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CH. 16

Physics of Diagnostic X-Rays

This chapter discusses the physical principles involved in the diagnostic use of x-rays in medicine.

- The x-ray photon (~ 50nm to ~ 10^{-1}Å); 1Å=10^{-10}m, 1nm=10^{-9}m=10Å, is a member of the electromagnetic (EM) spectrum (family) that includes light of all types (infrared IR, visible VIS, and ultraviolet UV, radio waves, radar and TV signals, and gamma rays ϒ; ~10^{-1}Å to~ 10^{-30}Å).
- X-rays was accidentally discovered by W.C.Roentgen, a physicist at the University of Wurzburg in Germany in 1895, when he was studying cathode rays in his laboratory. The first x-ray taken was the hand of Roentgen's wife!!
- The field of radiology has three major branches: *diagnostic radiology*, *radiation therapy*, and *nuclear medicine*. (each uses a part of the EM spectrum).

16.1. Production of x-ray beams

* A high-speed electron can convert some or all of its energy into an x-ray photon when it strikes an atom.

* The main (basic) components of a modern x-ray unit (tube) are (1) a source of electrons- a filament, or cathode; (2) an evacuated space in which to speed up the electrons; (3) a high positive potential HV to accelerate the negative electrons; (4) a target or anode (x-ray intensity depends on the anode material; nearly all x-ray tubes use tungsten, Z atomic number =74 and its melting point is about 3400°C, higher Z gives efficient x-ray), which the electrons strike to produce x-rays (Fig.16.3). An x-ray tube operating at 80 kV_p (kilovolt peak) will produce x-rays with a spectrum of energies up to a maximum of 80 keV. (1 keV =$1.6*10^{-9}$ erg =$1.6*10^{-16}$J).

* Diagnostic x-rays typically have energies of 15 to 150 keV, while visible light photons have energies of 2 to 4 eV.

* Depending on the thickness of the patient, x-ray studies of the breast (mammography) are usually done at 25 to 150 kV_p, while some hospitals use up to 350 kV_p for chest x-ray.

* The electron current that strikes the target is typically 100 to500 mA, some units have 1000 mA.

* The power at the target (P=IV) for I=1A, V=100kV is $1*10^5$ or 100 kW, and over 99% of this power appears as heat.(line-focus principle and rotating anode ,10^4 rpm, are adopted to avoid overheating the target).

* While the energy of most of the electrons striking the target is dissipated in the form of heat, remaining few electrons produce useful x-ray. Many times one of these electrons gets close enough to the nucleus of a target atom to be diverted from its path and emits an x-ray photon that has some of its energy (Fig. 16.7a).

It is called bremsstrahlung; German name that means *braking radiation* also called *white* radiation.

*Sometimes a fast electron strikes a K (shell) electron in a target atom and knocks it out of its orbit and free of the atom. The vacancy in the K shell is filled almost immediately when an electron from an outer shell of the atom falls into it, and in the process, a characteristic K x-ray photon is emitted.

*An x-ray photon emitted when electron falls from the L level to the K level is called a K_α characteristic x-ray, and that emitted when an electron falls from the M shell to the K shell is called a K_β x-ray. Table 16.1 gives the energies of the K_α x-ray of several elements.

Table16.1Approximate Energies of the K_α X-Rays and K-Edge for Several Elements

	K_α (keV)	K-Edge (keV)
Aluminum	1.5	1.6
Calcium	5	6
Copper	8	9
Molybdenum	17.5	20
Iodine	28	33
Tungsten	59	70
Lead	75	88

*The spectrum of x-rays produced by a modern x-ray generator is shown in Fig. 16.8. The broad smooth curve is due to the bremsstrahlung, and the spikes represent the characteristic x-ray. Many of the low-energy “soft” x-ray photons produced are absorbed in the glass walls of the x-ray tube.

16.2. How x-rays are absorbed

Heavy elements such as calcium Ca are much better absorbers of x-rays than light elements such as C, O, H, and as a result, structures containing heavy elements, like the bones, stand out clearly.

*The attenuation of an x-ray beam is its reduction due to the absorption and scattering of some photons out of the beam. The lower energy (soft) x-rays are absorbed more readily than the higher energy (hard) x-rays. The exponential equation describing the attenuation curve for a mono-energetic x-ray beam is

$$\mathbf{I = I_0\, e^{-\mu x}}$$

Where: I is the transmitted attenuated beam intensity (measured by an x-ray detector), I_0 is the un-attenuated beam intensity,

X is the thickness of the attenuator,

And μ is the linear attenuation coefficient of the attenuator, dependent on the energy of the x-ray photons; as the beam becomes harder, it decreases.

*The half-value layer (HVL) for an x-ray beam is the thickness of a given material that will reduce the beam intensity by one-half. The HVL is related to the linear attenuation coefficient by,

HVL = 0.693/μ.

In lead (Pb) the HVL would be about 0.1mm. A lead sheet 1.5mm thick would be about 15 HVLs and would reduce the beam intensity by a factor of 2^{15} about 30,000! This shows why lead is used for shielding material.

*The mass attenuation coefficient μ_m is used to remove the effect of density when comparing attenuation in several materials. Then I eq. can be rewritten as

$\mathbf{I = I_0\, e^{-(\mu/\rho)(\rho x)} = I_0}\, e^{-\mu_m(\rho x)}$, where $\mu/\rho = \mu_m$.

The quantity ρx is in grams per square centimeters and is sometimes called the area density; μ_m is in square centimeters per gram. Note that 1.0 g of lead covering an area of 1 cm^2 will absorb the same amount of x-rays whether its density is 11 g/cm^3 or whether it is mixed with plastic to reduce its density to 2 g/cm^3. The half-value layer in area density units (g/cm^2) is given by o.693/μ_m.

Figure 16.12 shows μ_m of fat, muscle, bone, iodine, and lead as a function of x-ray energy. Note that on gram-for- gram basis, iodine is a better absorber than lead from about 30 to about 90 keV. This phenomenon is due to the ***photoelectric effect.***

****The photoelectric effect*** is one way x-rays lose energy in the body. It occurs when the incoming x-ray photon transfers all of its energy to an electron which then escapes from the atom (Fig. 16.13a). The photoelectron uses some of its energy (the binding energy) to get away from the positive nucleus and spends the remainder ripping electrons off (ionizing) surrounding atoms   It is more apt to occur in the intense electric field near the nucleus than in the outer levels of the atom, and it is more common in the elements with high Z than in those with low Z. The binding energy of a K electron in iodine is 33 keV, while that in lead is 88 keV, and from 33 to 88 keV an x-ray photon can release a K electron from iodine but not from lead. When the energy of the x-ray is just slightly greater than the binding energy, the probability that the photoelectric effect will occur increases greatly, and this accounts for sharp rises *(K-edges)* in the curve for iodine at 33 keV and for lead at 88 keV in Fig. 16.12.

*Another important way x-rays lose energy in the body is by the ***Compton effect*** (Fig. 16.13b). This is most likely to occur when the x-ray has 511 keV energy. The number of Compton collisions depends only on the number of electrons per cubic centimeters, which is proportional to the density. A gram of bone has about the same number of electrons as 1 g of water, and thus the number of Compton collisions will be about the same.

****Pair production*** is the third major way x-rays give up energy (Fig. 16.13c). When a very energetic photon enters the intense electric field of the nucleus, it may be converted into two particles: an electron and positron (β^+), or positive electron. Providing the mass for the two particles requires a photon with an energy of at least 1.02 MeV, and the remainder of the energy over 1.02 MeV is given to the particles as kinetic energy. The positron is a piece of antimatter. After it has spent Its kinetic energy in ionization it does a death dance with an electron. Both then vanish, and their mass energy usually appears as two photons of 511 keV each called *annihilation radiation*.

*HOW ARE THESE INTERACTIONS RELATED TO DIAGNOSTIC RADIOLOGY?

Pair production is of no use in diagnostic radiology because of the high energies needed.

Photoelectric effect is more useful than the Compton effect because it permits us to see bones and other heavy materials such as bullets in the body.

At 30 keV bone absorbs x-rays about 8 times better than tissue due to the photoelectric effect. To make further use of the photoelectric effect radiologists often inject high Z materials, or *contrast media*, into different parts of the body (examples are compounds containing iodine or barium). Also it is possible to use air as a contrast medium since gases are poorer absorbers of x-rays than liquids and solids.

The Compton effect seriously degrades x-ray images of thick body parts since the scattered radiation that gets through the patient and strikes film reduces the useful information by reducing the contrast in the image.

16-3 Making an x-ray image (roetgenogram)

X-ray images are basically images of the shadows cast on film by the various structures in the body.

Most x-ray images are made on a special film sandwiched tightly between two intensifying screens-cardboards covered with a thin coating of crystals (e.g. $CaWO_4$) that absorb x-ray well and give off visible or UV light (Fluoresce) when struck by x-ray. The film is coated on both sides with a light-sensitive emulsion, and each side takes a "picture" of the light from the intensifying screen with which it is in contact.

Note: A dental x-ray taken with film alone (nonscreen technique) requires almost 30 times the x-ray exposure of a chest x-ray taken with intensifying screens. However, since the film records the light emitted by the screen rather than the x-rays striking it, the image is more blurred than when film alone is used.

Ex: A fluoroscope can operate continuously at a potential of 80 keV and a current of 3 mA. What is the power into the target? Sol: $P=IV=3*10^{-3}*8*10^{4}=240W$

Ex: If the x-ray tube in the above example has a tungsten target, what percentage of the energy goes into x-ray photons? *(the ratio of the energy that goes into x-ray photons to the energy that goes into heat is approximately $10^{-9}ZV$)*

Sol: $10^{-9}ZV=10^{-9}(74)(8*10^{4}) = 5.9*10^{-3}=0.59\%$

Ex: If the HVL of an x-ray beam is 3mm Al, what is the linear attenuation coefficient of the beam? Sol: $\mu = 0.693/3\ mm = .231\ mm^{-1}$

16.4. RADIATION TO PATIENTS FROM X-RAYS

#The unit used for radiation exposure is the *roentgen* (R), a measure of the amount of electric charge produced by ionization in air; 1 R = $2.58 * 10^{-4}$C/kg of air. (see table 16.2)

Since an exposure to a large area is more hazardous than the same exposure to a small area, a useful quantity for describing radiation to the patient is the exposure-area product (EAP), obtained by multiplying the exposure in roentgens by the area in square centimeters. A new unit called the *rap* (Roentgen-Area Product) has been proposed for this quantity; 1 rap = 100 R cm^2, and thus if you receive an exposure of 0.6 R to an area of 33 cm^2 (a typical dental exposure) you receive 20 R cm^2 or 0.2 rap.

The thickness of tissue the x-rays must pass through to reach the film affects the amount of radiation to the patient. The x-ray beam is reduced by a factor of about 2 for each 2.5 cm of tissue thickness, and thus a 25 cm thick patient reduces the intensity by a factor of about 2^{10} or 1000.

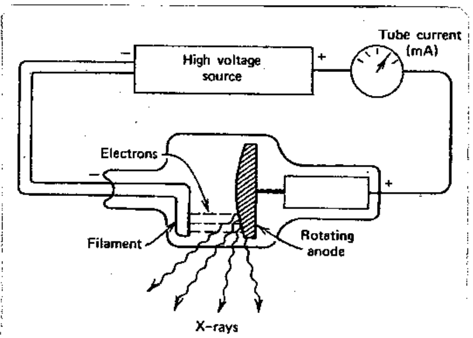

Figure 16.3. The basic components of an x-ray unit.

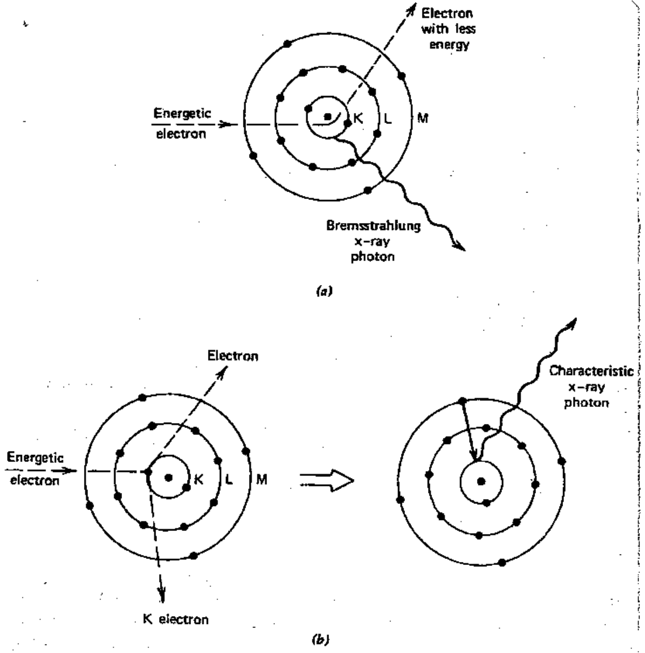

Figure 16.7. Generation of x-rays. (a) A fast electron is diverted near the nucleus and loses some of its energy as a bremsstrahlung x-ray photon. (b) A fast electron knocks a K electron free of the atom; when an outer electron falls into the vacancy an x-ray characteristic of the target atom is emitted.

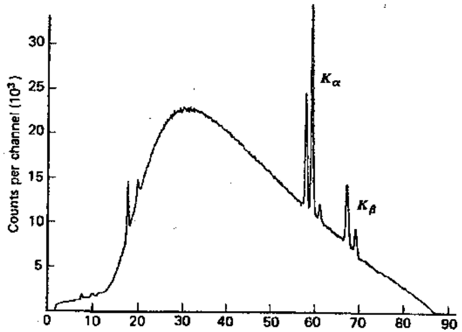

Figure 16.8. The spectrum from a tungsten target x-ray tube operated at 87 kVp. All of the photons below 12 keV and some of those in the 12 to 30 keV region are absorbed in the glass wall of the x-ray tube; the counts shown below 12 keV are due to electrical noise in the detector system. (Courtesy of Robert Jennings, University of Wisconsin, Madison, Wisc.)

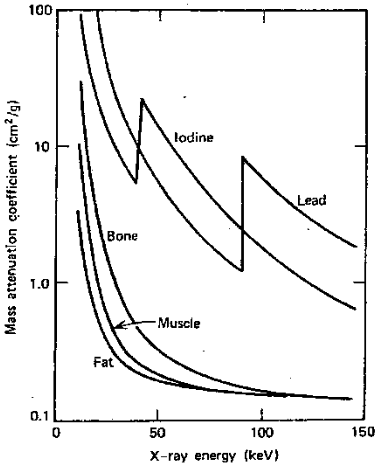

Figure 16.12. Mass attenuation coefficients for various tissues, lead, and iodine. Note that on a mass basis, all tissues attenuate about the same above 100 keV.

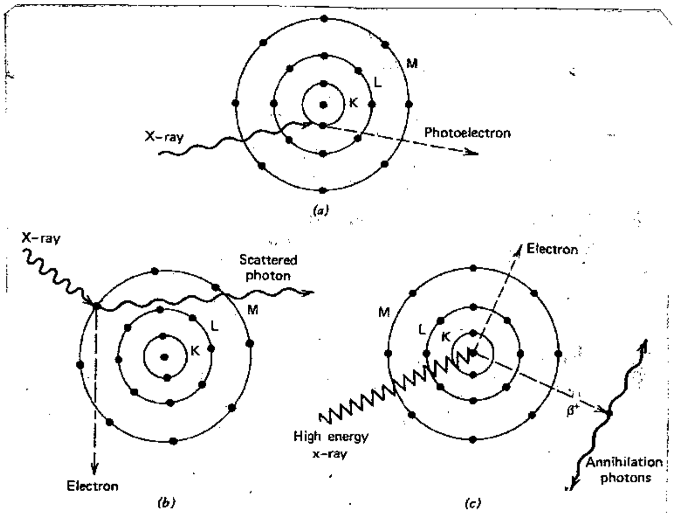

Figure 16.13. X-rays lose energy in three ways: (a) In the photoelectric effect, all of the photon energy is given to the photoelectron. (b) In the Compton effect, some energy is given to an electron and some goes into a scattered photon. (c) In pair production, a high-energy photon is converted into an electron and a positron (β^+). The β^+ annihilates to form two photons of 511 keV each that go in opposite directions.

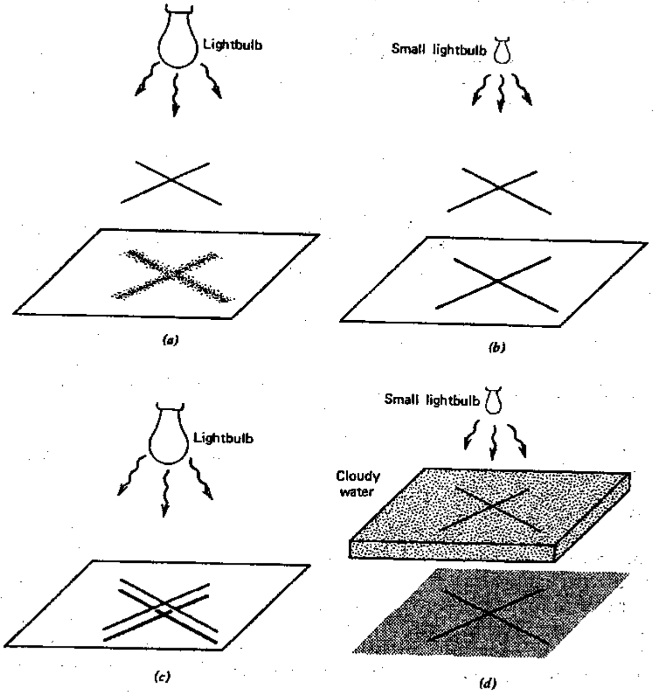

Figure 16.19. The principles involved in casting shadows with visible light. (*a*) The shadow of an object some distance from a piece of paper is blurred when a large lightbulb is used. This shadow can be made much sharper (*b*) by using a smaller diameter lightbulb or (*c*) by moving the object closer to the paper. (*d*) Cloudy water between the lightbulb and paper absorbs some light and scatters much of the rest, reducing the contrast of the shadow.

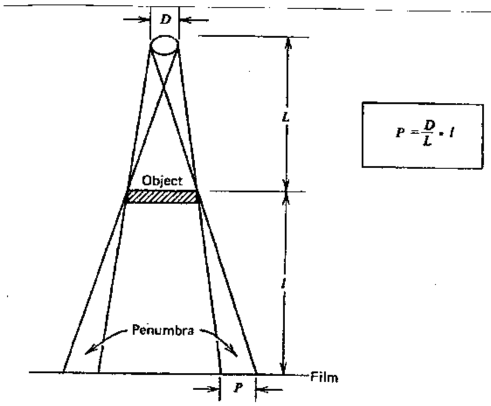

Figure 16.20. The width of the penumbra *P* can be calculated from the ratios of sides of similar triangles if we know the diameter *D* of the light source and the dimensions *L* and *l*.

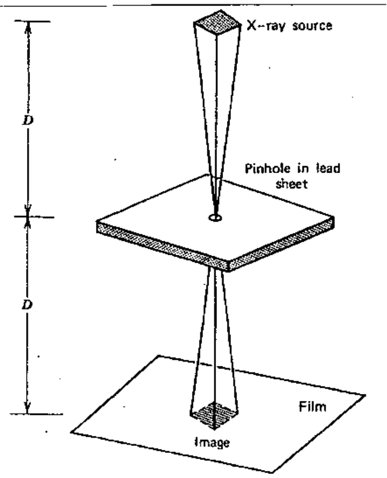

Figure 16.21. The focal spot can be measured by making a pinhole image of it on a piece of film. If the pinhole is midway between the x-ray source and the film, the image will be the same size as the source.

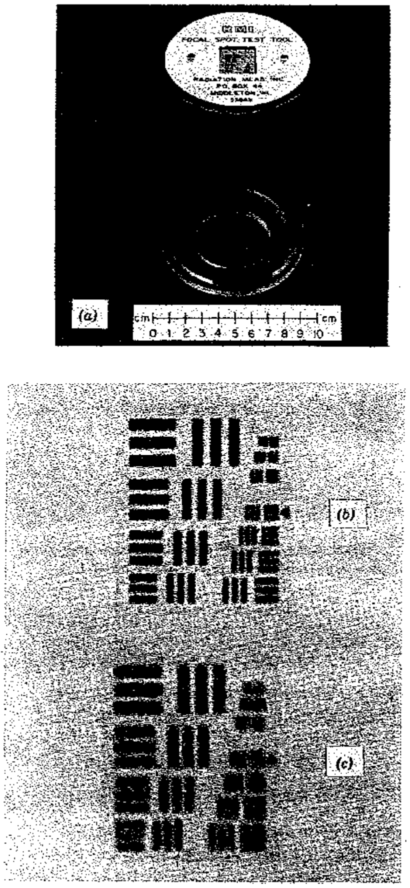

Figure 16.22. The Wisconsin focal spot test tool uses a pattern of rectangular holes (top of *a*) to cast an image on the film. The image *b* was made with a 1 mm focal spot, and the image c was made with a 2 mm focal spot. Notice the greater amount of blurring from the larger focal spot. (Courtesy of Radiation Measurements, Inc., Middleton, Wisc.)

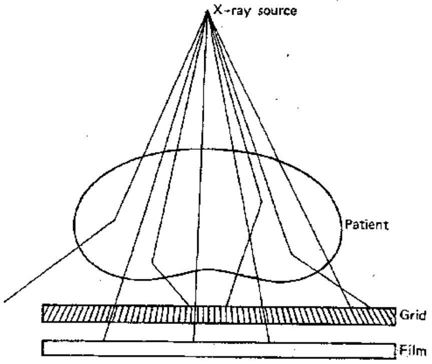

Figure 16.23. The grid consists of alternating thin lead strips and wide plastic strips. The unscattered x-rays pass through the plastic strips, while most of the scattered x-rays are absorbed by the lead strips.

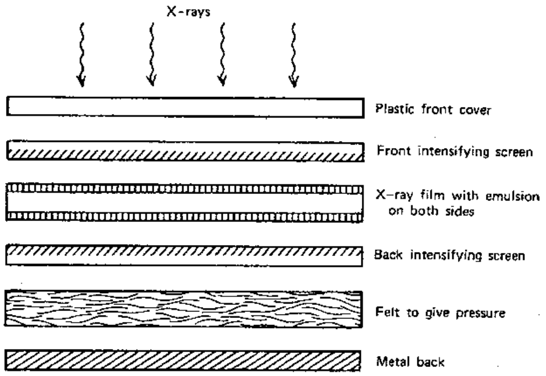

Figure 16.24. An expanded cross-section of part of an x-ray cassette. The intensifying screens absorb most of the x-rays and give off light that exposes the film. The felt holds the screens in close contact with the film.

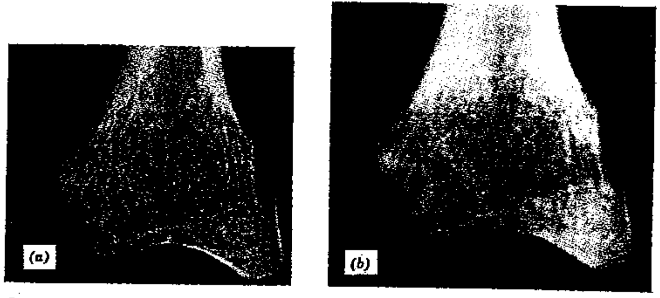

Figure 16.25. Two x-rays of the same bone taken with *(a)* nonscreen film and *(b)* parspeed screen film. Note that more detail is visible in *a*. However, the exposure for *a* was about 20 times greater than that for *b*.

Table 16.2. Typical Amounts of Radiation Received by Adults in the United States in 1974

X-Ray Study	Exposure (mR)	Beam Area/Film Area	Exposure-Area Product (raps)
Chest	23	2	0.5
Skull	270	1.1	1.3
Abdomen	560	1.1	4.7
Upper (cervical) spine	230	1.9	1.5
Lower (lumbar sacral) spine	790	1.1	6.6
Dental bitewing	650	2.9	0.2

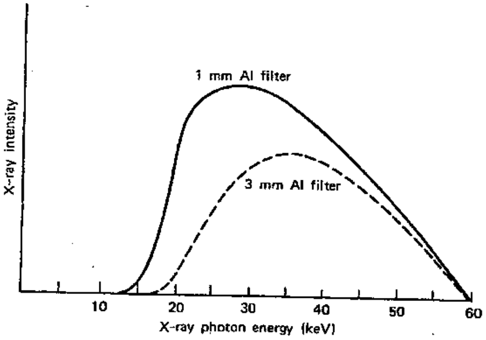

Figure 16.28. Filters primarily absorb low-energy x-ray photons. The amount of more penetrating high-energy photons is only slightly reduced.

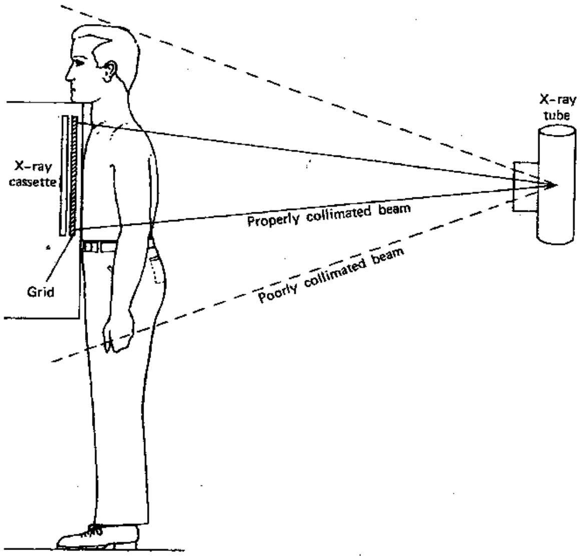

Figure 16.29. Excess radiation to the patient results from a poorly collimated x-ray beam. This is a major source of unnecessary radiation to the gonads.