Physics of Medical Imaging – An Introduction

Edwin L. Dove
Biomedical Engineering
The University of Iowa

Table of Contents

1. Introduction

Images of the human body are derived from the interaction of energy with human tissue. The energy can be in the form of radiation, magnetic or electric fields, or acoustic energy. The energy usually interacts at the molecular or atomic levels, so a clear understanding of the structure of the atom is necessary.

In addition to understanding the physics of the atom, learning imaging jargon is also necessary. For example:

- Tomography: a cross-sectional image formed from a set of projection images. The Greek word *tomo* means cut.
- CT: Computed (or Computerized) Tomography
- MR, or MRI: Magnetic Resonance Imaging. This was first called nuclear magnetic resonance (NMR), but the mention of anything nuclear scared patients, so the “N” was dropped.
- PET: Positron Emission Tomography. Understanding this phenomenon requires acceptance of the theory that there is antimatter in the universe, and when antimatter meets matter, then both kinds of matter are annihilated, and pure energy is formed.
- SPECT: Single Photon Emission Tomography
- Ultrasound: Sonar in the body
- OCT: Optical Coherent Tomography – the use of infrared light to image (particularity) the walls of an artery.

A modality is a method for acquiring an image. MR, CT, etc. are all imaging modalities. Modalities are sometimes categorized based on the amount of energy applied to the body. For example, the X-ray modality produces energy that is sufficient to ionize atoms (i.e., eject an electron from an orbit of an atom, thereby creating a positively charged ion that damages human tissue). The modalities that cause ionizing radiation are X-rays, CT, SPECT, and PET. Non-ionizing modalities include MR and ultrasound.

Other classification schemes are used in modern medical imaging. For example, many radiologists consider there to be four methods for obtaining images: X-ray transmission, radionuclide emission, magnetic resonance, and ultrasound. Other methods are “under research.” Each of the four methods depicts different categories of information reflective of anatomical or physiological processes. Table 1.1 compares the four medical imaging techniques.

Table 1.1 Comparison of medical imaging techniques

Method	Parameter measured	Medical applications
Transmission computed tomography	Density and average atomic number	Anatomy, mineral content, flow and permeability from movement of contrast material
Emission computed tomography (positron and single photon)	Concentration of radionuclides	Metabolism, receptor site concentration, flow
Magnetic resonance	Concentrations, relaxation parameters T_1, and T_2 and frequency shifts due to chemical form	Anatomy, edema, flow, and chemical composition
Ultrasound	Acoustic impedance mismatches, sound velocity, attenuation, frequency shifts due to motion	Anatomy, tissue structure characteristics, flow

Figure 1-1 depicts the major modes of medical imaging. Some modern imaging modalities (PET, CT and MR) require that the patient enter a ring of detectors. For some, this is challenging due to disease state, claustrophobia, or other. Ultrasound requires a simple probe be placed on the skin of the subject.

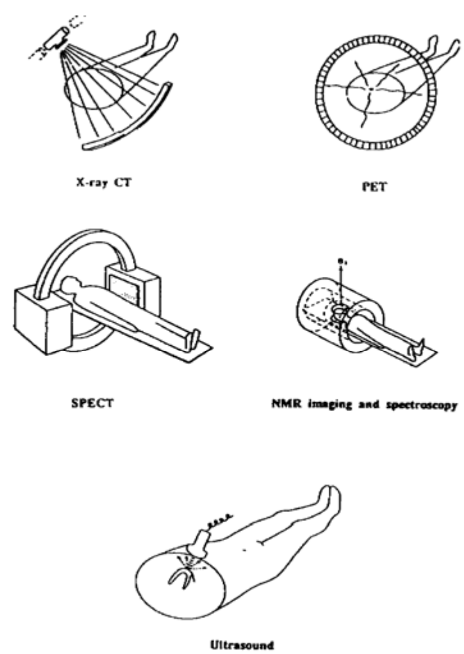

Figure 1-1 Schematic representation of major imaging modalities in medical imaging

.

An example of a PET image is shown in Figure 1-2.

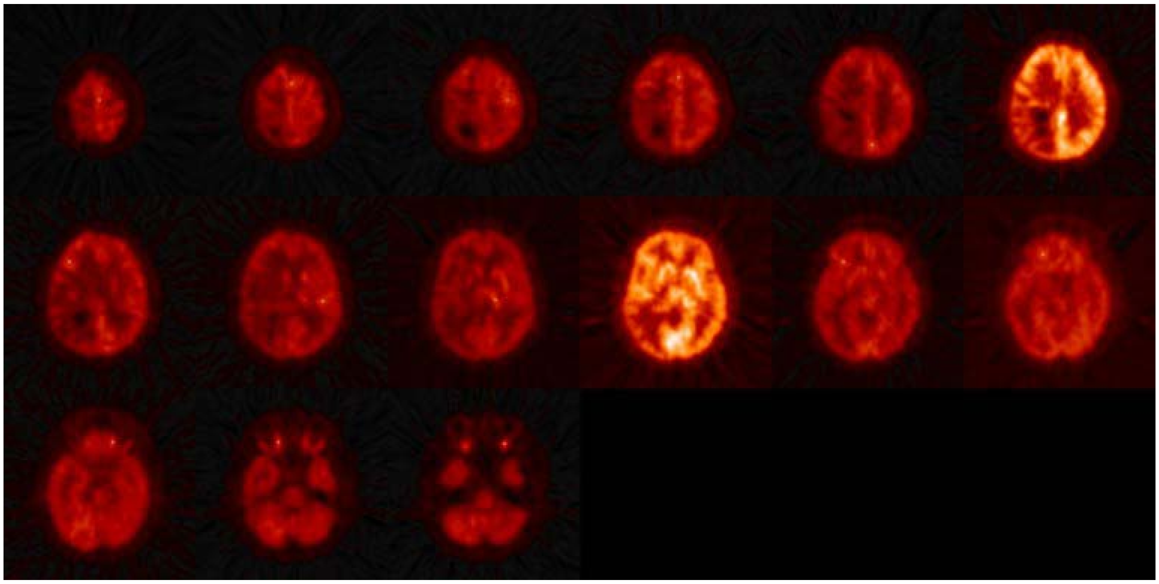

Figure 1-2 PET scans of a brain tumor (Taken from the Harvard Medical School Nuclear Division web site)

An example of a SPECT scan is shown in Figure 1-3.

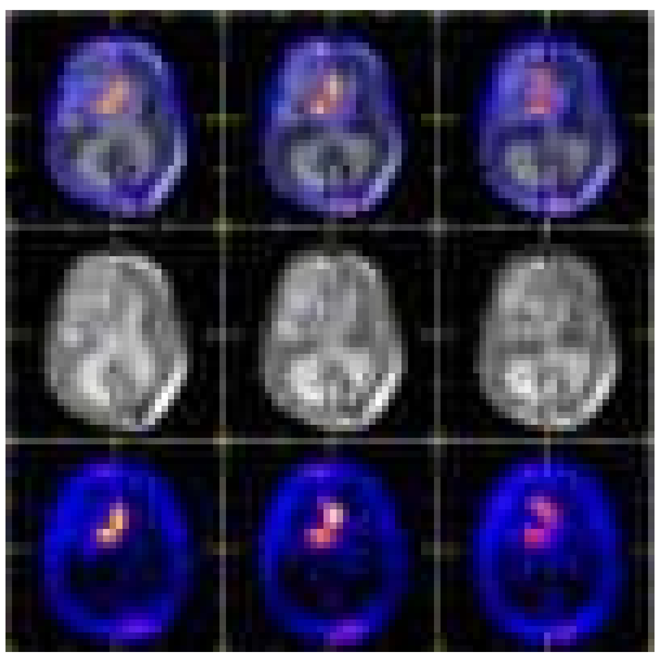

Figure 1-3 Bottom row - SPECT scans of a brain tumor (Taken from the Harvard Medical School Nuclear Division web site)

A schematic diagram of an MR machine is shown in Figure 1-4. A typical MRI image is shown in Figure 1-5.

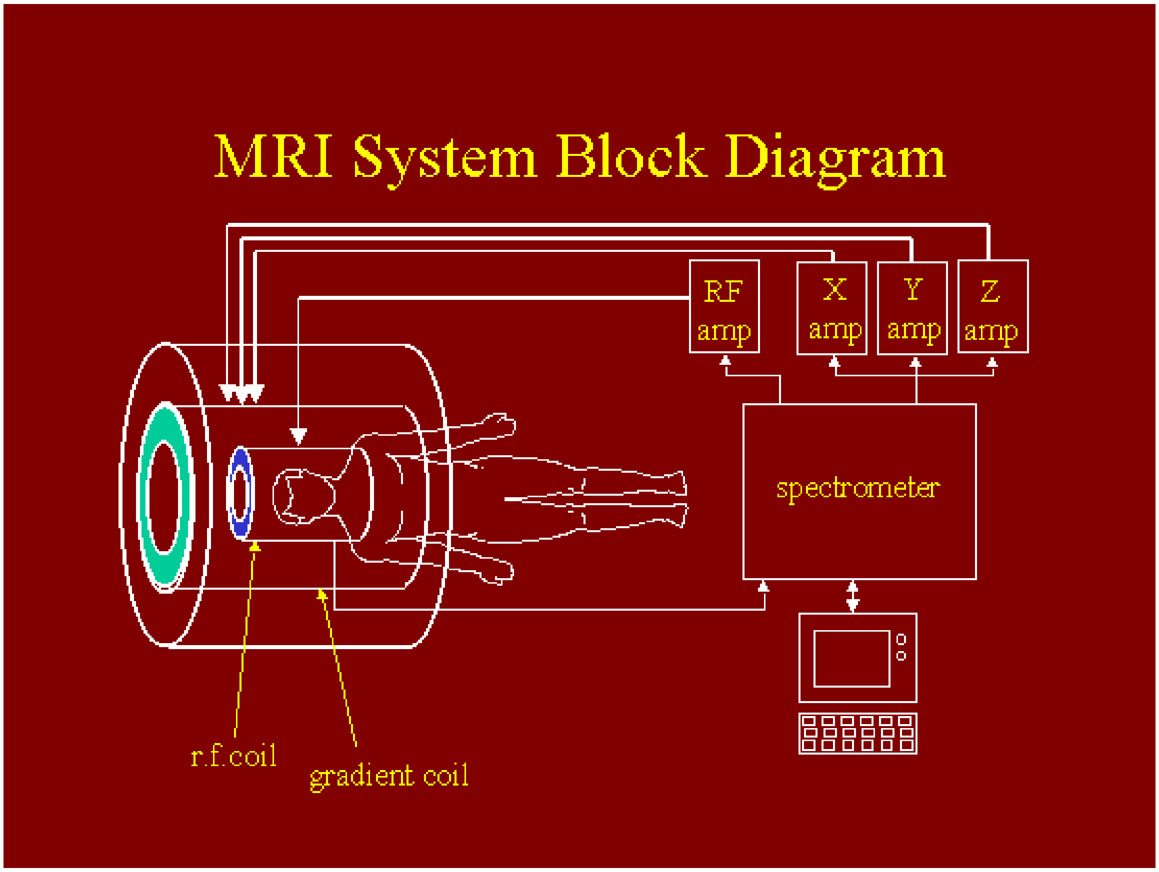

Figure 1-4 MRI block diagram

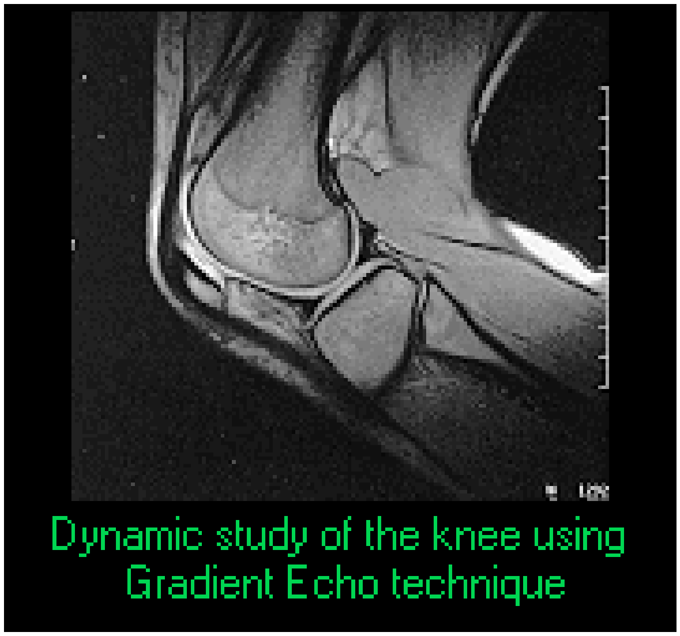

Figure 1-5 Knee study from MRI image

In this class we will only study primarily X-rays and ultrasound. The other modalities (and more advanced image processing algorithms) are coved in subsequent elective imaging courses (51:185, 188, and 189).

2. X-ray Modality

2.1 History

On Friday evening, 8 November 1895, Wilhelm Conrad Röntgen (also sometimes spelled Roentgen) discovered a "new kind of ray" that penetrated matter. Röntgen, a 50-year old professor of physics at Julius Maximilian University of Wurzburg, named the new kind of ray *X-strahlen* "X-rays" ("X" for unknown). Röntgen was looking for the "invisible high-frequency rays" that Hermann Ludwig Ferdinand von Helmholtz had predicted from the Maxwell theory of electromagnetic radiation. Röntgen's discovery was submitted for publication on 28 December 1895 and was published on 5 January 1896. A portable X-ray unit was available from the Sears catalog in late 1896. The cost was $15.

Röntgen developed the first X-ray pictures on photographic plates, and one of the first materials tested was human tissue. The most famous picture was an image of his wife's hand with a ring on her finger (Figure 2-1).

Figure 2-1 The first reported image of human tissue. Mrs. Röntgen's hand with a ring, taken in 1895

In 1901 Röntgen received the Nobel Prize for Physics, which was the first Nobel Prize in physics ever awarded. Unfortunately, Röntgen, his wife, and his laboratory workers all died prematurely of cancer.

The first medical use of the X-ray was on 13 January 1896 by Drs. Ratcliffe and Hall-Edwards, in which they showed the location of a small needle in a woman's hand. As a consequence, Dr. J.H. Clayton performed the first X-ray guided surgery nine days after the publication of the existence of X-rays.

Also in 1896 Randolph Hearst (of the famous Hearst publishing dynasty) offered a challenge to scientists to capture an image of the brain. Many tried, and all failed, even though some novel imaging enhancement techniques were invented. For example, air was injected into the fluid-carrying compartments of the brain (pneumoencephalography). The test subjects reported no major physical discomfort (the brain has no pain receptors), though they developed unusual behavior, mentation, cognition, and motion patterns.

Allan Macleod Cormack (Tufts University) and Godfrey Newbold Hounsfield (research labs of EMI, Ltd.) developed the necessary mathematics (1962) and the first hardware implementation of the CT scanner (1972) that was able to image the brain. This scanner was able to compute one CT image in about 24 hours. Cormack and Hounsfield shared the Nobel Prize in Physiology and Medicine in 1979. Note: Hounsfield never claimed that he invented CT. The original concept was published in 1917 by Radon. Oldendorf (1961) rotated a head phantom on a gramophone turntable and provided simultaneous translation by having an HO-gauge railway track on the turntable. This contraption was pulled slowly through a beam of X-rays falling on a detector. Oldendorf showed the internal structure of the phantom. Even earlier, there were reports (1957, 1958) from Russia (actually CCCP at that time) that a working CT machine was built.

2.2 X-ray physics

An X-ray is electromagnetic (EM) radiation similar to light, radio waves, TV waves, etc. Table 2.1 shows some of the components of the EM spectrum, their frequency, wavelength, energy, and use.

Table 2.1 Electromagnetic Wave Spectrum (from [Enderle et al.])

Energy (eV)	Frequency (Hz)		Wavelength (m)
4×10^{-11}	10^4		10^4
4×10^{-10}	10^5	AM radio waves	10^3
4×10^{-9}	10^6		10^2
4×10^{-8}	10^7	Short radio waves	10^1
		FM radio waves and TV	
4×10^{-7}	10^8		10^0
4×10^{-6}	10^9		10^{-1}
4×10^{-5}	10^{10}	Microwaves and radar	10^{-2}
4×10^{-4}	10^{11}		10^{-3}
4×10^{-3}	10^{12}	Infrared light	10^{-4}
4×10^{-2}	10^{13}		10^{-5}
4×10^{-1}	10^{14}	Visible light	10^{-6}
4×10^{0}	10^{15}	Ultraviolet light	10^{-7}
4×10^{1}	10^{16}		10^{-8}
4×10^{2}	10^{17}		10^{-9}
4×10^{3}	10^{18}	X−ray	10^{-10}
4×10^{4}	10^{19}		10^{-11}
4×10^{5}	10^{20}		10^{-12}
4×10^{4}	10^{21}	Gamma ray	10^{-13}
4×10^{7}	10^{22}	Cosmic ray	10^{-14}

Figure 2-2 graphically shows the electromagnetic spectrum and the corresponding energy of each component.

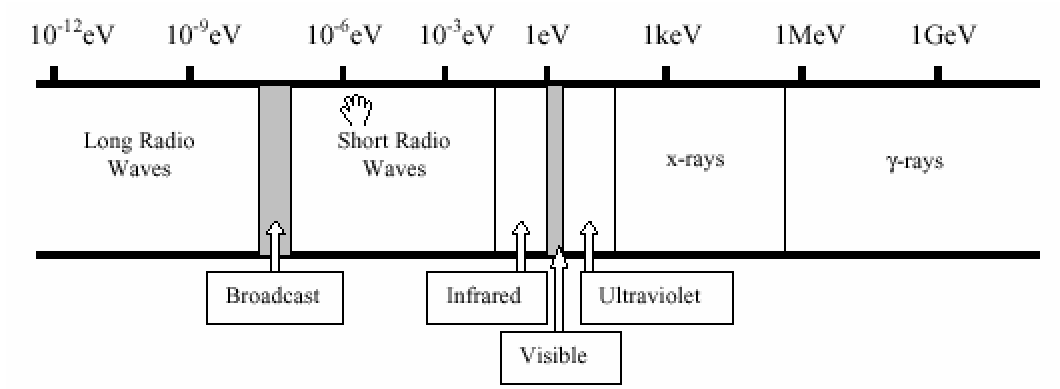

Figure 2-2 The Electromagnetic Spectrum. The photon energies are given in electron volts (eV).

Obviously there is a relationship between frequency and energy. The relationship between energy and frequency for EM waves is

$$E = hf \tag{2.1}$$

where E is energy in kilo electron volts (keV), h is Planck's constant (4.13×10^{-18} keV s, or 6.63×10^{-34} J s), and f is the frequency (Hz). (1 keV=1.6×10^{-19} joules) At least in a

vacuum, all EM waves propagate at the same speed, which is known as the speed of light ($c = 3.0\text{x}10^8$ m s^{-1}). The relationship is given by

$$c = \lambda f \tag{2.2}$$

where λ is the wavelength (m).

X-rays are also characterized as particles. This is a wonderful example of the duality of nature – energy is simultaneously both a wave and a particle. This is the message from Einstein's famous $E = mc^2$ equation. Viewed as a particle, an X-ray particle with velocity *v* and mass *m* has a momentum *p* given by

$$p = mv = mc = E/c = hf/\lambda f = h/\lambda \tag{2.3}$$

These X-ray particles are called photons, and these photons are delivered in packets called quanta. If the particle energy is greater than about 2-3 eV, then the photons are capable of ionizing atoms. Diagnostic radiation is typically in the range of 100 nm to about 0.01 nm, or from 12 eV to 125 keV.

An electron volt is the energy required to move a quantum of charge through 1 volt of potential energy. A quantum of charge is $1.60\text{x}10^{-19}$ coulombs, or the charge of one single electron. To break a chemical bond, one requires energies in the order of 2-10 eV, which can be delivered by EM waves in the ultraviolet region or above. Ultraviolet light breaks chemical bonds in tissue (i.e., ionizes tissue), thus it can be a danger to health. If the broken chemical bond breaks are located on the DNA molecule and in just the right place, skin cancer results.

The EM energies below the ultraviolet level cannot break chemical bonds, or produce ions. The most dangerous event from these low-energy photons is tissue heating. For instance, infrared light can heat objects by making them vibrate. Microwave ovens in the kitchen cause water molecules to tumble, which excitement in turn causes the temperature of the food to increase.

A classical experiment that shows the duality of EM energy is the double-slit experiment. If photons behaved like particles, then the result of the experiment would yield in two areas of the detector being exposed to particles. However, this is not the case. The results of the experiment sketched in Figure 2-3 are shown in Figure 2-4. If only one slit is open, however, one measures one bright spot (or point) on the detector behind the slit that is still open. Thus with one slit the EM radiation acts like a particle, but with two slits the radiation acts like a wave. In truth, the radiation is neither a particle nor a wave until we try to detect it, and then it acts one way or another, but not both. Which way it acts depends on what we are trying to measure.

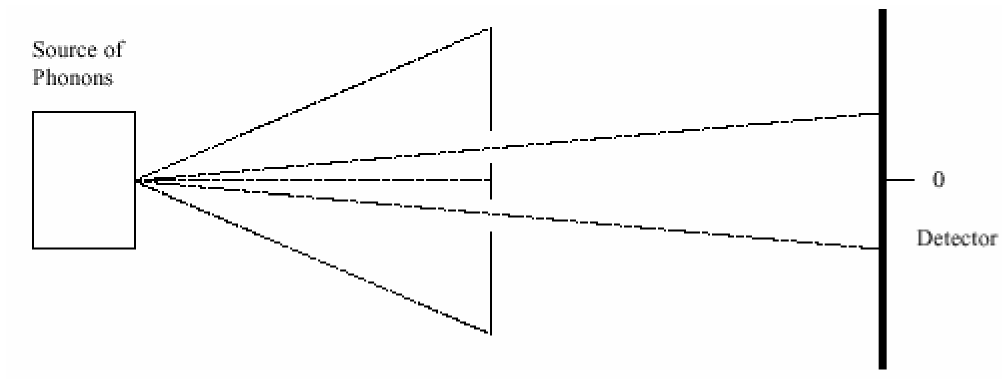

Figure 2-3 Classical double-slit experiment used to show dual nature of photons and electrons

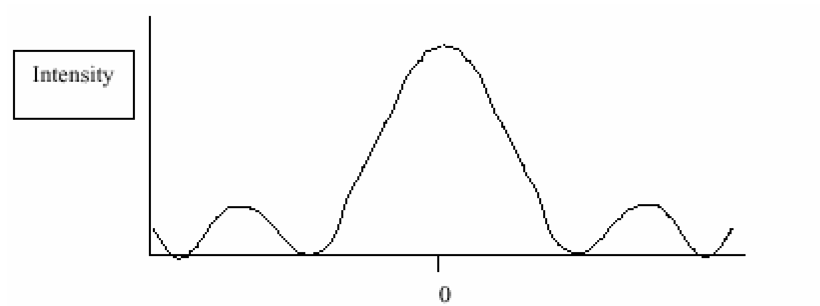

Figure 2-4 Results of the double-slit experiment when both slits are open

The results of the double slit experiment are exactly the same if electrons are used instead of EM radiation. Thus electrons can behave as particles and waves, just as EM radiation. Particle-wave duality holds for either EM radiation, or atomic particles. We don't perceive this duality for larger objects (like baseballs), though it exists, because the wavelength of its energy is very small and is confined within the size of the object.

2.3 Brief review of the structure of the atom

Realizing that the structure of the atom is first studied in high school, but also realizing that high school was a few years in the past, we will briefly review the structure of the atom. The reason for the review is that interaction of EM waves or particles with human tissue depends quite heavily on the structure of the atom. The review, in outline form, follows:

- Three basic particles of an atom are electron, proton, and neutron. Of course, there are many smaller particles that hold everything together, but study of these will be reserved for sub-atomic physicists who are experts in modern physics.
- The electron is negatively charged, the proton is positively charged, and the neutron is neutral. We will not try to answer how the nucleus (location of the protons and neutrons) stays together without flying apart due to all of those positive charges in close proximity. What is clear is that the nucleus would

explode due to the protons repelling each other if it weren't for the presence of neutrons.

- If the nucleus has too few neutrons, then the nucleus will be unstable, and fall apart. If the nucleus is too big, or has too many protons and neutrons, the nucleus will also become unstable. There are no stable isotopes of atoms above lead (Pb-208).
- The number of protons is called the atomic number. Hydrogen has only one proton, and its atomic number is one.
- To be neutral, an atom must have the same number of protons as electrons. If the atom is charged, then it is called an ion.
- The sizes of the neutron and proton are almost equal (proton rest mass is 1.67×10^{-27} kg; neutron rest mass is 1.68×10^{-27} kg). The rest mass of the electron is much smaller (9.11×10^{-31} kg. The atomic mass is thus defined as the number of neutrons plus the number of protons.
- The electron cloud surrounding the nucleus largely determines the volume of space occupied by an atom.
- The electrons cannot go just anywhere – due to their wave-nature, electrons are confined to orbitals of specific energies (frequencies). This notion is called the Bohr model named after Niels Bohr who promulgated this notion.
- The Bohr model consists of the following (for the first few shells)

Shells	**Orbitals**	**Number of electrons**
K	1s	2
L	1s, 3p	2+6=8
M	1s, 3p, 5d	2+6+10=18

- Each shell has a different energy (frequency), and each orbital within the shell has a unique energy.
- Wolfgang Pauli (1921) later reformulated the Bohr model in terms of quantum mechanical principles. Pauli observed that an atom can be defined by four quantum numbers:
  - n is the quantum number, which is an integer and scalar quantity;
  - l is the angular momentum quantum number, a vector quantity that has integer values ranging from 0 to n-1;
  - m_l is the magnetic quantum number with integral values ranging from –1 to 1; and
  - m_s is the spin magnetic quantum number, which has value –½ to ½.

  According to the **Pauli Exclusion Principle**, no two electrons in an atom can have the same set of quantum numbers.

- Thus only two electrons can have the "same" energy value within an atom. In fact, the model states that two electrons having the "same" energy must have unique energies. Stated otherwise, each electron must have a unique energy since the same energy within a single orbital must have different spins (one being +½,

and the other being –½). For any one atom, there can only be one electron for each unique energy level.

- The energy that we are interested in is the binding energy of the electron in each energy level. This will tell us how much energy we need to impart to the atom in order to dislodge that electron from the atom. Electron binding energies are high, usually on the order of 1-100 keV. Thus at least EM waves with the frequency (energy) of X-rays are necessary to change the electronic structure of an atom. As an example problem, is an EM signal with wavelength λ=1 nm ionizing? We need to calculate the energy of the wave. If it exceeds 1-2 keV, then the wave is considered ionizing, and potentially dangerous to human health.

$$E = hf = (4.13\times10^{-18}\ \mathrm{keV\cdot s})\left(\frac{3\times10^{8}\mathrm{m\cdot s^{-1}}}{1\times10^{-9}\mathrm{m}}\right) = 1.2\mathrm{keV}$$

- Since X-rays can dislodge electrons and make the atom an ion, X-rays are ionizing radiation. This radiation can change the chemical bonds of important substances, such as DNA. Diagnostic X-ray radiation is typically in the range of 100 nm to about 0.01 nm, or from 12 keV to 125 keV.
- Even higher energies are required to change the nuclear structure of atoms. Gamma rays provide sufficient energies to cause ions, but also cause a transformation of the atom from one type to another through a change in the atomic mass and number.
- Radio frequencies are not energetic enough to interact with the atom at all. Instead, radio frequencies interact with the spin of an electron. This property is used in building MR images.

3. Interaction between X-rays and matter

There are several modes of interaction of X-rays with matter. This is more than just a passing curiosity; the study of X-ray interaction is important for understanding the development of image contrast in medical images, and in understanding how X-ray detectors work. At the present time, there are five possible modes of interaction:

1. Coherent (Rayleigh) scattering
2. Photoelectric effect
3. Compton scattering
4. Pair production
5. Photo-disintegration

The probability of each mode is determined primarily by the energy of the incident photon and the atomic number of the item. This is a stochastic (random) process, and can be adequately described only by using statistical models of the interaction. We will not delve into this topic in such detail.

3.1 Coherent (Rayleigh) scattering

Coherent scattering describes the collision of a photon with an electron such that the photon is deflected into a new direction. Little energy is lost by the low energy photon, which has insufficient energy to ionize the atom. This is not an ionizing interaction.

This scattering modality is of little importance to medical imaging, EXCEPT for ^{125}I, which is used in nuclear scans of the thyroid. The resolution of the thyroid scans suffers due to coherent scattering of the emitted photons.

3.2 Photo-disintegration

This is the stuff of nuclear reactions. The photons interact with or are absorbed by the nucleus of the target atoms. In this modality, one or more nuclear particles are ejected. This results in one element becoming a different element. This elemental transformation would be extremely damaging to human tissue. This modality can occur if the photon has a very high energy (frequency). Typical energies for these photons are > 1MeV.

3.3 Photo-electric effect

Albert Einstein won the Nobel Prize for physics for explaining this modality. Even though the explanation involved quantum mechanics, the explanation is not different from the qualitative description of the relation between energy, frequency, particles, and waves that we have been considering thus far.

Recapitulating (with a slight twist) our earlier discussion, according to the quantum theory, EM radiation is quantized into discrete packets or quanta called photons. Each photon has an energy E that depends on the frequency f. The relationship between the energy and frequency is $E = hf$, which is Equation (2.1) above.

A single photon has one and only one frequency (and thus one and only one energy state), and can interact with one and only one electron. A photon cannot share its energy with several electrons. Since a photon travels at the speed of light, relativity theory (which we have not talked about yet, but which any educated person should at least attempt to understand, keeping in mind that Niels Bohr said that anyone who understands relativity hasn't thought about it long enough) predicts that the photon has zero resting mass, i.e., the energy is entirely kinetic. If the photon interacts with an electron, then it imparts its total energy to the electron and the photon disappears. If the energy required to hold the electron in place in the atom is less that the energy imparted to the electron by the photon, then the electron can escape thus producing a photoelectron. The kinetic energy of this photoelectron will depend on how much energy above the binding energy the incident photon had.

What happens if the bombarded electron is associated with an atom? If the photon has an energy level equal to or greater than the binding energy of the K shell of the atom, then the photon will "kick out" one of the K-shell electrons. However, atoms do not like to have their lowest energy levels empty – it makes them terribly nervous. As a consequence, an electron from a higher energy level will move to fill the lower energy level. This can happen either by one of the outside shell electrons moving to the unfilled energy level, or it can happen as a cascade event in which an L-shell electron moves to the K-shell, a M-shell electron moves to the L-shell, etc.

As an electron moves from a higher energy shell to a lower energy shell, it must give up (get rid of) the excess energy. This process either produces photons, or the excess energy can actually cause other electrons to become free of their shells. The energy in the photons produced by this falling-down process is called fluorescent or characteristic energy; the radiation is called characteristic radiation. The photoelectron produced is called an Auger electron. This process is illustrated in Figure 3-1.

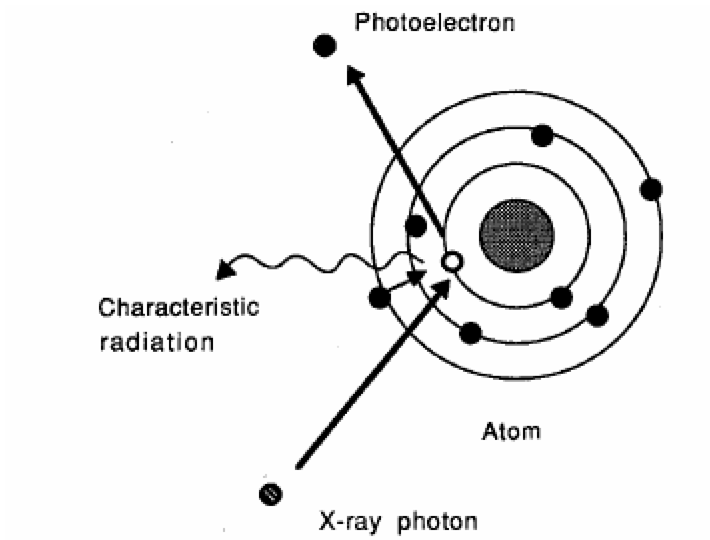

Figure 3-1 Drawing of photoelectric effect (from [Sung et al.]).

For example, suppose that the incident photon has energy *E*. It imparts all of its energy to the K-shell electron. If this electron has a binding energy E_b, then this is the amount of energy required to remove the electron from its shell. If $E>E_b$, then the remainder of the energy ends up as kinetic energy. This moving electron is the photoelectron. Thus, $E = hf = \frac{1}{2}m_0v^2 + E_b$ where m_0 is the resting mass of the electron.

The next event will be that an electron from a higher-energy shell will move down the energy gradient to the K shell. This electron will give up its excess energy, which is released as a photon. The energy of this photon will be the difference in binding energies between the upper (higher energy) shell and the lower shell. If this excess energy is greater than or equal to the binding energy of another electron, then this energy can be used to free the second electron. This secondary electron is called Auger electrons.

As a quantitative example, consider the following. The binding energies for Iodine are:

Shell	Binding Energy (keV)
K	-33.2
L	-4.3
M	-0.6

A photon of 9.86×10^{18} Hz kicks out a K-shell electron. An M-shell electron fills its place, so the change in energy is 32.6 keV. Thus, characteristic radiation with photon energy of 32.6 keV will be emitted.

3.4 Compton scattering

In Compton scatter, a photon interacts with an electron, but in contrast with the photoelectric effect, only a part of the photon energy is transferred to the electron. The

photon continues on its way, but with reduced energy (i.e., a lower frequency). This is equivalent to a reduction in the momentum of the photon. The electron is still emitted from its shell. This phenomenon is illustrated in Figure 3-2.

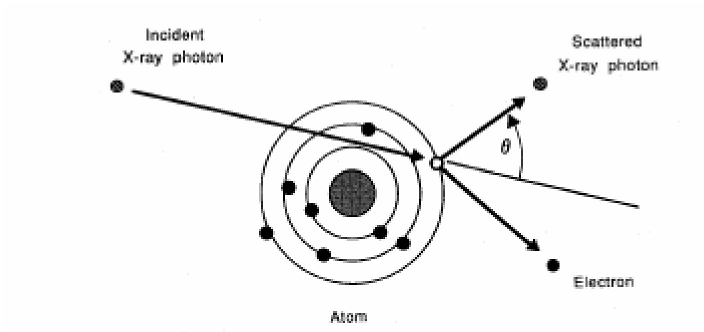

Figure 3-2 Illustration of the Compton scattering phenomenon

The momentum of a photon is given by the following equation.

$$P = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda} \tag{3.1}$$

Thus the momentum of an EM wave depends on its frequency. The direction of the momentum is along the direction of propagation of the wave.

Considering a particle nature of a photon, one can use conservation of energy and momentum to describe the collision between a photon and a charged particle. This interaction is graphically illustrated in Figure 3.3.

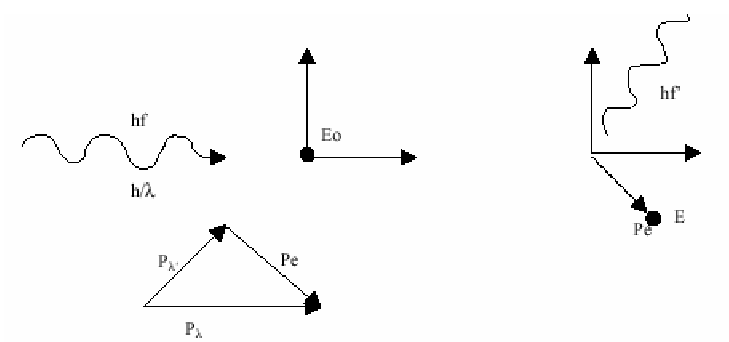

Figure 3-3 Illustration of the interaction between a photon and a charged particle

The momentum of the incident photon is h/f while the momentum of the resulting photon is h/f'. The momentum of the electron is $m_0 v$. Using the Law of Cosines and the triangle drawn in Figure 3-3, we can write an equation based on the conservation of momentum.

$$P_{\lambda}^{2} + P_{\lambda'}^{2} - 2P_{\lambda}P_{\lambda'}\cos(\theta) = P_{e}^{2} \tag{3.2}$$

This equation can be solved for the change in wavelength (or energy) as

$$\Delta\lambda = \lambda' - \lambda = h/_{m_0 c}\left(1-\cos(\theta)\right) \tag{3.3}$$

From this the energy of the scattered photon is

$$E' = \frac{E}{1+\frac{E}{m_0 c^2}\left(1-\cos(\theta)\right)} \tag{3.4}$$

The wavelength of the scattered photon increases over the incident photon, and thus its energy decreases. The change in energy and wavelength depends only on the rest mass of the electron, the speed of light, Planck's constant, and the angle of the scattered photon. The value $m_0 c^2$ is ubiquitous (we will see this over and over again), and is equivalent to 511 keV.

High-energy photons exhibit more Compton scattering than low energy photons. Unfortunately, Compton scattering is the major source of background noise in X-ray images. In addition, Compton scattering is the major source of tissue damage due to X-rays. For these reasons, this phenomenon is very undesirable.

If the incident energy E is low, then the scattered energy E' is roughly independent of scattering angle θ. If, on the other hand, incident energy is high, then the scattered energy E' is higher for small θ. This indicates that scattered photons with higher energies will continue in approximately the same direction.

3.5 Pair production

Pair production is characterized by a photon-nucleus interaction. In this, high-energy photons are absorbed by a nucleus; a positron (a positive electron: a form of anti-matter) is emitted along with an electron. This interaction is extremely unusual in diagnostic radiology due to the high energies required. However, pair production describes anti-matter formation that is used in PET scanning. We will talk more about this a bit later.

3.6 Summary

The primary modes of interaction are

1. Photoelectric in which a photon is absorbed, characteristic radiation is emitted along with photo-electrons, and possibly Auger electrons.

2. Compton scatter in which a photon is not absorbed but rather scattered. The photon energy is reduced, and an electron is ejected. This is the major source of noise in X-ray (and CT) images.
3. Pair production in which a photon is absorbed by the nucleus, a positron is emitted, and an electron is ejected.

The frequency of occurrence (the probability) depends on the incident energy *E*, configuration of the electrons around the atom, atomic number and mass of the target tissue, etc. Figure 3-4 shows the relative probability of different absorption mechanisms for X-rays in carbon. Most human tissue types have similar curves. This figure is key to understanding the physics of medical X-rays. At the energy levels of most medical X-rays (50 keV to 200 keV), most of the energy absorbed by human tissue is due to the photoelectric effect. Also playing an important role is Compton Scattering, which we will find adds noise to the image. Pair production occurs at energy levels that are usually out of the frequency range of medical X-rays.

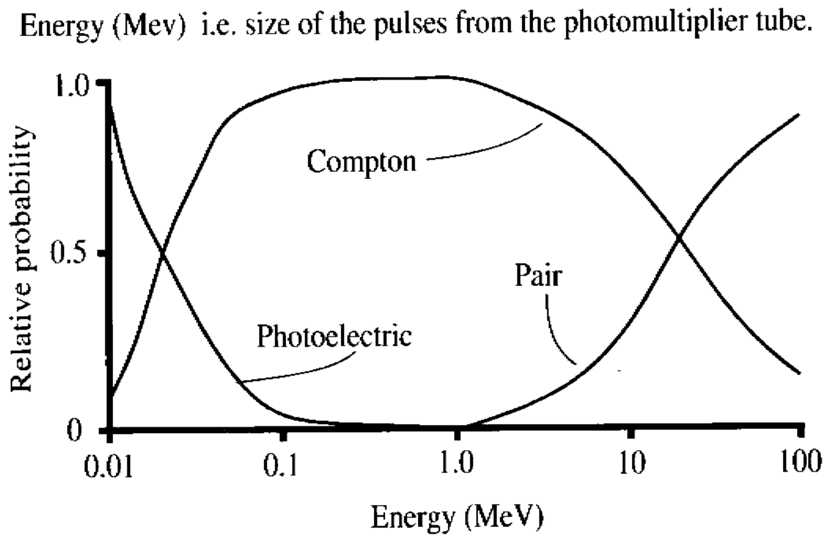

Figure 3-4 Relative probabilities of three absorption mechanisms. Low energy photons are absorbed primarily by photo-electric mechanism, high energy photons by pair production, and mid-level energy photons by Compton scattering

4. Dose and Exposure

In order to protect people from ionizing radiation, or to calculate the risk/benefit ratio for exposing a patient to possibly necessary radiation, it is obviously necessary to measure radiation to which the subject is exposed. Within a radiation field close to a radiation source there will be a *fluence* of particles that has been defined as dN/da where N is the number of particles incident on a sphere of cross-section a. The unit of exposure used to be the roentgen (R) that was defined as "That quantity of radiation that will release an electrical charge of 2.58×10^{-4} coulombs in one kilogram of dry air." This is equivalent to about 1.3×10^{15} electrons. The new unit has no name (this is the actual truth), but is just given as 1 R = 2.58×10^{-4} C kg^{-1} dry air.

A more useful measure is derived from the concept of *radiation dose*, which describes the dose of radiation absorbed by human tissue. Another measure is the *dose equivalent*, which takes into account the fact that some types of radiation are more damaging than others.

The absorbed dose is measured in terms of the energy absorbed per unit of mass of tissue. Energy is measured in joules, and mass in kilograms. The unit of dose is the 'gray' (Gy) where

$$1 \text{ Gy} = 1 \text{ J kg}^{-1} \text{ of tissue}$$

There is an old unit of dose that is still used, the rad (radiation absorbed dose), that is related to the gray by

$$1 \text{ rad} = 0.01 \text{ Gy} = 0.01 \text{ J kg}^{-1} \text{ of tissue}$$

As an illustrative (hopefully) example, if 1000 quanta (particles) are completely absorbed in 1 kg of tissue, then the energy absorbed by the tissue will be 1000 times the energy of each particle. Radiation energy is usually measured in keV (or MeV), but you can convert these energies to joules:

$$1 \text{ J} = 6.2 \times 10^{18} \text{ eV}$$

A dose of 1 Gy means that 6.2×10^{18} eV of energy have been absorbed in 1 kg of tissue. This could arise from 6.2×10^{12} X-ray photons of energy 1000 keV, or other combination of numbers.

Absorbed dose is difficult to measure. It is first calculated be measuring the exposure and then calibrating from knowledge of mass absorption coefficients for air and tissue (more later).

4.1 Dose equivalent

The unit of dose equivalent is that dose that gives the same risk of damage or detriment to health whatever the type of radiation. This unit is called the sievert (Sv):

$$1 \text{ Sv} = 1 \text{ J kg}^{-1} \text{ tissue x } \textit{constant}$$

The constant, called the radiation weighting factor, depends on the type of radiation. There is an old unit that is still used, the rem, that is related to the sievert by

$$1 \text{ rem} = 0.01 \text{ Sv} = 0.01 \text{ J kg}^{-1} \text{ tissue x } \textit{constant}$$

The dose equivalent in Sv is obtained by multiplying the dose in Gy by a constant:

$$\text{dose in Sv} = \text{dose in Gy x } \textit{constant}$$

The radiation weighting factor for X-rays and γ-rays is unity (1), for neutrons the constant is 10, and for α particles the constant is 20. Therefore, if you had your choice, you would rater be radiated by X-rays than α particles. Table 4.1 gives some idea of the sizes of the units of dose.

Table 4.1 Typical figures for X-ray doses for five different conditions

Dose due to background radiation in 1 year (in Iowa)	1 mSv=0.1 rem
Level set as the maximum dose to the general population in 1 year (a larger dose is sometimes allowed in 1 year provided the 5-year average does not exceed 1 mSv).	1 mSv = 0.1 rem
Level set as the maximum dose to people who work with radiation (50 mSv is the maximum any one year)	20 mSv = 2 rem
Dose exposure that will cause nausea, sickness, diarrhea in most people	0.5 Gy = 50 rad
Dose exposure that will kill many people in a few months following exposure	6 Gy = 500 rad

4.2 Maximum permissible levels

Maximum permitted doses set in the various codes of practices are expressed in units of dose equivalent. The International Commission on Radiological Protection (ICRP) recommends maximum annual dose equivalent for radiation workers as 50 mSv (5 rem), with a 5-year average less than 20 mSv per year. Larger doses are allowed to specific body parts. For members of the public, the recommended whole-body dose is 1 mSv (0.1 rem) averaged over 5 years.

Table 4.2 Maximum permitted doses from ICRP

Condition	Dose
Radiation worker	50 mSv = 5 rem (5-yr average < 20 mSv = 2 rem)
Public	1 mSv = 0.1 rem over 5 years

The US Nuclear Regulatory Commission has adopted standards that limit maximum exposure for the general public to 0.5 rem per year. Limits for occupational exposure are 1.25 rem/3 months for the whole body, and 18.75 rem/3 months for the extremities. Routine personal monitoring is usually done with film badges and ring-type finger badges.

The maximum permitted dose levels have been reduced over the last 70 years. In 1931, the maximum permitted level was 15 mSv (1.5 rem) PER WEEK. It is possible that further reductions will be made. The reason is that even small doses have long-term effects, and it is these effects that are the cause of continuing controversy in setting "safe" settings. The biological effects can only be expressed in statistical terms as the chance that a generic change, or a leukemia (or other cancer) might develop over a given period of time. The assessment of risk is complicated because there are also natural causes of these changes. The existence of long-term effects is the reason why young people, and particular the unborn fetus, are subject to the greatest risk for ionizing radiation, and thus are subject to their own specific maximum radiation exposure levels. For example, it is recommended that, under the "10 day rule," women are only exposed to diagnostic X-ray procedures during the 10 days following menstruation when pregnancy is unlikely.

4.3 Environmental dose

We are exposed to radiation from many different sources during our lives. Some of the sources are natural, some are man-made. Table 4.3 quantifies the body doses of various of these sources. You should compare these with the maximum allowed dose given above.

Table 4.3 The doses correspond to six different situations (values are approximate).

Cosmic radiation	200 µSv (20 mrem) over 1 year
Natural radioactive materials (e.g., ^{238}U)	300 µSv (30 mrem) over 1 year
Naturally occurring radioactive materials in the body (e.g., ^{40}K)	300 µSv (30 mrem) over 1 year
Chest X-ray	500 µSv (50 mrem) skin dose for one X-ray
Coronary angiogram	20 mSv (2 rem) skin dose for one procedure
Nuclear power station	< 1mSv (100 mrem) over 1 year 1 km from the station

4.4 Body parts – whole body dose

There is a maximum permitted dose of 20 mSv (2 rem) for radiation workers, and 1 mSv (0.1 rem) for the general public. The basis for these levels of is the risk of biological damage. Some feel that it is too easy to exaggerate radiation hazards when making comparisons with other hazards of life. For example Table 4.4 shows figures in terms of an equal risk of causing death on 1 year.

Table 4.4 All of these activities carry the same risk. They give a 1 in 20000 chance of causing death in 1 year (from E.E. Pochin, 1974)

Exposure to 5 mSv (0.5 rem) whole-body radiation
Smoking 75 cigarettes
Traveling 2500 miles by motor car
Traveling 12 500 miles by air
Rock climbing for 75 minutes
Canoeing for 5 hours
Working in a typical factory for one year
Being a man aged 60 for 16 hours
Being a man aged 30 for 20 days

The information in Table 4.4 is not meant to minimize in the engineer's mind the damaging effects of radiation; the information is meant to put the risk into perspective. Remember, these data are based on statistical models, and not on measured laboratory data.

Table 4.5 gives some typical doses obtained in clinical practice. Note that some of the doses are fairly close to the recommended limits (0.1 mSv averaged over 5 years for the general public).

Table 4.5 Doses for some common radiological examinations

Examination	**Dose (mGy)**
CC Breast	1.2
AP Chest	0.3
AP Lumbar spine	9.2
AP Pelvis	6.6
AP Skull	4.4

CC = Cranio-caudal view or projection
AP = Anterio-posterior view or projection

The ICRP have suggested the use of the quantity *effective dose equivalent*, which is a prescription for calculating the dose that, if given to the whole body, would produce the

same detriment as the actual exposure received to the patient. The calculation of EDE is complicated and uses Monte-Carlo procedures, but the result is a number that represents the whole body "danger" of the clinical procedure. Each clinical procedure has an EDE – choose one with a low EDE (as if the patients really have a choice). Table 4.6 gives the effective dose equivalent and selected organ doses for various diagnostic procedures.

Table 4.6 Effective dose equivalent (mSv) and organ doses (mGy) for breast, red bone marrow, lung, thyroid, skin, ovaries, and testes for selected radiological examinations (from [Webb])

Examination		**Doses per Examination**						
	EDE	Breast	RBM	Lung	Thyroid	Skin	Ovary	Testes
Barium meal	3.8	2.2	2.6	8.7	1.1	2.1	3.6	0.3
Barium enema	7.7	0.7	8.2	3.2	0.2	5.1	16.0	3.4
IVP	4.4	0.7	1.9	7.0	0.2	1.9	0.8	0.1
Cholecystogram	1.0	0.4	0.8	1.6	0.1	0.8	0.4	0.0

The literature on ionizing radiation hazards is enormous. A general qualitative understanding for the situation can be gained, however, by consensus statements such as "the average risk of inducing a fatal malignancy in human tissue subjected to a dose of 10 mSv is in the region of 10^{-4}," or "the overall risk associated with a tissue dose, in the developing embryo or early fetus, of 10 mSv may lie in the range of 0-1 per 1000 for all serious malformations and cancers" [Webb]. **The message is to keep the dose as low as reasonably achievable, but especially for the very young.** Current practice leads to tissue doses in the range of 0.1-100 mSv per examination. Nuclear medical procedures often exceed this range. Procedures based on CT often exceed this range. We will investigate what this means for the medical imaging engineer.

5. Propagation model

X-ray images are formed by X-ray photons interacting with an X-ray detector (more later on detector details). This is a *transmission image* since some of the applied energy is absorbed by the body, and some of the energy passes through the body to the detector. An image represents the transmission (or attenuation) distribution of the patient under study.

5.1 Simple transmission imaging

The transmission image, $I(x, y)$, is a 2-D projection of a 3-D distribution of X-ray attenuation (interaction) properties of the tissues. Consider Figure 5-1 in which an X-ray beam with intensity I_0 is incident on a block of uniform tissue. Assume that the cross-sectional area of the beam is *A* and the cross-sectional area of an atom in the tissue is σ.

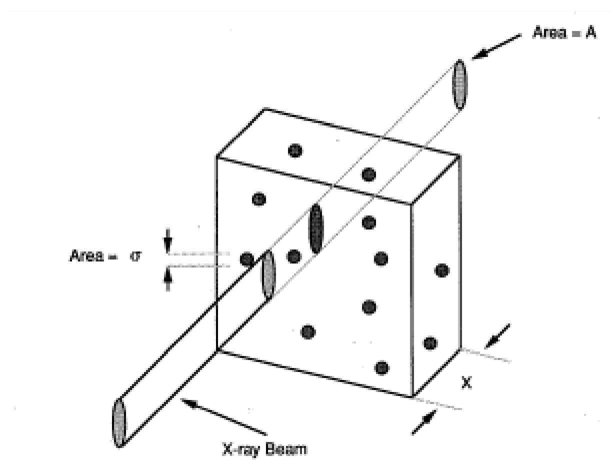

Figure 5-1 X-ray beam of cross-section *A* intersects tissue of thickness *x*

Let *n* represent the number of atoms per unit volume in the block of tissue. Then $n\sigma$ is the total cross-sectional area of the atoms per unit volume. The beam has cross-sectional area of *A* units. Thus the total area of atoms hit by the beam is $An\sigma$. The probability of a photon in the beam interacting with an atom is then

$$\frac{An\sigma}{A} = n\sigma \tag{5.1}$$

Next assume that any interaction completely attenuates the X-ray energy beam. This of course is not the usual case. If true, then the change in beam intensity within a small slab of the beam thickness *dx* is

$$dI = -n\sigma I dx \tag{5.2}$$

or

$$\frac{dI}{dx} = -n\sigma I \tag{5.3}$$

Solving this simple equation yields the simple by critically important solution given by

$$\boxed{I(x) = I_0 e^{-\mu x}} \tag{5.4}$$

where $\mu = n\sigma$ is called the *linear attenuation coefficient* (1/cm), and *x* is the *path length* (cm) through the material. $I(x)$ is the photon intensity at position *x*, I_0 is the intensity from the X-ray source, and μ is the attenuation coefficient. This development is valid only for homogeneous tissue, and mono-energetic X-ray photons. The linear attenuation coefficient is actually a function of the photon energy.

5.2 Attenuation coefficient

It is a common practice to normalize μ by the tissue's density ρ. This yields a *mass-attenuation coefficient*. The reason is that the attenuation coefficient becomes independent of the physical state of the tissue being studied. Consider water with a 50 keV X-ray beam passing through.

Table 5.1 Attenuation coefficients for water in different states

State	**μ (cm^{-1})**
Liquid	0.214
Solid	0.196
Vapor	0.00013

If we compute the mass-attenuation coefficient, then for all states:

$$\frac{\mu}{\rho} = 0.214\,\text{cm}^2\,\text{gm}^{-1}$$

Figure 5-2 depicts the mass-attenuation coefficients for different tissue types and other materials as a function of the energy levels of the X-ray incident photons.

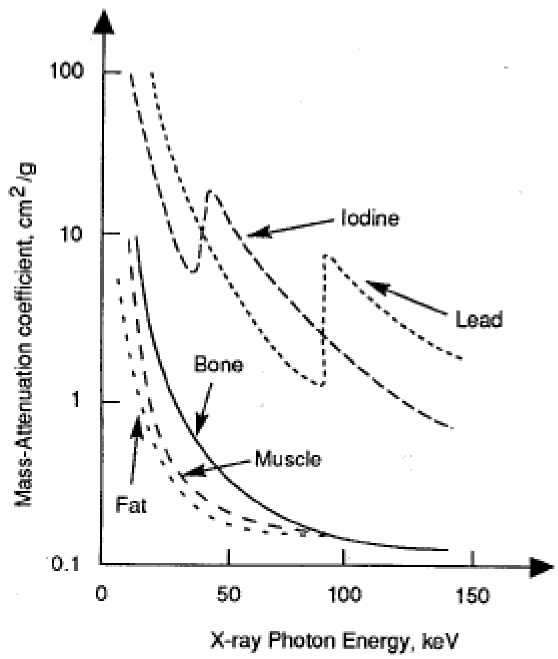

Figure 5-2 Mass-attenuation coefficients of several media as functions of X-ray energy

This figure is used to select the desired photon energy. For example, to assure good contrast between bone and muscle, one would use a beam made of 30 keV photons, but not 100 keV photons. Note the large mass-attenuation coefficient of Iodine. This is the reason that Iodine is often used as a contrast agent.

Some materials exhibit "discontinuities" in the mass-attenuation coefficient. For example, the sudden increase in the coefficient magnitude for Iodine around 35 keV is because this is approximately the bonding energy of the K-shell electrons orbiting the nucleus. This discontinuity is called the *K-edge*.

The attenuation coefficient can be used to calculate the *half-value layer* (HVL), which is the thickness required to attenuate the beam intensity by 50%. Solving Equation (5.4) for the value of x we get:

$$I(x) = I_0 e^{-\mu x} = \frac{I_0}{2} \tag{5.5}$$

which yields

$$x = -\frac{\ln(0.5)}{\mu} = \frac{0.693}{\mu} \tag{5.6}$$

The HVL is sometimes known as the *half-value thickness*.

As an example, water (in liquid state) has an attenuation coefficient μ=0.214 cm^{-1} at 50 keV. The HVL is then

$$x = \frac{0.693}{0.214} \approx 3\,\text{cm}$$

So 3 cm into the material the beam intensity is reduced to $I_0/2$, 6 cm into the material the intensity is $I_0/4$, etc.

Representative HVLs for soft tissue are: 22 mm at 30 keV, 35 mm at 60 keV, and 45 mm at 120 keV. This indicates that HVLs are a function of the energy of the X-ray beam.

5.3 Transmission imaging

The formulation used to derive Equation (5.4) is based on a thin beam passing through a homogeneous block of tissue, and assuming that the attenuation coefficient is constant along *x*.

Consider Figure 5-3 in which the X-ray beam passes through lung, water, soft tissue, and bone. In this case, the attenuation coefficient is not constant.

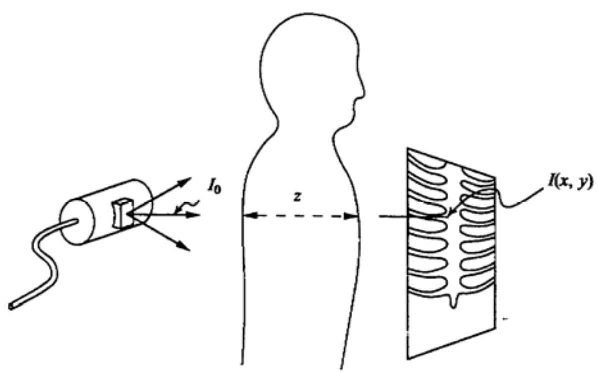

Figure 5-3 The geometry of X-ray transmission imaging

The intensity arriving at the film (or detector) is more generally written

$$I(x,y) = I_0 \exp\left(-\sum_i \mu(x,y,z_i)\Delta z_i\right) \tag{5.7}$$

where the path is divided into intervals Δz_i.

An example of the application of Equation (5.7) is (hopefully) instructive. Suppose that we wish to calculate the contrast or intensity difference between a lung tumor region and

the surrounding normal tissue as recorded on a conventional (not CT) X-ray image. The photons pass through about 35 cm of the chest. The photons first encounter about 3 cm of chest wall tissue, then 29 cm of lung air and tissue, and then 3 cm of chest wall tissue (if the beam passes through the inter-costal space). The total attenuation is the following:

$$\begin{aligned} I(x=3) &= I_0 e^{-\mu_1 3} \\ I(x=3+29) &= \left(I_0 e^{-\mu_1 3}\right) e^{-\mu_2 29} \\ I(x=3+29+3) &= \left(\left(I_0 e^{-\mu_1 3}\right) e^{-\mu_2 29}\right) e^{-\mu_1 3} \\ &= I_0 e^{-(\mu_1 6+\mu_2 29)} \end{aligned} \tag{5.8}$$

The attenuation coefficients for chest wall tissue and lung are μ_1=0.14 cm^{-1} and μ_2=0.05 cm^{-1}. Thus the intensity of the image arriving at the detector is

$$\frac{I}{I_0} = e^{-(0.14x6+0.05x29)} = 0.10 \tag{5.9}$$

With a 3 cm round tumor with attenuation coefficient of 0.14, we will need to add attenuation given by $e^{-(0.14x3)}$, which will result in a decrease in intensity by

$$\frac{I}{I_0} = e^{-(0.14x6+0.05x26+0.14x3)} = 0.077 \tag{5.10}$$

This is a change in contrast of 23%. If photons pass through two 1.5 cm thick ribs with a bone attenuation coefficient of 0.4 cm^{-1}, then we observe

$$\frac{I}{I_0} = e^{-(0.14x6+0.05x29+0.4x3)} = 0.046 \tag{5.11}$$

Recall that as the number of photons decreases, the smaller the exposure to the film (or detector), and the "whiter" the image in the region. It is often useful to examine the logarithm of the ratio of the incoming intensity to the exit intensity:

$$P(x,y) = \ln \frac{I_0}{I(x,y)} = \sum_i \mu(x,y,z_i)\Delta z_i \tag{5.12}$$

Note that the logarithm of the intensity ratio, which is named the projection $P(x,y)$, is simply the line integral of attenuation coefficients if the $\Delta z's$ approach zero. In this case,

$$P(x,y) = \int_{Source}^{Detector} \mu(x,y,z)dz \tag{5.13}$$

This sum is called a *ray sum*. You will work with the ray sum extensively when computing CT images in subsequent courses.

6. Brief Summary So Far

X-ray imaging is mainly an anatomical procedure. Some of the energy applied to the body passes through without interacting with the tissues, and some of the energy interacts with the tissue. The difference between those photons (quanta) that interact and those that do not determines the contrast in the image.

The photons that interact can cause ionization by primarily the photoelectric effect, and Compton scattering. The equations that we have derived that describe these effects, and the equations that describe the intensity as the X-ray beam passes through the body (especially Equation (5.4)), apply to only monochromatic radiation. X-ray photons generated by X-ray sources typically are heterogeneous or polychromatic. Since photons of different energies are attenuated differently (see Figure 5-2), the transmission of photons of different energies is complex. In practice, the energy of a monochromatic beam that has the same half-value layer as a polychromatic beam is considered the effective energy of the polychromatic beam.

An important concept is “beam hardening.” The polychromatic beam, after traversing a medium, contains fewer photons in the lower energy range, causing the effective energy of the beam to increase. This phenomenon is called “beam hardening.”

7. Generation of X-rays

X-rays are generated when electrons with high energy strike a target made from materials such as tungsten or molybdenum. The high-energy electrons can interact with the nuclei of the materials producing general (white) radiation. This is often termed Bremsstrahlung radiation, which refers to radiation emitted by a charged particle under acceleration. In particular, the term is used for radiation caused by decelerations (the word is German for braking radiation) when passing through the field of atomic nuclei *(external bremsstrahlung* – check out http://rd11.web.cern.ch/RD11/rkb/PH14pp/node16.html for a more complete discussion of this phenomenon). Radiation emitted by a charged particle moving in a magnetic field is called synchrotron radiation. The energy spectrum of X-rays due to bremsstrahlung of electrons decelerated in the field of atomic nuclei depends on the energy levels of the atomic electrons, due to the screening effect they have on the moving particle, and on the particle velocity. Another possibility is that the electrons can interact with orbital electrons producing characteristic radiation.

This phenomenon is represented in the following cartoon:

Figure 7-1 Cartoon illustrating Bremsstrahlung

7.1 White radiation

When an electron passes near the positively charged nucleus, the electron is attracted to the nucleus and is deflected away from its original trajectory. The electron may or may not lose energy. If it does not lose energy, the process is called elastic scattering, and no X-ray photon is produced. If it does lose energy, then the process is called inelastic scattering, and a photon will be produced. The radiation thus produced is called white radiation. This is depicted in Figure 7-2.

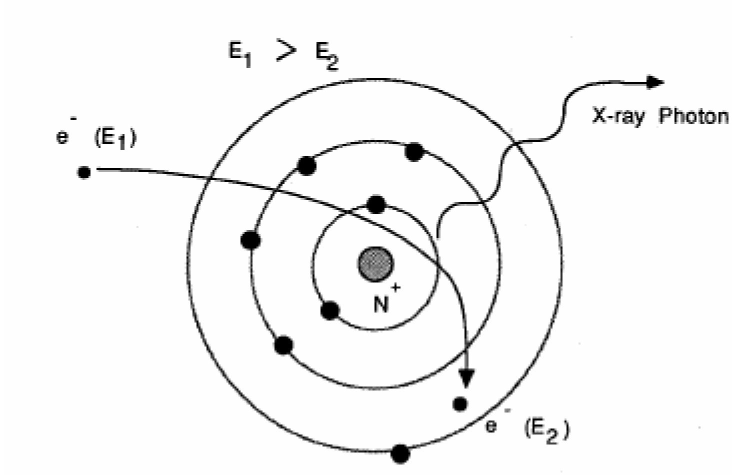

Figure 7-2 Deflection of high-energy electron by nucleus produces white radiation

The probability of the electron to lose energy increases as the atomic number of the atom increases. In the high-energy limit the probability density is given in E. Lohrmann, Hochenergiephysik, Teubner Studienbücher, 1981.

The electron may interact with many nuclei, therefore the energies of the X-ray photons generated by this process are distributed over a wide range of values, as shown in Figure 7-3.

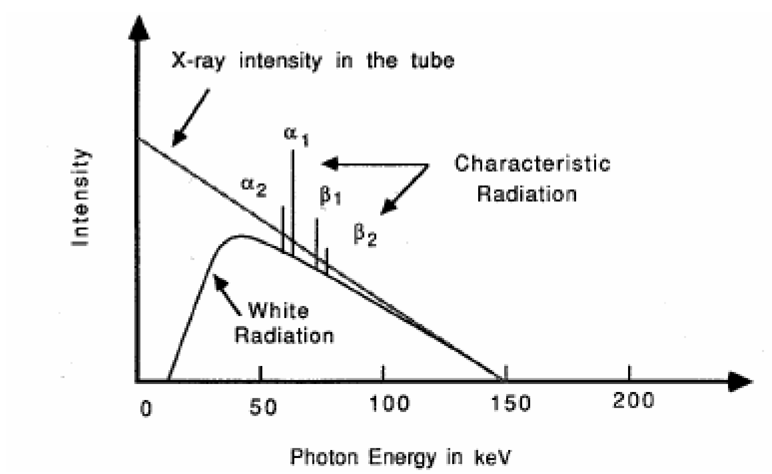

Figure 7-3 X-ray spectrum produced by the tungsten target of an X-ray tube

7.2 Characteristic radiation

When the high-energy electron strikes the inner shell of the target atoms, characteristic radiation occurs. This is similar to the photoelectric effect. Figure 7.2 shows the characteristic radiation resulting from L-shell electrons falling into the K shell (59.3 keV and 57.9 keV) and M and N-shell electrons falling into K shells (67.2 keV and 69 keV), respectively.

Most elements emit x-rays when properly bombarded with electrons. Heavier elements (like tungsten) are best because they emit a higher intensity through bremsstrahlung, but there are plenty of heavy elements to choose from. The real issue is engineering: Most electrons that hit the tungsten don't do anything special at all -- no bremsstrahlung, no K-shell emission. All of the energy from the electrons' impact then goes into heating the tungsten. Tungsten is used because it can withstand this bombardment, as it has a high melting point and can conduct heat away very well.

7.3 X-ray generators

The basic components of an X-ray tube are shown in Figure 7-4. The tube is operated in a vacuum, thus allowing independent control of the number and speed of acceleration of the electrons striking the anode. The anode is made of either tungsten or molybdenum. The cathode is composed of two parts: the filament made of tungsten, and a focusing cup. The filament is a helical coil about 0.2 mm in diameter. When current flows through the coil and the wire heats up; this energizes the electrons. If the heat is high enough, then the electrons escape from the metal. These electrons are then accelerated towards the anode by applying a high-voltage potential across the anode and cathode.

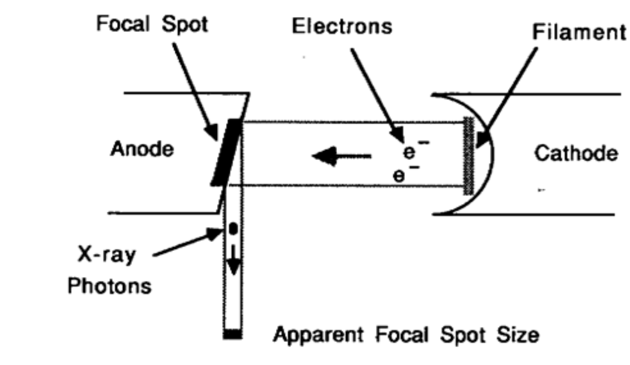

Figure 7-4 Basic components of an X-ray source

Most of the energy carried by the electrons is converted to heat at the focal spot. The anode angle causes the electron flow configuration to be focused to a narrow focal spot. The target material rotates in order to avoid heating a hole in the cathode (see Figure 7-5).

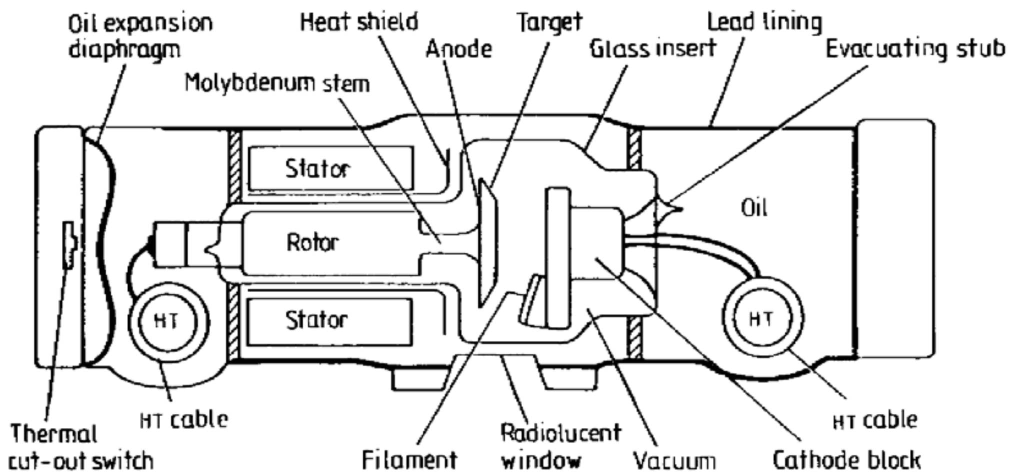

Figure 7-5 Drawing of a typical X-ray tube.

The X-ray tube electrical diagram is schematically shown in Figure 7-6. The tube voltage V_t can be dc or ac. The intensity of the X-ray beam is proportional to the power delivered to the tube from the supply voltage; thus, the beam intensity is proportional to the tube voltage V_t squared. Typical tube voltages range from a few kilovolts to about 150 kV.

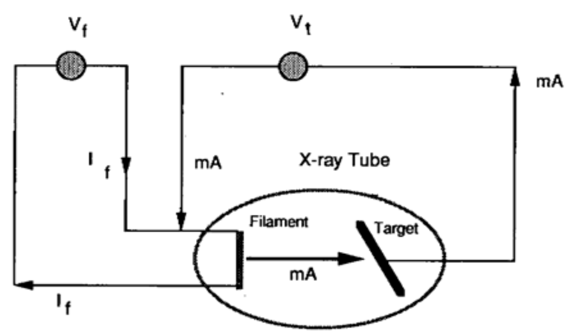

Figure 7-6 Electrical circuits associated with an X-ray generator

The number of X-ray photons produced by the tube depends on the number of electrons striking the target material, and therefore should depend on the tube current. It has been experimentally found that the number of photons emitted is linearly proportional to the tube current. Typically tube currents range from a few milliamperes to a few hundred milliamperes.

The tube current increases initially as the tube voltage is increased at a fixed filament current. However, as the tube voltage increases, a point will be reached after which an increase in potential difference has no effect of tube current. This is called the saturation current. In this region, the tube current is limited by the filament temperature (or equivalently the filament current). Typical values of filament current are a few amperes. If the tube is saturated, which is the normal operating condition, then the beam intensity

is proportional to the tube current. Radiology technicians always state that **the beam intensity is proportional to mA**.

In theory, the beam intensity is actually proportional to the tube current, and also the tube voltage squared. In practice, however, the beam intensity is adjusted by changing the tube current, which is usually varied by changing the filament current. Thus, a change in filament current changes the intensity of the X-ray photons.

The X-ray beam coming off the cathode material is polychromatic. Usually only a portion of the beam spectrum is desirable. Filtering out the undesired portion of the X-ray spectrum can substantially reduce the radiation dose delivered to the patient. Remember, the low-energy photons don't have enough energy to make it through the body (see Figure 5-2). As a result, the body absorbs almost all of the low energy photons, and no energy reaches the detector. This situation increases the chances of iatrogenic effects.

The glass surrounding the X-ray tube filters part of the X-ray beam. Usually a sheet of aluminum is placed immediately underneath the X-ray tube (i.e., between the tube and the patient). This sheet further filters the low-end of the beam's spectrum. A 3 mm aluminum layer can attenuate more than 90% of the X-ray energy at 20 keV. Copper is also used in the filter sheet. Copper is an effective filter of the high-end of the beam's spectrum.

7.4 Grids

X-rays are scattered, primarily by photoelectric effect and/or Compton scattering effects. The scattered photons appear on the X-ray image as noise that degrades image quality and increases patient exposure. Therefore, great efforts are expended in minimizing scattering. The most effective method is to place an X-ray grid under the patient and before the detector as shown in Figure 7-7.

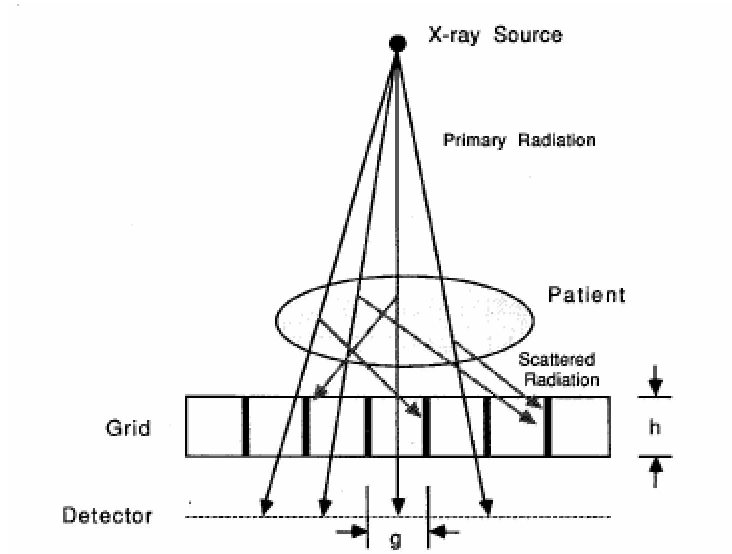

Figure 7-7 Scattered X-ray photons can be removed from the image by positioning a grid between the patient and the detector (or film).

Grid strips are usually made of lead, which is an effective X-ray absorbing material. If the grid strips are thin enough, then their image on the detector may be negligible. However, if the image quality requirements necessitate thick lead strips, then the grid may be moved during exposure to blur out the image of the grid lines. The grid shown in Figure 7-7 is called a linear grid. Other forms of grid have been used. For example, when the grid strips are focused towards the X-ray source, then grid is called a focused grid.

7.5 Detectors

The human eye cannot see X-ray photons. Our rods and cones of our eyes respond to lower frequency EM waves, not the high-frequency X-ray EM waves. As a consequence, the distribution of transmitted X-ray energy must be converted into a form that we can "see." This conversion is usually done by

1. exposing a photographic film: the X-ray energy excites the silver halide crystals, which are washed off leaving a viewable film;
2. estimating the photon density by measuring the ionization in a gas;
3. converting the X-ray photons to visible light, amplify this light with a photomultiplier tube, and view; or
4. building a solid state detector with current flow proportional to incident photon density.

The resulting images suffer from the non-ideal nature of the X-ray source and detectors. These non-deal qualities are due to geometric unsharpness, beam size, and object magnification.

Figure 7-8 illustrates the blurring effect of a finite focal point. If the X-ray beam has a beam width of f then a point in the patient appears as a smeared or blurred point with width d. This type of unsharpness is sometimes called *geometric unsharpness*, or the *penumbra*. To reduce this effect, increase S by moving the source further from the patient, reduce t by moving the patient as close as possible to the detector, or reduce f by installing a point collimator near the tube.

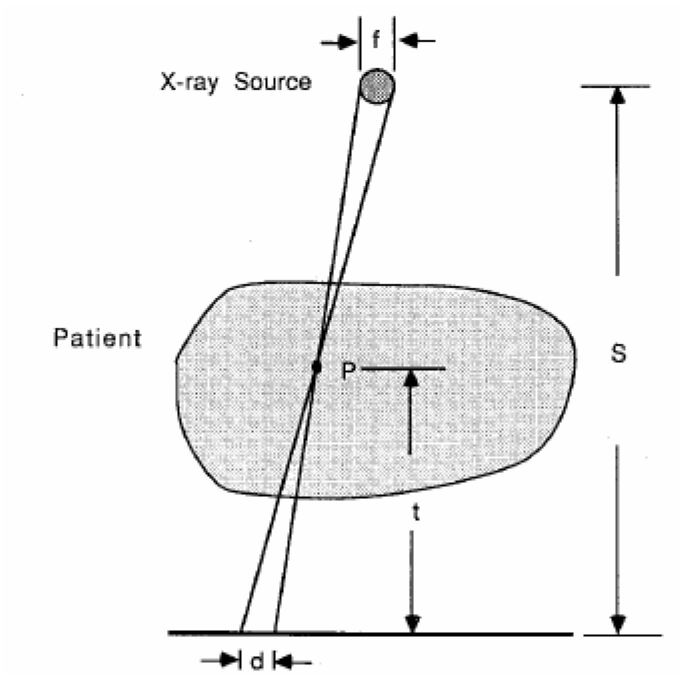

Figure 7-8 Finite aperture of X-ray source causes blurring of the image

Figure 7-9 illustrates the effect of beam size divergence. The beam size increases with increasing distance from the source because the photons do not travel in exactly parallel trajectories. To reduce this effect, decrease the distance from the source to the patient. Of course, this solution exacerbates the penumbra blurring effect. Oh well.

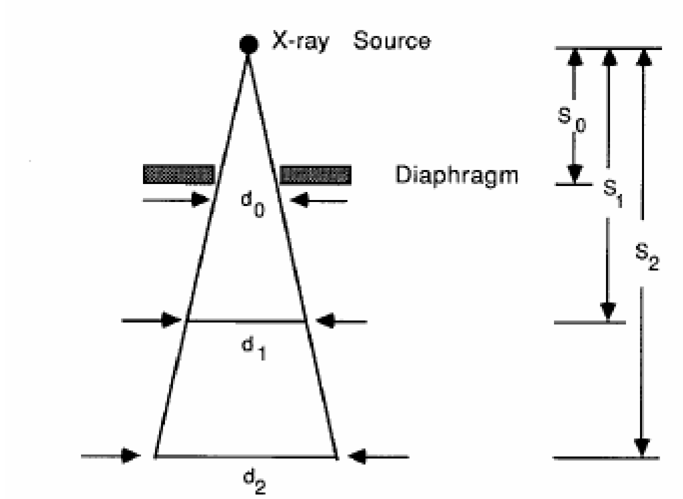

Figure 7-9 Effect of diverging X-ray beam size

Figure 7-10 illustrates the magnification effect. The apparent size of an object is affected by its position in the scanner field of view. Objects closer to the source appear larger than similarly sized objects located further from the source. To minimize this effect, increase the distance form the patient to the source. Oh well, again.

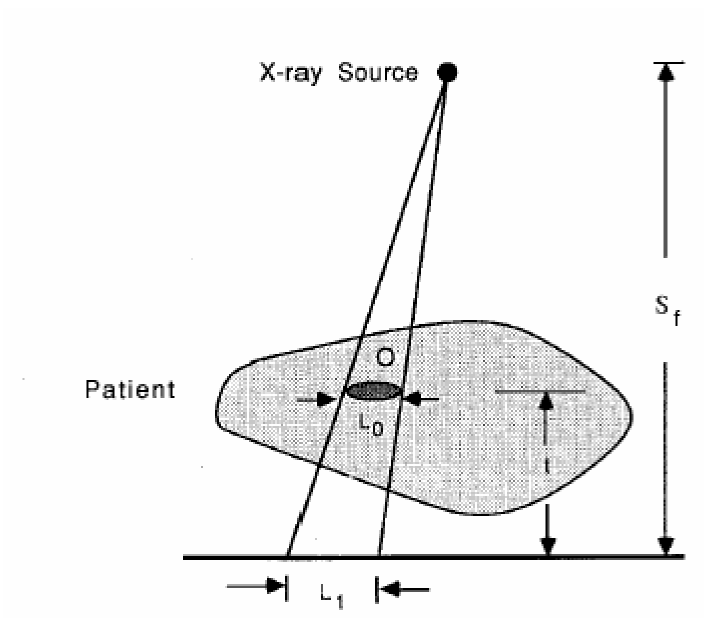

Figure 7-10 X-ray image of object magnified by ratio $\left(S_f / S_f - t \right)$**.**

Since the human eye cannot see the information carried by the X-ray directly, the images must be converted to a "visualizable" form. Usually this process is initiated with an

intensifying screen. An intensifying screen is basically a layer of phosphor (from 0.05 to 0.3 mm thick) that emits light photons when struck by X-ray photons. The most popular phosphors are calcium tungstate ($CaWO_4$) and terbium-activated rare-earth oxysulfide, though newer phosphors are sometimes used. The efficiency of $CaWO_4$ is only 5%, whereas the newer phosphors (such as gadolinium (Gd_2O_2S)) can achieve efficiencies of greater than 15%. These new phosphors emit light in narrow bands (usually green or blue).

Many electronic imaging systems use image intensifiers (show schematically in Figure 7-11). The incoming X-ray photons that have propagated through the patient will be absorbed by the fluorescent screen (usually 15 to 35 cm in diameter) with emission of light photons. The light photons strike the photocathode kept at ground potential, causing it to emit electrons in a number in proportional to the brightness of the screen. The photocathode is usually made of antimony or cesium compounds. The electron beam will be accelerated and focused onto the output fluorescent screen by the anode, which sets about 25 kV higher than the cathode. The output screen is usually only 1.5 to 2.5 cm in diameter.

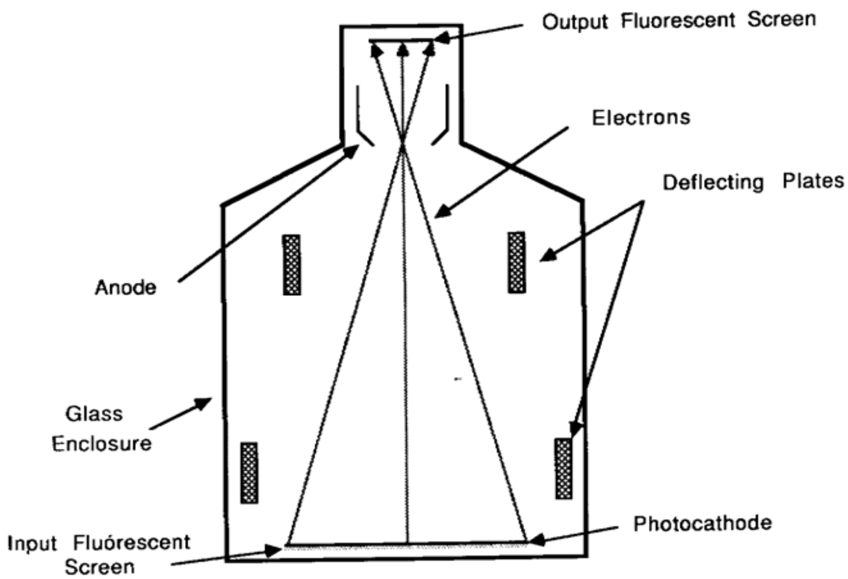

Figure 7-11 Physical construction of an image intensifier.

Two types of radiation detectors are currently used for X-ray detection: scintillation detectors and ionization chamber detectors. Figure 7-12 shows a scintillation detector, which consists of a scintillation crystal (usually sodium iodide with traces of thallium) coupled with a photomultiplier tube.

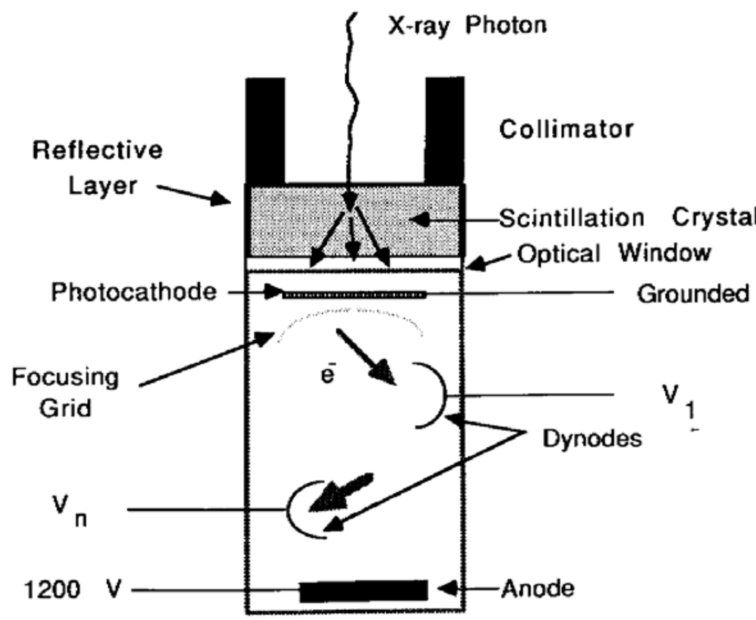

Figure 7-12 Physical construction of a scintillation detector with a photomultiplier tube

The photocathode emits electrons when struck by light. The electrons are accelerated by the dynodes, which is covered by material that emits secondary electrons when struck with an electron. In this way the number of electrons is multiplied as the electron beam passes from dynode to dynode. The output current is proportional to the number of electrons striking at V_n. The efficiency of this type of device is greater than 85%.

The second type of detector is the ionization chamber shown in Figure 7-13. This detector consists of a chamber filled with a gas (usually xenon). The molecules in the chamber are ionized by the X-ray photons. The ions are then attracted to the electrodes by a voltage difference between the electrodes. This device is cheap, and has a relatively small form factor (small size).

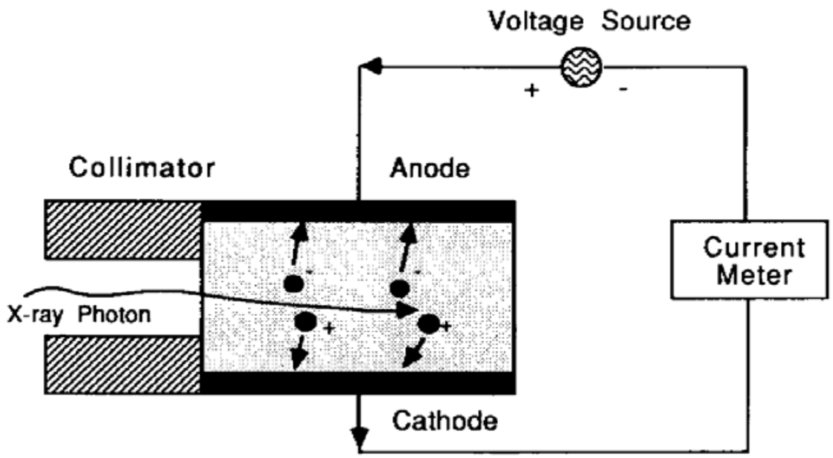

Figure 7-13 Physical construction of a radiation detector: ionization chamber

7.6 Miscellaneous X-ray procedures

There are many X-ray based procedures used in medical diagnosis. Some are fluoroscopy, mammography, and Xeroradiography.

X-rays can be captured on film, or viewed directly on a fluorescent screen. Figure 7-14 illustrates a conventional fluoroscope. In a typical fluoroscopic procedure for examining the GI tract, a contrast medium (usually barium sulfate) is taken orally or by enema. Figure 7-15 shows a colon radiograph where colon containing the contrast medium appears darker than the surrounding tissues. Because the patient is being continuously exposed to X-ray radiation, the radiation dose can be very high.

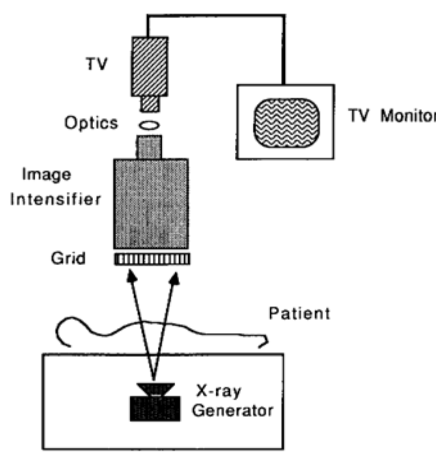

Figure 7-14 Basic components of fluoroscopy

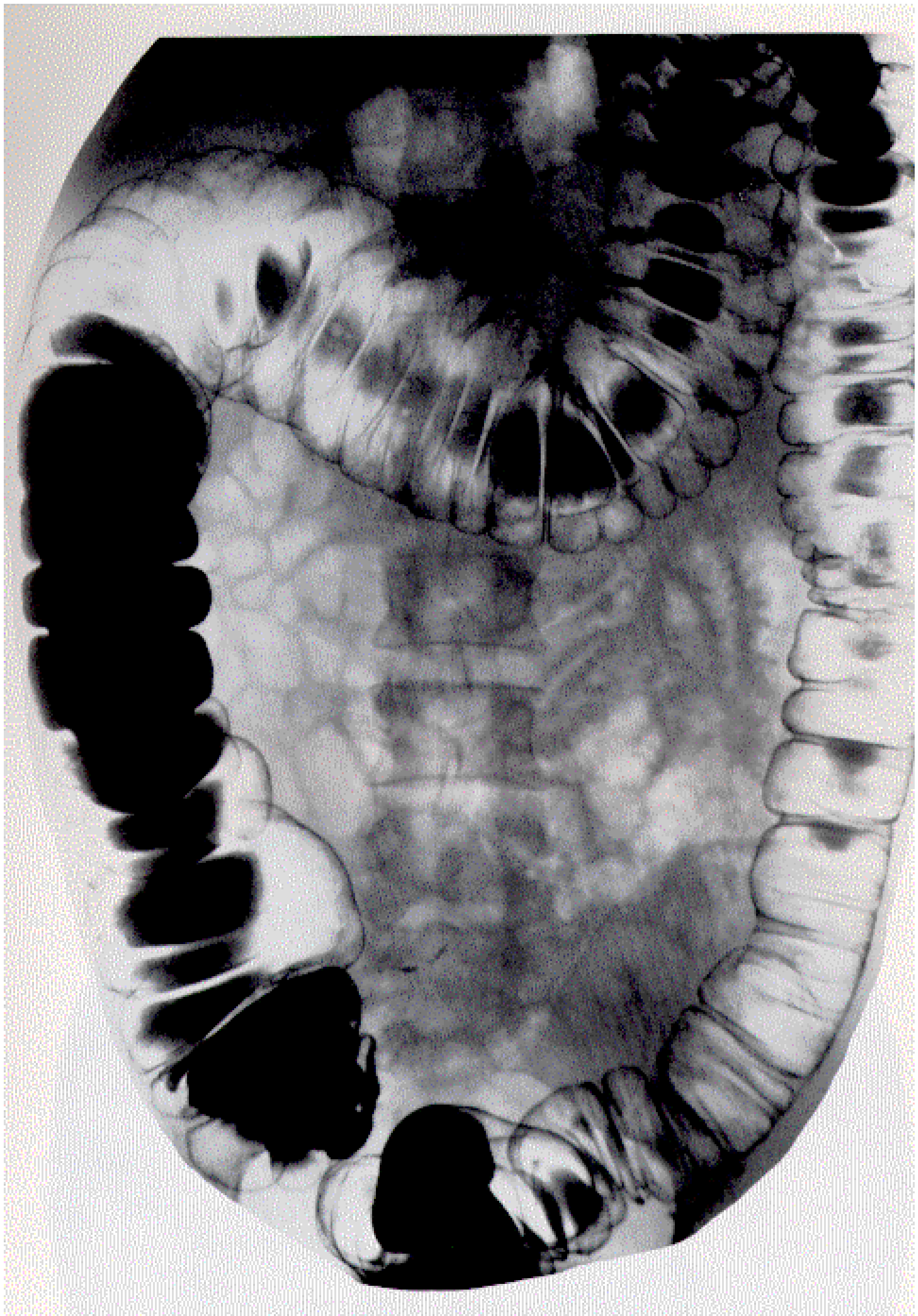

Figure 7-15 X-ray radiogram of the colon following air-barium double-contrast enema

X-ray mammography is usually performed without contrast injection. Mammography has a couple of special requirements. For example, low energy (typically 20 keV) X-rays are used since the tissues are soft. As a result, the anode in the X-ray tube is made of molybdenum. Modern mammography units can achieve spatial resolution of better than 0.1 mm with very low radiation dose.

Xeroradiography is an X-ray technique developed by the Xerox Corporation that uses X-ray energies between 35 and 45 keV and an electrostatic technique similar to the Xerox photocopy machine. Figure 7-16 illustrates the physical attributes of such a machine. Figure 7-17 shows a typical xeroradiographic image of a breast.

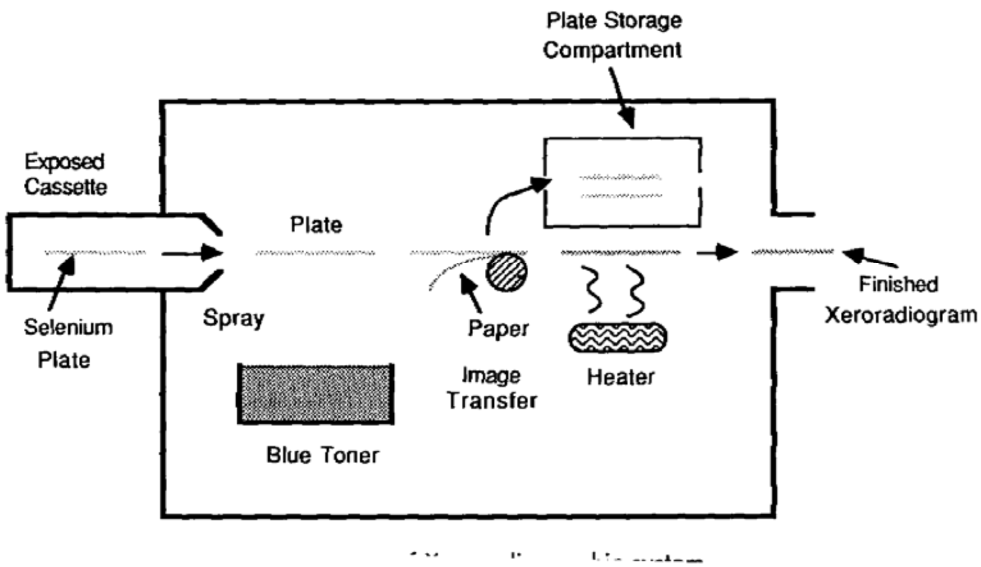

Figure 7-16 Physical construction of Xeroradiographic system

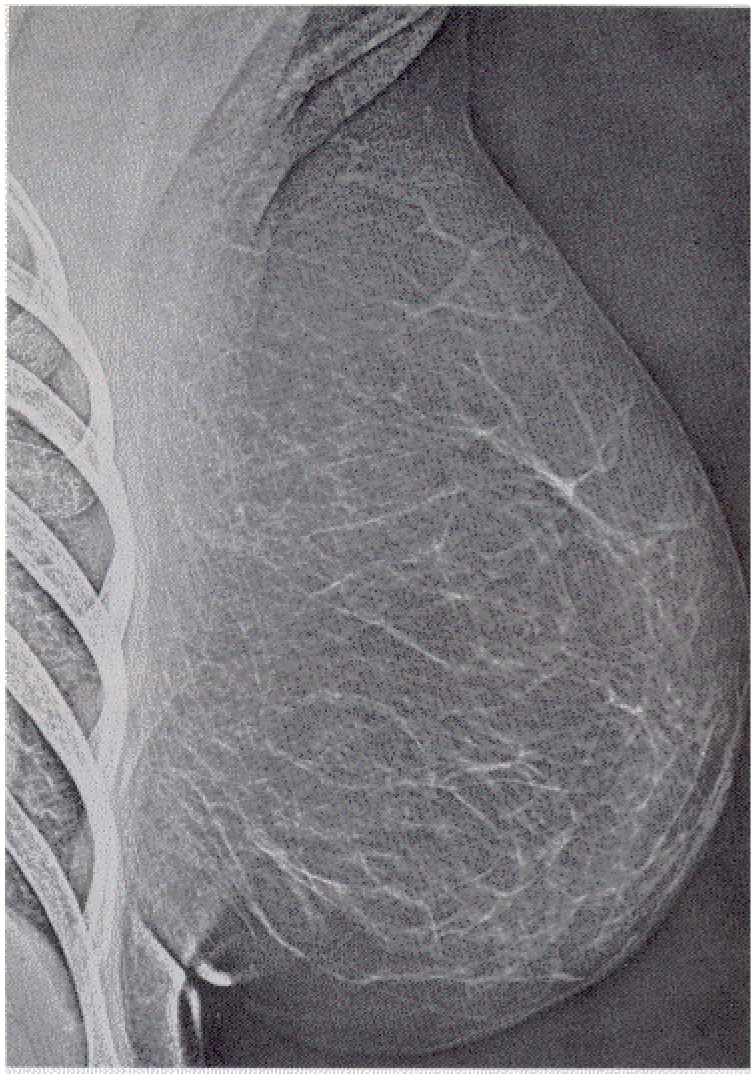

Figure 7-17 Xeroradiogram of breast where ribs and breast vasculature are seen

8. Summary and history

Before X-rays were discovered by Dr. Röntgen, the first role of a physician was to diagnose what was wrong with the patient before considering the prognosis and providing treatment. Accurate diagnosis was most dependent on the history obtained and the physician's skill at questioning the patients. But at the same time the physician used the senses, sight, touch, hearing, smell and even taste to identify abnormalities in the patient. This is illustrated, in part, as shown below:

Figure 8-1 The Grecian- Roman era of medical diagnosis

Hippocrates had developed observation of the patient and the progress of their disease as the science of medicine. He described the appearance of the patient, felt their temperature, and smelled their vomit. Although doctors became particularly skilled at examining the lumps, cuts and breaks of the body (i.e., "external" medicine), they rarely tried to examine the inside of the body. There were exceptions such as when Hippocrates shook the patient with pleurisy to detect a splash when there was fluid in the pleural space; thus the Hippocratic Succussion Splash.

Observations are considered to be more scientific if measurement of them can be made. In Alexandria, Herophilus 300 BCE would feel the pulse and count it using a water clock. Galen, 129 ACE, relied heavily on touch or palpation for diagnosis and essential skill for assessing wounds and injuries. Galen had practiced sports medicine with the gladiators. He would describe the general appearance of the patient but also tasted sweat for jaundice and listen to the rumbling abdomen. Galen learned much from feeling the pulse, which he did in both wrists using three fingers. The pulse was thought to reveal disorders of the

organs of the body. There is much in common with what was understood by him from the pulse and Chinese medicine - perhaps a spread of ideas along the Silk Road. The Chinese did not measure the pulse but were said to learn many things from its feel.

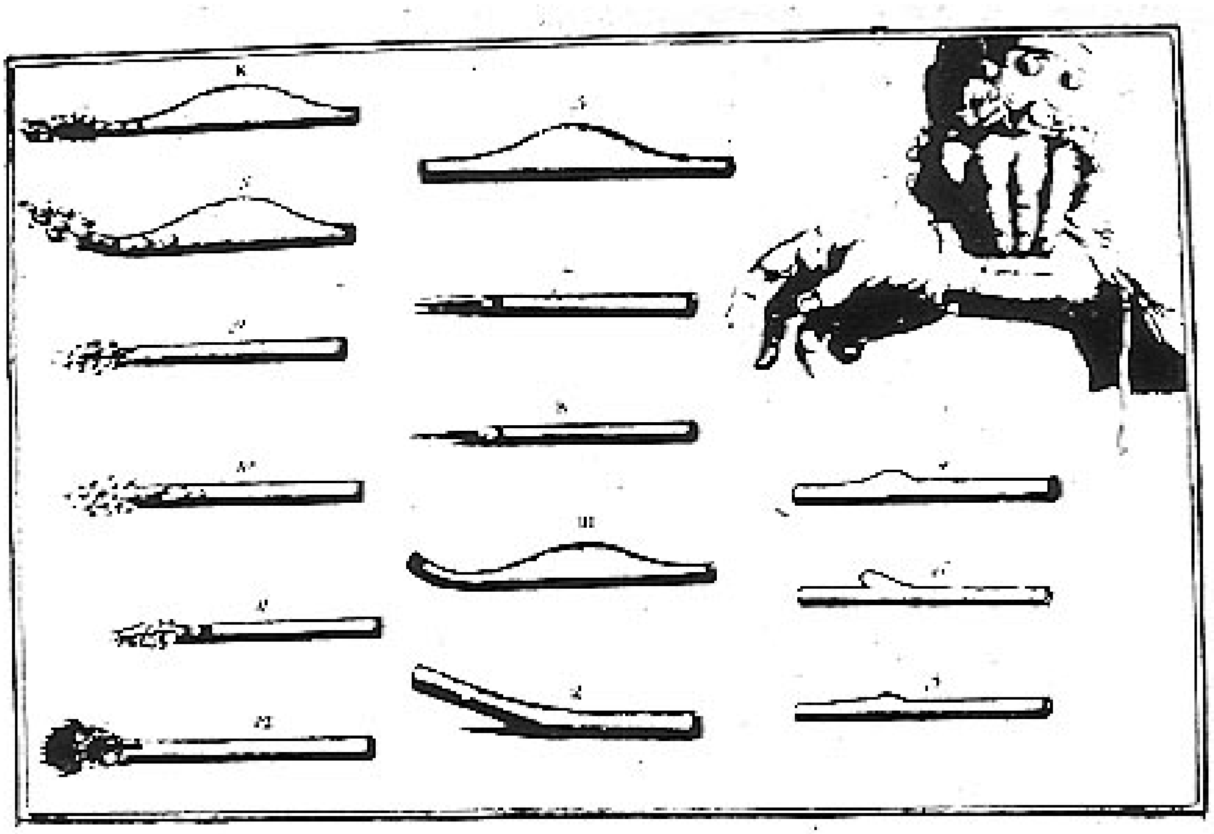

Figure 8-2 Methods of feeling the pulse, and interpreting the information gained.

In 1583 a medical student was bored by a sermon and observed that the swinging of the altar lamp was unvarying and that this could be used to measure time. The student was Galileo (1564-1642) who, as we know, gave up medicine for astronomy fame and ill fortune at the hands of the Catholic Church. Galileo's pendulum clock was adapted by Sanctorius (1561-1636) to measure the pulse (Figure 8-2). Sanctorius was considered to be a major physiologist because he used a thermometer to measure temperature, and a weighing chair to measure the intake and output of food and fluid. But since there was little understanding of the function of the body, these measurements did not advance medicine. This was to change with the Italian Renaissance and the lessons of the anatomists who identified the true state of the organs of the body and set the scene for understanding their function.

The work of the Englishman William Harvey (1575-1657) who had studied in Italy described the circulation of the blood but added nothing to the diagnosis of disease. He thought the heart distributed the humours and spirits. In 1707 Sir John Floyer (1649-1743) introduced the pulse watch and thought it of more value than Harvey's work. Physicians began to count the pulse regularly and would note it in various ways. In 1731

a new dimension was added to the measurement of the body with the work of Stephen Hales (1677-1771) who studied the pressure in arteries and veins. He would insert a cannula into the vessels and measure the height of the column of blood – that is he measured the blood pressure (see Figure 8-3). But these advances were relatively meaningless until the understanding that diseases were often abnormalities of the structure or function of organs.

Figure 8-3 Schematic of Harvey's blood pressure measurement system.

After Dr. Röntgen's discovery, medicine inalterably changed (of course, X-ray discovery was not the only impetus for medical change, others included anesthesia, the notion of sepsis, etc.). It wasn't long before knowledge of the knee or hip (for example) was provided without the knife as in the following example images.

Figure 8-4 Anatomic information obtained from a modern X-ray study.

Figure 8-5 Acetabular fracture on the left posterior lip

9. References

Berger, S., W. Goldsmith, and E. Lewis (eds.) *Introduction to Bioengineering*, Oxford, New York, 1996. This reference is complete, but it is written at a beginning graduate level. The section on medical imaging is brief, but useful.

Brown, B., R. Smallwood, D. Barber, P. Lawford, and D. Hose. *Medical Physics and Biomedical Engineering*, Institute of Physics Publishing, Bristol, 1999. This was to be our textbook for the semester.

Dhawan, A., *Medical Image Analysis*, IEEE/John Wiley Press, 2003.

Shung, K. M. Smith, B. Tsui. *Principles of Medical Imaging*, Academic Press, San Diego, 1992. This is a wonderful brief text from which many of the images are drawn. Unfortunately, this text is out of print.

Webb, S. (ed) *The Physics of Medical Imaging*, Institute of Physics Publishing, Bristol, 1992. This is a complete text covering all aspects of medical imaging. Unfortunately, this text is out of print.

Many electronic images are stored in DICOM format, which is promulgated by the IEEE and NEMA. See: http://www.ctmed.ru/DICOM_HL7/ which states: Наряду с бурным ростом компьютерных технологий, в медицине все более остро встает вопрос о создании единых международных стандартов обмена медицинскими данными.В разных странах этот вопрос решается по-разному и именно поэтому существует множество различных медицинских стандартов: ASTM, ASC X12, IEEE/MEDIX, NCPDP, HL7, DICOM и т.п. Как правило, стандарты носят названия групп/комитетов и прочих некоммерческих организаций их разрабатывающих.