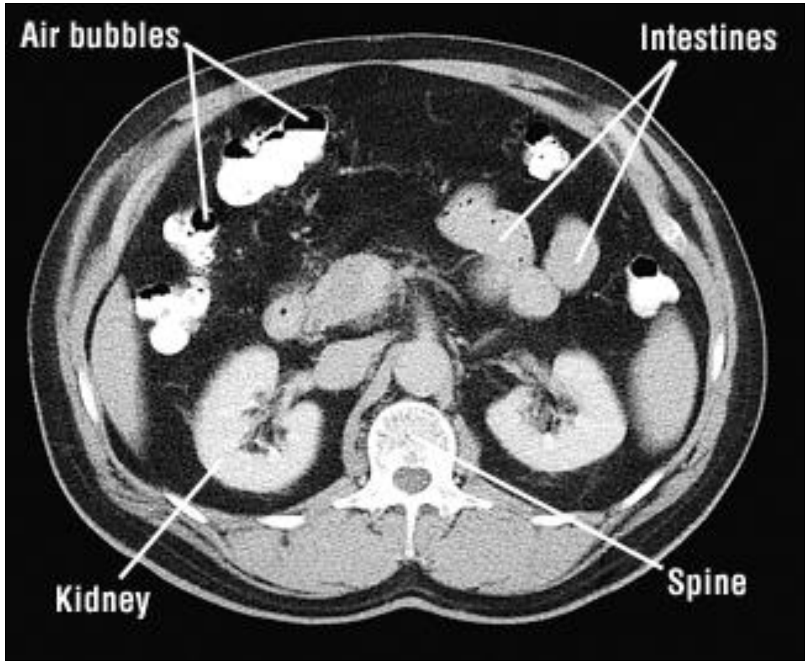
Detector array

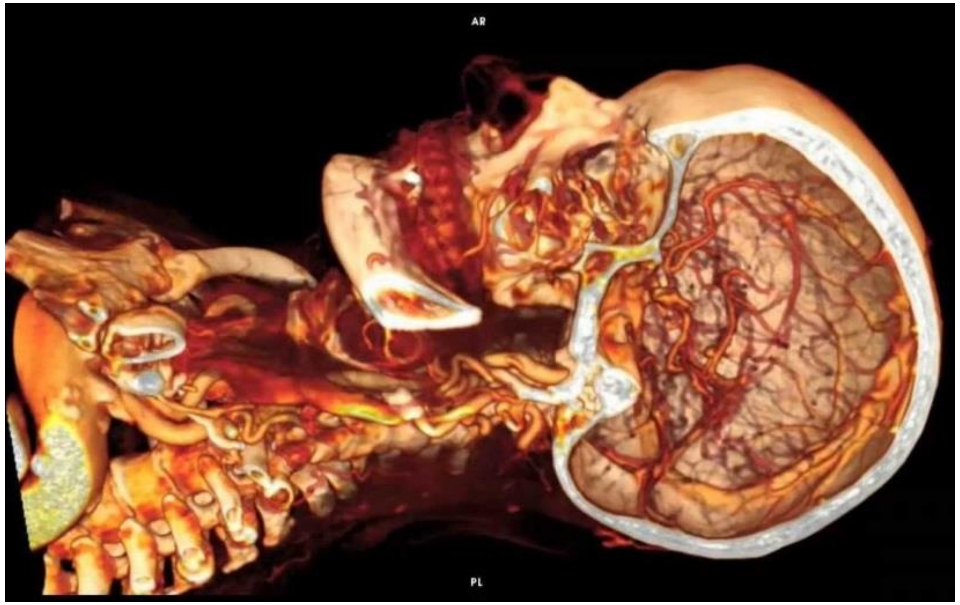




Computed Tomography (CT)

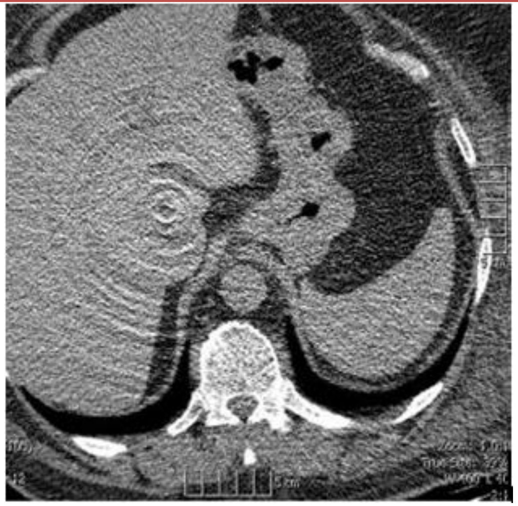
- A cross section image of human body obtained by CT is shown in the first figure. By stacking the cross-section images together, a 3-D model can be constructed and presented in appropriate format for diagnostic or educational purposes.
- The second figure shows an example of CT head scan with contrast media.
- The processing of CT images is an interesting problem in image processing. Faithful model of the attenuation of the X-ray beam through the body tissues and appropriate computational approach are essential.





Computed Tomography (CT)

- When an inadequate processing algorithm is applied, or when there are inappropriate imaging arrangements, CT images can exhibit artifacts which degrade image quality.
- The top figure shows the "ring artifact" which results from a mis-calibrated or defective detector element. The artifact shows up as bright or dark rings centered on the center of rotation.
- The bottom figures illustrate the "beam-hardening" artifact.
- X-ray beam is usually not mono-chromatic. As seen in earlier slides, higher energy X-rays are more penetrative than lower energy X-rays. As a result, when an X-ray beam goes through a thicker body part, the average energy of the X-ray beam increases. This is known as beam hardening.
- When this effect is not adequately modelled in the image processing algorithm, beam-hardening artifacts appear. In Image (A), the patient position his arms next to the body, and artifacts appear at the abdomen, In Image (B), the patient raises his arms over his head, and the artifact is much reduced.



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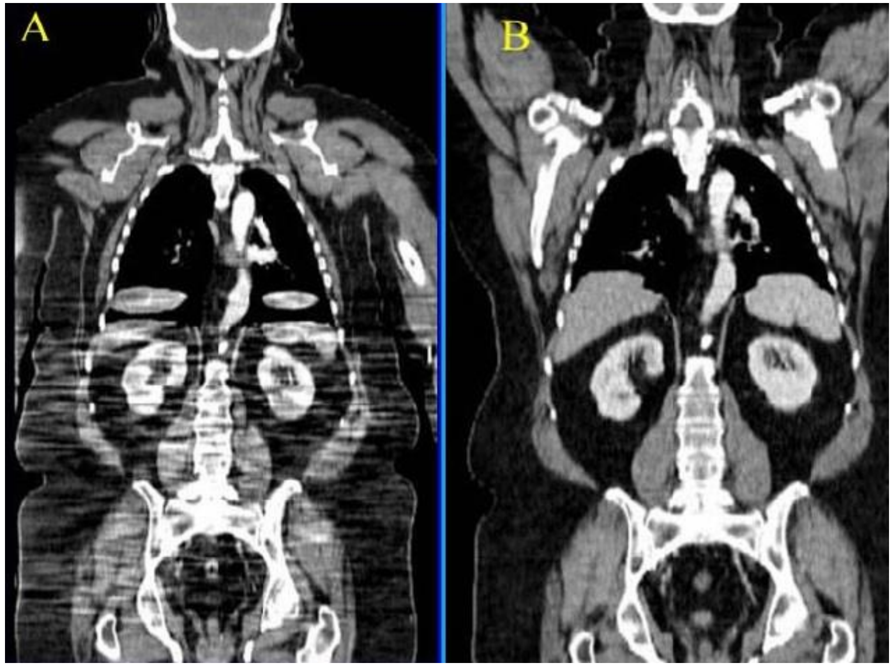

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Typical X-ray Doses

- X-ray images and CT scans are valuable diagnostic tools. But the use of X-ray also exposes the patient to radiation dose. The best approach is to use as low radiation as possible (***As Low As Reasonably Achievable***), *without compromising on intended clinical purpose*.
- The radiation dose of X-ray imaging is usually quite low. The most common X-ray examination is the front-view chest X-ray. It imparts an average effective dose of about 0.02 mSv. ***For comparison, a person on average receives a radiation dose of about 3 mSv per year from the natural environment.***
- The average dosages for other X-ray examinations are as follows (http://rpop.iaea.org):

Examination	Mean Eff. Dose (mSv)	Examination	Mean Eff. Dose (mSv)
Skull X ray	0.1	Spine Computed tomography (CT)	6
Thoracic spine/lumbar spine X ray	1.0 – 1.5	Chest CT/pulmonary embolism	1 – 16
Mammography	0.4	Abdomen/pelvis CT	6 – 8
Pelvis/hip/abdomen X ray	0.6 – 0.7	Head/neck CT	2 – 3
Knee/other extremities	0.001 – 0.005	CT coronary angiography	16
Intra-oral/panoramic X ray	0.005 – 0.01	CT virtual colonoscopy	10

Radioactive Tracers

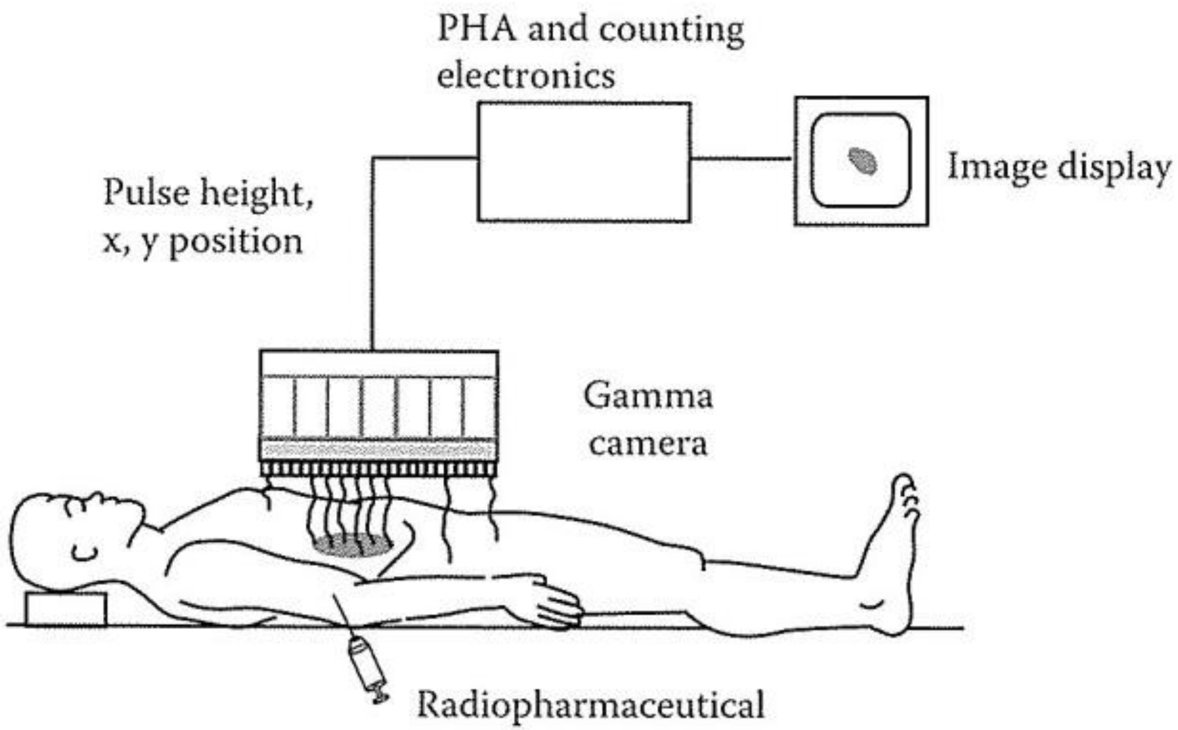
- For diagnostic use, radioisotopes are attached to a pharmaceutical that targets a specific organ.
- The pharmaceutical is then introduced into the patient by injection, inhalation, or ingestion.
- After an appropriate interval, the distribution of the pharmaceutical is detected by the radiation emitted by the radioisotopes attached to it.
- The radioisotopes basically act as **tracers** for the specific physiological processes under examination.
- Diagnostic nuclear medicine examinations are used to identify abnormalities in the brain, thyroid, lung, kidney, liver, spleen, and bone.
- Technetium ($^{99m}_{43}\mathrm{Tc}$) is one of the most commonly used radioisotopes. It combines with many chemical compounds, and its half-life of 6 hours is short enough to keep the long-term dose to the patient low, but long enough to allow adequate time for a good signal.
- Some commonly used tracer radioisotopes are listed in the table.

Radioisotope	Half-life	Decay mode	Organ scanned
$^{123}_{53}\mathrm{I}$	13 hours	EC, γ	Thyroid
$^{131}_{53}\mathrm{I}$	8 days	β^-, γ	Thyroid
$^{198}_{79}\mathrm{Au}$	2.7 days	β^-, γ	Liver
$^{201}_{81}\mathrm{Tl}$	3.0 days	EC, γ	Heart
$^{111m}_{49}\mathrm{In}$	7.7 mins	IT*, γ	Blood
$^{85}_{38}\mathrm{Sr}$	65 days	EC, γ	Bone

* Isomeric Transition

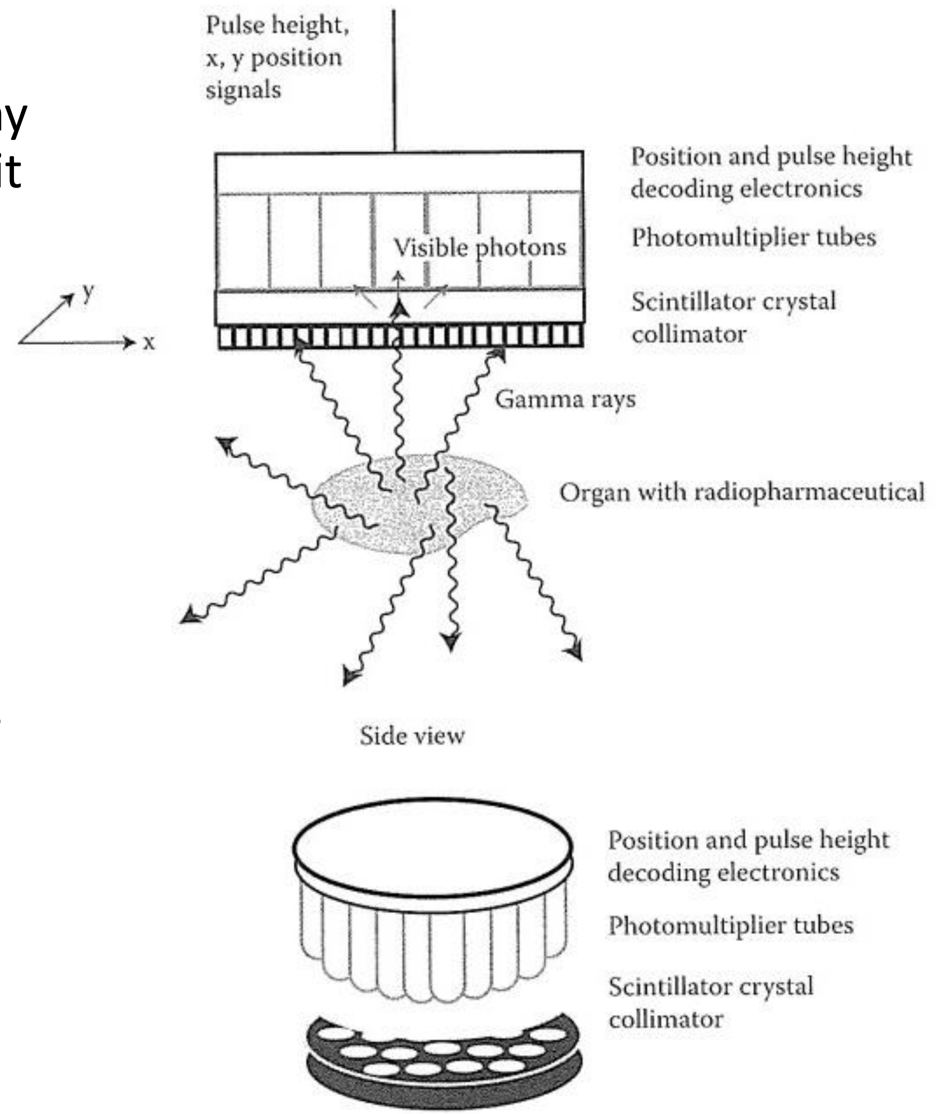
Gamma Camera Imaging

- The γ-ray emitted by the radioisotope in the patient is detected by a gamma camera, or Anger camera. The left figure is a schematic diagram of the imaging set-up, and the right figure shows a scan in progress.



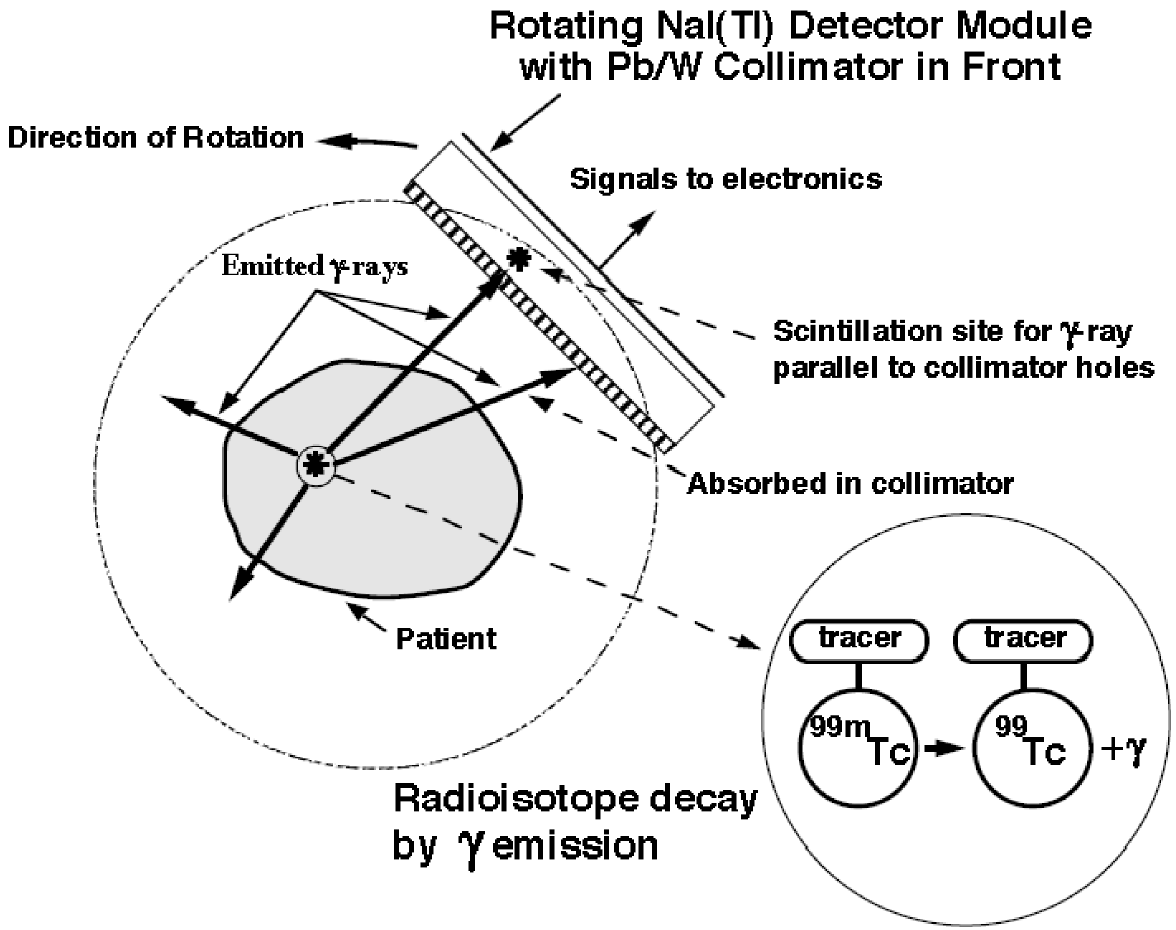
Gamma Camera Imaging

- A gamma camera consists of four parts as shown
- Nearest to the patient body is a collimator. It is a flat sheet of γ-ray absorbing metal perforated with hollow channels. The holes admit only γ-rays that are emitted nearly directly below them.
- Above the collimator is a large, flat scintillation crystal which, on absorption of a γ-ray photon from the patient, emits flashes of visible light.
- Above the scintillation crystal is an array of photomultiplier tubes (PMTs) which amplify the flashes of light emitted by the scintillation crystal.
- The electronic circuit attached to the back of the PMTs then keeps track of the γ-ray energy received at each location (x, y), and pass the data to a computer.
- The computer then construct an image from the data based on an appropriate imaging model and numerical algorithm.



Single Photon Emission Computed Tomography (SPECT)

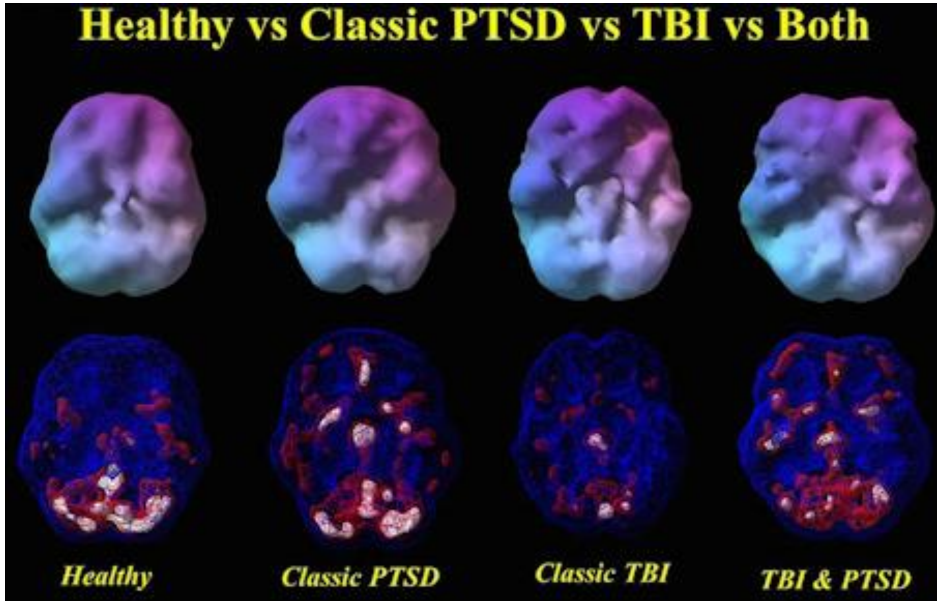
- The gamma camera produce a 2-D image similar to the radiograph.
- Single Photon Emission Computed Tomography (SPECT) is the technology to produce cross sectional slices or full 3-D model by combining many gamma camera images taken from different directions around the patient, as illustrated in the figure.
- Instead of just taking a picture of anatomical structures, a SPECT scan monitors level of biological activity at each place in the 3-D region analyzed. With radiopharmaceutical injected into the blood stream, emissions from the radionuclide indicate amounts of blood flow in the capillaries of the imaged regions.



Single Photon Emission Computed Tomography (SPECT)

- Image on right shows nuclear medicine image of a whole-body bone scan, indicating any of abnormal increased bone activity, such as fracture, metastatic disease, infection or tumour.
- The image below compares the SPECT images of a healthy person and veterans with PTSD, TBI, or both disorders. The veteran with PTSD shows increased perfusion, particularly in the frontal lobes. The veteran with TBI shows decreased perfusion throughout the same brain region. A veteran with both PTSD and TBI has perfusion that is intermediate -- lower than in the person with PTSD, but higher than in the individual with TBI.

PTSD – Posttraumatic Stress Disorder
TBI – Traumatic Brain Injury



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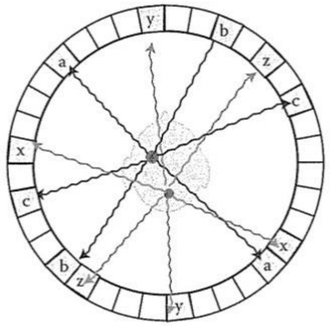
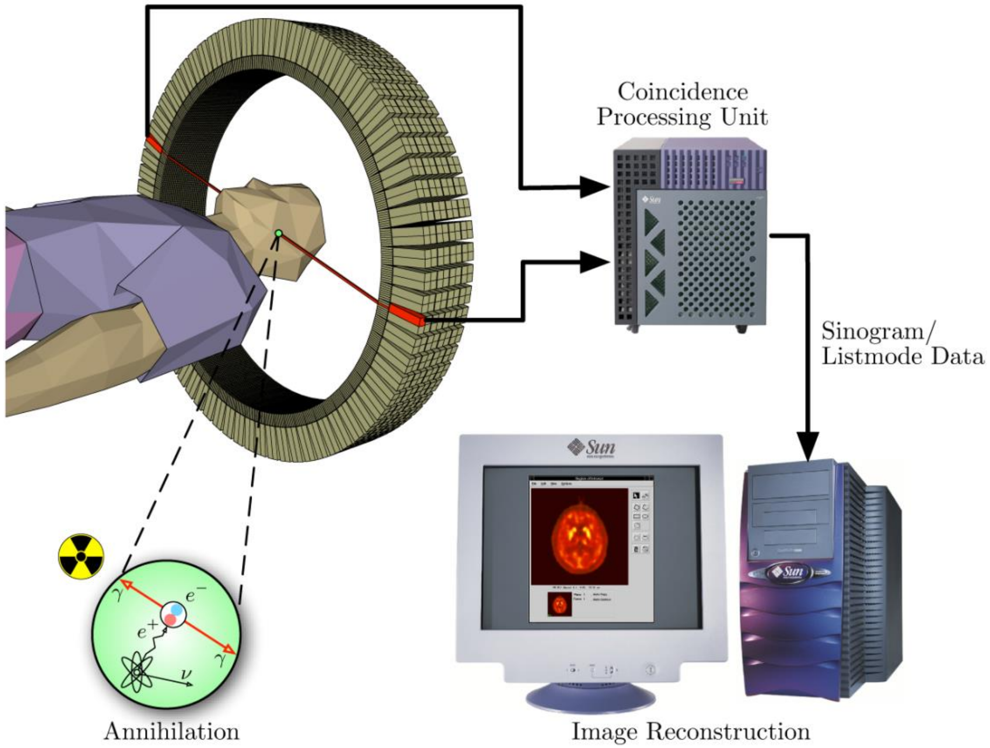
https://www.pinterest.com/pin/162903711496527206/

Positron Emission Tomography (PET)

- **Positron emission tomography (PET)** is a functional imaging technique for observation of metabolic processes in the body. Radioisotopes which undergo β^{+}-decay are introduced into the patient. The positron emitted in a decay event will travel a short distance (~1 mm) before it encounter an electron and annihilate each other. Two γ-ray photons of 0.511 MeV are generated and travel away from the location in opposite directions.
- The patient is surrounded by a ring of detectors tuned to receive 0.511 MeV photons. When two photons are detected nearly exactly the same time at two detectors, an event is registered.
- The event must have originated from somewhere along the straight line linking the two coincident detection.
- With sufficient number of coincident photon pairs, the emission locations can be determined (see diagram)
- For fast detectors, the slight difference in the arrival time of the two photons may also help to locate the event.





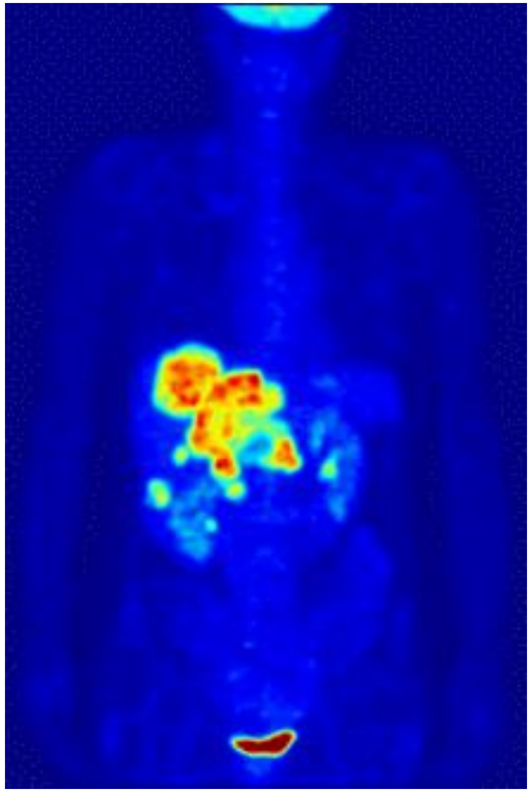
https://en.wikipedia.org/wiki/Positron_emission_tomography#/media/File:PET-schema.png

Positron Emission Tomography (PET)

- The radioisotopes commonly use for PET are as listed in the table.
- All the radioisotopes, except ${}^{18}_{9}\mathrm{F}$, have very short half-life. It is necessary to have an on-site cyclotron to produce the radioisotopes for use in PET.

Radioisotope	Half-life (mins)	Max β^+ energy (MeV)
${}^{11}_{6}\mathrm{C}$	20	0.96
${}^{13}_{7}\mathrm{N}$	10	1.19
${}^{15}_{8}\mathrm{O}$	2	1.70
${}^{18}_{9}\mathrm{F}$	110	0.64
${}^{82}_{37}\mathrm{Rb}$	1	3.15

- PET is very useful for cancer detection. Fluorodeoxyglucose (FDG) has F-18 substituting for an oxygen. It is taken up by glucose-using cells but once in the cell, it does not metabolize further. So it accumulates in tumours and serves as an excellent marker.



A 3D PET scan from Wikipedia. The brain and bladder are clearly visible, as are some tumours.

https://en.wikipedia.org/wiki/Positron_emission_tomography

A note on Magnetic Resonance Imaging (MRI)

- An important new diagnostic and research tool is Magnetic Resonance Imaging (MRI). MRI is based on the phenomenon of nuclear magnetic resonance. The technique was originally called Nuclear Magnetic Resonance Imaging (NMRI). The word nuclear was removed to help enhance public acceptance.
- In a very strong magnetic field, the nuclei of atoms all line up along the magnetic field. A radio wave is used to tilt the nuclei away from the magnetic field. When the radio wave is turned off, the nuclei spiral back into alignment, emitting radio signals in the process. MRI processes these radio signals to construct 3-D models of the body being imaged.
- It is to be noted that MRI does **not** involve any ionizing radiation or radioactive materials. This is the reason we do not include a discussion of MRI in this module.

Announcement – Guest Lecturer for Lecture on 31 March 2023

- We have invited a guest lecturer, A/Prof James Lee, Chief Radiation Physicist of National Cancer Centre Singapore, to give a lecture on Applications of Radiation in Therapeutic Treatment (Lecture 16).
- It will be given on Friday, 31 March 2023 during the usual lecture slot.