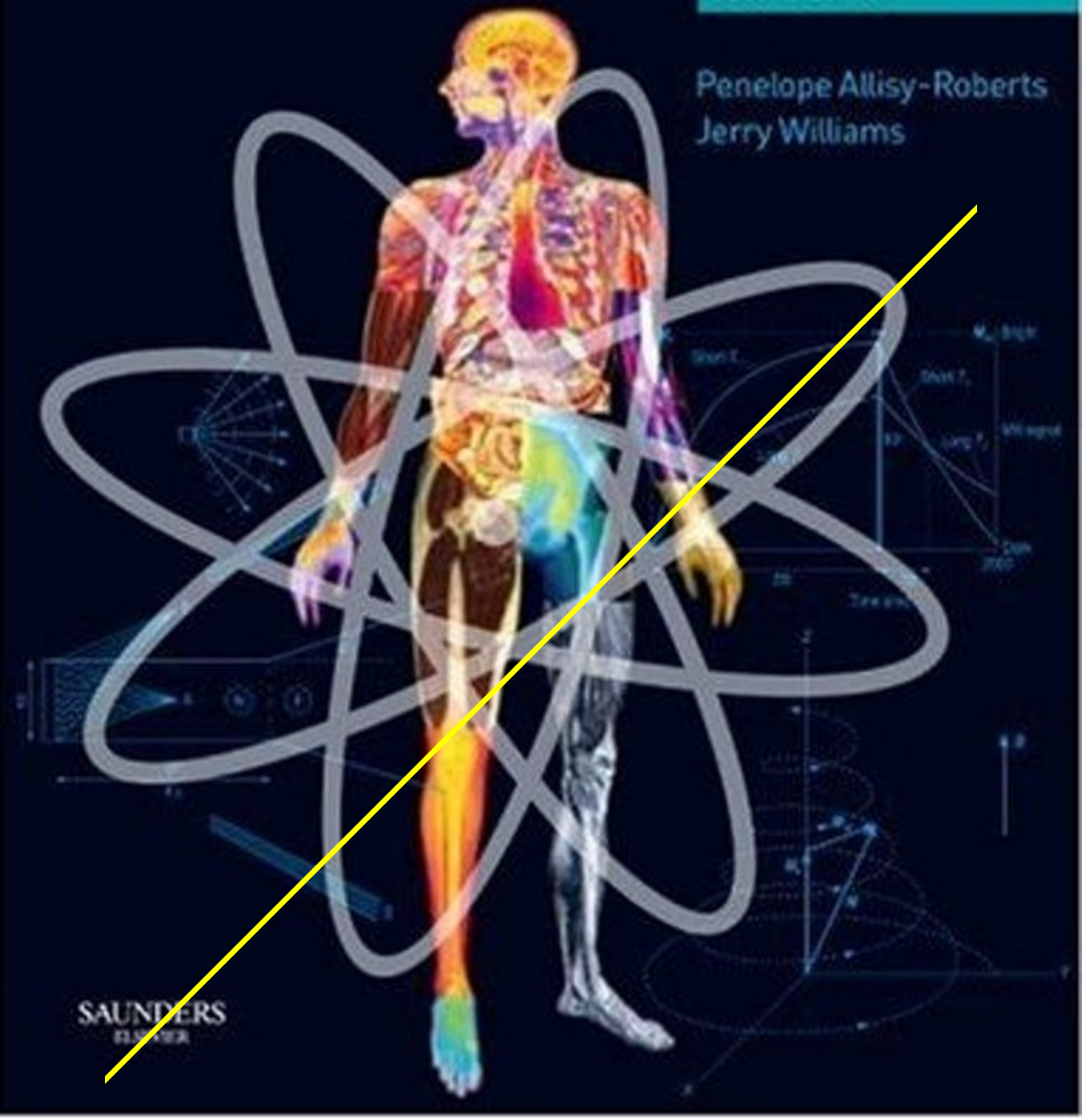
Farr's Physics for Medical Imaging

SECOND EDITION

Penelope Allisy-Roberts
Jerry Williams



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Radiation physics

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Diagnostic imaging employs radiations – X, gamma, radiofrequency and sound – to which the body is partly but not completely transparent, and it exploits the special properties of a number of elements and compounds. As *ionizing* radiations (X-rays and gamma rays) are used most, it is best to start by discussing the structure of the atom and the production of X-rays. Some properties of the particles making up the atom and described elsewhere in this text are given in Table 1.1.

1.1 STRUCTURE OF THE ATOM

An atom consists mainly of empty space. Its mass is concentrated in a central nucleus that contains a number A of nucleons (protons and neutrons), where A is called the mass number. The nucleus comprises Z protons, where Z is the atomic number of the element, and $(A - Z)$ neutrons. A nuclide is a species of nucleus characterized by the two numbers Z and A. The atomic number is synonymous with the name of the element. Thus, $^{12}_{6}C$ refers to a carbon atom with

Table 1.1 Some fundamental particles

	Relative mass	Relative charge	Symbol
Nucleons			
Neutron	1	0	n
Proton	1	+1	p
Extranuclear			
Electron	0.00054	−1	e^-, β^-
Other			
Positron	0.00054	+1	e^+, β^+
Alpha particle	4	+2	α

Silver bromide is an example of an *ionic crystal*, and consists of equal numbers of positive silver ions (silver atoms that have each lost their single valence electron) and negative bromine ions (bromine atoms that have each gained an outer shell electron). The two kinds of ion hold each other, by electrostatic attraction, in a highly regular three-dimensional lattice. This accounts for the well-known properties of such crystals. Other examples encountered in imaging equipment are sodium iodide and caesium iodide.

Binding energy

An atom is described as *ionized* when one of its electrons has been completely removed. The detached electron is a negative ion and the remnant atom a positive ion. Together, they form an ion pair.

The binding energy (E) of an electron in an atom is the energy expended in completely removing the electron from the atom against the attractive force of the positive nucleus. This energy is expressed in electronvolts (eV), explained in Box 1.1.

The binding energy depends on the shell ($E_K > E_L > E_M \ldots$) and on the element, increasing as the atomic number increases. For example, for tungsten (W; $Z = 74$) the binding energies of different shells are $E_K = 70$, $E_L = 11$, and $E_M = 2$ keV.

The K-shell binding energies of various elements encountered in X-ray imaging are given in Table 1.2.

An atom is *excited* when an electron is raised from one shell to another further out. This involves the expenditure of energy; the atom as a whole has more energy than normal and so is said to be excited. For example, a valence electron can be raised to one of the unoccupied shells further out, shown dashed in Figure 1.1. When it falls back, the energy is re-emitted as a single 'packet' of energy or photon of light (visible or ultraviolet). This is an example of the quantum aspects of electromagnetic radiation.

Table 1.2 Atomic number (Z) and K-shell binding energy (E_K) of various elements

Element	Z	E_K (keV)
Aluminium	13	1.6
Calcium	20	4
Molybdenum	42	20
Iodine	53	33
Barium	56	37
Gadolinium	64	50
Tungsten	74	70
Lead	82	88

1.2 ELECTROMAGNETIC RADIATION

This is the term given to energy travelling across empty space. All forms of electromagnetic radiation travel with the same velocity (c) as light when in vacuo, very close to $3 \times 10^8 \,\mathrm{m\,s^{-1}}$ and not significantly less in air. They are named according to the way in which they are produced and the special properties they possess. X-rays (emitted by X-ray tubes) and gamma rays (emitted by radioactive nuclei) have essentially the same properties and differ only in their origin.

Quantum aspects

Electromagnetic radiation can be regarded as having particle-like properties. But rather than being composed of particles, the radiation is represented as a stream of packets or quanta of energy, called photons, that travel in straight lines.

Wave aspects

Electromagnetic radiation can also be regarded as sinusoidally varying electric and magnetic fields, travelling with velocity c when in vacuo. They are transverse waves: the electric and magnetic field vectors point at right angles to each other and to the direction of travel of the wave.

At any point, the graph of field strength against *time* is a sine wave, depicted as a solid curve in Figure 1.2a. The peak field strength is called the amplitude (A). The interval between successive crests of the wave is called the period (T). The frequency (f) is the number of crests passing a point in a second, and $f = 1/T$. The dashed curve refers to a later instant, showing how the wave has travelled forwards with velocity c.

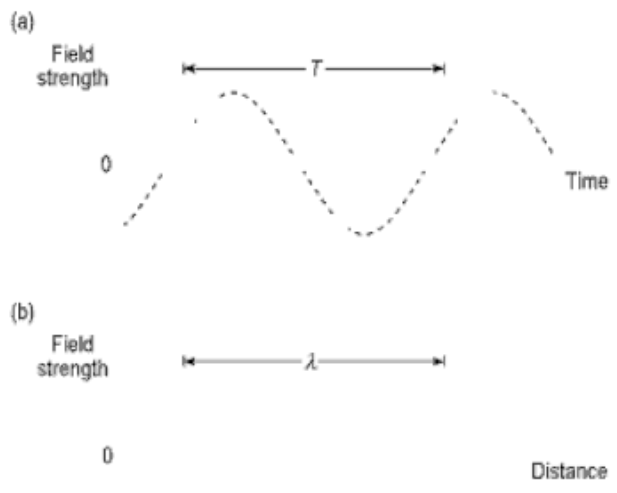

Figure 1.2 Electromagnetic wave. Field strength versus (a) time and (b) distance.

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Table 1.3 Electromagnetic spectrum

Radiation	Wavelength	Frequency	Energy
Radiowaves	1000–0.1 m	**0.3–3000 MHz**	0.001–10 μeV
Microwaves	100–1 mm	**3–300 GHz**	10–1000 μeV
Infrared	**100–1 μm**	3–300 THz	10–1000 meV
Visible light	**700–400 nm**	430–750 THz	1.8–3 eV
Ultraviolet	**400–10 nm**	750–30 000 THz	1.8–100 eV
X- and gamma rays	1 nm–0.1 pm	$3 \times 10^5 - 3 \times 10^9$ THz	**1 keV–10 MeV**

At any instant, the graph of field strength against *distance* is also a sine wave, as shown in Figure 1.2b. The distance between successive crests of the wave is called the wavelength (λ).

Wavelength and frequency are inversely proportional to each other:

$$\text{wavelength} \times \text{frequency} = \text{constant}.$$

Their product is equal to the velocity ($\lambda f = c$). This relation is true of all kinds of wave motion, including sound, although for sound the velocity is about a million times less.

The types of electromagnetic radiation are listed in Table 1.3, in order of increasing photon energy, increasing frequency, and decreasing wavelength. The values are rounded and the boundaries between the types of radiation are not well defined, other than for visible light, for which the boundaries are defined by the properties of the receptor, i.e. the human eye. The nomenclature that is most commonly used in practice is emphasized in bold in the table.

Wave and quantum theories combined

Photon energy is proportional to the frequency. The constant of proportionality is called *Planck's constant* (h). Thus $E = hf$.

More usefully, because frequency is inversely proportional to wavelength, so also is photon energy:

$$E \text{ (in keV)} = 1.24/\lambda \text{ (in nm)}.$$

For example:

Blue light	$\lambda = 400$ nm	$E \approx 3$ eV
Typical X- and gamma rays	$E = 140$ keV	$\lambda \approx 0.1$ nm.

Intensity

Radiation travels in straight lines called rays that radiate in all directions from a point source. A collimated set of rays is called a beam. A beam of radiation can be visualized by taking at some point a cross-section at right angles to the beam (Fig. 1.3a).

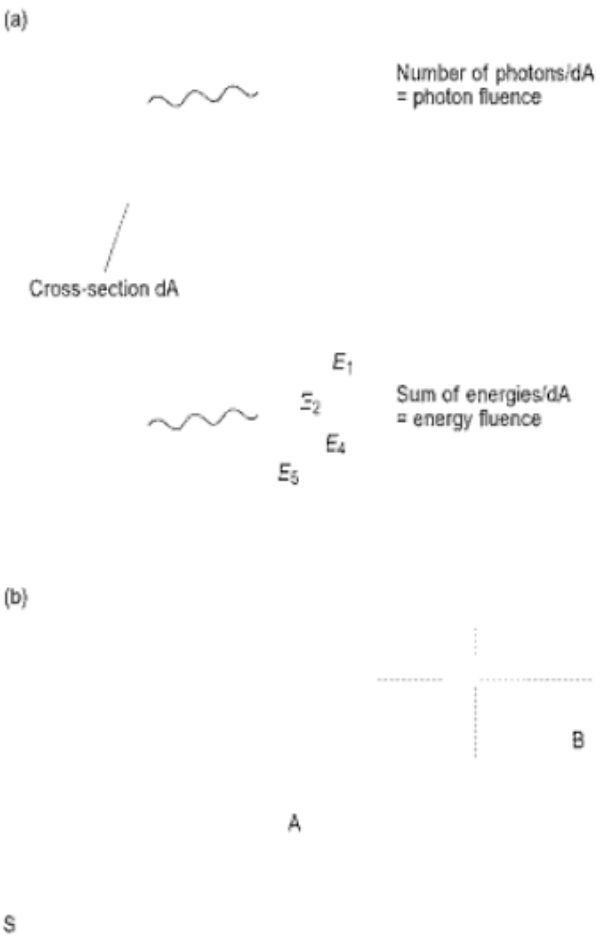

Figure 1.3 (a) Photon fluence and energy fluence. (b) The inverse square law applying to a point source S.

Suppose the beam is switched on for a given (exposure) time. Simply counting the photons allows the number per unit area passing through the cross-section in the time to be determined, and is called the *photon fluence* at the point. A beam may contain photons of different energies. Adding up the energies of all the individual photons gives the total amount of energy per unit area passing through the cross-section in the time, and is called the energy fluence at the point.

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The total amount of energy per unit area passing through the cross-section *per unit time* (watts per square millimetre) is called the energy fluence rate at the point, and is also referred to as the beam *intensity*. In wave theory, intensity is proportional to the square of the amplitude (*A*, see Fig. 1.2), measured from the peak of the wave to the axis.

Energy fluence and intensity are not easy to measure directly. As explained in section 1.6.2, in the case of X- and gamma rays an easier indirect measurement of energy fluence is usually made, namely *air kerma*, and, instead of intensity, air kerma rate. The relationship between these quantities is discussed later in section 1.6.4.

Inverse square law

Because electromagnetic radiation travels in straight lines, it follows that the dimensions of the beam are proportional to the distance from a point source S, as is shown in Figure 1.3b. As a result, the area of the beam is proportional to the square of the distance from a point source. Therefore the air kerma is inversely proportional to the square of the distance from the source.

With reference to Figure 1.3b:

$$\frac{\text{air kerma at B}}{\text{air kerma at A}} = \frac{(\text{distance to A})^2}{(\text{distance to B})^2}$$

For the inverse square law to hold, it is essential that the radiation comes from a point source and that there is no absorption or scatter of radiation between the source and the points of measurement. Figure 1.3b has been drawn such that the distance from the source doubles in going from A to B. In this instance, the air kerma reduces by a factor of 4.

1.3 PRODUCTION OF X-RAYS

The X-ray tube

X-rays are produced when fast-moving electrons are suddenly stopped by impact on a metal *target*. The kinetic energy of the electrons is converted into X-rays (no more than 1%) and into heat (≥99%).

An X-ray tube, depicted in Figure 1.4, consists of two electrodes sealed into an evacuated *glass envelope*:

- a negative electrode (*cathode*) that incorporates a fine tungsten coil or filament
- a positive electrode (*anode*) that incorporates a smooth flat metal target, usually of tungsten.

The *filament* is heated by passing an electrical current through it to a temperature at which it is white hot (incandescent). In this state, it emits electrons by the process of thermionic emission. At such high temperatures (~2200°C), the atomic and electronic motion in a metal is sufficiently violent to enable a fraction of the free electrons to leave the surface despite the net attractive pull of the lattice of positive ions.

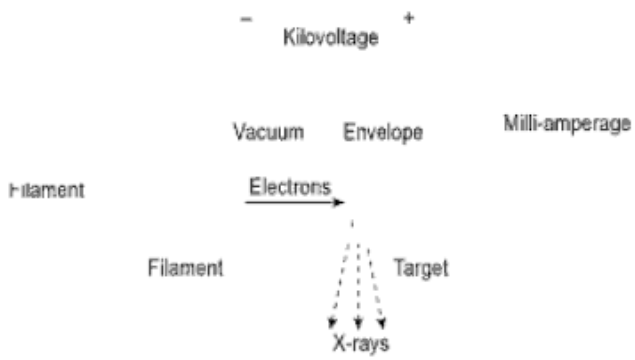

Figure 1.4 An X-ray tube and its power supplies.

The electrons are then repelled by the negative cathode and attracted by the positive anode. Because of the *vacuum*, they are not hindered in any way and bombard the target with a velocity around half the speed of light.

Kilovoltage and milliamperage

Two sources of electrical energy are required and are derived from the alternating current (AC) mains by means of transformers. Figure 1.4 shows:

- the filament heating voltage (about 10 V) and current (about 10 A)
- the accelerating voltage (typically 30–150 kV) between the anode and cathode (referred to as tube potential, high voltage, kilovoltage or kV); this drives the current of electrons (typically 0.5–1000 mA) flowing between the anode and cathode (referred to as tube current, milliamperage or mA).

The mA is controlled by adjusting the filament voltage and current and thus filament temperature. A small increase in temperature produces a large increase in tube current.

An X-ray set is designed so that, unlike most electrical components, increasing or decreasing the tube voltage does not affect the tube current. It is also designed so that the kV is unaffected by changes in the mA. The two factors can therefore be varied independently.

The *waveform* of a high-voltage generator can be described graphically to demonstrate how voltage varies with time. Figure 1.5 depicts the waveforms of four types of high-tension voltage supply. These are explained in Box 1.2.

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The dashed line (B) in Figure 1.8 shows the spectrum of bremsstrahlung produced near the target nuclei. In fact, the target itself, the glass wall of the tube, and other materials collectively referred to as the filtration, substantially absorb the lower-energy photons. There is therefore a low-energy cut-off, at about 20 keV, as well as a maximum energy. The latter depends only on the kV and the former on the filtration added to the tube (see section 1.5).

For the X-rays emerging from an X-ray tube operated at constant potential, the peak of the continuous spectrum (i.e. the most common photon energy) is typically between one-third and one-half of the kV. The average or *effective energy* is greater, between 50 and 60% of the maximum. Thus an X-ray tube operated at 90 kV can be thought of as emitting, effectively, 45-keV X-rays. As the operating kV is greater than the K-shell binding energy, characteristic X-rays are also produced. They are shown in Figure 1.8 as lines superimposed on the continuous spectrum.

The area of the spectrum represents the total output of all X-ray photons emitted. Figure 1.9 compares the spectrum from a tube with a tungsten target, operating at three different kV values. As the tube voltage is increased, both the width and height of the spectrum increase.

In the range 60–120 kV, the intensity of the emitted X-rays is approximately proportional to $kV^2 \times mA$, the exact exponent being dependent on the filtration. This may be compared with the electrical power supplied, which is proportional to kV × mA. The *efficiency* of X-ray production is the ratio

$$\frac{\text{X-ray output}}{\text{electrical power supplied}}$$

and increases with the kV. The efficiency is also greater the higher the atomic number of the target.

Controlling the X-ray spectrum

To summarize, there are five factors that affect the X-ray spectrum. The following are the effects of altering each in turn, the other four remaining constant.

- Increasing the kV shifts the spectrum upwards and to the right, as shown in Figure 1.9. It increases the maximum and effective energies and the total number of X-ray photons. Below a certain kV (70 kV for a tungsten target), the characteristic K-radiation is not produced.
- Increasing the mA does not affect the shape of the spectrum but increases the output of both bremsstrahlung and characteristic radiation proportionately.
- Changing the target to one of lower *atomic number* reduces the output of bremsstrahlung but does not otherwise affect its spectrum, unless the filtration is also changed. The photon energy of the characteristic lines will also be less.
- Whatever the kV *waveform* (see Fig. 1.5), the maximum and minimum photon energies are unchanged. However, a constant potential or three-phase generator produces more X-rays and at higher energies than those produced by a single-phase pulsating potential generator when operated with the same values of kV and mA. Both the output and the effective energy of the beam are therefore greater. This is because in Figure 1.5c,d the tube voltage is at the same peak value throughout the exposure. In Figure 1.5a,b, it is below peak value during the greater part of each half cycle.

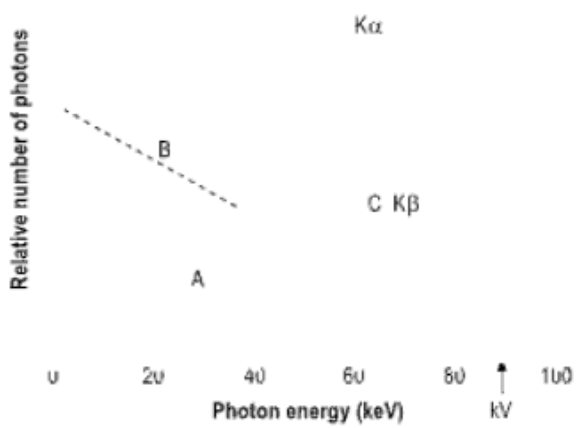

Figure 1.8 An X-ray spectrum.

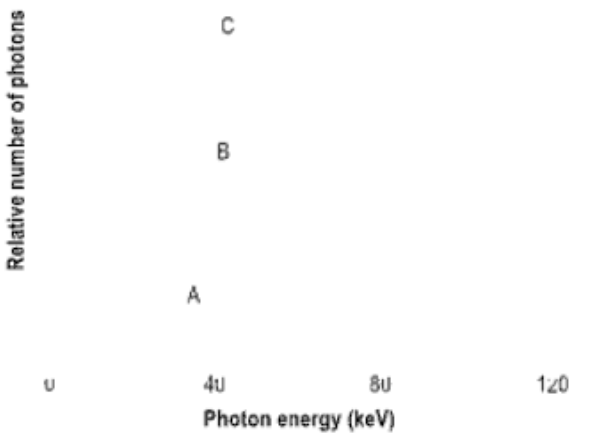

Figure 1.9 Effect of tube kilovoltage (kV) on X-ray spectra for three tube potentials: A, 40 kV; B, 80 kV; and C, 120 kV.

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A half wave–rectified, single-phase generator (Fig. 1.5a) produces useful X-rays in pulses, each lasting about 3 ms during the middle of each 20-ms cycle of the mains.

For the effect of the fifth factor, *filtration*, see section 1.5.

1.4 THE INTERACTION OF X- AND GAMMA RAYS WITH MATTER

Where the following refers to X-rays, it applies equally well to gamma rays. Figure 1.10 illustrates the three possible fates of the individual photons when a beam of X- or gamma rays travels through matter. They may be any of the following.

- *Transmitted*: pass through unaffected, as primary or direct radiation.
- *Absorbed*: transferring to the matter all of their energy (the photon disappearing completely).
- *Scattered*: diverted in a new direction, with or without loss of energy transferring to the matter, and so may leave the material as scattered or secondary radiation.

X-ray absorption and scattering processes are stochastic processes governed by the statistical laws of chance. It is impossible to predict which of the individual photons in a beam will be transmitted by 1 mm of a material, but it is possible to be quite precise about the fraction of them that will be, on account of the large numbers of photons the beam contains.

The X-ray image is formed by the transmitted photons. Those that are absorbed or scattered represent attenuation by matter. An understanding of how the properties of X-rays and the materials through which they travel affect the relative amounts of attenuation and transmission gives an understanding of how the X-ray image is formed.



Figure 1.10 Interaction of X- or gamma rays with matter.

1.4.1 Attenuation

Attenuation refers to the fact that there are fewer photons in the emerging beam than in the beam entering the material. It is represented by the photons that are completely absorbed and those that are scattered.

It is helpful to consider first the attenuation in a simple case.

A narrow, monoenergetic beam of X-rays

The fundamental law of X-ray attenuation states that, for a monoenergetic beam, equal thicknesses of an absorber transmit equal fractions (percentages) of the radiation entering them. This is illustrated in Figure 1.11a, where each sheet reduces the beam by 20%.

In particular, the *half-value layer* (*HVL*) is the thickness of stated material that will reduce the intensity of a narrow beam of X-radiation to one-half of its original value. For example, as is shown in Figure 1.11b, two successive HVLs reduce the intensity of the beam by a factor $2^2 = 4$ from 1024 to 256. Ten HVLs would reduce the intensity of the beam by a factor $2^{10} = 1024$, i.e. down to 1 in this example.

The HVL is a measure of the penetrating power or effective energy of the beam. It is useful to have a parameter that quantifies the attenuating properties of the material. This is the *linear attenuation coefficient* (μ), which is inversely proportional to the HVL:

$$\mu = 0.693/\text{HVL}$$

More precisely, the linear attenuation coefficient measures the probability that a photon interacts (i.e. is absorbed or scattered) per unit length of the path it travels in a specified material.

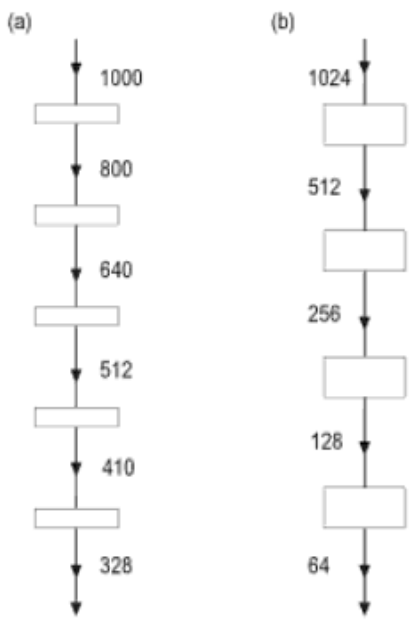

Figure 1.11 Examples of exponential attenuation for narrow monoenergetic beams.

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However, the linear attenuation coefficient applies only to narrow monoenergetic beams. The HVL can be used for beams that are not monoenergetic but applies only to narrow beams.

The HVL decreases and the linear attenuation coefficient therefore increases as:

- the density of the material increases
- the atomic number of the material increases
- the photon energy of the radiation decreases.

For example, lead is more effective than either aluminium or tissue at absorbing X-rays, because of its higher density and atomic number. X-rays of 140 keV are more penetrating and are said to be 'harder' than those of 20 keV.

The mass attenuation coefficient (μ/ρ) is obtained by dividing the linear coefficient by the density of the material. It is therefore independent of density and depends only on the atomic number of the material and photon energy.

Exponential graph

However thick the absorber, it is never possible to absorb an X-ray beam completely. This is shown, in Figure 1.12a, by the shape of the graph of percentage transmission versus thickness d, both being plotted on linear scales. This is an exponential curve described by the equation

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

in which I_0 is the intensity of X-rays incident on the absorber with a linear attenuation coefficient equal to μ and thickness d and I is the intensity transmitted through it.

If, as in Figure 1.12b, the percentage transmission is plotted on a logarithmic scale, a linear graph results, making it easier to read off the HVL and calculate μ.

The experimental arrangement for measuring HVL and the attenuation coefficient is illustrated in Figure 1.13a. The beam is restricted by means of a lead diaphragm or collimator to just cover a small detector. The diaphragm B and sheets of the absorbing material C are positioned halfway between the source A and detector D. This arrangement minimizes the amount of scattered radiation S entering the detector.

Attenuation of a wide beam

The measured percentage transmission depends on the width of the beam. For the narrow beam in Figure 1.13a, a relatively small amount of scatter is produced in the absorbing material. However, the amount of scatter produced, and thus detected, is very much greater for the broader beam illustrated in Figure 1.13b. In the latter case, the measured HVL would be increased.

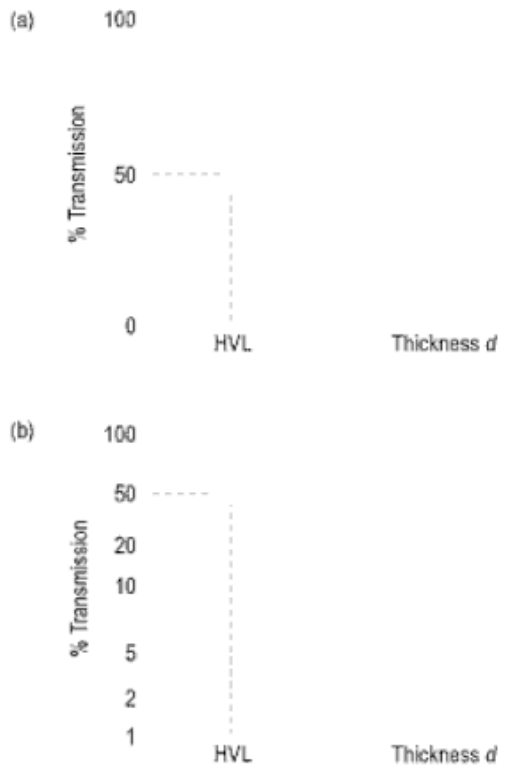

Figure 1.12 Exponential attenuation, half-value layers: (a) linear scale, (b) logarithmic scale. HVL, half-value layer.

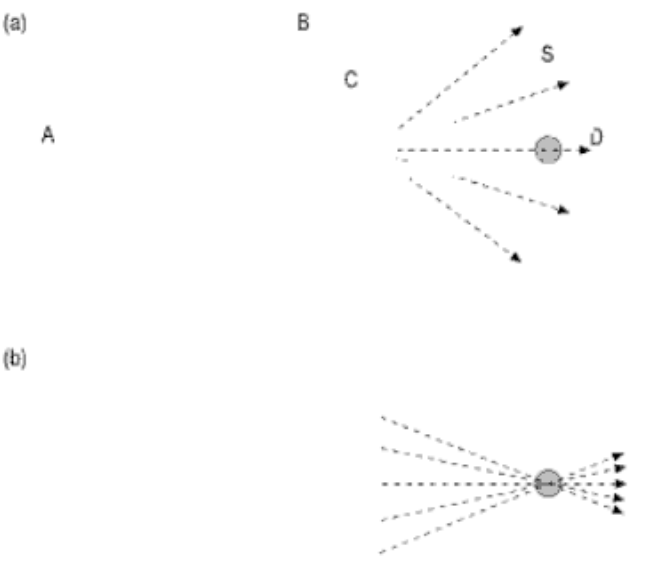

Figure 1.13 (a) A narrow beam is used for the measurement of the half-value layer. (b) Transmission of a wide beam.

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Attenuation of a heterogeneous beam

The beams produced by X-ray tubes are heterogeneous (polyenergetic), i.e. they comprise photons of a wide range of energies, as shown in the spectrum in Figure 1.8. As the beam travels through an attenuating material, the lower-energy photons are attenuated proportionally more than the higher-energy photons. The exponential law does not therefore apply exactly. It is still, however, correct to refer to the HVL of the beam. The HVL of a typical diagnostic beam is 30 mm in tissue, 12 mm in bone and 0.15 mm in lead.

As the beam penetrates the material, it becomes progressively more homogeneous. The proportion of higher-energy photons in the beam increases, a process described as beam hardening.

The average energy of the photons increases – the beam becomes harder or more penetrating. The second HVL, which would reduce the beam intensity from 50 to 25%, is thus greater than the first HVL, which reduces it from 100 to 50%.

The X-ray beams used in practice are usually both wide and heterogeneous, and the exponential law of absorption does not strictly apply. However, it is still possible to use the exponential law of X-ray attenuation in approximate calculations together with an effective attenuation coefficient.

Interaction processes

Three processes of interaction between X-rays and matter contribute to attenuation:

- interaction with a loosely bound or free electron – usually referred to as the Compton effect but also described as inelastic or non-coherent scattering scatter (see section 1.4.2)
- interaction with an inner shell or 'bound' electron – photoelectric absorption, a process in which the photon is totally absorbed (section 1.4.3)

and, less importantly,

- interaction with a bound electron – elastic scatter (see Box 1.4).

1.4.2 Compton effect

As depicted in Figure 1.14, the photon passing through the material bounces off a free electron, which recoils and takes away some of the energy of the photon as kinetic energy. The photon is scattered, i.e. diverted in a new direction, with reduced energy.

The angle of scatter θ is the angle between the scattered ray and the incident ray. Photons may be scattered in all directions. The electrons are projected only in sideways and forwards directions.

Effect of the angle of scattering

Figure 1.14 illustrates three different angles of scattering. The lengths of the arrows indicate the relative energies of the recoil electrons. It will be seen that the greater the angle of scatter,

- the greater the energy and range of the recoil electron, and also
- the greater the loss of energy (and increase of wavelength) of the scattered photon.

Thus a back-scattered photon ($\theta = 180°$) is less energetic or is 'softer' than a side-scattered photon ($\theta = 90°$), which in turn is softer than a forward-scattered photon ($\theta = 0$).

Effect of initial photon energy

The higher the initial photon energy,

- the greater the remaining photon energy of the scattered radiation and the more penetrating it is, and also
- the greater the energy that is carried off by the recoil electron and the greater its range.

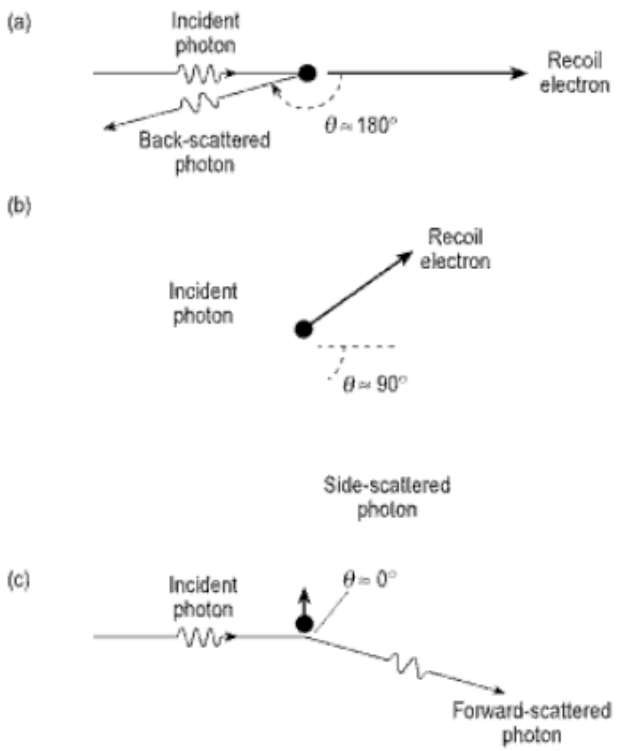

Figure 1.14 Compton scattering by a free electron.

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The probability of the Compton effect occurring (which is proportional to σ) depends on the number of electrons per unit *volume* while being otherwise independent of atomic number. It therefore depends on

(mass per unit volume) × (number of electrons per unit mass).

The former is the usual physical density, and the latter is called the electron density.

Because the number of atoms per unit mass is proportional to $1/A$, and the number of electrons per atom is proportional to Z, the number of electrons per unit mass must be proportional to Z/A.

Apart from hydrogen (for which $Z/A = 1$), almost all light elements relevant to radiology have $Z/A = 0.5$. As a result, hydrogenous materials have slightly more electrons per gram than materials without a hydrogen content. The electron density of bone, air, fat, muscle and water does not vary by more than 10%. On account of this small variation, we often simply say that Compton attenuation is proportional to physical density.

Air-equivalent materials and tissue-equivalent materials must have the same electron density as air and soft tissue, respectively, as well as having the properties stated in section 1.6.3.

This is seen in the following examples.

Incident photon	Back-scattered photon	Recoil electron
25 keV	22 keV	3 keV
150 keV	100 keV	50 keV

The softening effect of Compton scatter is therefore greatest with large scattering angles as well as with high-energy X-rays.

The Compton effect contributes to the total linear attenuation coefficient μ an amount σ that is called the Compton linear attenuation coefficient. The probability that the Compton process will occur is proportional to the physical density (mass per unit volume) of the material, as with all attenuation processes. It is also proportional to electron density, as explained in Box 1.3. It is independent of the atomic number of the material, as it concerns only free electrons for which the binding energy is negligible in comparison with the photon energy. Finally, it decreases only slightly over the range of photon energies encountered in diagnostic radiology, and may be thought of as being very approximately proportional to $1/E$.

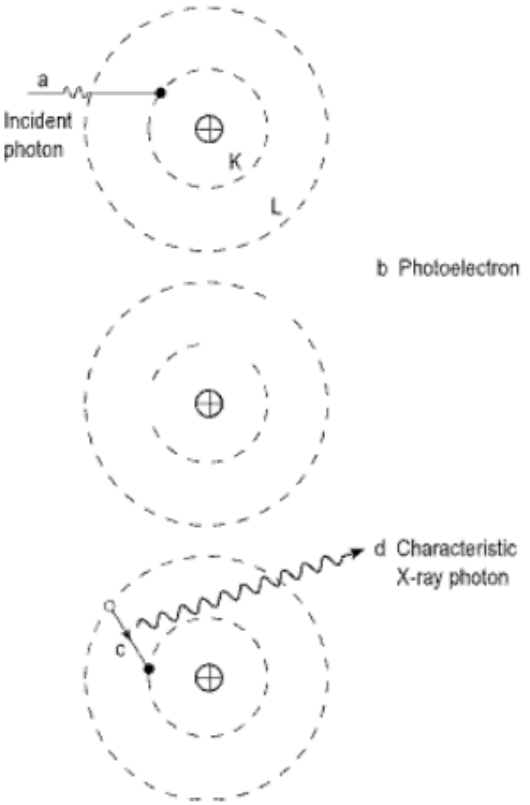

Figure 1.15 Photoelectric absorption.

To summarize, σ is proportional to ρ/E and is independent of Z.

The mass attenuation coefficient for the Compton effect, σ/ρ, is the same within 10% for such diverse materials as air, tissue, bone, contrast media and lead. They are all represented by a single dashed curve in Figure 1.16, which shows how σ/ρ varies with photon energy.

The energy carried off by the recoil electron is said to have been absorbed by the material, and the remainder, carried by the photon, to have been scattered. The Compton effect therefore represents only a partial absorption of the photon energy. In the diagnostic energy range, no more than 20% of the energy is absorbed, the rest being scattered.

1.4.3 Photoelectric effect

When, as in Figure 1.15, an X- or gamma ray photon (a) collides with an electron in (say) the K-shell of an atom, it can, if its energy is greater than the binding energy of the shell, eject the electron (b) from the atom. The energy of the photon is completely absorbed in the process, i.e. the photon disappears. Part of its energy, equal to the binding energy of the

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them. The track of the electron is therefore dotted with ion pairs. When travelling through air, the electron loses an average of 34 eV per ion pair formed. This is accounted for by about 3 eV being needed to excite an atom and about 10 eV to ionize it, and there being about eight times as many excitations as ionizations.

When it has lost the whole of its initial energy in this way, the electron comes to the end of its *range*. The greater the initial energy of the electron, the greater is its range. The range is inversely proportional to the density of the material.

For example, when 140 keV photons are absorbed in soft tissue, some of the secondary electrons are photoelectrons having an energy of 140 keV, able to produce some 4000 ion pairs with a range of about 0.2 mm in tissue. However, most of the secondary electrons are Compton recoil electrons with a spectrum of energies averaging 25 keV and an average range of about 0.02 mm. The ranges in air are some 800 times greater than in tissue. Because of their continual collisions with the atoms, the tracks of secondary electrons are somewhat tortuous.

It is the excitations and ionizations produced by the secondary electrons that account for various properties of X- and gamma rays.

- The ionization of air and other gases makes them electrically conducting: used in the measurement of X- and gamma rays (see section 1.6.3).
- The ionization of atoms in the constituents of living cells causes biological damage: responsible for the hazards of radiation exposure to patients and staff and necessitating protection against radiation (see Ch. 2).
- The excitation of atoms of certain materials (phosphors) makes them emit light (luminescence, scintillation or fluorescence): used in the measurement of X- and gamma rays and as a basis of radiological imaging (see section 1.7 and Chs 4–8).
- The effect on the atoms of silver and bromine in a photographic film leads to blackening (photographic effect): used in the measurement of X- and gamma rays (see Ch. 2) and as a basis of conventional radiography (see Ch. 4).
- The greater part of the energy absorbed from an X- or gamma ray beam is converted into increased molecular motion, i.e. heat in the material, and produces an extremely small rise in temperature.

Other ionizing radiations

Some ultraviolet radiation has a sufficiently high photon energy to ionize air. Beta particles emitted by many radioactive substances, and other moving electrons (in a TV monitor, for example) also possess the above properties. Alpha particles (helium nuclei, ^4He), which are particularly stable combinations of two neutrons and two protons, are also emitted by some radioactive substances. Both alpha and beta particles are charged particles and are *directly ionizing*.

X- and gamma rays are *indirectly ionizing*, through their secondary electrons; the secondary ions produced along the track of a secondary electron being many times more than the single primary ionization caused by the initial Compton or photoelectric interaction. Neutrons also ionize tissue indirectly through collisions with hydrogen nuclei.

1.5 FILTRATION

When a radiograph is taken, the lower-energy photons in the X-ray beam are mainly absorbed by and deposit dose in the patient. Only a small fraction, if any, reaches the film and contributes to the image. The object of filtration is to remove a large proportion of the lower-energy photons before they reach the skin. This reduces the dose received by the patient while hardly affecting the radiation reaching the film, and so the resulting image.

This dose reduction is achieved by interposing between the X-ray tube and patient a uniform flat sheet of metal, usually aluminium, and called the *added* or *additional filtration*. The predominant attenuation process in this filter should be photoelectric absorption. Because this varies inversely as the cube of the photon energy, the filter will attenuate the lower-energy photons (which mainly contribute to patient dose) much more than it does the higher-energy photons (which are mainly responsible for the image).

The X-ray photons produced in the target are initially filtered within the target itself, because they may be generated below its surface, and then by the window of the tube housing, the insulating oil and the glass insert. The combined effect of these disparate components is expressed as an equivalent thickness of aluminium, typically 1 mm Al, and is called the *inherent filtration*. The light beam diaphragm mirror also adds to the filtration, as does the dose area product (DAP) chamber (see section 1.6.3). When inherent filtration must be minimized, a tube with a window of beryllium ($Z = 4$) instead of glass may be used.

The *total filtration* is the sum of the added filtration and the inherent filtration. For general diagnostic radiology, it should be at least 2.5 mm Al equivalent. This will produce an HVL of about 2.5 mm Al at 70 kV and 4.0 mm at 120 kV. The amount of added filtration is therefore typically 1.5 mm Al.

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Choice of filter material

The atomic number should be sufficiently high to make the energy-dependent attenuating process, photoelectric absorption, predominate. It should not be too high, because the whole of the useful X-ray spectrum should lie on the high-energy side of the absorption edge. If not, the filter might actually soften the beam.

Aluminium ($Z = 13$, $E_K = 1.6$ keV) is generally used, as it has a sufficiently high atomic number to be suitable for most diagnostic X-ray beams. The most common alternative is copper ($Z = 29$), with added filter thicknesses in the range of 0.1–0.3 mm being typical. Copper is a more efficient filter, but it emits 9 keV characteristic X-rays. These must be absorbed by a backing filter of aluminium on the patient side of the compound filter.

Effects of filtration

Figure 1.18 shows the spectrum of X-rays generated at 60 kV after passing through 1, 2 and 3 mm Al. A filter attenuates the lower-energy X-rays more in proportion than the higher-energy X-rays. It therefore increases the penetrating power (HVL) of the beam at the cost of reducing its intensity. It reduces the skin dose to the patient while having little effect on the radiological image. It is responsible for the low-energy cut-off of the X-ray spectrum, depicted in Figure 1.18.

Increasing the filtration has the following effects. It causes the continuous X-ray spectrum to shrink and move to the right, as seen in Figure 1.18. It increases the minimum and effective photon energies but does not affect the maximum photon energy. It reduces the area of the spectrum and the total output of X-rays. Finally, it increases the exit dose:entry dose ratio or film dose:skin dose ratio.

Above a certain thickness, there is no gain from increasing the filtration, as the output is further reduced with little further improvement in patient dose or HVL. In addition, the reduction in total output of X-rays may require the exposure time for a radiograph to be increased to an extent that patient movement becomes a problem. It may also require an increase in tube current during fluoroscopy that cannot be sustained because of excess heat production.

K-edge filters

Filter materials with K-edges in the higher-energy part of the X-ray spectrum can be used. These remove both high- and low-energy X-rays but are relatively transparent to the energies just below the K-edge. An example of an 80-kV beam filtered with a 0.1-mm erbium filter ($Z = 68$, $E_K = 57$ keV) is shown in Figure 1.19. K-edge filters are rarely used except in mammography (Ch. 4.6).

Compensating or wedge filter

A shaped filter may be attached to the tube to make the exposure across the film more uniform and compensate for the large difference in transmission by, for example, the upper and lower thorax, neck and shoulder, or foot and ankle. In fluoroscopy equipment, the filter may be incorporated into the beam diaphragm and can be driven into the beam to prevent flaring of the image at the edges of the body while not totally obscuring the underlying anatomy. These filters may be referred to as soft or wedge filters.

1.6 RADIATION DOSIMETRY

1.6.1 Absorbed dose

The effects of ionizing radiations described above may be correlated with the energy deposited as ionization and excitation of the atoms of the material

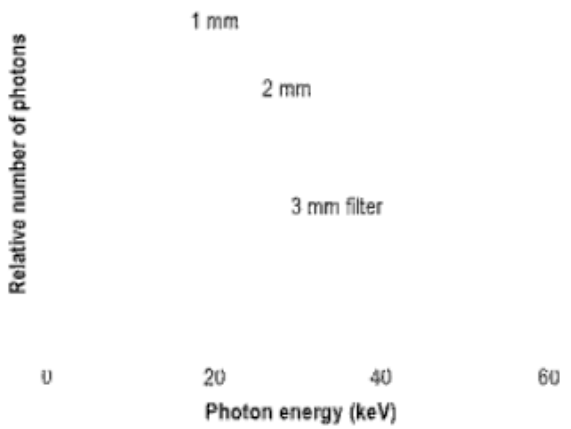

Figure 1.18 Effect of increasing aluminium filtration on the X-ray spectrum.

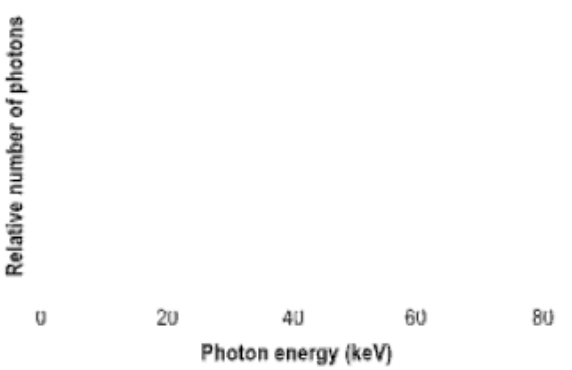

Figure 1.19 Effect of a 0.1 mm erbium filter on the spectrum at 80 kV compared with the same beam filtered by 2.5 mm Al.

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irradiated. The absorbed dose is the energy deposited per unit mass of the stated material (in joules per kilogram). The SI unit of absorbed dose is the gray (Gy); $1\,Gy = 1\,J\,kg^{-1}$. Absorbed dose rate is measured in grays per second, with the usual multiples and submultiples. Absorbed dose is commonly used to define the quantity of radiation delivered at a specified point in the radiation field. Its definition is therefore concerned with the vanishingly small quantities of energy absorbed and of mass of material. It can be thought of as the concentration of energy delivered to the position of measurement.

The concept of absorbed dose applies to all directly and indirectly ionizing radiations and to any material. It is particularly valuable when considering tissue and biological effects. The term *dose* is applied loosely to several dosimetric quantities used to describe radiation fields and their effects on biological systems. When encountering the word 'dose', it is necessary to decide on the quantity being referred to from the context. Within this text, whenever 'dose' is used alone, it is taken to mean absorbed dose in the material specified.

Before 1980, the international unit of absorbed dose was the rad. It is used in some old textbooks. The conversion factor is 1 Gy = 100 rad; 1 rad = 1 cGy = 10 mGy.

1.6.2 Kerma

Another quantity sometimes used is kerma, which is also measured in grays. The difference between kerma and absorbed dose is subtle. Kerma is an acronym for *kinetic energy released to matter*. It is the energy *transferred* per unit mass of irradiated material, from photons to electrons at the specified position. In contrast, absorbed dose is the energy *deposited* (as ionization and excitation) by secondary electrons at that position. The only practical difference between the two is that at high energies (greater than about 1 MeV) a small part of the energy of the electrons may produce bremsstrahlung radiation, and the energy transferred to electrons at a specific location will be deposited away from that location because of the increased electron range. For diagnostic energies, they are effectively equal and, in the subject matter of this text, absorbed dose and kerma can be used interchangeably.

The reader should be aware that there is an obsolete quantity, *exposure*, that may be encountered in some older publications. Unlike kerma, it applies to X- and gamma rays only (kerma also applies to neutrons). Exposure describes the quantity of ionization produced by a photon beam per unit mass of air. Its units are therefore C kg^{-1}. Exposure was historically useful, because it could be measured directly (although only for photon energies up to about 500 keV). Before the adoption of SI units, exposure had the special unit, roentgen (R). In reading older literature, the roentgen can be taken to be approximately equal to 10 mGy.

1.6.3 Measurement of X- and gamma ray dose

It is extremely difficult to measure absorbed dose in solids or liquids directly. In theory, this can be done by measuring temperature rise, but in practice, because the temperature change for a relatively high absorbed dose of 1 Gy would lead to a temperature rise not much greater than 10^{-4}°C (0.1 mK), it is impractical. It is more usual to measure the dose delivered to air (or air kerma) under the same conditions and to multiply it by a conversion factor to obtain the dose in the specified material such as tissue. The conversion factor depends on the relative amounts of energy absorbed in air and the material.

Like the mass attenuation coefficients, the factor depends on the effective atomic number of the material and on the effective energy of the X- or gamma rays. For X-rays used in radiology, the following are approximate values of the conversion factor:

- for muscle, the atomic number of which is not very different to that of air and in which the Compton process predominates, the ratio is close to unity and varies only between 1.0 and 1.1 over the whole kV range
- for compact bone, with its higher atomic number and in which photoelectric absorption is important, the ratio varies from about 5 at low keV to 1.2 at 150 keV
- for fat, with its lower atomic number, the ratio varies in the opposite direction, from about 0.6 at low keV to 1.1 at high keV.

Ionization chamber

Air kerma is commonly determined by measuring the amount of ionization produced by the photon beam in air. The instrument used is known as an *ionization chamber*, and a simple version of it is the *thimble* chamber shown in Figure 1.20. The chamber consists of a plastic thimble-shaped outer wall (A) surrounding an air-filled cavity (B), and with an insulator separating it from a thin central electrode (C). It is positioned at the point of interest.

Each X-ray photon (X) absorbed in the wall liberates a secondary electron (e^-), which produces ion pairs along its track. (Although in the diagram the track is for simplicity idealized as a straight line, it is in fact quite tortuous.) For each ion pair, approximately 34 eV of energy is deposited. Therefore for each

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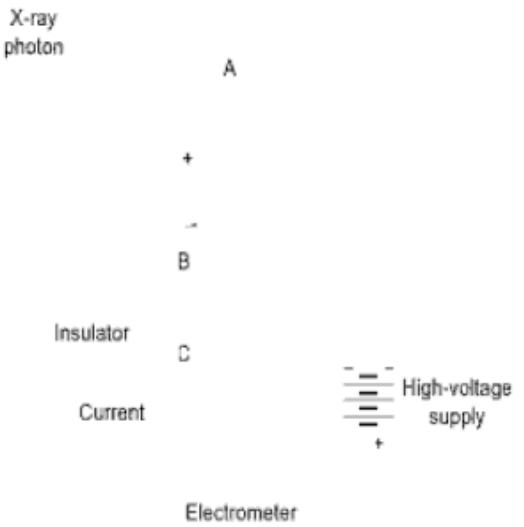

Figure 1.20 Ionization chamber.

coulomb of charge (and remembering the definition of electron volt as being the energy in J multiplied by the electron charge, Box 1.1), 34 J of energy will have been deposited. Theoretically therefore, the air kerma is 34/mass of air in the chamber.

To measure the charge, the ions are separated before they can recombine by applying a polarizing voltage (typically in the range of 100–300 V) between the outer thimble wall and the central electrode. The positive ions are attracted to the negative electrode and the negative ions (electrons) to the positive electrode. The ionization current is measured by a device known as an electrometer. It is proportional to air kerma rate and the total charge collected to air kerma.

The chamber wall must be made of a suitable material. As Figure 1.20 shows, the air in the thimble is ionized by secondary electrons that have been set moving by X-rays absorbed in the wall and electrode. So far as the X-rays and their secondary electrons are concerned, these components should be indistinguishable from air, except in density. They must be made of *air-equivalent material* that matches air in terms of its effective atomic number, and so absorbs energy from an X-ray beam, whatever its energy, to the same extent as the same mass of air. The density is not important. There are other conditions to be fulfilled, such as electrical conductivity and mechanical stability. Generally, a compromise is made with a plastic material being used ($Z \approx 6$) with graphite deposited on its inner wall to make it electrically conducting.

The chamber wall must be sufficiently thick so that the electrons produced outside the chamber will not penetrate the wall to deposit ionization in the cavity; 0.2 mm is sufficient for photoelectrons from 140 keV X-rays, for example. If the wall is too thick, it will attenuate unduly the radiation being measured. This is of particular concern in mammography beams, for which thinner walled chambers are used.

Another correction has to be applied if the ambient temperature or pressure differs from standard values. At high pressures and/or low temperature, the chamber will over-read because of increased density and therefore mass of air in the cavity. However, the correction is small and is generally ignored.

As indicated above, there is a theoretical relationship between the measured charge and air kerma. In practice, however, there would be a need to apply several corrections, in particular to account for the non-air equivalence of the chamber and the attenuation in the chamber wall. Ionization chambers and their associated electronics are therefore sent to a standards laboratory for calibration at the energies at which they are to be used.

Figure 1.20 illustrates a particular shape of ionization chamber. In principle, any shape of cavity could be used, but the commonest chambers are either cylindrical (as illustrated here) or consist of parallel electrodes. The so-called parallel plate chamber typically has two outer electrodes (generally circular) defining the cavity, with a central collecting plate between the two, the three plates being separated by insulators.

The sensitivity of an ionization chamber (charge per unit of air kerma) is proportional to volume. In general, for diagnostic radiology chambers with a volume of approximately 10–30 cm^3 are used for measurements in the radiation beam, with chambers of 150 cm^3 or bigger being suitable for the measurement of scatter radiation.

Air is chosen as the standard material for dosimetry because:

- it has an effective atomic number (7.6) close to that of tissue (7.4), so that the factor used to convert absorbed dose in air to absorbed dose in tissue can be made easily and accurately
- it is applicable for measurement over a wide range of X- and gamma ray energies
- large and small doses and large and small dose rates are easily and accurately measured
- it is universally available with an invariable composition.

Dose area product meters

Dose area product meters are used for the assessment of patient dose (DAP). They use an ionization chamber mounted on the collimator of the X-ray tube. The chamber is a parallel plate type, generally with square plates. It has an area bigger than the maximum beam size at the position at which it is mounted. It is a

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sealed chamber so as to avoid changes in calibration caused by changes in temperature and pressure. The amount of ionization produced within the chamber is proportional not just to dose but also to the area of beam. Thus it is measuring the product of dose and area with unit of Gy cm^2. Different submultiples may be used by different manufacturers, two common examples being cGy cm^2 and μGy m^2. Use of DAP for patient dose audits is discussed in Chapter 2.8.3.

Other dosimeters

It is often convenient to measure radiation dose by means of:

- lithium fluoride thermoluminescence dosimeters used for both personal dosimetry (see Ch. 2.5.5) and patient dosimetry (see Ch. 2.8.3)
- the photographic effect in silver bromide, used in a film badge (see Ch. 2.5.5)
- photoconductivity in silicon diodes to be used in direct reading electronic personal dosimeters and dosimeters used for quality assurance.

Films and diodes use high atomic number materials, so that factors to correct their readings to air kerma are critically dependent on the energy spectrum. To provide meaningful results, they are used with filters so that their readings can be correctly interpreted.

1.6.4 Radiation quantity and quality

In this text, the amount or quantity of radiation has been discussed in terms of intensity (energy fluence rate) or air kerma rate. It has been shown that they are:

- approximately proportional to the square of the kV
- proportional to the mA
- inversely proportional to the square of the distance F from a point source.

Thus air kerma rate is proportional to $kV^2 \times mA/F^2$.

The energy fluence or air kerma is, in addition,

- proportional to the exposure time: air kerma is proportional to $kV^2 \times mAs/F^2$, where mAs is the product of mA and exposure time (in seconds).

In addition, these quantities are:

- decreased as the filtration is increased
- greater for a constant potential than a pulsating potential
- greater for high rather than low atomic number targets.

Quality is a term used to describe the penetrating power of an X-ray beam. The most complete description of quality is the spectrum of X-ray energies, but in practice a simpler, single-figure description is preferred. It may be specified as the HVL of the beam in a stated material, usually aluminium for diagnostic X-rays. Alternatively, it may be described by the average or *effective energy* of the spectrum. This may be deduced from the measured HVL. The greater is the HVL, the greater the effective energy. The effective energy can be defined as the photon energy of monoenergetic X-rays that have the same HVL as the polyenergetic beam being assessed. For example, 100-kV X-rays filtered with 2 mm Al have the same HVL (3 mm Al) as 30-keV photons. When filtered with 10 mm Al, the effective energy is increased to 50 keV.

The HVL and effective energy of an X-ray beam:

- increase as the applied kV is increased
- are greater for constant potential than pulsating potential
- are unaffected by the mA or exposure time
- increase as the filtration is increased
- are unaffected by the distance from the target.

Further descriptive terms may be applied. A hard X-ray beam is produced by a high kV and a thick filter, a soft beam by a low kV and a thin filter. Because the two principal factors affecting HVL or effective energy are kV and filtration, and because the latter is normally not changed, it is common in radiography to describe the quality of X-rays simply by stating the tube kV.

1.7 LUMINESCENCE

Luminescence is a general term to describe the process in which a material absorbs energy from an external source and re-emits that energy in the form of visible light. The external energy source may be one of many including chemical, biological and physical sources, but in the context of radiology we are concerned only with radiation sources for which the term *photoluminescence* may be used.

Luminescence can be divided into two types:

- *fluorescence*, which is (more or less) the instantaneous emission of light following energy input
- *phosphorescence*, which describes delayed light emission referred to as afterglow.

The distinction between the two is somewhat arbitrary, with the delay time being of the order of 10^{-6} s. A material that has luminescent properties is described as a *phosphor*. It should be noted that crystalline materials with luminescent properties that are used for the detection of gamma radiations are commonly referred to as *scintillants*.

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Radiation hazards and protection

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2.1 IONIZING RADIATION INTERACTIONS WITH TISSUE

When ionizing radiations such as X- and gamma rays interact with living tissue, it is the absorption of radiation energy in the tissues that causes damage. If the radiation passed through the tissue without absorption, there would be no biological effects and no radiological image would be produced. Whenever radiation is absorbed, chemical changes are produced virtually immediately, and subsequent molecular damage follows in a short space of time (seconds to minutes). It is after this, during a much longer time span of hours to decades, that the biological damage becomes evident (Fig. 2.1).

There are many examples of *radiation-induced damage*: to the skin and hands suffered by the early radiologists, excess leukaemias in patients treated with radiation for ankylosing spondylitis, and radiation accidents in various parts of the world. However, the current estimates of radiation risk for cancer induction have been mostly derived from the outcomes, since 1945, of those exposed to nuclear explosions, particularly the 90 000 survivors of the atomic bomb attacks on Hiroshima and Nagasaki.

The principal radiation source for medical exposures is diagnostic X-rays; other important sources include gamma-emitting radionuclides in nuclear medicine and radiotherapy sources including beta emitters, electron beams, and gamma and X-ray sources (and in very rare cases neutron and proton beams).

Whenever a beta particle or an electron passes through tissue, ionizations and excitations occur repeatedly until eventually the particle comes to rest, giving up all its energy. Being relatively light, such electrons are easily deflected by the negatively charged orbital electrons of the tissue atoms that they

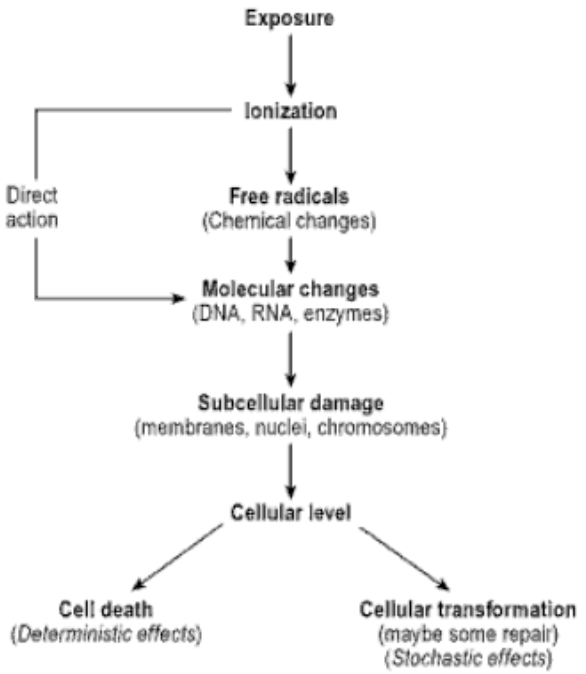

Figure 2.1 Chain of events following exposure to ionizing radiation.

encounter, and so follow a very tortuous path. The total range involved in tissue interactions is of the order of a few millimetres at most. Hence electrons are easily absorbed by a shield of a few millimetres of perspex or by thin sheets of metal, depending on their initial energy.

Unlike beta particles, X- and gamma radiations do not have a maximum depth of penetration associated with them, but they simply undergo progressive attenuation. That is, the intensity of the radiation beam continues to fall as it interacts with tissue but at any given depth a residual beam always remains, however much less intense (see Ch. 1.4.1).

During radiation exposures, it is the *ionization* process that causes the majority of immediate chemical changes in tissue. The critical molecules for radiation damage are believed to be the proteins (such as enzymes) and nucleic acid (principally DNA). The damage occurs in two basic ways: by producing lesions in solute molecules directly (e.g. by rupturing a covalent bond) or by an indirect action between the solute molecules and the free radicals produced during the ionization of water.

Indirect damage arises more commonly, because living tissue is about 70–90% water. If a pure water molecule is irradiated, it emits a free electron and produces a positively charged water ion, which immediately decomposes:

$$H_2O + \text{radiation} \rightarrow H_2O^+ + e^-$$

$$H_2O^+ \text{ decomposes} \rightarrow H^+ + OH.$$

The hydroxyl free radical OH is a highly reactive and powerful oxidizing agent that produces chemical modifications in solute organic molecules. These interactions, which occur in microseconds or less after exposure, are one way in which a sequence of complex chemical events can be started, but the free radical species formed can lead to many biologically harmful products and can produce damaging chain reactions in tissue.

The exact mechanism of these complex events is incompletely understood, but biological damage following exposure to ionizing radiations has been well documented at a variety of levels. Figure 2.1 shows the chain of events. At a *molecular level*, macromolecules such as DNA, RNA and enzymes are damaged; at the *subcellular level*, cell membranes, nuclei, chromosomes, etc. are affected; and at the *cellular level*, cell division can be inhibited, cell death brought about, or transformation to a malignant state induced. Cell repair can also occur, and is an important mechanism when there is sufficient time for recovery between irradiation events.

2.2 RADIATION DOSES AND UNITS

To study the effects of radiation, it is necessary to quantify the amount of radiation received. In Chapter 1.6, the physical quantities *kerma* and *absorbed dose* were introduced, as well as their unit, the gray (Gy). These are measurable quantities related to the energy transferred (kerma) or absorbed (absorbed dose) from the radiation beam. While it is reasonable to assume that biological effects will be related to energy absorption, there are biological factors that need to be considered, in particular the influence of radiation type and the relative radiosensitivities of the different organs and tissues within the body. Two further dosimetry quantities to account for these effects are therefore introduced: *equivalent dose* and *effective dose*. These incorporate empirical weighting factors based on observations of radiation effects.

Equivalent dose

X- and gamma rays are indirectly ionizing radiations, ionization being produced by electrons generated in the photon interactions with tissue. Electrons produce ionization over a distance that is relatively large compared with cellular dimensions and are considered to have a low ionization density. This is described by the quantity *linear energy transfer* (*LET*), being the sum of the energy deposited in tissue per unit path length. In contrast, alpha particles, being the nucleus of the helium atom with two protons plus two neutrons, are very much heavier. For the same initial energy as an

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electron, an alpha particle travels a much shorter distance. For these high-LET particles, ionizing events are much more closely spaced and within distances comparable with the dimensions of a single strand of DNA. For this reason, the damage caused by high-LET radiations is much more likely to be non-repairable than is the case for electrons (low-LET radiation). This difference in radiation effects is described by the term *relative biological effectiveness* (*RBE*), which is the ratio of absorbed doses required to induce the same biological end point for two radiation types. RBE is generally expressed in terms of a comparison with a reference beam of X-rays. It is highly dependent on a number of factors, including biological end point, and may be 20 or greater for alpha particles, implying that they produce the same biological end point as X-rays with 5% or less absorbed dose.

Equivalent dose is a quantity used only in radiation protection, i.e. for relatively low levels of dose. It is derived from absorbed dose multiplied by a radiation weighting factor w_R. The factor depends on radiation type and is defined as being unity for X- and gamma rays, electrons and beta particles. For alpha particles, it is set equal to 20, and for protons and neutrons equal to 5, 10 or 20 depending on radiation energy. The SI unit of equivalent dose is $J\,kg^{-1}$ given the special name sievert (Sv) to distinguish it from absorbed dose.

Effective dose is a second radiation protection dosimetry quantity that incorporates factors to account for the variable radiosensitivities of organs and tissues in the body. It also has the unit sievert. Effective dose is considered in more detail in section 2.3.2.

This text is concerned with the diagnostic use of ionizing radiations and deals exclusively with the use of X- and gamma rays for which the radiation weighting factor w_R is unity. Absorbed dose and equivalent dose are therefore numerically equal. To avoid confusion caused by the use of the same unit (Sv) for two distinct radiation protection dose quantities, when reference is made to the dose to specific organs or tissues (sometimes referred to as *organ dose*) doses are given in terms of the absorbed dose in Gy. The exception to this is for the dose limits (see section 2.5.2). These apply to all types of radiation, and it is necessary to use equivalent dose (in Sv) for those limits that apply to specific organs or tissues and effective dose (in Sv) for the whole body limits.

2.3 EFFECTS OF RADIATION

There are two categories of radiation effect: *somatic* effects, which occur in the individual exposed, and *genetic* or *hereditary* effects, which occur in the descendants of those individuals as a result of lesions in the germinal cells. These effects may be further described as being either *deterministic* or *stochastic* in nature.

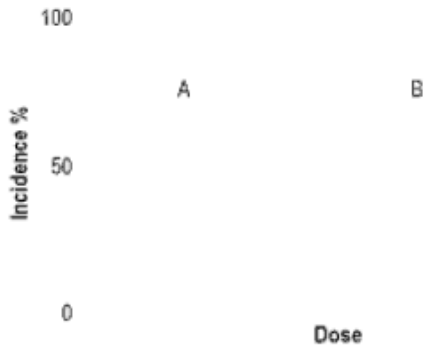

Figure 2.2 Dose–incident curves for deterministic effects. Curve A represents a relatively mild, low-dose effect compared with the effect represented by curve B.

2.3.1 Deterministic effects

Threshold dose

Deterministic effects (sometimes called non-stochastic) are characterized as having a threshold dose below which the effect will not occur. The value of the threshold may vary to a small extent from individual to individual. Once the threshold dose is exceeded, the likelihood of the effect occurring increases rapidly with dose up to a level at which the effect will invariably occur. This is illustrated in Figure 2.2, in which two dose–incidence curves are shown. Curve A might represent relatively mild damage, for example skin erythema, for which the threshold dose is relatively low. Curve B in Figure 2.2 represents more severe damage, such as irreversible ulceration of the skin, with a very much higher dose threshold. Some examples of deterministic effects and approximate threshold doses are given in Table 2.1.

Cataracts are produced above a threshold of about 5 Gy to the lens of the eye. The damage to the eye is cumulative. Attention therefore has to be paid to the lifetime dose for those working in radiation-intense areas such as interventional radiology. This is considered further in section 2.5.2.

Unlike damage to the eye, most deterministic effects have repair mechanisms such that the rate at which the dose is delivered influences the threshold dose. For example, the threshold dose for skin erythema is in the region of 2–5 Gy. If somebody were to receive 20 mGy $week^{-1}$ to the skin over

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RADIATION PHYSICS

- Diagnostic imaging employs radiations - X, gamma, radiofrequency and sound - to which the body is partly but not completely transparent.
- IONIZING RADIATION (X-rays and gamma rays) are used most

1.1 STRUCTURE OF THE ATOM

	Relative mass	Relative charge	Symbol
Nucleons			
▪ Neutron	1	0	n
▪ Proton	1	+ 1	p
Extranuclear			
▪ Electron	$\frac{1}{1840}$	- 1	e^- , β^-
Other			
▪ Positron	$\frac{1}{1840}$	+ 1	e^+ , β^+
▪ Alpha particle	4	+ 2	α

Table 1.1 Some fundamental particles

- The diameter of the nucleus of an atom is about 5×10^{-15} m.
  The diameter of the entire atom is about 5×10^{-10} m (100,000 times larger)
  ∴ Most of an atom is an empty space.
- *Rutherford and Bohr model* → an atom is a massive positively charged nucleus surrounded by electrons in orbits of specific diameters.

NUCLEUS:

- Has a positive electrical charge, and contains almost all the mass of an atom.
- Made of several types of particles "***NUCLEONS"*** only ***protons*** & ***neutrons*** considered.
- The proton has a positive electric charge numerically equal to the charge of the electron, while the neutron has zero electrical charge.
- The neutron and proton have about the same mass (1.66×10^{-24} gm), which is approximately 1840 times greater than the mass of an electron.
- ***The atomic number of the atoms "Z"*** = the number of protons in the nucleus → synonymous with element name.
- ***The mass number "A"*** = the total number of protons and neutrons in the nucleus.
  Gold (Au) has a nucleus with 79 protons (*Z = 79*) and 118 neutrons (*A = 197*)
- All atoms of an element have the same atomic number (Z), but may have different mass numbers (isotopes).
  ISOTOPES have the same number of protons in the nucleus "same atomic number" but have different numbers of neutrons "different mass numbers".
  - ${}^{12}_{6}C$ refers to a carbon atom with A = 12 & Z = 6 → shortened ${}^{12}C$ "Carbon-12".
  - Carbon-14 still has Z = 6 but has two more neutrons → unstable and radioactive. It is called a ***Radionuclide***.

ELECTRON ORBITS AND ENERGY LEVELS:

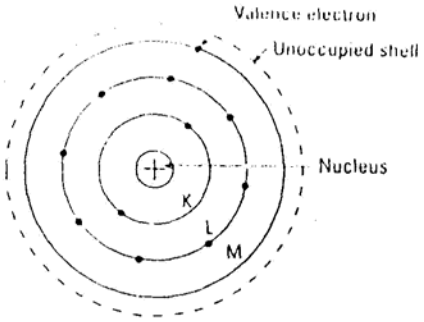


Fig. 1.1 Electron shells in a sodium atom.

- An atom is composed of a central positive nucleus + electrons with negative charges revolving around the nucleus in circular orbits.
- A neutral atom contains an equal number of protons and electrons.
- The electron orbits are designated by letters: K, L, M, N, O, and so on.
  The atomic system allows 2 electrons in the first orbit, 8 in the second, 18 in the third, 32 in the fourth, and 50 in the fifth ***($2N^2$)***.
- An electron in the K shell is called a K electron. L electrons are in the L shell.

➢ ***Valence shell:***

- Outermost shell.
- Concerned with the chemical, thermal, optical & electrical properties of the element.
- Can't have more than 8 electrons (called 'free electrons').

- **X-rays** involve the inner shells, and **radioactivity** concerns the nucleus.
- The diameters of the electronic shells are determined by *the nuclear force* on the electron, and by *the angular momentum and energy* of the electron.

BINDING ENERGY:

- ***The "binding force" of the electron*** = the attractive force between the positively charged nucleus and the negatively charged electron, that keeps the electrons in the atom.
- The binding force is *inversely proportional* to *the **square** of the distance between the nucleus and electron* → K electron has a larger binding force than an L electron.
- ***Binding energy*** = the energy expended in completely removing the electron from the atom against the attractive force of the positive nucleus → expressed in *electronvolts **(eV)***.
  - Never greater than 100 keV.
  - The binding energy depends on
    1. The shell ($E_K > E_L > E_M$ …).
    2. The element (↑ Atomic number → ↑ binding energy)

  For example;

In the case of tungsten (W; Z = 74) the binding energies of different shell are

E_K	E_L	E_M
70	11	2 keV

In the case of the K shell, the binding energies of different elements are

W (Z = 74)	I (Z = 53)	Mo (Z = 42)	Cu (Z = 29)
70	33	20	9 keV

- An electron cannot have any more or less energy than shell energy, but electron may jump from one energy shell to another "higher or lower" energy shell
  - × ***Electron movement to a lower energy shell*** results in the emission of energy.
    - ✓ *Emitted energy* = the difference in the binding energy between the two shells.
    - ✓ The energy may take the form of an x ray photon.
  - × ***Electron movement to a higher energy*** e.g. absorption of an x-ray photon.
- Each atomic energy shells, except K, has ***SUBSHELLS*** of slightly different energies

Ionisation & Excitation:

- Ionized atom → if one of its electrons has been completely removed → ***ion pair*** "electron + positive ion"
- Excited atom → if an electron is raised from one shell to a farther one with the absorption of energy → the atom has more energy than normal.
  When it falls back → energy is re-emitted as *a single 'packet' of energy* or *light photon*.

1.2 ELECTROMAGNETIC RADIATION

Energy traveling across empty space

- All EMR travel with velocity (*c*) of light in vacuo "**3×10^8 m\sec**".
- Named according to the way of production and the special properties they possess.
  e.g. X-rays (emitted by X-ray tubes) & gamma rays (emitted by radioactive nuclei) have essentially the same properties and differ only in their origin.

Quantum aspects:

Electromagnetic radiation is *a stream of 'packets'* or *quanta of energy* "***PHOTONS***" traveling in straight lines.

Wave aspects:

- EMR is sinusoidally varying electric & magnetic fields traveling with velocity **c** when in vacuo.
- They are transverse waves; with the electric and magnetic field vectors point at right angles to each other and to the direction of travel of the wave.

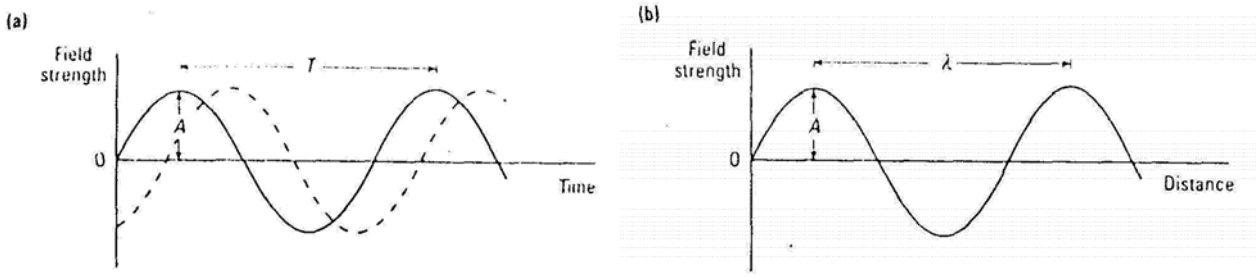


Fig. 1.2 Electromagnetic wave. Field strength versus (a) time and (b) distance.

Definitions:

- Amplitude ***(A)*** = the peak field strength.
- The Period ***(T)*** = the time interval between successive crests of the wave.
- The Wavelength ***(λ)*** = the distance between successive crests of the wave.
- The frequency ***(f)*** = the number of crests passing a point in a second.

$$f = 1 / T$$

- Wavelength and frequency are inversely proportional to each other,

wavelength x frequency = constant (velocity)

- The types of radiation are listed in Table 1.2, in order of increasing photon energy, increasing frequency, and decreasing wavelength.

	Wavelength	***Frequency***	***Energy***
Radio waves	30-6 m	**10-50 MHz**	40-200 neV
Infrared	**10000-700 nm**	30-130 THz	0.12-1.8 eV
Visible light	**700-400 nm**	430-750 THz	1.8-3 eV
Ultraviolet	**400-100 nm**	750-3000 THz	3-12 eV
X- and gamma	60-2.5 pm	5 x 10^6–120 x 10^6 THz	**20-500 keV**

- When the energy is less than 1 keV the radiation is usually described in terms of its ***frequency***, except **that visible light** → described in ***wavelength***.
- Only radiations at the ends of the spectrum penetrate the human body sufficiently to be used in imaging → radio waves and X- or gamma rays.
- *N.B. sound is a mechanical wave not an electromagnetic wave (MCQ).*

PHASE

- Two objects are said to move in synchronism when their phase difference is constant.
- The two sine waves in Fig. 1.2a are *out of phase*. They have the same period or frequency but the dashed curve lags behind the solid curve "i.e. reaching its maximum at a later time".
- Phase difference = the time interval between their peaks expressed as ***an angle***, lying between 0 and 360°, on a scale which makes the period T correspond to 360°.
- In single-phase mains supply → the current rises and falls as a single sine wave.
  In a three-phase supply → the current rises and falls as three sine waves having phase differences of 120°.

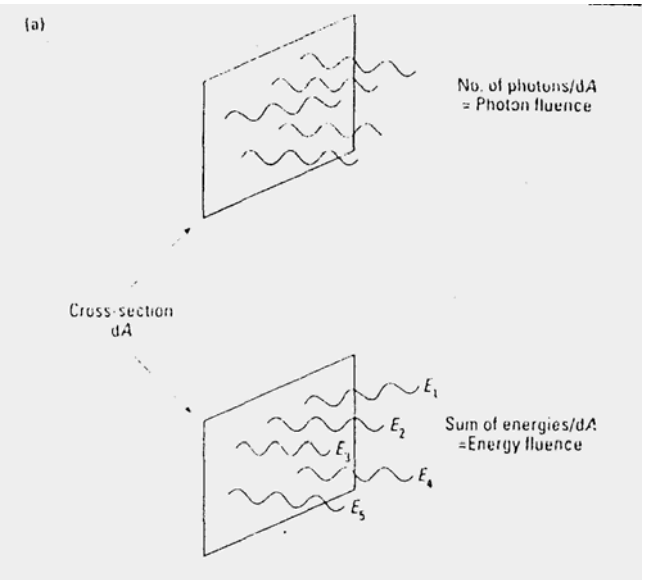
Wave and quantum theories combined

- Photon energy is proportional to the frequency.
- The constant of proportionality is called ***Planck's constant (h)***. Thus, $E = hf$
- Since frequency is inversely proportional to wavelength, so also is photon energy:

E (in keV) = 1.24 / λ (in nm)

For example:

Blue light	**λ** = 400nm	**E** = 3 eV
Typical X- and gamma rays	**λ** = 0.1 nm	**E** = 140 keV



Intensity

- Radiation travels in straight lines ***"= RAYS"*** radiating in all directions from a point source.
- ***BEAM*** = a collimated set of rays (Fig. 1.3a).
- ***The photon fluence at the point*** = the number of photons per unit area passing through the cross section in the time.
- ***The energy fluence at the point*** = the total amount of energy "*the sum of the energies of all the individual photons*" per unit area passing through the cross-section in the time.

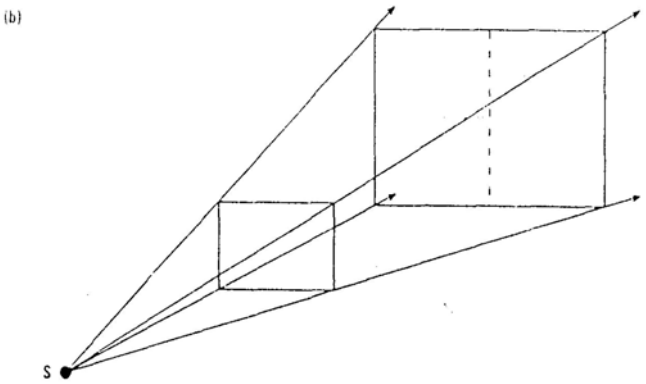
- ***The energy fluence rate at the point (= beam intensity)*** is the total amount of energy per unit area passing through the cross-section per unit time **(watts per square millimeter)**.

Intensity is proportional to the square of the amplitude (A), see Fig. 1.2.

- Energy fluence and intensity are not easy to measure directly.
  Instead, an easier indirect measurement is made:

☒ ***'Air kerma'*** instead of energy fluence. ☒ ***"Air kerma rate"*** instead of intensity.

INVERSE SQUARE LAW



- ***The intensity of the radiation is inversely proportional to the square of the distance from a point source***
- When the distance is changed:

$$\frac{\text{New intensity}}{\text{Old intensity}} = \frac{(\text{Old distance})^2}{(\text{New distance})^2}$$

or

$$\frac{\text{New air kerma rate}}{\text{Old air kerma rate}} = \frac{(\text{Old distance})^2}{(\text{New distance})^2}$$

∴ ***Halving*** the distance quadruple's the intensity or air kerma rate & ***doubling*** the distance reduces them by a factor of 4.

N.B.

Only the intensity of the x-ray will decrease with distance but the energy of the photons not change.

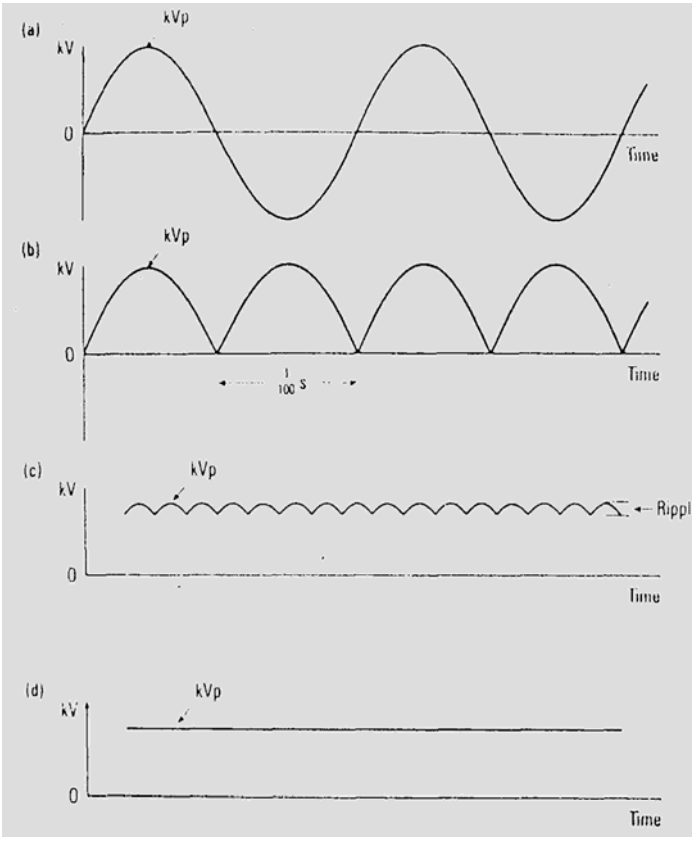
PRODUCTION OF X RAYS

X-RAY GENERATORS

- X-ray generator is the device that supplies electric power to the X-ray tube.
- ***Two sources of electrical energy are required and are derived from the alternating current (AC) mains by means of transformers. Figure l.4 shows:***
  - **The filament heating voltage** (about 10 V) **and current** (about 10 A),
    → produced by a step-down low-voltage transformer → for heating of the filament.
  - **The accelerating voltage** (30-150 kV) between the anode and cathode **('high tension', 'kilovoltage', or 'kV')**, produced by a high-voltage transformer.
    → accelerates the current of electrons (typically 0.5-1000 mA) flowing between the anode and cathode **('tube current', 'milliamperage', or 'mA')**.
- The mA is controlled by varying the filament temperature.
  A small ↑ in filament temperature, voltage, or current → large ↑ in tube current
- kV & mA can be varied independently in the X-ray set.
- The anode-cathode voltage = $\mathbf{kV_p}$ or **kV**.

THE WAVEFORM & RECTIFICATION:

- **Rectification is the process of changing alternating current into direct current.**
- Using an alternative current for X-ray tube → makes electrons moves in one half of the cycle from the cathode to anode, in the other half of cycle the electrons with move in opposite direction → ***undesirable***, because:
  1. ↑↑ heating of the filament → ↓↓ lifetime. ***2.*** wouldn't produce useful X-ray.
- *Figure 1.5 depicts the waveforms of 4 types of high-tension voltage supply:*



1. *Alternating voltage* ('self-rectification').
2. *Pulsating direct current (DC)* ('full wave rectification, single-phase').
3. *'Constant potential'*, which is steady DC with a small ripple from a 'three-phase' generator.
4. High frequency which is *steady DC* with negligible ripple.

DIAGNOSTIC X-RAY TUBES

- X rays are produced by *energy conversion* when a fast-moving stream of electrons is suddenly decelerated in the "target" anode of an x-ray tube.
- X-ray tube is made of *Pyrex glass* encloses vacuum & contain 2 electrodes (***diode tube***).
- Electrodes are designed so that electrons produced at ***cathode*** (-ve electrode or filament) accelerated by high potential difference toward the ***anode*** (+ve electrode or target)
  Electrons are produced by the heated tungsten filament and accelerated across the tube by the accelerating tube voltage to hit the tungsten target → x rays production.

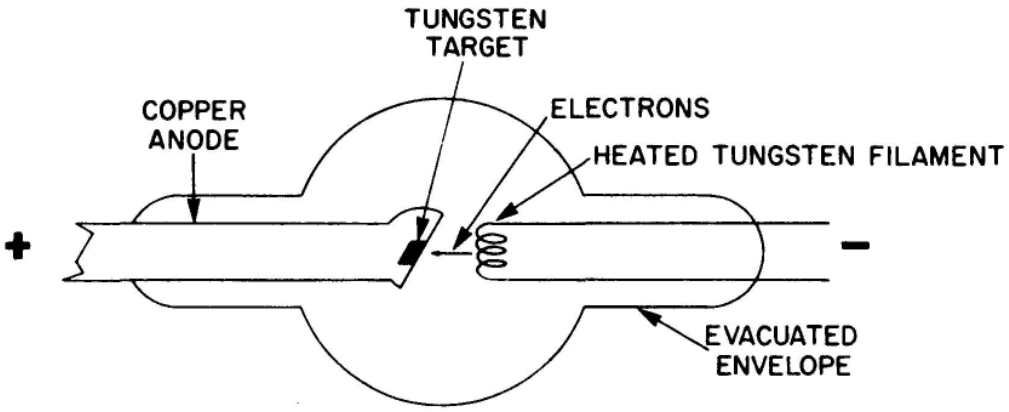


Figure 2-1: The major components of a stationary anode x-ray tube

GLASS ENCLOSURE

- Necessary to seal the two electrodes of the x-ray tube in a vacuum.
- Vacuum → allow **number** & **speed** electrons to be controlled independently.
- The connecting wires must be sealed into the glass wall of the x-ray tube.
- Special alloys, having approximately *the same coefficients of linear expansion* as Pyrex glass, are generally used in x-ray tubes.

CATHODE

- The negative terminal of the x-ray tube.
- **Composition of the cathode:**
  - ***The filament***, which is the source of electrons for the x-ray tube.
    Tungsten wire, ***0.2 mm*** in diameter coiled into a vertical spiral ***0.2 cm*** in diameter and ***1 cm*** in length
  - ***The connecting wires***.
  - ***A metallic focusing cup***.
- **The number (quantity) of x rays produced depends entirely on the number of electrons** that flow from the filament to the target (anode) of the tube.
- The x-ray tube current is measured in milliamperes (1 mA = 0.001 A).
  & refers to *the number of electrons flowing per second from the filament to the target*
  For example, in a given unit of time, a tube current of 200 mA is produced by twice as many electrons as a current of 100 mA, and produces twice as many x rays.

Where these electrons come from? → "THERMIONIC EMISSION"

Def.: the emission of electrons resulting from the absorption of thermal energy.

- A pure tungsten filament must be heated to a temperature of at least **2200° C** to emit a useful number of electrons (thermions).
  - Tungsten is not as efficient an emitting material as alloys of tungsten, for example.

- But, it is chosen for use in x-ray tubes, because:
  1. It can be drawn into a thin wire that is quite strong.
  2. Has a high melting point (3370° C).
  3. Has little tendency to vaporize.

  ∴ Tungsten filament has a reasonably long life expectancy.

- When current flows through tungsten wire → heated → its atoms absorb thermal energy → some of the electrons acquire energy → move small distance from the metal surface → form a small cloud in the vicinity of the filament "***the space charge***".
- The electron cloud, produced by thermionic emission, also termed ***"Edison effect".***

SATURATION VOLTAGE

- If the potential applied across the tube is insufficient to cause almost all electrons to be pulled away from the filament when they are emitted → ***Space Charge Effect:*** cloud of negative charges tends to prevent other electrons from being emitted from the filament until they have acquired sufficient thermal energy to overcome the force caused by the space charge → limit the number of electrons → limits X-ray tube current.

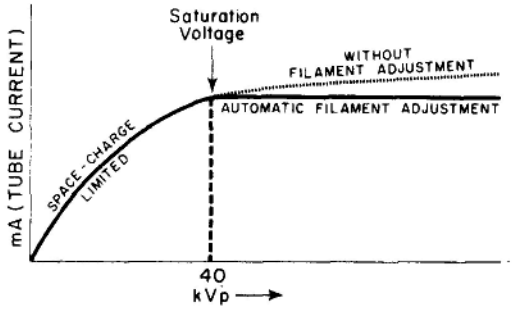


Figure 2-7: Saturation voltage

- **Below the saturation point,**
  - The tube current is limited by **the space charge effect** (space-charge-limited).
  - ↑↑ kV → significant ↑↑ in x-ray tube current although filament heating is the same.
- **Above the saturation voltage,**
  - The space charge effect has no influence on the x-ray tube current.
  - The tube current is determined by **the number of electrons** made available by the heated filament (emission-limited or temperature-limited).
  - ↑↑ kV → very little change in tube current

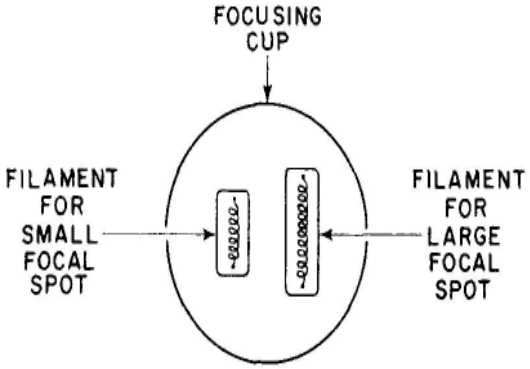
THE AMPERE

- The unit of electric current.
- ***Def.:*** the "flow" of 1 coulomb of electricity through a conductor in 1 sec.
- ***The coulomb*** = the amount of electric charge carried by 6.25×10^{18} electrons.

  Therefore, an x-ray tube current of 100 mA (0.1 A) may be considered as the "flow" of 6.25×10^{17} electrons from the cathode to the anode in 1 sec.
- Electron current across an x-ray tube is in one direction only (always cathode to anode).

Cathode focusing cup:

- Surrounds the filament & maintained at the same negative potential as the filament.
  So, *its electrical forces cause the electron stream to converge onto the target anode in the required size and shape* → prevent bombardment of a large area on the anode caused by mutual repulsion of the electrons (Figs. 2-2 and 2-4).
- The focusing cup is **made of nickel**.
- Modern x-ray tubes may be supplied with a single or, more commonly, a double filament (Fig. 2-2).



Vaporization of the filament when it is heated:

- Filament becomes too thin → break up "acts to shorten the life of an x-ray tube".
- Tungsten is deposited on the inner surface of the glass wall of the x-ray tube → produces *bronze-color "sunburn"*.

This tungsten coat has two effects:

1. Filter the x-ray beam.
2. Increases the possibility of arcing between the glass and the electrodes at higher kilovoltage (kVp) values → tube puncture.

ANODE :

Anodes (positive electrodes) of x-ray tubes are of two types, ***stationary*** *or* ***rotating****.*

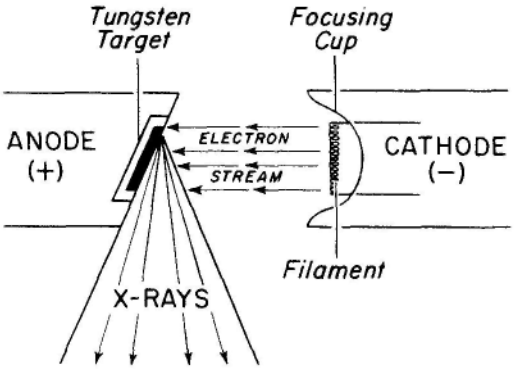


Figure 2-4

Stationary Anode:

- Consists of a **small plate of tungsten** "target" embedded in **a large mass of copper**.
- Target is **2-3 mm** thick, square or rectangular in shape, **>1 cm** in dimensions.
- The anode angle is usually **15 to 20°**.
- ***Tungsten*** *is chosen as the target material for several reasons.*
  1. It has a **high atomic number (74)** → more efficient for the production of x rays.
  2. Withstand the high temperature produced "high melting point = **3370° C**".
  3. Reasonably good for the absorption & rapid dissipation of heat.
  However, it cannot withstand the heat of repeated exposures → the massive copper anode acts to ↑↑ the total thermal capacity of anode and to speed its rate of cooling.
- The actual size of the tungsten target > the area bombarded by the electron stream (Fig. 2-4) because ***copper has a relatively low melting point*** (**1070° C**) → the heat produced could melt the copper in the immediate vicinity of the target.
- Tungsten and copper have different expansion coefficient on heating → needs

satisfactory bonding otherwise the tungsten target would peel away from copper anode.

2.7.2 ROTATING ANODE TUBE

- Rotating anode is used to produce x-ray tubes capable of withstanding the heat generated by large exposures.
- **The anode assembly, seen in cross-section, consists of:**
  - ✓ An *anode disk*, 7-10 cm or more in diameter.
  - ✓ A thin *molybdenum stem*.
  - ✓ A blackened *copper rotor* "part of the induction motor which rotates the target stem".
  - ✓ *Bearings*, lubricated with a soft metal such as **silver**.
  - ✓ *An axle*, sealed into the glass envelope, which supports the target assembly.

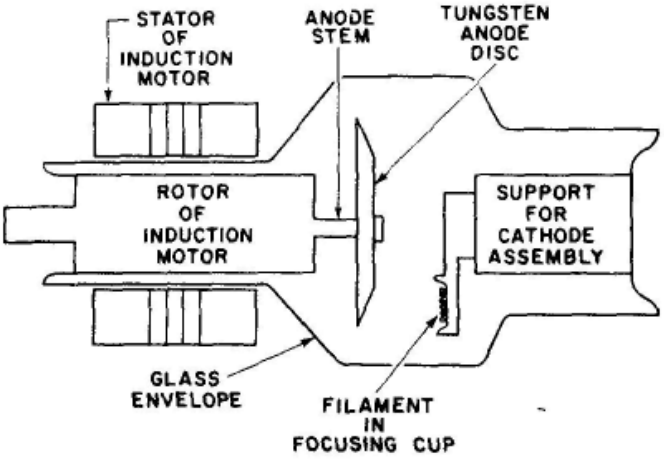
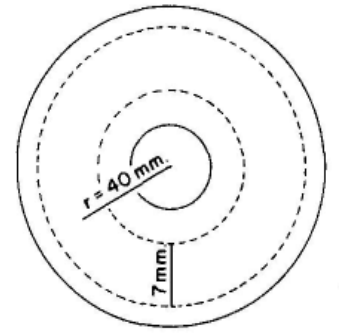


Figure 2-6: The rotating anode x-ray tube

- The anode of a rotating anode tube consists of a large disc of **tungsten** or an **alloy of tungsten** ***"tungsten-rhenium alloy"*** → better thermal characteristics than pure tungsten and does not roughen with use as quickly.
- Typical disc diameters measure **75, 100, or 125 mm**.
  The diameter of the tungsten disc determines the total length of the target track→ affects the maximum permissible loading of the anode.
- The anode rotates at a speed of about **3600 revolutions per minute (rpm)** using ***single-phase mains supply***.
  Any area of the tungsten disc is found opposite the electron stream only once every 1/60 sec & during the remainder of the time heat generated during the exposure can be dissipated.
  High-speed anodes are energized with ***three-phase mains*** & rotate at about ***9000-17000 rpm***.



- The tungsten disc has a beveled edge. The angle of the bevel may vary from **6 to 20°**. The bevel is used to take advantage of the ***line focus principle***.
- The purpose of the rotating anode is to **spread** the heat produced during an exposure over a large area of the anode while **the apparent or effective focal spot size** has remained the same.

- **To make the anode rotate, some mechanical problems must be overcome:**
  - ***Power to the rotating anode*** → Stator coils.
  - ***Lack of durable bearings*** → Metallic lubricants e.g. silver.
  - ***Heat dissipation*** → Molybdenum stem.
  - ***Inertia*** → short stem, using 2 sets of bearings & ↓ anode weight by using an anode made of molybdenum (lighter than tungsten) + target made of tungsten-rhenium alloy.
  - ***Roughening & pitting of anode surface, which*** ↑↑ target scatter & X-ray absorption in target itself → target made of tungsten-rhenium alloy, anode discs with grooves on the target surface & coating the back of anode disc with black substance e.g. carbon.

How the anode cools

- Heat produced on the focal track → **conducted** quickly and stored temporarily in the anode disk → **transferred by radiation** to the insulating oil → stored temporarily then **transferred by convection** to the housing → lost by **radiation and by fan-assisted convection** through the surrounding air.
- The molybdenum stem is sufficiently long and narrow to control the amount of heat that is conducted to the rotor → so that it is not in danger of overheating.
- Heat radiation is promoted by blackening the anode assembly.
- High-powered tubes used in CT & angiography pump the oil through external heat exchanger

GRID-CONTROLLED X-RAY TUBES

- Conventional x-ray tubes contain two electrodes (cathode and anode).
- The grid-controlled tube has a 3rd electrode → control the flow of electrons from the filament to the target.

  The third electrode is ***the focusing cup*** *that surrounds the filament.*
- In conventional x-ray tubes a focusing cup is electrically connected to the filament.
- In the grid-controlled tube, the focusing cup is ***electrically negative relative to the filament*** اكثر سلبيه.
  - The voltage across the filament-grid produces an electric field along the path of the electron beam → pushes the electrons even closer together.
  - If the voltage is large enough → the tube current may be *completely pinched off* "act like a on & off switch for the tube current → used in cinefluorography".

TUBE SHIELDING AND HIGH-VOLTAGE CABLES

- X-rays are emitted with **equal intensity** in every direction from the target.
  In addition, the x rays are **scattered in all directions** following collisions with various structures in and around the tube.
- The tube housing is lined with lead except a plastic window through which useful X-ray beam emerges → absorb 1ry and 2ry x-rays that would otherwise produce a high intensity of radiation around the tube → needless exposure of patients and personnel + excessive film fogging.
- **The effectiveness of the tube housing in limiting leakage radiation** must meet the specifications listed in The National Council of Radiation Protection and Measurements Report No. 49, which states that:

  "The leakage radiation measured at a distance of 1 meter from the source shall not exceed 100 mR in 1 hour when the tube is operated at its

maximum current & maximum tube potential".

- **Another function of the tube housing**
  "Mineral oil around the tube" → provide shielding for the high voltages & prevent short-circuiting between the grounding wires and the tube.

Other aspects of tube and generator design

- The glass insert is immersed in oil → 1) convects heat away from the tube & 2) act as an electrical insulator for tube.
- The high tension and filament transformers are contained in **oil-filled earthed metal tank** and connected to the tube housing by a pair of highly insulated flexible cables.
- **Dental X-ray tube:** low-powered - small - stationary anode tube.

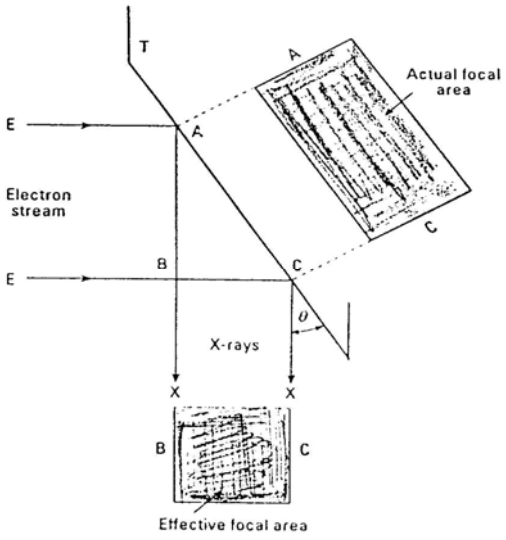
2.7 LIMITATIONS OF THE X-RAY TUBE

There are two important limiting factors in imaging with X-rays:

1. The dose of radiation delivered to the patient, and
2. The heat which inevitably accompanies the production of X-rays.
   If heat accumulate in X-ray tube → shorten or damage the tube.

2.7.1 LINE FOCUS PRINCIPLE

- ***The actual focal spot*** is the area of the tungsten target bombarded by electrons from the cathode→ the area over which heat is produced and which determines the tube rating (see Section 2.7.3).
- The size and shape of the focal spot are determined by the size and shape of the electron stream when it hits the anode.
  The size and shape of the electron stream are determined by ***1)*** the dimensions of the filament tungsten wire coil, ***2)*** the construction of the focusing cup "also called ***electron lens***", and ***3)*** the position of the filament in the focusing cup.



- The target anode angle = **6 - 20°**.
  If it is 17° and the effective focal spot is 1 x 1 mm, the actual focal spot must be 4x1 mm.

The problems posed by

1) The need for a large focal spot to allow greater heat loading.

2) The conflicting need for a small focal area to produce good radiographic detail, as larger focal area will lead to blurring of the image "geometrical blurring".

- ***The line focus principle*** (Figure 2-3) → the surface of target is inclined so that it forms an angle with the plane ⊥ to incident beam.

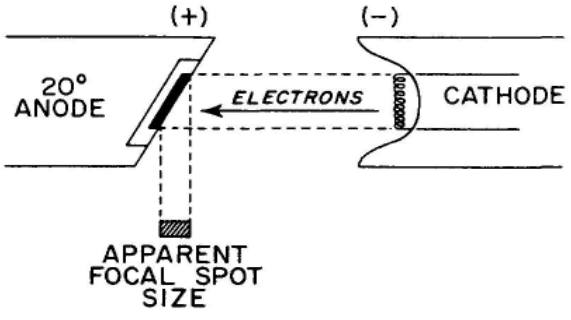
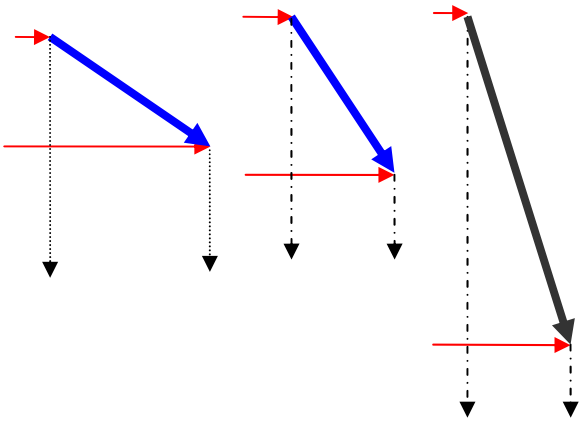


Figure 2–3 The line focus principle

- This angulation makes the ***effective 'or apparent' focal spot*** BC foreshortened & is considerably **smaller** than that of the actual focal spot & is **square** in shape.
  This makes the focal spot blurring small and fixed whatever the orientation of a structure.
- The effective focal spot varies across the film → **elongated** from the cathode side of the film & **contracted** from the anode side.
- Angle θ → the angle between the central ray and the target face
- ***The size of the projected focal spot is directly related to the sine of the angle of the anode.***

∴ The smaller the angle of the anode, the smaller the apparent focal spot



TAKE CARE:

- The steeper the target *for the same actual focal spot and target heat rating* → **the smaller the effective focal spot**.
- The steeper the target for the same effective focal spot → **the larger the actual focal spot and target heat rating**.
- The steeper the target → **the narrower the useful X-ray beam** and **the smaller the field covered**.

- Some newer 0.3-mm focal spot tubes may use an anode angle of only 6°.
  ✶There is a limit to which the anode angle can be decreased as dictated by ***the heel effect*** (the point of anode cutoff).
  MCQ: For general diagnostic radiography done at a 40-inches focus-film distance (1 m), the anode angle is usually ***no smaller than 15°***.
- Focal spot size is expressed in terms of **the apparent or projected focal spot**; sizes of **0.3, 0.6, 1.0, and 1.2 mm** are commonly employed.
- Usually, an X-ray tube has two filaments and two focal spots of different sizes which are selected from the control panel.
  The smaller focal spot is selected where small fields are needed & for better resolution "in mammography and in cineradiography with a small field image intensifier" and **the larger one** for thicker parts of the body where a greater intensity of X-rays is needed "in general radiography using large films" (Table 2.1).

Table 2.1 Typical effective focal sizes (mm)

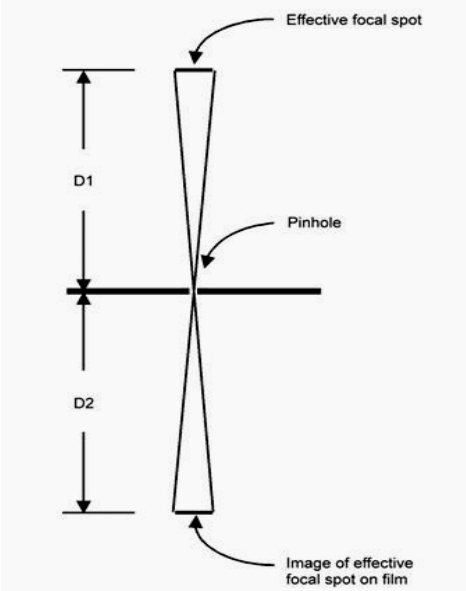
Macromammography	0.1
Mammography	0.3
Macroradiography	0.3
Radiography	0.6-1.2
Fluoroscopy	0.6

MCQ ***X-ray output*** DOES NOT depend on focal size, only sharpness and effective field of view do.

MEASUREMENT OF THE EFFECTIVE FOCAL SPOT

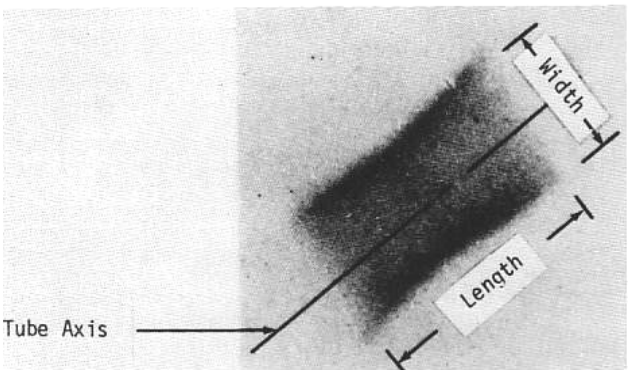
There are two principal methods of measuring the effective focal spot.

'PINHOLE CAMERA':



- This consists of a hole drilled in a disk of heavy metal, such as gold, incorporated in a lead sheet.
- Must be positioned **half way between the focal spot and the film**.
  The pinhole is may be positioned closer to the tube anode than to the cassette → magnified image of the effective focal spot → knowing the magnification enables the true size of the effective focal spot to be calculated.
- It is important to **align the pinhole to central beam of the X-ray tube accurately**.
- The pinhole must be **several times smaller than the focal spot** (e.g. pinhole of **0.03 mm** for focal spots below 1mm, and **0.08 mm** for focal spots from 1 to 2.5 mm).
- Although X-rays diverge in all directions from each point on the target, only one of them passes through the pinhole, and it produces ***a dot of blackening*** on the film.

Notice the following:



- Pinhole size of 0.03mm is very small, so special equipments are needed for accurate measurement.
- Intensity is more towards periphery of the focal spot (**edge band distribution** → commonest pattern, though undesired).
- **The resulting image (Fig. 2.12b) shows:**
  a. **The size & shape** of the **effective** focal spot.
  b. Density pattern represents **intensity distribution** & any lack of uniformity is shown.
  c. Reveals any **extra-focal X-radiation** "*which degrades image*.

STAR TEST TOOL:

- This technique is **used in measuring focal spots less than 0.3 mm**
- A **'star test' tool** comprises a number of tapered 'spokes' of lead mounted on a Perspex disk **(Figure).**
- This is mounted partway between the film and the tube (not in contact with film).

- Exposure produces a **magnified** and **unsharp** image of the star **(Fig. 2.13b), shows following features:**
  1. ***RING OF BLURRING*** → Diameter of ring is used to calculate the effective focal spot size.
  2. Outside this ring a sharp ***NEGATIVE*** image is produced.
  3. Paradoxically, inside the ring there is a ***POSITIVE*** and sharp image of the spokes.

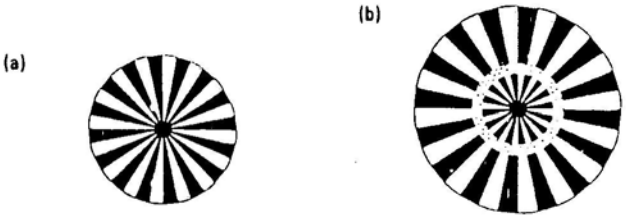


Fig. 2.13: Measurement of the effective focal spot with a 'star test' tool, (a) The star test tool, (b) Image with a blurring diameter

Blooming

✓ Blooming = unwanted increase in focal spot size which occurs when the tube is operated at ***high milliamperage***.

✓ Occurs because the negative charge of the focusing cup is less effective, so electrons emitted from the filament are not well focused in a regular beam → hit a larger area > actual focal spot.

✓ It occurs particularly at ***low kV*** values and with ***small focal spots***.

Regarding focal spot:

- The focal spot size can limit **the spatial resolution** "geometric unsharpness", depends on the location of the object in the source-to-detector direction.
- The resolution impact of the focal spot increases with geometric magnification, i.e. increasing distance between the object and the film or detector if FFD is fixed.

Thus, a small focal spot is desired in order to optimize spatial resolution.

- The focal spot size also sets the upper limit on X-ray tube current or output rate **(heat loading)**.
  - ***If an X-ray tube is operating at its instantaneous power limit***, decreasing the size of the focal spot will require a decrease in the tube current (radiation output).

∴ There is a trade-off between **spatial resolution** due to the size of the focal spot & **image noise** in a fixed exposure time due to the decreased X-ray intensity and imaging time.

2.7.4 UNIFORMITY OF THE X-RAY BEAM

- **The useful X-ray beam** is taken in ***a direction perpendicular to the electron stream*** "at right angles to the tube axis from the center of the focal spot ". (**B** in Fig. 2.15).
  → It is usually pointed toward the center of the area of interest in the body.
  - ❝ Toward the anode edge of the field, the beam **A** is cut off by the face of the target. Toward the cathode edge, the beam **C** is cut-off by the edge aperture in the lead shield.
  - ❝ Thus, the X-ray field is made symmetrical around the central ray B, → A and C are the limits of the useful beam.
- In fact the useful beam is narrower than suggested because of *THE HEEL EFFECT*.

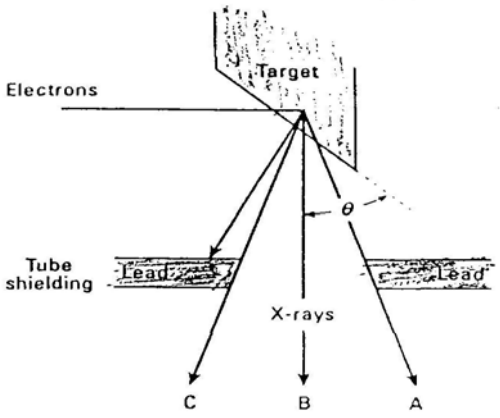
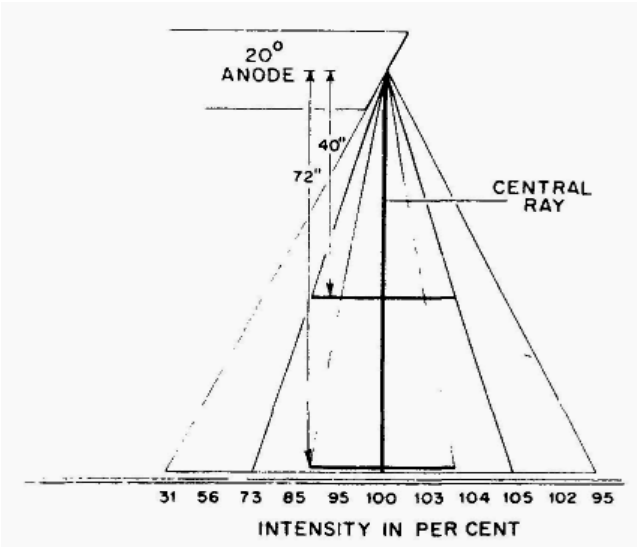


Fig. 2.15 Heel effect.

THE HEEL EFFECT

The intensity of the x-ray beam that leaves the x-ray tube is not uniform but depends on the angle at which the x rays are emitted from the focal spot.

- ***Mechanism:***
  - ✓ ***Electrons*** penetrate a few micrometers into the target before being stopped by a nucleus → so; ***the X-rays*** produced are attenuated and filtered by the target material on their way out.
  - ✓ X-rays traveling toward the anode edge of the field have more target material to cross → ∴attenuated more than those traveling toward the cathode edge
    → ***the intensity of the beam decreases toward the anode end of the fields***
    (Less importantly, ***the HVL increases*** because of the filtration effect).



- ***Factors affecting the heel effect:***
  1. **Anode angle:** the steeper the target → ↑↑ heel effect.
  2. **FFD:** ↑↑ FFD → ↓↓ heel effect "with fixed film size".
  3. **Film size:** ↓↓ film size → ↓↓ heel effect "with fixed FFD".
  4. **Roughening of the target surface** → ↓↓ X-rays output & ↑↑ the heel effect.

- In radiographs of body parts of different thicknesses → the thicker parts should be placed toward the cathode (filament) side of the x-ray tube.
  e.g. **AP film of the thoracic spine** → anode end over the upper thoracic spine where the body is less thick & the cathode end of the tube is over the lower thoracic spine where thicker body structures will receive the increased exposure.

2.7.3 HEAT RATING

The heat loading of an X-ray tube (calculated in **joules**)
= **kV x mAs** for a constant potential (three phase).
= **0.7 x kV x mAs** for a pulsating single-phase generator.

Single radiographic exposure

- In order to 'freeze' and display movement, **individual exposures should be as short as the heating of the X-ray tube permits**.
- **The allowable mAs at a particular kV increase as the exposure time is lengthened (MCQ).**
- Any combination of kV, mA, and exposure time should be such that, at end of the exposure, the temperature of the anode does not exceed its safe value, i.e. *there should be no risk of the target melting, vaporizing or roughening*.
- ***The rating is usually stated as the allowable mA, and this:***
  - ✓ Decreases as the exposure time is increased.
  - ✓ Decreases as the kV is increased.
  - ✓ **Increases with the effective focal spot size** (because increase effective focal spot means increase actual focal spot for a fixed anode angle)…and,
    Increases with smaller target angles for a fixed effective focal spot, (*Drawing above explain it*, because the actual focal spot then larger).
  - ✓ Is greater for a rotating than a stationary anode.
  - ✓ Is greater for a 10 cm disk than a 7 cm disk.
  - ✓ Is greater for a high-speed anode.
  - ✓ Is greater for a three-phase constant potential than for a single-phase pulsating potential - because the former produces heat more evenly throughout the exposure.
- The foregoing information is stored on a microprocessor in the control circuit which prevents any exposure being made which would exceed the rating of the tube.

Repeated radiographic exposures

- To display movement, e.g. angio- or cineradiography, a rapid series of exposures is made.
- Each exposure must be ***sufficiently short*** & ***within the rating*** of the focal area.
- For repeated exposures → depends also on the ability of the anode assembly and the oil **to accumulate heat** → **both not allowed to exceed its maximum safe temperature**.
- **The rapidity with which a series of such exposures can be made** depends on:
  a) سعة التخزين The maximum amount of heat that can be temporarily stored in the anode in particular & the tube housing as a whole; and
  b) سرعة التوزيع The rate at which they lose heat by cooling.
- **The heat storage capacity of the anode may be increased by** soldering to the back of the tungsten plate a disk of molybdenum and/or solid graphite (both have a higher heat capacity per unit mass than tungsten).
- Microprocessor in control circuit calculates the max. total number of exposures allowed.
- If the **anode heat capacity (typically 0.2 MJ)** has been reached → need at least **15 min** to cool down completely;
  & **the entire assembly (typical heat capacity 1.0 MJ)** may need **an hour**.

Continuous operation: fluoroscopy

- Heat must be removed at the same rate as it's produced from the housing "not allowed to accumulate in the oil".

  ∴ The rating depends only on ***the cooling rate*** (and whether or not the fan is on) and

  NOT at all on *the focal spot size or the type of generator*.
- In fluoroscopy the anode is **stationary** or **rotating at reduced speed**, to ↓ bearing wear.

Other ratings:

- **Maximum kV** also depends on the ***insulation*** of the tube, cables, etc.
- **Maximum mA** → is low at a low kV than at a high kV (d.t. ***'space charge effect'***).

  N.B. allowable mA (tube rating) is low at high kV.

2.7.5 QUALITY ASSURANCE OF EXPOSURE PARAMETERS

~ At installation; each X-ray tube and generator should be checked for compliance to a certain specification.

~ X-ray generators need to be checked periodically → for ***exposure parameters*** (e.g. kV and mAs), and ***tube parameters*** (e.g. focal spot and filtration). ***More details in Section 3.8***

Focal spot and filtration

- **Focal spot** should be measured at installation.
- If the HVL and the kV measured carefully → **the total filtration** can be deduced from a set of published graphs.

Kilovoltage and output

- **The kV** can either be measured:
  - ✓ **Directly** (invasively) by **potential divider** applied across the high tension leads
  - ✓ **Indirectly** (non-invasively) by **a penetrameter** method.

    A calibrated electronic penetrameter is placed in the beam → compares the differentially filtered response of detectors contained within it → gives **equivalent kV**.
- **The tube output** → measured by a ***dosemeter***, often an ionization chamber.
- *For constant mAs,* the output is a function of kV^X. "X ≈ 2".
- *For a constant kV*, the output is a linear function of mA and exposure time.

Field definition and uniformity

- The size of the X-ray field is delineated using lead diaphragms + a light beam incorporated in overcouch tube.
- Regular checks should be made to ensure that:
  - **a.** The light beam and field outline match.
  - **b.** The center of the field, on the cross wires of the light beam diaphragm, coincides with the center of the X-ray field.
- The extent of the heel effect and field non uniformity can be measured by exposing a large, plain film and measuring the density differences across the field.

PROCESSES OCCURRING IN THE TARGET OF AN X-RAY TUBE

Each electron arrives at the surface of the target with a kinetic energy (in kiloelectronvolts "keV") = the kV between the anode and cathode.

INTERACTION WITH THE K-SHELL: LINE SPECTRUM, CHARACTERISTIC RADIATION

- Electron (a) from the filament collides with an electron (b) in the K-shell of an atom → ejected from the atom, **provided that the energy of the bombarding electron is greater than the binding energy of the shell**.
- The remaining energy is shared between the initial electron & the ejected electron → both leave the atom
- The hole created in the K-shell is most likely to be filled by an electron (c) falling from the L-shell → emission of a single X-ray photon (d) of energy equal to the difference in the binding energies of the two shells, $E_K - E_L$.

  The photon is referred to as ***K_α radiation***.

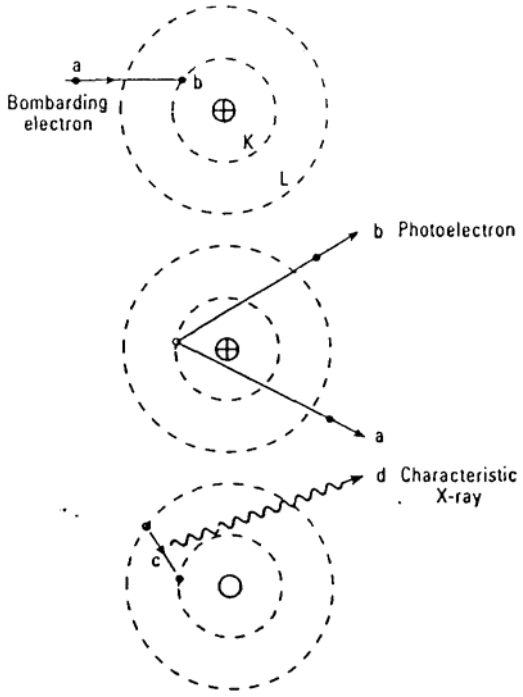


Fig. 1.6 Production of characteristic radiation.

- Alternatively, but less likely, the hole may be filled by an electron falling from the M-shell → emission of a single X-ray photon of energy $E_K - K_M$. (***K_β radiation***)

In the case of the usual target material, **Tungsten "W" (Z = 74)**,

E_K = 70 keV, E_L = 12 keV, and E_M = 2 keV.

$\therefore$ K_α radiation has photon energy of **58 keV**

& K_β radiation has photon energy of **68 keV**.

- The x-ray photon energy is a "characteristic" of the K shell of a tungsten atom regardless of the energy of the electron that ejected the K-shell electron

L-radiation → if hole created in the L-shell is filled by an electron from farther shell.

Even in the case of tungsten, L-radiation photons have only energy = *10 keV* → insufficient to leave the X-ray tube assembly "no part in radiology".

- Characteristic X-ray photons have discrete photon energies → ***line spectrum***.

In the case of another target material, **Molybdenum (Z = 42)**,

E_K = 20 KeV, E_L = 2.5 keV

∴ K_α radiation has a photon energy of 17.5 keV

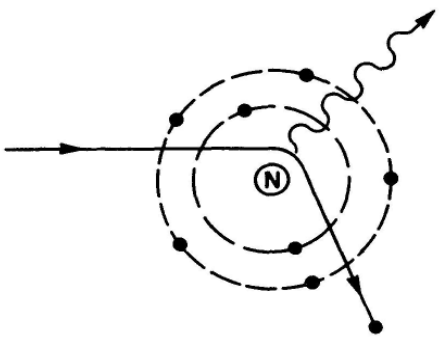
& K_β radiation has a photon energy of 20 keV.

∴ ***The energy of the K-radiation photons:***

1. Increases → with ↑ atomic number of the target.
2. It is *characteristic* of the target material.
3. **Not affected by the tube voltage**, **except that:**
   - A K-electron cannot be ejected if the peak tube voltage is less than E_K.
   - The rate of production of the characteristic radiation increases as the kV is increased above this value.

- **Contribution of characteristic radiation to the total production of x rays?**
  1. **Below 70 kVp** → no K-shell characteristic radiation.
  2. **Between 80 and 150 kVp** → K-shell characteristic radiation contributes about **10% (80 kVp)** to **28% (150 kVp)** of the useful x-ray beam.
  3. **Above 150 kVp** the contribution of characteristic radiation decreases, and it becomes negligible **above 300 kVp**.

INTERACTION WITH THE NUCLEUS: BREMSSTRAHLUNG, CONTINUOUS SPECTRUM



- When an electron penetrates K shell & passes near the nucleus of a tungsten atom → the +ve charge of the nucleus acts on the -ve charge of the electron.

  ∴ *The electron is* ***deflected*** *from its original direction &* ***slowed*** *down*

- The kinetic energy lost by the electron is emitted directly in the form of ***a photon of radiation*** called ***general radiation or bremsstrahlung*** ("braking radiation" in German)

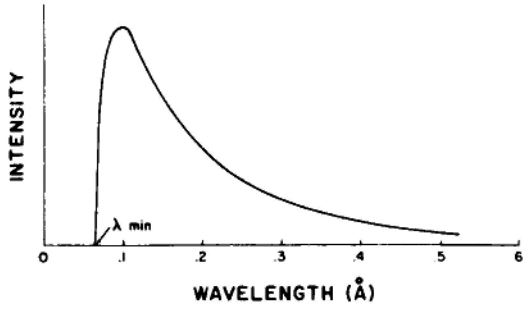
- **Except in mammography**, **80% or more of the X-rays** emitted by a diagnostic X-ray tube are bremsstrahlung.
- ***Most electrons*** that strike the target:
  - Make interactions with a number of atoms & loses only part of its energy at each interaction which appear in the form of radiation.
  - Penetrate many atomic layers before giving up all their energy; therefore, not all x-rays are produced on the surface of the target.
- ***Occasionally,*** the electron will collide head-on with a nucleus → **single photon of energy = kVp**. ***"the largest photon energy that can be produced at this kilovoltage"***

- Most of the radiation will have little energy, and will appear as heat "over 99% of all reactions" + few x rays will appear.
- The energy of a photon of radiation is related to the kinetic energy (keV) of the electron, which is related to the potential difference (kVp) across the x-ray tube.
- Remember, Energy of photon of radiation is inversely related to wavelength.
- In case of a head-on collision between the electron and nucleus. All the energy of the electron is given to the resulting x-ray photon. The minimum wavelength (in angstroms) of this x-ray photon can be calculated:

$$\lambda_{min} = 12.4 / kVp$$

For example,

- 0.124 Å is the shortest wavelength (highest energy) x-ray photon that can be produced with an x-ray tube potential of 100 kVp.
- Most of the x rays produced will have wavelengths longer than 0.124 Å.



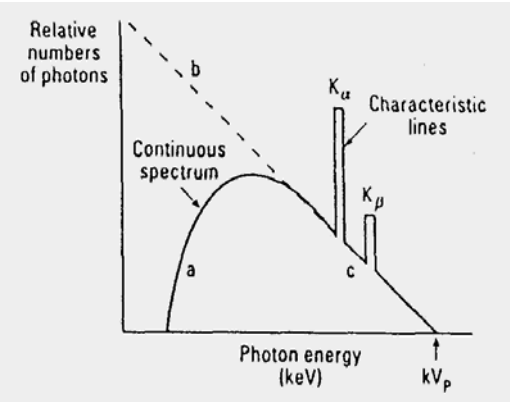
- Figure 2-14 is a graph of continuous spectrum of the wavelengths of x rays. **Notice that:**
  1. There is well defined minimum wavelength (λ_{min}) → depend on the kVp.
  2. The x-ray beam contains all wavelengths of x rays longer than λ_{min}.
  3. ***Filters*** are used to remove the long wavelength from the beam.

Conclusion,

- **The highest energy x-ray photon leaving the x-ray tube depends on the kVp.**
- **The lowest energy x-ray photon leaving the x-ray tube depends on the filtration.**

X-RAY SPECTRUM:

- Figure 1.8 plots the relative number of photons having each photon energy (in keV)



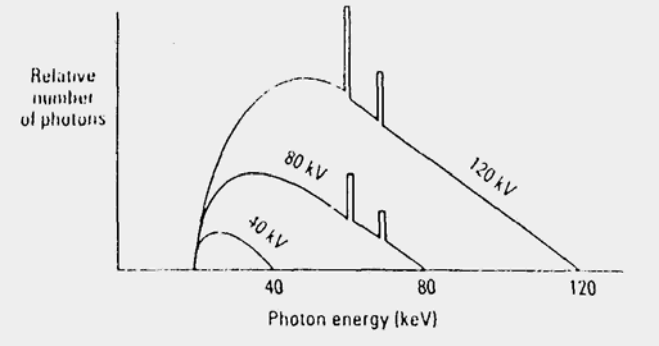
- The bremsstrahlung forms a *continuous spectrum* (a).
- The maximum photon energy (kiloelectronvolts) is equivalent to the kVp.
- If peak kV > K-shell binding energy, ***characteristic X-rays*** are also produced. They are shown at (c) in Fig. 1.8 as lines superimposed on the continuous spectrum.
- The dashed line (b) shows the spectrum of bremsstrahlung of low-energy which is absorbed by ***the target itself*** & ***the glass wall of the tube "FILTRATION"***.

∴ There is low-energy cut-off, at about 20 keV (depends on the filtration added to the tube), as well as a maximum energy (depends only on the kV).

- The area of the spectrum represents the total output of all X-ray photons emitted.

- The average or ***effective energy*** of the continuous spectrum = *1/3 to 1/2 of the kVp*.
  Thus, an X-ray tube operated at 90 kVp can be thought of as emitting, effectively, 45 keV X-rays.

Figure 1.9 compares the spectrum from a tube with a tungsten target, operating at three different kV values.



- As the tube voltage is increased → both the width and height of the spectrum increase → the area increases → ∴ the output of X-rays increases, which is proportional to kV^2.
- ***The intensity of X-rays*** emitted is proportional to kV^2 x mA.
- ***The efficiency of X-ray production*** is the ratio

$$\frac{\text{X-ray output}}{\text{electrical power supplied}}$$

& the efficiency

a. Increases with the kV.
b. Is greater, the higher the atomic number of the target.

CONTROLLING THE X-RAY SPECTRUM

INTENSITY OF X-RAY BEAMS

Intensity of x-ray beam = *no. of photons in the beam X the energy of each photon*

The intensity is commonly measured in roentgens / minute (R/min, or C/kg)

X-ray beam intensity varies with kilovoltage, tube current, target material & filtration.

- ✓ ***The quantity (number)*** of the x rays generated is proportional to the atomic number of the target material **(Z)**, the square of the kilovoltage **[(kVp)2]**, and the milliampere of x-ray tube current **(mA)**.
- ✓ ***The quality (energy)*** of the x rays depends almost entirely on the **kVp**.

TARGET MATERIAL:

I- For continuous spectrum, the target material determines the quantity of x-ray produced at a given voltage.

The ↑↑ the atomic number of target atoms → the ↑↑ the efficiency of x-ray production

- For example, **Tungsten (Z = 74)** would produce much more bremsstrahlung than **Tin (Z = 50)** if compared at identical tube potential (kVp) and current (mA).
- **Tungsten** is used as the target material because of its *relatively high atomic number (74)* and its *high melting point (3370° C)*.
  Platinum, with a more favorable atomic number of **78**, has a melting point of **1770°C**,

and **stable gold (Z = 79)** melts at **1063° C**.

II- For characteristic radiation.

↑↑ Atomic number → ↑↑ photon energy (quality) of characteristic radiation

For example, the K-shell characteristic x rays for

- **Tin (Z = 50)** vary from **25 to 29 keV**;
- **Tungsten (Z = 74)** vary from **57 to 69 keV**;
- **Lead (Z = 81)** have energies between **72 and 88 keV**.

To summarize,
The atomic number of the target material determines the quantity (number) of bremsstrahlung produced and determines the quality (energy) of the characteristic radiation.

MOLYBDENUM TARGET

- **With a high atomic number anode** like tungsten, the x-ray beam consists almost entirely of bremsstrahlung radiation & the contribution from characteristic radiation varies with tube voltage, but it never makes up a large percentage of the total beam.
- **With lower atomic number anodes,** bremsstrahlung production is less efficient (& diminishes more as the tube voltage is decreased)

  ∴ The combination of a low atomic number anode & low tube voltage → ↓↓ efficiency of bremsstrahlung → characteristic radiation assumes greater importance
- **Molybdenum anode tubes** used to take advantage of this principle for ***Mammography***.
- Maximum tube voltage for mammography is approximately 40 kVp. At this voltage the 17.5 keV K-alpha and 19.6 keV K-beta characteristic radiation of molybdenum makes up a significant portion of the total radiation output of a molybdenum target x-ray tube.

VOLTAGE (kVp) APPLIED:

- The energy of the photons emitted from the x-ray tube depends on the energy of the electrons in the electron stream that bombards the target of the x-ray tube, which in turn, determined by the peak kilovoltage (kVp).

  ∴ The kVp determines the maximum energy (quality) of the x rays.
- **In addition, higher kVp techniques will also increase the quantity of x rays**.

  ∴ The amount of radiation produced increases as the square of the kilovoltage:

  Intensity is proportional to (kVp)2
- **The wavelength of the characteristic radiation** produced by the target **is not changed by the kVp**.

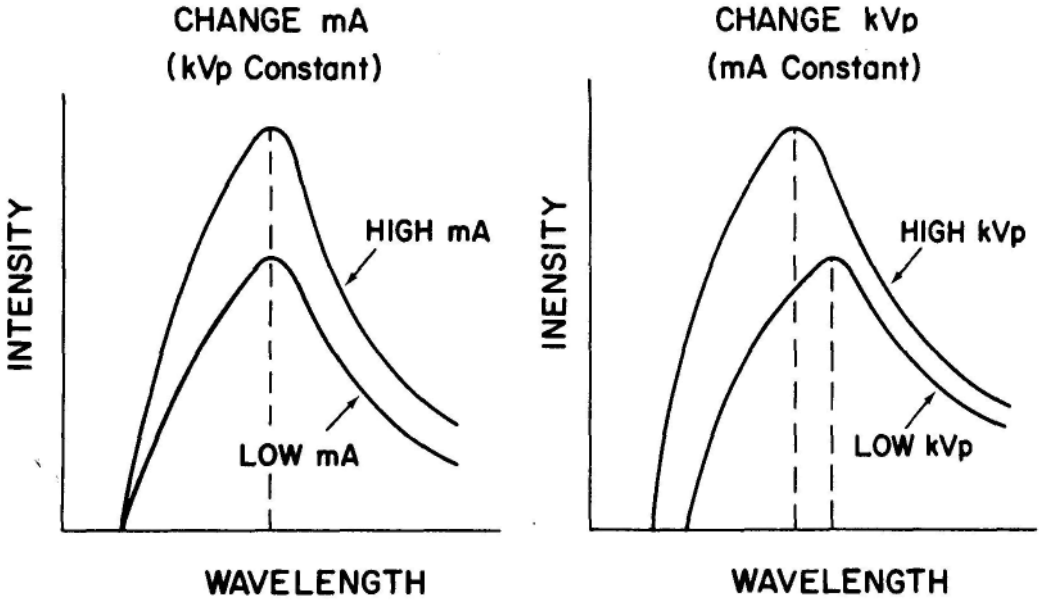
  But, the applied kilovoltage must be high enough to excite the characteristic radiation.

  For example, using a tungsten target, at least ***70 kVp*** must be used to cause the K-characteristic x rays to appear.

X-RAY TUBE CURRENT

↑↑ mA → ↑↑ number of electrons that strike the target of the x-ray tube → ↑↑ number (quantity) of x ray photons

- The effect of x-ray tube potential (kVp) and mA (x-ray tube current) on ***the wavelength*** (quality) and intensity of the x-ray beam is illustrated in Figure 2-17.



To summarize, there are ***5 factors*** affecting the X-ray spectrum.

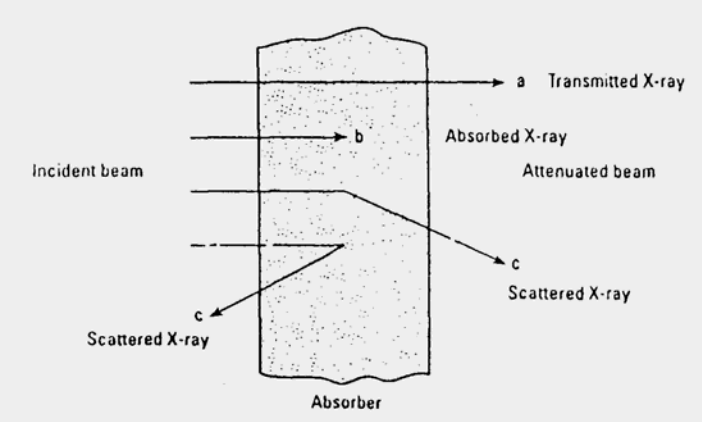
The following are the effects of altering each in turn, the other four remaining constant:

↑ ***kV***	▪ Shifts the spectrum upward and to the right (Fig. 1.9) ▪ It increases the maximum and effective energies and the total number of X-ray photons ▪ Below a certain kV (70 kV for a tungsten target) the characteristic K-radiation is not produced
↑ ***mA***	▪ Does not affect the shape of the spectrum ▪ ↑ both bremsstrahlung and characteristic radiation output in proportion
↑ ***Z number of Target***	▪ ↑ The output of bremsstrahlung but does not affect shape of spectrum. ▪ The photon energy of the characteristic lines will also increase (Fig. 3.9)
Change Kilovoltage waveform	▪ The maximum and minimum photon energies are unchanged. ▪ However, a constant potential (3-phase) generator produces **more X-rays and at higher energies** than those produced by a single-phase pulsating potential generator, at the same values of kVp and mA **∴ Both the output & the effective energy of the beam is greater** i.e. in Fig. l.5.c the tube voltage is at the same peak value throughout the exposure. In Fig. 1.5.b it is below peak value during the greater part of each half cycle. ▪ A single-phase generator produces useful X-rays in pulses, each lasting 30 ms during the middle of each 100 ms half cycle of the mains
Filtration	▪ Section 1.9

1.4 THE INTERACTION OF X-AND GAMMA RAYS WITH MATTER

Where the following refers to X-rays it applies equally well to gamma rays.

When a beam of X- or gamma rays travels through matter → figure 1.10 illustrates the 3 possible fates of the photons.



Transmitted:

Pass through unaffected, as primary or direct radiation.

Absorbed:

Transferring to the matter all of their energy ***(complete absorption)*** or some of it ***(partial absorption)***

Scattered:

Diverted in a new direction, with or without loss of energy, and so may leave the beam (as scattered or secondary radiation).

X-ray absorption and scattering processes are stochastic احتماليه processes, governed by the statistical laws of chance. It is ***impossible*** to predict which of the individual photons in a beam will be transmitted by 1 mm of a material, but it is ***possible*** to be quite precise about the fraction of them that will be, on account of the large numbers of photons in the beam.

ATTENUATION

- ***Definitions:***

  X-ray beam Quantity: the number of photons in the beam.

  X-ray beam Quality: refers to the energies of the photon in the beam.

  Intensity: the product of number & energy of photons (depends on both the quantity & quality).

  Attenuation = **the reduction in the X-ray beam intensity as it traverses a matter by either absorption or scattering of photons**.

ATTENUATION = ABSORPTION + SCATTER

∴ It depends on both the **quantity** & **quality** of the X-ray beam.

ATTENUATION OF NARROW MONOENERGETIC BEAM OF X-RAY:

In the module of monochromatic radiation → attenuation = reduction of quantity only

The fundamental law of X-ray attenuation

Equal thicknesses of an absorber transmit equal percentages of the radiation entering them.

In Fig. 1.11a, where each cm of the matter remove 20% of beam photons (↓ quantity) with no change in energy of transmitted photons (quality)

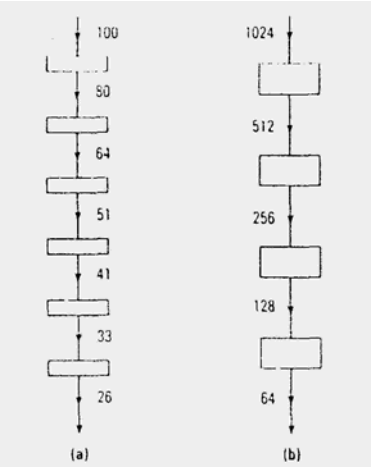


Fig. 1.11 Examples of exponential attenuation for narrow mono-energetic beams.

Linear Attenuation Coefficient (μ):

- ***Def:*** ***The linear attenuation coefficient measures the probability that a photon interacts (i.e. is absorbed or scattered) per unit length of the path it travels in a specified material.***

Quantitative parameter → measures the attenuating properties of the material.

- The unit of μ is **cm^{-1}**.
- ***The linear attenuation coefficient*** **only applies to narrow monoenergetic beams**.
- μ is specific for both the energy of X-ray beam & the type of absorber.
  When the radiation energy ↑ → ↓ no. of attenuated X-ray photons → ↓ μ.
- The exponential equation for X-ray attenuation:

$$N = N_0 e^{-\mu X}$$

where: N_0 = *no. of incident photons.*
N = *no. of transmitted photons.*
E = *base of natural logarithm*
μ = *Linear attenuation coefficient.*
X = *thickness of absorber in cm.*

Half-Value Layer (HVL)

- HVL is the ***thickness of stated material required to reduce the intensity of a narrow beam of X-radiation to 1/2 of its original value***.
  Two successive half-value layers reduce the intensity of the beam by a factor 2x2 = 4.
  Ten HVLs reduce the intensity of the beam by a factor $2^{10} = 1000$.
- The HVL **is a measure of the penetrating power (quality) of the X-ray beam** "i.e. a beam with high HVL is more penetrating than one with low HVL".
- **The linear attenuation coefficient (μ) is inversely proportional to the HVL:**

$$\mu = 0.69 / \text{HVL} \quad \rightarrow \quad \text{HVL} = 0.69 / \mu$$

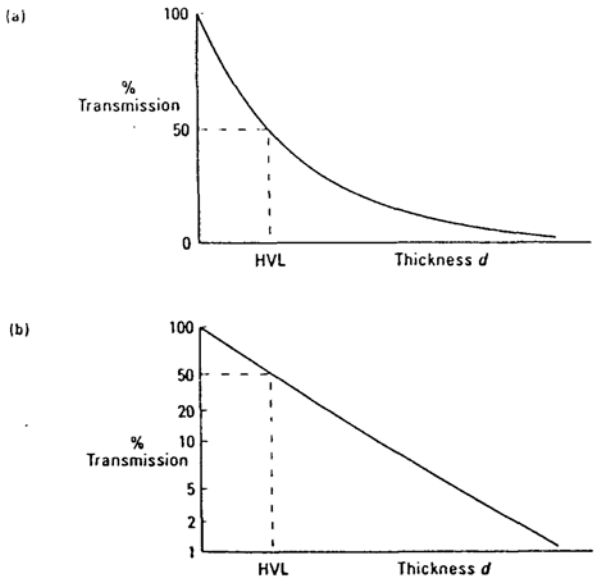
- ***The HVL*** **applies only to narrow beams**, but they **need not be monoenergetic**.
- ***The HVL decreases and the linear attenuation coefficient therefore increases as:***
  1. The density of the material increases.
  2. The atomic number of the material increases;
  3. The photon energy of the radiation decreases.

For example, lead is more effective than either aluminum or tissue at absorbing X-rays because of its higher density and atomic number.

The mass attenuation coefficient (μ / ρ)

- The unit of the mass attenuation coefficient is **per gm \ cm^2** ***(or*** **cm^2 \ gm*)***
- Is obtained by dividing the linear coefficient by the density of the material → depends only on the atomic number and photon energy.

EXPONENTIAL GRAPH



- When **no. of transmitted photons** are plotted on linear scale against **absorber thickness** → **Curved line** (Fig. 1.12a)
  - However thick the absorber, it is never possible to absorb an X-ray beam completely.
- This is shown, in Fig. 1.12a, by the shape - an exponential curve.
- If, as in Fig. 1.12b the percentage transmission is **plotted on a logarithmic scale** → **Linear graph = exponential curve** "i.e. decrease with constant percentage with each increment of absorber, making it easier to read off the HVL and calculate ***μ***.

- The experimental arrangement for measuring HVL and the attenuation coefficient is illustrated in Fig. 1.13a

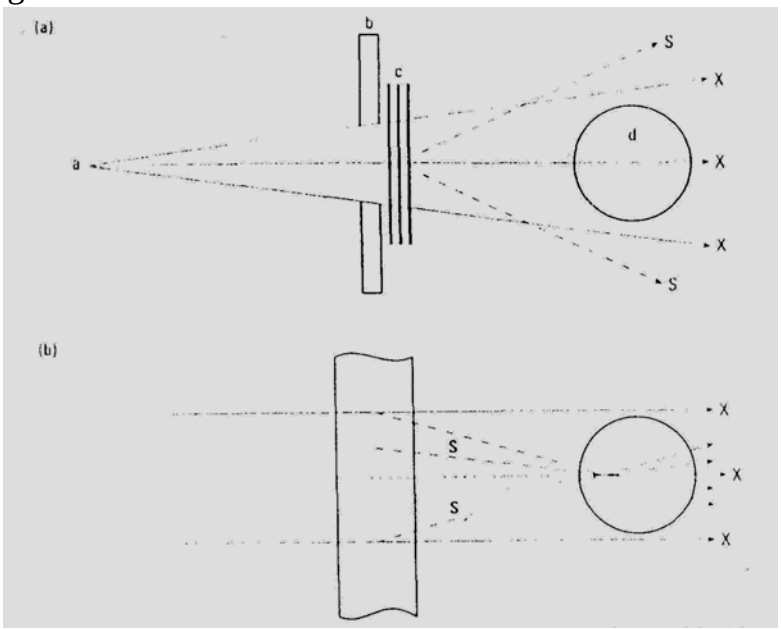


Fig. 1.13 (a) A narrow beam is used for the measurement of the HVL
(b) Transmission of a wide beam.

This arrangement, referred to as ***'good geometry'*** → minimizes the amount of scattered radiation SS entering the detector

- The beam is restricted by means of a lead diaphragm to just cover a small detector.
- The diaphragm b and sheets of the absorbing material c are positioned halfway between the source a and detector d.
- A second collimator may be placed in front of the detector.

FACTORS AFFECTING ATTENUATION:

I- Energy:

- ↑ beam energy → ↓ attenuation (μ) → ↑ percentage of transmitted photons.
- ↑ beam energy → ↑ HVL.
- **Beam energy determines the dominant interaction type**:

  1. With low radiation energy → photoelectric effect is dominant → ↓ transmitted photons.

  2. With increasing the energy → ↑ Compton scattering & ↓ PEE → ↑ transmitted photons.

  3. With high energy → most interactions are Compton interaction.
  & with increasing the energy within high ranges → ↑ % transmitted photons but with small differences (both within Compton interaction)

II- Atomic number (A):

- Generally, ↑ atomic no. → ↑ attenuation.
- The only exception is with high atomic no. absorber, if the beam energy exceeded the binding energy of an inner shell electron *(see absorption edge)*.

III- Density:

- Density determines the no. of electrons in a given thickness.

  So, ↑ density → ↑ attenuation in a linear relationship

  ∴ Doubling the density for the same thickness → doubles attenuation of that thickness
- The difference in tissue densities is responsible for the X-ray film contrast.

IV- Electrons per gram:

- Mass unit → depends on the no. of neutrons in the absorber atoms.
- Actually, the no. of electrons \ cm^3 "which is a volume unit" is more important.
- We obtain the e \ cm^3 by multiplying e \ gm in density.

$$\frac{e}{gm} \times \frac{gm}{cm^3} = \frac{e}{cm^3}$$

- **When Compton interactions predominate, the no. of e \ cm^3 becomes the most important factor in attenuation.**
- Example: bone has fewer e \ gm than water, but attenuates radiation more because it has more e \ cm^3.

ATTENUATION OF A WIDE BEAM

The percentage transmission by the same object of a wide beam of X- or gamma rays is greater than that of a narrow beam of photons of the same energy because a wide beam produces more scatter SS and much of it stays within the beam. Fig. 1.13b

Attenuation of a heterogeneous beam

- The beams produced by X-ray tubes are ***Heterogeneous (Polyenergetic)***, i.e. they comprise photons of a wide range of energies (spectrum of energies).
- The max. energy of the beam = peak kVp.
  The mean energy is between 1/2 – 1/3 of peak energy.
- As the beam travels through an attenuating material,
  - **↓ Beam quantity** → same as monochromatic radiation.
  - **↑ Beam quality** as, the lower-energy photons are attenuated proportionally more

than the higher-energy photons & as the lower energy photons are removed from the beam → ↑ mean energy of the remaining photons.

- **The exponential law does not** apply for a heterogenous beam. However, it is still correct to refer to **the HVL** of the beam.
- As the beam penetrates the material: ***a process of FILTRATION occurs***
  - The beam becomes progressively more homogeneous.
  - ↑↑ Proportion of higher-energy photons in beam → ↑↑ average energy → the beam becomes 'harder' or more penetrating.
  - ***The 'second HVL'*** which would reduce the beam intensity from 50 to 25% > ***the 'first HVL'***, which reduces it from 100 to 50%.
- When the transmission % of polyenergetic radiation plotted on logarithmic scale → **Curved line**.

The HVL of a typical diagnostic beam is

30 mm in tissue 12 mm in bone 0.15 mm in lead

INTERACTION PROCESSES

5 processes of interaction between X-rays and matter contribute to attenuation

1. Interaction with a loosely bound or 'free' electron → Compton process "modified scatter"
2. Interaction with inner shell or 'bound' electron → Photoelectric absorption.
3. Interaction with a bound electron → Unmodified scatter.
4. Pair production.
5. Photodisintegration.

Unmodified scatter

- It is also known variously as ***coherent, classical, elastic, or Thomson scattering***
- The photon bounces off an electron which is firmly bound to its parent atom → the photon is scattered with no loss of energy.

∴ No secondary electron - No ionization.

- This process occurs with low-energy photons and at very small angles of scattering

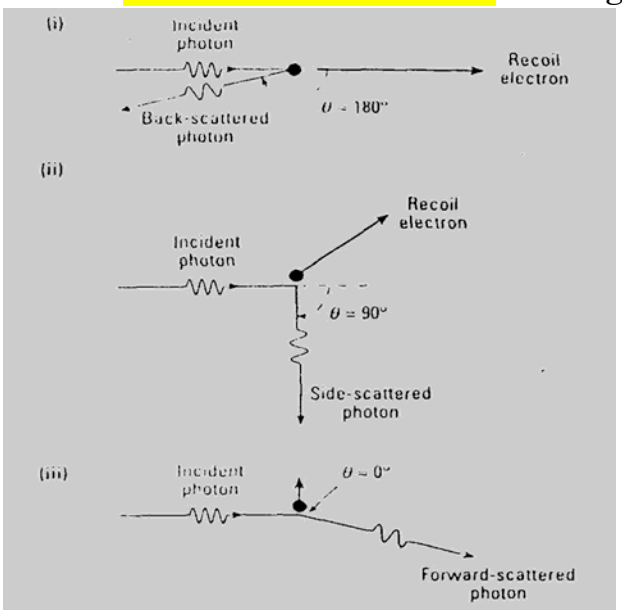
  ∴ The scattered radiation does not leave the beam → little significance in radiology.

PAIR PRODUCTION & PHOTODISINTEGRATION:

Both interactions don't occur within the diagnostic energy range (which rarely use energies > 150 keV).

1.5 COMPTON PROCESS (MODIFIED SCATTER)

Responsible for almost **all the scatter radiation** in diagnostic radiology



- The photon bounces off a **free electron** which recoils, taking away some of the energy of the photon as kinetic energy → the **photon is scattered** with reduced energy.
- ∴ The energy of the incident photon is distributed between:
  1. Kinetic energy of the recoil electron.
  2. Energy retained by deflected photon

Compton photon never gives up all its energy unlike in photoelectric interaction

- The reaction produces:
  - Ion pair "+ve ion & -ve electron – called recoil electron"
  - Scattered photon.
- The energy carried off by the recoil electron is said to be ***absorbed*** by the material, and the remainder, carried by the photon, to have been ***scattered***.
  In the diagnostic range of energies **no more than 20% of the energy is absorbed**, the rest being scattered.

  ∴ The Compton process is partial absorption.
- **The angle of scatter θ** is the angle between the scattered ray and the incident ray.
  Photons may be scattered in all directions.
  The electrons are projected only in sideways and forward directions.
- Unlike PEE in which most of photon's energy is expended to free electron bond → Recoil electron is already free (so no energy needed for this).
- 2 factors determine the amount of energy retained by scattered photon:
  1. Initial photon energy.
  2. Angle of scatter θ.

EFFECT OF THE ANGLE OF SCATTERING

- It will be seen that **The greater the angle of scatter**
  1. *The greater the energy and range of the recoil electron*
  2. *The lower the energy of the scattered photon (i.e. the greater the loss of energy).*

∴ **Scattered photons at small angles retain most of original energy:**

1. As they scatter at small angle → they remain within the 1ry beam → film fogging.
2. They are too energetic → can't be removed by filters.
3. Scattered radiation - even those scattered at large angles – still have much energy → safety hazards to medical staff especially in fluoroscopy.

∴ A back-scattered photon (θ = 180°) is less energetic *'softer'* than a side-scattered photon (θ = 90°), which in turn is softer than a forward-scattered photon (θ = 0°).

EFFECT OF INITIAL PHOTON ENERGY

- Higher energy photons are more difficult to deflect (more momentum).
- ↑↑ **initial photon energy**
  1. *↑↑ the remaining photon energy of the scattered radiation → more penetrating. However, ↑ photon energy → ↓ no. of reactions → ↑ probability to pass through body than low energy photons*
  2. *↑↑ the kinetic energy of the recoil electron and ↑↑ its range.*

This is seen in the following examples:

Incident photon	*Back-scattered photon*	*Recoil electron*
25 keV	22 keV	3 keV
150 keV	100 keV	50 keV

∴ The softening effect of Compton scatter is greatest with large scattering angles & high energy X-rays.

The Compton process contributes to the total linear attenuation coefficient μ, an amount σ which is called the Compton linear attenuation coefficient.

- *In diagnostic energy range (up to 150 keV):*
  Photon retains most of its original energy (i.e. very little transferred to recoil electron)
- The probability σ that the Compton process will occur
  1. Proportional to the physical density, as with all attenuation processes.
  2. Proportional to electron density.
  3. Independent of the atomic number, as it concerns only 'free' electrons.
  4. Approximately proportional to l / E.

To summarize

σ is proportional to ρ / E and is independent of Z .

The mass Compton attenuation coefficient σ / ρ *is the same* within 10% for such materials as air, tissue, bone, contrast media, and lead → *represented by a single curve in Fig. 1.16, which shows how* ***σ/ρ varies with photon energy***.

Free electron:

- An electron which binding energy is much less than energy of incident photon.
- In diagnostic radiology range (10 – 150 keV):
  - ❝ In high atomic no. elements → outer shell electrons are free.
  - ❝ In low atomic no. elements (as in soft tissue) → all electrons are free.

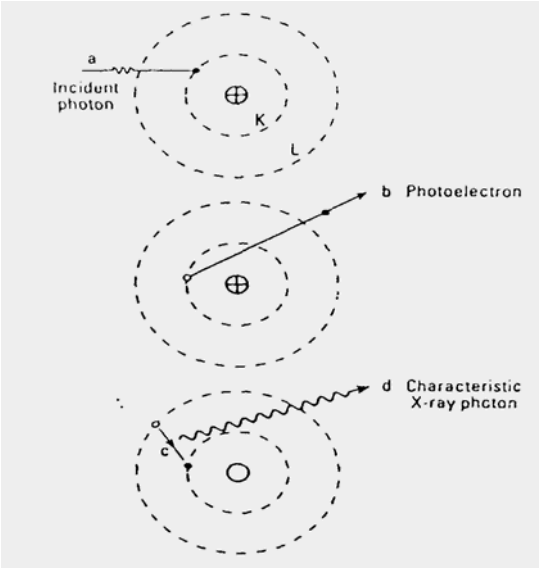
1.6 PHOTOELECTRIC ABSORPTION

When a **photon (a)** 'collides' with an **electron (b)** in the K-shell of an atom & **if its energy > the binding energy of the shell** → it can eject the electron b from the atom.

The photon disappears:

1. Part of its energy, equal to the binding energy of the K-shell, is expended in removing the electron from the atom.
2. The remainder becomes the kinetic energy (KE) of that electron.

KE of the electron = photon energy - E_K



Less often, the X- or gamma ray photon may interact with an electron in the L-shell of an atom → ejected from the atom with KE = photon energy - K_L.

- The electrons so ejected are called **photoelectrons**.
- The 'holes' created in the atomic shell are filled by electrons falling in from a shell farther out, with the emission of a series of **photons of characteristic radiation**.
- **The photoelectric interaction yields 3 end products:**
  1. –ve Ion (photoelectron).
  2. +ve ion (atom deficient by one electron).
  3. Characteristic radiation
- ***In the case of air, tissue & bone (light-atom materials):***

  Calcium which has highest atomic no. of all body elements, emits **only 4 keV** max. energy of characteristic radiation

  ∴ *The characteristic radiation is so soft* → absorbed immediately with the ejection of a further, low-energy, photoelectron or ***'AUGER' ELECTRON***.

  ∴ **All** the original photon energy is converted into the energy of electronic motion.

  ∴ **Photoelectric absorption in such materials is complete absorption.**
- ***In the case of barium and iodine in CM (high atomic number materials):***

  Characteristic radiation is sufficiently energetic to leave the patient & fog x-ray film → only **partial absorption** "like ***Compton effect***".

Photoelectric absorption contributes to the total linear attenuation coefficient μ an amount τ which is called the photoelectric linear–attenuation coefficient.

$$\therefore \mu = \sigma + \tau$$

- The more tightly the electron is bound to the atom and the nearer the photon energy is to its binding energy, the more likely photoelectric absorption is to happen.

The probability τ that photoelectric absorption:

1. τ is **inversely proportional** to **the cube of the photon energy E^3** → decreases markedly as the photon energy of the radiation increases.
   (Provided that photon energy > binding energy)
2. τ is **proportional** to **the cube of the atomic number Z^3** → increases markedly as the atomic number of the material increases.
3. τ is **proportional** to **the density of the material**, as with all attenuation processes.

- Photoelectric effect can't take place with free electron → called forbidden interaction.

To summarize:

$$\tau \propto \rho\, Z^3 / E^3$$

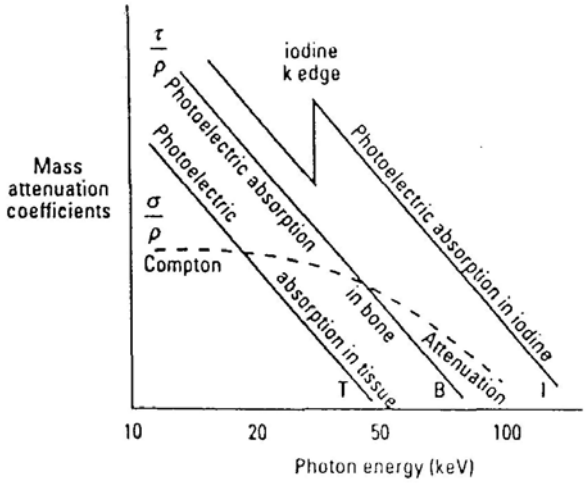


Fig. 1.16 shows how the mass photoelectric attenuation coefficient τ / ρ varies with photon energy in the case of **soft tissue with Z = 7.4, bone with Z = 13**, and **iodine with Z = 53**.

The graphs are straight lines because logarithmic scales are used on both axes.

Applications of photoelectric effect in diagnostic radiology:

Good role

Photoelectric effect produces radiographic images of excellent quality due to:

1. No scattered radiation.
2. Enhancement of natural tissue contrast (i.e. PEE interaction depends on 3rd power of atomic no. → magnify contrast between tissues)

∴ PEE is desirable from point of view of film quality.

Bad role:

PEE increase patient exposure, as all the incident photon is absorbed by the pt. while in Compton reaction, only part of the incident photon's energy is absorbed.

∴ PEE is undesirable from point of view of patient exposure.

∴We should use highest energy (kVp) techniques which not distort the diagnostic quality of X-ray ray films.

MCQ:

Radiographic image contrast is less with Compton reaction than with PEE.

Characteristic radiation in photoelectric interactions:

- Same principle as characteristic radiation production either in the X-ray target or in photoelectric effect, the only difference is **the method used to eject the inner shell electron** (**high speed electron** in the x-ray tube & **x-ray photon** in PEE)
- Characteristic radiation is usually referred to as ***2ry radiation***, to differentiate from ***Scatter radiation***.

EFFECTIVE ATOMIC NUMBER

Effective atomic number = a (weighted) average of the atomic numbers of the constituent elements.

= the cube root of the average of the cube roots of the atomic numbers of the constituents الجذر التربيعى لمتوسط الجذور الجذور التربيعيه.

Fat	Air	Water, muscle	Bone
6	7.6	7.4	13

ABSORPTION EDGES

The K-absorption edge:

i.e. as the photon energy is increased, photoelectric attenuation decreases until the binding energy E_K of the material is reached → the photoelectric absorption jumps to a higher value and start to decrease again as the photon energy further increases.

- The reason is that photons with less energy than E_K can only eject L-electrons and can only be absorbed in that shell. Photons with greater energy than E_K can eject K-electrons as well, and can therefore be absorbed in both shells.
- This is **an exception** to the general rule that attenuation decreases with increasing energy
- **K-absorption edge** occurs at different photon energies with different materials.

*Fig. 1.16 illustrated **K-absorption edge** for iodine.*

> ***For example,***
> *In the case of **iodine**, E_K = 33 keV and photons of energy 31 keV are attenuated much less than photons of energy 35 keV.*
> *The K-edges of **low atomic number materials** such as air, water, tissue, and aluminum have no significance as they occur at E_K = 1 keV or less.*

- **The higher** the atomic number of the material, **the greater** is E_K and the greater is the photon energy at which the edge occurs.
- When max. X-ray absorption is desired, the K-edge of an absorber should be close to the energy of the X-ray beam
  e.g. **In Xeroradiography**, **Selenium** is used for low energy radiation (30-35 kVp) like mammography. While, **Tungsten** is used for high energy radiation (350 kVp) like CXR.
- **The absorption edge is important in:**
  1. Choosing materials for 'K-edge filters'.
  2. Contrast media.
  3. Imaging phosphors.

Relative Importance of Compton and photoelectric attenuation

The photoelectric coefficient is proportional to Z^3 / E^3, and is particularly high when the photon energy is just greater than E_K.

The Compton coefficient is independent of Z and little affected by E.

Accordingly,

1. **Photoelectric absorption is more important with high-Z materials & low-energy photons.**
2. **Compton process is more important with low-Z materials & high-energy photons.**

The photon energy at which the ***two processes happen to be equally important*** depends on the atomic number of the material:

30 keV *for air, water, and tissue*
50 keV *for aluminum and bone*
300 keV *for iodine and barium*
500 keV *for lead*

- **As regards diagnostic imaging with X-rays (20-140 keV),** therefore:
  1. The Compton process is the predominant process for air, water, and soft tissues (except at very low photon energy "20 – 30 keV" →PEE reaction predominate)
  2. Photoelectric absorption predominates for contrast media, lead, and the materials used in films, screens, and other imaging devices;
  3. While both are important for bone (intermediate atomic no.).
     - PEE is more common at low energies.
     - Compton scattering in dominant at high energies.
  4. Coherent scattering play only a minor role throughout diagnostic energy range.
  5. Attenuation is greater when the PEE predominates (complete absorption).

SECONDARY ELECTRONS

- ***'Secondary radiation'*** refers to *Compton scattered radiation*;
  'Secondary electrons' to *the recoil electrons and photoelectrons*
- As they travel through the material, the secondary electrons interact with the outer shells of the atoms they pass nearby, and *excite or ionize them* → the track of the electron is tortuous & dotted with ion pairs.
- When traveling through air **the electron loses an average of 34 eV per ion pair**.
  3 eV *needed to excite an atom &* ***10 eV*** *to ionize it, and there*
  & there about 8 times as many excitations as ionizations.
- When it loses the whole of its initial energy → the electron comes to the end of its range.
  The greater the initial energy of the electron, the greater its range
  The range is inversely proportional to the density of the material.

The ranges in air are some 800 times greater than in tissue

For example, when 140 keV photons are absorbed in soft tissue,

Some of the secondary electrons are **photoelectrons** having energy of 140 keV, able to produce some 4000 ion pairs and having a range of about 0.2 mm.

Most of the secondary electrons are **recoil electrons** with a spectrum of energies averaging 25 keV and an average range of about 0.02 mm.

1.9 FILTRATION

- The lower-energy photons in the X-ray beam are mainly absorbed by and deposit dose in the patient → so, don't reach the film or contribute to the image.
- Filtration remove a large proportion of the lower-energy photons before they reach the skin "so, reduces the patient dose" while hardly affecting the radiation producing image.
- Filtration is **the process of shaping the X-ray beam to increase the ratio of useful photons to the photons that increase the patient dose or decrease image contrast**.

INHERENT Filtration:

- The X-ray photons produced in the target are first filtered by:
  Principally, the target material itself. The window of the tube housing.
  The glass envelope. The light beam diaphragm mirror
  The insulating oil.
- Inherent filtration is measured in **Aluminum Equivalents** = the thickness of Al that would produce the same degree of attenuation as the inherent filtration.
  Typically, inherent filtration = **0.5-1 mm Al equivalent**.

In few cases, unfiltered radiation is desirable

As filtration ↑↑ the mean energy of an X-ray beam → it ↓↓ tissue contrast

- With lower energy radiation (< 30 kVp) this loss of contrast affects image quality
- When inherent filtration must be minimized, a tube with a window of ***beryllium (Z = 4)*** instead of glass is used e.g. Mammography.

ADDED "or Additional" Filtration:

- Uniform flat sheet of metal, usually **Aluminum** placed between the X-ray tube & patient
- *Ideal filter material* → the one which absorbs all low energy photons & transmit all high energy photons (such material doesn't exist).
- The predominant attenuation process should be **photoelectric absorption**, which varies inversely as the cube of the photon energy. The filter will therefore attenuate the lower-energy photons much more than it does the higher-energy photons.

The total filtration is the sum of the added filtration and the inherent filtration.
For general diagnostic radiology it should be at least **2.5 mm Al equivalent**.
(This will produce a beam with effective energy of **HVL = 2.5 mm Al at 70 kV**, and **4.0 mm at 120 kV**.)

CHOICE OF FILTER MATERIAL

The Atomic Number should be **sufficiently high** to make the energy-dependent attenuating process, photoelectric absorption, predominate.

It should **not be too high**, since **the whole of the useful X-ray spectrum should lie on the high-energy side of the absorption edge**. If not, the filter might *soften* the beam.

- ***Aluminum (Z= 13)*** is generally used: has sufficiently high atomic number to be suitable for low energy radiation & most diagnostic X-ray beams **(general purpose filter)**.
- With the higher kV values, ***Copper (Z = 29)*** is used, being a more efficient filter.

Disadv.: Copper filters can't be used alone because photoelectric interaction with the copper emits ***9 keV*** characteristic X-rays → if reaches patient skin, will increase the skin dose → must be absorbed by a ***'backing filter' of aluminum*** on the patient side of the 'compound filter'.

- ***Molybdenum or Palladium filters*** have absorption edges (20 or 24 keV, respectively) favorable for mammography.
- ***Erbium (58 keV)*** has been used at moderate kV values, called ***'K-edge filter'***.

FILTER THICKNESS:

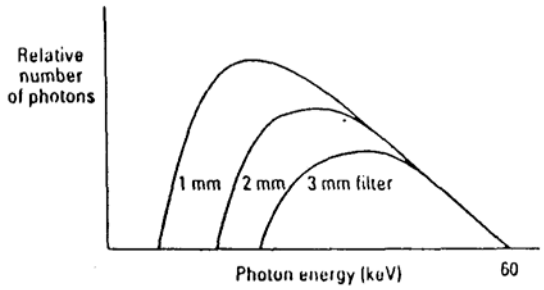
- The total filtration for diagnostic radiology as recommended by The national council of radiation protection and measurements:

kVp	*Total filtration*
Below 50 kVp	0.5 mm Al
50 – 70 kVp	1.5 mm Al
Above 70 kVp	2.5 mm Al

- **Increased filtration has definite disadvantage;**
  Excessive filtration → absorption of high energy photons → the quality of the beam is not altered significantly but the intensity is greatly diminished → needs ↑ exposure time which may ↑ movement blurring.

EFFECTS OF FILTRATION

- Figure 1.18 shows the spectrum of X-rays generated at 60 kV after passing through 1, 2, and 3 mm aluminum.



- Filters attenuates lower-energy X-rays more in proportion than higher-energy X-rays → **↑↑ the penetrating power (HVL) of the beam but ↓↓ intensity**
- It is responsible for the low-energy cut-off of the X-ray spectrum.
- **Increasing the filtration has the following effects:**
  It causes the continuous X-ray spectrum to shrink and move to the right, Fig. 1.18.
  1. It **selectively** reduces the total number of photons "the area of the spectrum" and the total output of X-rays → removes much more low energy photons than high energy.
  2. **↑↑ Minimum & Effective photon energies** but not affect **maximum photon energy**
  3. ↑↑ **the exit dose/entry dose ratio**, or film dose/skin dose ratio.

COMPENSATING OR WEDGE FILLER

- A wedge-shaped filter may be attached to the tube to make the exposure across the film more uniform and **compensate for the large difference in transmission**, for example, between the upper and lower thorax, neck and shoulder, or foot and ankle.
- Similarly, a compensating filter may sometimes be used in **mammography**.

1.7 PROPERTIES OF X-AND GAMMA RAYS

The excitations and ionizations produced by the secondary electrons which account for the various properties of X- and gamma rays:

1. **The ionization of air and other gases** → makes them electrically conducting: used in the measurement of X- and gamma rays.
2. **The ionization of atoms in the constituents of living cells** cause biological damage & the hazards of radiation exposure.
3. **The excitation of atoms of certain materials (phosphors)** → makes them emit light (luminescence, scintillation, or fluorescence): used in the measurement of X- and gamma rays and as a basis of radiological imaging.
4. **The effect on the atoms of silver and bromine in a photographic film** → leads to blackening (photographic effect): used in the measurement of X- and gamma rays and as a basis of radiography.

LUMINESCENCE

1. When a phosphor absorbs X-rays, the secondary electrons set in motion raise valence electrons to a higher energy level.
2. The electrons stay in energy 'traps' and the absorbed energy is stored in the phosphor until the electrons return to the valence shells, with the emission of photons of light.
    1. This may happen spontaneously, either:
        - ✓ Instantaneously → **fluorescence**
        - ✓ After a noticeable interval of time → **phosphorescence**.

        The latter is called afterglow or lag, and is generally to be avoided in imaging.

    OR

    2. The emission of the light may require stimulation:
        - ✓ By heat → **thermoluminescence**.
        - ✓ By intense light from a laser → **photostimulation**.

Other ionizing radiations

- **Some ultraviolet radiation** has a sufficiently high photon energy to ionize air.
- **Beta particles**, emitted by many radioactive substances and **other moving electrons** (in a television monitor, for example) also possess the above properties.
- **Alpha rays** (helium nuclei ^{4}He), (which are particularly stable combinations of two neutrons and two protons) are also emitted by some radioactive substances.

Both alpha and beta rays are charged particles and are directly ionizing.

- **X- and gamma rays** are **indirectly ionizing**, through their *secondary electrons*; *the 'secondary' ions* produced along the track of a secondary electron being many times more than the single 'primary' ionization caused by the initial Compton or photoelectric interaction.
- **Neutrons** also **ionize tissue indirectly** through the hydrogen nuclei they collide with.

1.8 ABSORBED DOSE

- The SI unit of absorbed dose is **GRAY (Gy)**; 1 Gy = 1 J \ kg.
- The absorbed dose is **the energy absorbed as ionization or excitation per unit mass of the material irradiated** (in joules per kilogram).
- **Dose rate** is measured in **Grays per Second**.

The concept of absorbed dose applies to all kinds of direct and indirect ionizing radiations and to any material.

- Before 1980 the international unit of absorbed dose was the ***RAD***,

1 Gy = 100 rad & 1 rad = 1 cGy = 10 mGy.

KERMA

- Kerma is the kinetic energy (of the secondary electrons) released per unit mass of irradiated material.

Absorbed Dose is energy deposited (as ionization & excitation) by those 2ry electrons

- Kerma is measured in **GRAY** & is synonymous with absorbed dose.
- In most radiodiagnostic situations they are equal and can be used interchangeably.

MEASUREMENT OF X- AND GAMMA RAY DOSE

- It is extremely difficult to measure dose in solids or liquids directly.

  First we **measure the dose delivered to air ('air kerma')** under same conditions & then multiply it by a **conversion factor** to obtain the dose in the material.
- The conversion factor:

$$\frac{\text{Dose in stated material}}{\text{Dose in air}}$$

∴Depends on the relative amounts of energy absorbed in air and the material.

- Like the mass absorption coefficients, the factor depends on:
  1. The effective atomic number of the material.
  2. The effective energy of the X- or gamma rays.
- For X-rays used in radiology, **approximate values of the conversion factors are:**

1. For muscle,

- Muscle atomic number nearly equal that of air & **Compton process** predominates

∴ The ratio is close to unity and only varies between **1.0 - 1.1** over the kilovoltage range

2. For compact bone,

- With higher atomic number and **Photoelectric absorption** is important.
- The ratio varies from about **4.5 at low keV energies** to **1.2 at high keV**.

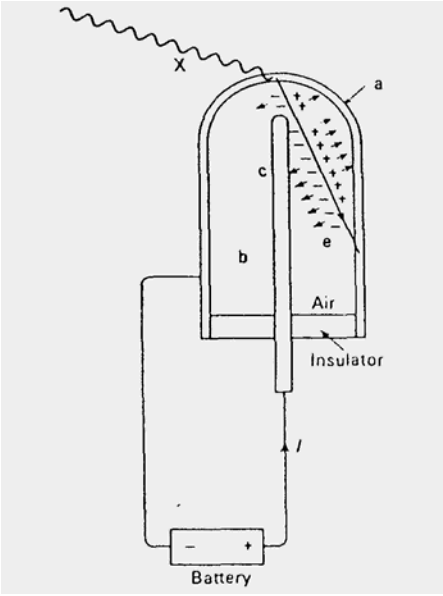
3. For fat,

- With lower atomic number → ∴ the ratio varies in the opposite direction, from about **0.6 at low keV energies** to **1.1 at high keV energies**.

4. For the soft tissue elements in cavities within bone

The ratio lies between bone and muscle → depends on the size of cavity & photon energy.

THIMBLE OR CAVITY CHAMBER



- The air dose or kerma can be measured by placing at the point in question a plastic 'thimble' ***(a)*** containing a small mass of air ***(b)***, which is indirectly ionized by the X-radiation. Each X-ray photon ***(X)*** absorbed in the wall liberates a secondary electron ***(e)***, which produces ion pairs along its tortuous track.
- **For each ion pair, 34 eV of energy will have been deposited**. Therefore,
  For each coulomb of charge (either positive or negative) carried by the ions, 34 J of energy will have been deposited.
- To measure the charge, the ions are separated before they can recombine by applying a polarizing voltage between the outer thimble wall and a thin central electrode ***(c)*** → **Ionization current (I) flows, proportional to the dose rate of the radiation & the mass of air in the chamber**.
- **Charge** can be collected → **Air Kerma** indicated on a meter or digital read-out; or **Current** can be measured → **Air Kerma Rate**.
- **A polarizing voltage of 100 V** is usually sufficient to collect all the ions and produce **'SATURATION CURRENT'**.
  If the voltage is too low, some of the positive and negative ions recombine, and the ionization current measured is too low.
  Above a certain 'saturation' voltage, all the ions are separated, and ionization current is constant.
- **Air has been chosen as the standard material for dosimetry because:**
  1. Effective atomic number of air (7.6) is close to that of tissue (7.4)
  → ∴the conversion factor is close to unity
  2. Applicable to the measurement of a wide range of X- and γ ray photon energies.
  3. Large & small doses and large & small dose rates are easily and accurately measured.
  4. Air is available, cheap, universal with invariable composition.

WALL MATERIAL

The chamber wall must be made of a suitable material.

- The material of wall and electrode must be indistinguishable from air, except in density. They must be made of **air-equivalent material** (specially compounded plastic is used).
- An air-equivalent material matches air as regards **Effective atomic number**
  → absorbs energy from an X-ray beam to the same extent as the same mass of air.
  Density is not important; it can conveniently be a solid.
- The thimble wall is made of **plastic (Z = 6)**, made conducting by an internal coat of graphite, and the inner electrode made of **thin aluminum wire (Z = 13)**.
  By adjusting **the length of the wire**, *the average or effective atomic number of*

the combination can be made equal to that of air.

The chamber is said to be 'air wall'

- Air thimble measures **the air dose** whatever the photon energy of the radiation → 'energy-independent' "However, corrections are needed, as discussed below".

WALL THICKNESS

The chamber wall must be sufficiently thick

- The dosemeter is designed to measure the air dose at the center of the thimble → the overall dimensions should **be small**.
- Typical values are **length 17 mm**, **diameter 7 mm**, and **wall thickness 0.7 mm**.
- If the wall is too thin, electrons which have been set moving by the X-rays at points in the surroundings can penetrate into the air cavity and contribute to the ionization, giving a false reading.

∴ **The wall thickness should be greater than the maximum range of the secondary electrons set in motion by the hardest X-rays to be measured**

(For example, 0.2 mm for the photoelectrons from 140 keV X-rays)

So, the ionization is unaffected by the X- and gamma dose rate at points outside thimble

- However, if the wall is too thick it attenuates unduly the radiation being measured.

AIR VOLUME:

- The larger the air volume, the more sensitive the dosemeter.
  A 30 ml chamber is often used to check the output of an X-ray set
  A larger one to measure the low-intensity stray radiation near an X-ray set or in a radionuclide calibrator to assess radioactivity (see Section 5.6).

ENERGY DEPENDENCE: CORRECTION FACTORS

× In practice, the dosemeter is likely to give an incorrect measure of the air dose for two reasons:
  1. It is not possible to make the wall and electrode exactly air-equivalent.
  2. The X- or gamma rays being measured are attenuated by the walls of the chamber, thus reducing the reading, particularly when measuring low-energy X-rays.

  ✓ Accordingly, the dosemeter reading has to be multiplied by a correction factor, ***N***, which varies with the photon energy, i.e. the dosemeter is 'energy-dependent'.

× Another correction has to be applied if the ambient temperature or pressure differ from standard values. If the pressure is too high or if the temperature is too low, air will leak out of the chamber, and the reading will be too low; and vice versa. Such a correction is not needed with sealed chambers.

STANDARD, FREE AIR CHAMBER

- The correction factor N is measured at a national standards laboratory (such as the National Physical Laboratory in the UK), where the thimble dosemeter is compared with a standard instrument, ***The Free Air Chamber***.
- This is designed to measure air dose exactly, whatever the energy of the radiation.
- The 'wall' of the chamber is ***ordinary air***, and so its 'thickness' has to be some 800 times that appropriate for a thimble chamber. This makes it a very large chamber which is inconvenient for departmental use.

SEALED PARALLEL PLATE CHAMBERS

- These are mounted on the light beam diaphragm for measuring the product (air kerma x area of beam).
- It effectively measures the total energy entering the patient, most of which is deposited in the tissues, although some re-emerges as scatter.
- It is referred to as ***a kerma-area*** or ***Jose-area product monitor***.
- This is easier to measure than the skin dose and is also a better index of the risk to the patient.
- This chamber must be:
  1. Transparent to light and to X-rays.
  2. It must be broader than the widest beam of X-rays used.
  3. It must not cast a shadow on the film, and is made of Perspex. The electrodes are made conducting by a transparent layer, a few atoms thick, of a metal such as gold.
- Another type of sealed parallel plate chamber can be inserted between the patient and the film cassette for ***automatic exposure control*** (see Section 3.8).

EXPOSURE

- Not all dosemeters in current use ere calibrated to read air kerma in grays. Some are calibrated to read exposure, which is defined as

$$\frac{\textit{ionization charge collected}}{\textit{mass of air in the thimble chamber}}$$

- ***The obsolescent quantity 'exposure'*** only applies to X- and gamma rays and not to alpha particles, beta particles, or neutrons
  Whereas, *air kerma* applies to them all.
- The SI unit of exposure is coulombs per kilogram:

$$\textbf{\textit{absorbed dose to air (Gy) = 34 x exposure (C kg}}^{\textbf{\textit{-1}}}\textbf{\textit{)}}$$

- The factor ***34*** is numerically equal to the energy in electronvolts expended per ion pair.
- An older unit of exposure is the ***roentgen (R)***.
  In reading the earlier literature, 'roentgen' can be taken as roughly synonymous with 'rad' or 10 mGy.

OTHER DOSEMETERS

- ***It is often convenient to measure radiation dose by means of:***
  1. The photographic effect in silver bromide, used in a film badge (see-Section 6.9.1).
  2. The fluorescent effect in sodium iodide, used in a scintillation counter (see also the gamma camera, Section 5.3).
  3. The thermoluminescence in lithium fluoride, used in a 'TLD' (see Section 6.9.2).
  4. The photoconductivity in germanium or silicon, used in an 'electronic' dosemeter.
- The first two employ materials having a high atomic number, are highly energy dependent, and need calibration against an air wall thimble chamber. Lithium fluoride is sufficiently air or tissue equivalent to be adequate for the measurement of patient and staff doses.
- ***An electronic dosemeter*** consists of a small semiconducting crystal in series with a battery and a digital measuring device. X-rays absorbed by the crystal make it conduct an electric current which is proportional to the dose rate.

PHANTOMS

- When measuring the dose delivered to a patient, the latter is often substituted by a phantom of the same general size and shape as the relevant part of the body and made of tissue-equivalent material.
- Tissue-equivalent material = a material which matches tissue as regards density and effective atomic number. It therefore absorbs and scatters an X-ray beam, whatever its energy, in the same manner and to the same extent as the same volume of tissue.
- These conditions are most easily met by water in a thin-walled plastic container.
  - ✓ Alternatively, specially compounded rubber or waxes may be used.
  - ✓ Phantoms used in mammography are often based on ***Ferspex***, which attenuates the X-ray beam more than the same thickness of tissue, for which allowance must be made.

QUANTITY AND QUALITY

- *The intensity or air kerma rate of an X-ray beam is:*
  - proportional to the square of the kV;
  - greater for a constant potential than a pulsating potential,
  - proportional to the mA;
  - decreases as the filtration is increased;
  - inversely proportional to the square of the distance F from the target;
  - greater for high rather than low atomic number targets
- The energy fluence or air kerma is, in addition, proportional to the exposure time:

$$Dose\ rate \propto kV^2 \times mA / F^2$$

$$Dose \propto kV^2 \times mAs / F^2$$

- ***The Quality*** (i.e. penetrating power of an X-ray beam) may be specified as *the HVL of the beam in a stated material*, usually aluminum with diagnostic X-rays.
- Alternatively, the quality may be described by ***the average or effective energy of the X-ray spectrum***.
  This may be deduced from the measured HVL. The greater the HVL the greater the effective energy.
- The effective energy can be defined as the photon energy of monoenergetic X-rays which have the same HVL as the polyenergetic beam being assessed. For example, 100 kV X-rays filtered with 2 mm Al have the same HVL (3 mm Al) as 30 keV photons. When filtered with 10 mm Al the effective energy is increased to 50 keV.
- The HVL and effective energy of an X-ray beam:
  - increase as the applied kV is increased;
  - are greater for constant potential than pulsating potential;
  - are unaffected by the mA or exposure time;
  - increase as the filtration is increased;
  - are unaffected by the distance from the target
- A 'hard' X-ray beam is produced by a high kV and a thick filter; a 'soft' beam by a low kV and a thin filter.
  Since the two principal factors affecting HVL or effective energy are kV and filtration, and since the latter is normally not changed, it is common in radiography to describe the quality of X-rays simply by stating ***the tube kV***.

1.10 APPENDIX

UNITS

The SI units of energy and power are the joule (J) and the watt (W):

$$1\ W = 1\ J / s$$

The SI units of electric charge and current are the coulomb (C) and ampere (A):

$$1\ A = 1\ C / s$$

$$1\ C = 1\ As$$

A smaller unit of current is the milliampere (mA).

A smaller unit of charge is the milliampere-second (mAs).

The SI unit of electrical potential difference (PD) and electromotive force (EMF) is the volt (V).

When a charge of 1 C passes through an EMF of 1 V it acquires 1 J of energy.

A smaller unit of energy is the electronvolt (eV), which is the energy acquired by a single electron when it passes through an EMF of 1 V.

There are as many electronvolts in a joule as there are electrons in a coulomb (= 6.25 x 10^{18}).

MULTIPLYING FACTORS

Tera-	Giga-	Mega-	Kilo-	Milli-	Micro-	Nano-	Pico-
Γ	**G**	**M**	**k**	**m**	**μ**	**n**	**p**
10^{12}	10^{9}	10^{6}	10^{3}	10^{-3}	10^{-6}	10^{-9}	10^{-12}

ELECTRON DENSITY

- In point of fact, the probability of the Compton process depends on the number of electrons per unit volume while being otherwise independent of atomic number. It therefore depends upon

  Mass per unit volume x No. of electrons per unit mass

- The former is the usual ***'physical density'*** and the latter is called the ***'electron density'***.
- Since the number of atoms per unit mass is $\propto 1/A$, and the number of electrons per atom is $\propto Z$

  $\therefore$ The number of electrons per unit mass must be $\propto Z / A$

- Apart, from hydrogen (for which Z/A = 1), almost all light elements relevant to radiology have Z/A = 0.5.

  As a result, hydrogenous materials have slightly more electrons per gram than materials without hydrogen content.

  The electron density of bone, air, fat, muscle, and water does not vary by more than 10%. On account of this small variation we often simply say that Compton attenuation is proportional to physical density.

- Air-equivalent materials and tissue-equivalent materials must have the same electron density as air and soft tissue, respectively; as well as having the properties stated in Section 1.8.

Photon and energy fluence and air kerma

- The relative (spectral) distributions of these three quantities are shown in Fig. 1.19 for a typical 70 kV X-ray beam. By way of example, consider a beam of photons of energy 30 keV. An air kerma of 20 mGy at a poi.'it is produced by an energy fluence of about **1 μJ mm^{-2}**, which corresponds to a photon fluence of 300 million photons mm^{-2}.

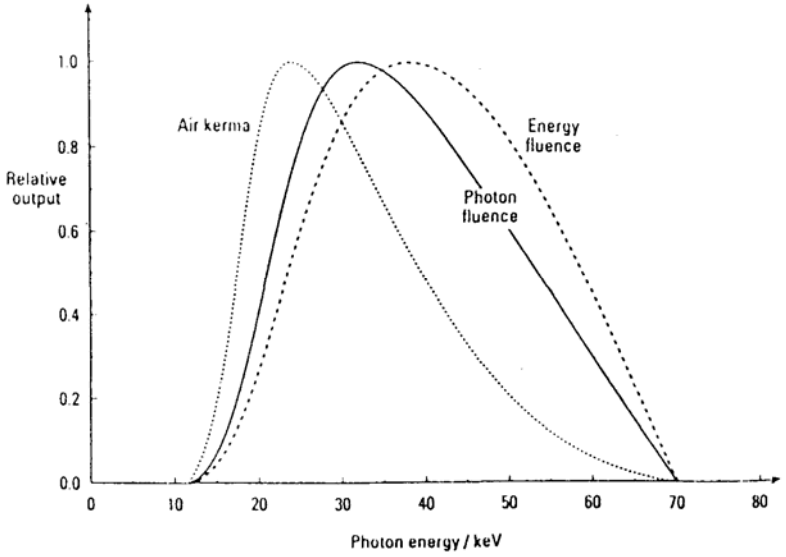


Fig 1.19 Photon fluence, energy fluence, and air kerma distributions.

IMAGING WITH X-RAYS

2.1 ATTENUATION OF X-RAYS BY THE PATIENT

- ***In conventional projection radiography,*** a fairly uniform, featureless beam of X-radiation falls on the patient → differentially absorbed by the tissues of the body → the X-ray beam emerging from the patient carries a pattern of intensity which is dependent on *the* ***thickness*** and ***composition*** *of the organs in the body*.
  - Superimposed on the absorption pattern is an overall pattern of scattered radiation.
  - The X-rays emerging from the patient are captured on a large flat phosphor screen → converts the invisible X-ray image into a visible image of light, which then is either:
    - Recorded as a negative image on film, to be viewed on a light box (illuminator); or
    - Displayed as a positive image on a video monitor.
- In this chapter, we consider the invisible X-ray image and some consequences of the properties of X-rays described in the previous chapter, namely:
  1. They travel in straight lines; and
  2. They are absorbed and scattered when traveling through matter.

LIMITING PATIENT DOSE

- The film-screen or any other imaging system used to convert the X-rays into light requires a specific or minimum dose to produce a satisfactory image. (About ***1 µGy*** per radiograph when using sensitive rare-earth screens; ***1 µGy per second*** of fluoroscopy). This is ***THE EXIT DOSE*** emerging from the patient.
- ***THE ENTRANCE DOSE*** "that to the skin proximal to the tube" has to be much higher because of the high attenuation of X-rays by the patient.
  - 10 times greater for a posteroanterior chest,
  - 100 for an anteroposterior abdomen or skull,
  - 1000 for a lateral pelvis.
- ***THE AVERAGE DOSE*** lies somewhere between the entrance and exit doses.
- ***THE EFFECTIVE DOSE***, for reasons given in Chapter 6, is smaller.
- One of the limiting factors in X-ray imaging is ***THE ACCEPTABLE DOSE*** of radiation that can be delivered to the patient. Patient dose should be as small as possible, consistent with producing an image satisfactory for clinical purposes.

Effect of tube kilovoltage on patient dose

- ↑↑ Kilovoltage (kV) → beam is more penetrating → ↑↑ the proportion of high-energy photons which reach the film-screen & ↓↓ no. of low-energy photons absorbed in skin & body soft tissue.

  ∴ A lower ***entrance dose*** is needed for the same ***exit dose***.

  ∴ ↑↑ kV → ↓↓ the skin dose and, to a lesser extent, the dose to deeper tissues.
- ***N.B.:***

  Whereas the output of the X-ray tube (Intensity) and the skin dose rate are proportional to kV^2, the film-screen dose is nearly proportional to kV^4 (The exponent is 3-5, dependent on patient thickness and field size). (See Section 1.3)

Effect of focus-film distance on patient dose

Increasing the focus-film distance (FFD) reduces the dose to the patient.

- This is illustrated in Fig. 2.1.
  - In delivering a specific dose to the film-screen AB, a sufficient number of photons need to enter the skin.
  - At the shorter FFD, with the focal spot at T', they are concentrated onto a smaller surface area C'D' and produce a higher skin dose;
  - While at the longer FFD, with the focal spot at T → the beam area is larger (according to the inverse square low) → So, the beam are spread over a larger surface area of skin CD and produce a lower skin dose.

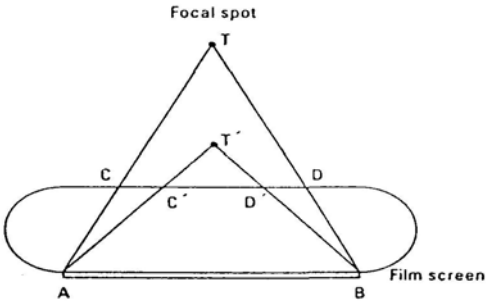


Fig. 2.1: Effect of focus-film distance on patient dose.

While increasing the FFD necessitates ↑↑ the charge (mAs) to produce the desired number of photons at the film-screen (to overcome reduction in intensity with ↑distance according to inverse square low), however still the skin dose incurred in producing an acceptable image is ↓↓, and to a lesser extent the dose to deeper tissues.

e.g. in case of a digital radiography machine, abdomen AP view at 90 kV needs about 4.5 mAs at 110 cm FFD, while it takes 8.5 mAs at 150 cm FFD to produce the same image quality.

BUT, still dose is less to the skin in the second case, in spite of the increased mAs.

Other factors affecting skin dose:

- ↑↑ Filtration → reduces the skin dose in spite of the fact that an increase in mAs is needed (see chapter 1).
- Other ideas are emphasized in Section 6.8 and Table 6.4.
- Skin dose increases linearly with mAs.

SUBJECT CONTRAST

A structure in the patient is demonstrated by two things:

- ***Resolution, sharpness***, or lack of blurring of the image of its boundary (see Section 2.5).
- ***Contrast*** between it and adjacent tissues caused by differences in the transmission of X-rays.

We study ***CONTRAST*** first, with the aid of a very simple example.

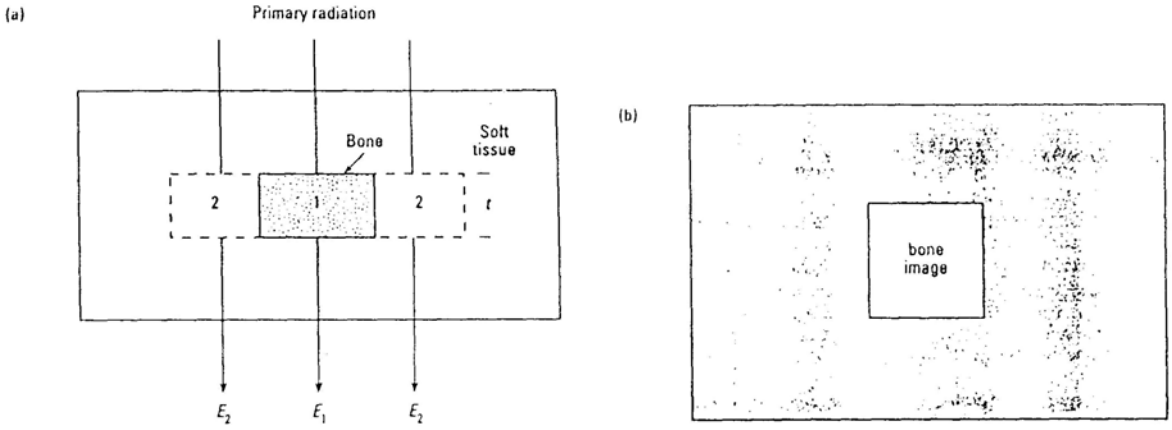


Figure 2.2a shows X-radiation passing through a single structure 1 (e.g. bone, contrast medium, or gas) surrounded by another material 2 (e.g. soft tissue).

Figure 2.2b shows the pattern of X-rays 'seen' in the image.

- Contrast in the pattern of X-rays leaving the subject compares:
  E_1, the intensity or dose rate of the rays which have passed through such a structure and ***E_2***, the intensity of those which have passed through the adjacent tissue.
  While, all the rays suffer the same attenuation by the tissue layers lying above and below the structure.
- Contrast is due to ***the differential attenuation by the structure of thickness t and by an equal thickness of the adjacent tissues***.
- Accordingly, subject contrast ***C*** depends on:
  - The thickness *t* of the structure.
  - The difference in linear attenuation coefficients "μ_1-μ_2" of the tissues involved.

Thus

$$C \propto (\mu_1 - \mu_2)\, t$$

- ✓ ↑ Structure thickness → ↑ contrast.
- ✓ As attenuation depends on tissue density and atomic number:
  The more the two tissues differ in these respects → the greater the contrast.
- ✓ The higher the kV → the smaller the attenuation coefficients → the less the contrast.

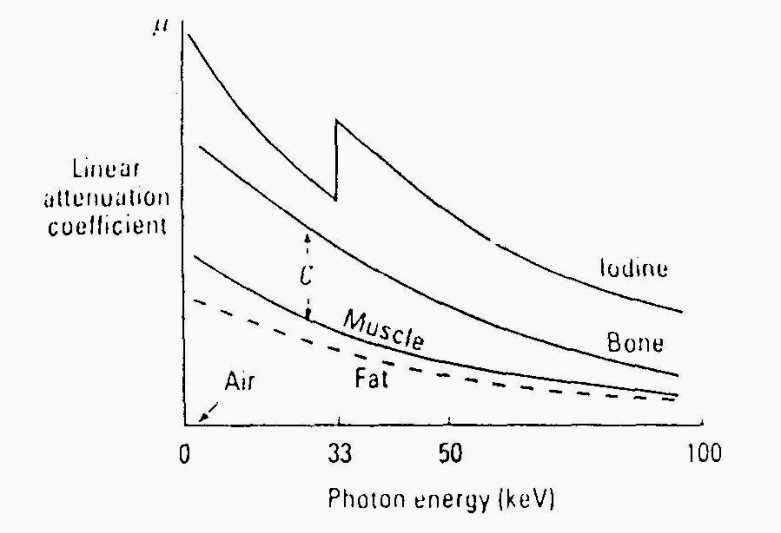


Figure 2.3 shows how the *linear attenuation coefficient* depends on photon energy in the case of air, fat, muscle, bone, and iodine contrast medium.
It will be seen that:

- ❝ Contrast *C* between ***bone*** (Z = 13) and ***muscle***, *which is proportional to the vertical distance between the two curves*, ***is large*** but *decreases* noticeably when the tube kV is increased, due to the effect of photoelectric absorption in bone;
- ❝ The same is true of the contrast between iodine contrast media and soft tissue.
- ❝ The contrast between the low atomic number tissues, e.g. ***fat (Z = 6) and muscle (Z = 7.4)***, ***is small*** and does not decrease very much when the tube kV is increased.
- ❝ The contrast between air and tissue, which have similar atomic numbers, is due to the large difference in ***density***.

Contrast media

- One of the problems in radiography is the low contrast between soft tissues.
  - o One way of increasing contrast is to use ***a lower kV***;
  - o Another is to use a ***contrast medium***.
- Radio opaque media are chosen to have ***1)*** high atomic number to maximize photoelectric absorption & ***2)*** high density.
- Ideally, ***the absorption edge*** should lie just to the left of the major part of the spectrum of X-rays leaving the patient.
- **Figure 2.3** shows that this is the case with *iodine* (Z = 53, E_K = 33 keV).
  - ✓ *Barium* (Z = 56, E_K = 37 keV) also has a favorably placed absorption edge, and in addition a high density. Contrast media are compounds of one or other of these elements.
  - ✓ *Air* and other *gases* (negative contrast media) → the use of which as contrast media relied on their low density have been replaced by CT and MRI.

2.2 EFFECT OF SCATTERED RADIATION

- The primary radiation carries the information to be imaged, while the scattered radiation obscures it. This is similar to the way in which the light in a room affects the image seen on a television screen.
- The amount (S) of scattered radiation reaching a point on the film-screen may be several times the amount (P) of primary radiation reaching the point.
- ***The ratio S/P*** *depends on the* ***thickness*** *of the part and the* ***area*** *of the beam.*
  The ratio is typically 4:1 for a PA chest (∴only 20% of the photons recorded by the film-screen carry useful information) & 9:1 for a lateral pelvis.
- Since the scattered radiation is more or less uniform over the image, it acts like a veil and reduces the contrast which would otherwise be produced by the primary rays by the factor (1 + S/P), which may be anything up to 10 times.
- This is illustrated in **Fig. 2.4a**, which shows the same structure as in Fig. 2.2a, while **Fig. 2.4b** shows the pattern of X-rays 'seen' in the image with reduced contrast owing to scatter.
- If, however, the structure is very close to the film, as in Fig. 2.4c → the scattered rays help to form the image → improves contrast.

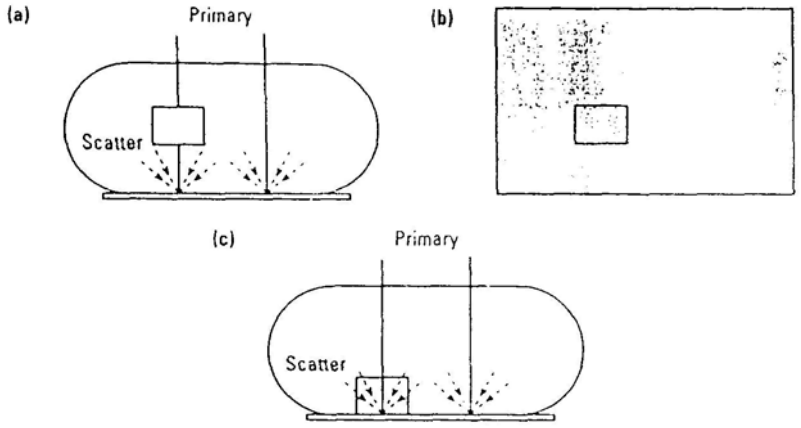


Fig. 2.4: Effects of scattered rays on contrast, (a) the same structure as in Fig 2.2a. (b) The X-ray pattern seen in the image,.(c) Moving the structure very close the film improves contrast as the scattered rays now help to form the imaging.

2.2.1 SCATTER REDUCTION AND CONTRAST IMPROVEMENT:

I- Measures to reduce the amount of scatter produced by the patient (relative to primary):

1- Field size:

Reducing the field area (collimation), by the use of cones or the light beam diaphragm (beam restrictors) → reduces the volume of scattering tissue → ↓↓ scatter & improves contrast.

2- Compression of the patient:

Compression moves overlying tissues laterally → ↓↓ the volume of scattering tissue → ↓↓ scatter & improves contrast.

These first two measures happily also reduce the effective dose to the patient but, use of the following four methods of scatter control require an increase in mAs thus carrying a penalty of increased patient dose and tube loading.

3- Kilovoltage: Using a ***lower kV*** produces

- ✓ Less forward scatter and more side scatter.
- ✓ Less penetrating scatter, so scatter produced at some distance from the film is less likely to reach it. In practice, these effects may not be very significant.

So, reducing the kV → increase the contrast, but primarily because of the increased photoelectric absorption, it also increases the patient dose.

4- Reduction of subject-film distance: as in that case, scattered rays help in forming the image, e.g. chest radiogram is taken PA, so that the heart is closer to the film, resulting in more contrast (in fact, chest radiograms are taken PA to reduce heart shadow magnification, that's the main reason)

5- Use of contrast media

II- Measures to reduce the amount of scatter after it has left the patient:

The amount of scatter (relative to the primary rays) reaching the film-screen may be reduced and contrast increased by interposing between it and the patient:

1- Grid:

As described in Section 2.3, the grid acts like a Venetian blind حصيره شباك. The lead strips absorb (say, 90% of) the scattered rays which hit the grid obliquely, while allowing (say, 70% of) the primary rays to pass through the gaps and reach the film.

2- Air gap:

- × If, as in ***Fig. 2.6***, the film-screen is moved some 30 cm away from the patient, much of the obliquely traveling scatter (shown dashed) misses it, and the contrast is improved.

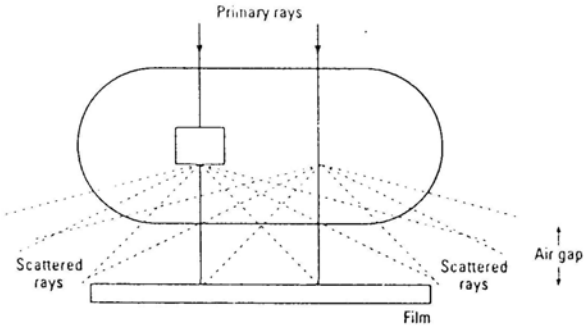


Fig. 2.6: Using an air gap between patient & film-screen.

- Due to the inverse square law, ***the increased distance*** causes
  1. ***A small reduction in the intensity of the primary radiation*** which comes from the anode, some distance away, but
  2. ***A large reduction in the intensity of the scattered radiation***, since that comes from points within the patient, much nearer.

  Disadv. of the use of an air gap
  1. Necessitate an increase in the kV or mAs.

     Reminder: Dose α kV^2 mAs / F^2

     Where F is distance from source
  2. Results in a magnified image.

3- Flat metal filter:

- Such a filter, placed on the cassette, absorbs the softer and obliquely traveling scatter more than the harder direct rays.
- This is ***not*** very effective, and necessitates an increase in the mAs.

To summarize the important points in reduction of scatter and improving contrast:

1. Collimation (decrease field size)
2. Compression
3. Low kV
4. Subject nearer to film
5. Use of contrast medium
6. Grid
7. Air gap
8. Flat metal filter

2.3.1 EFFECT ON SCATTERED RAYS

- 'Antiscatter' grid, seen in cross-section in **Fig. 2.5**, consists of thin (0.07 mm) strips of a heavy metal (such as lead) sandwiched between thicker (0.18 mm) strips of interspace material (plastic, carbon fiber, or aluminum, which are transparent to X-rays), encased in aluminum or carbon fiber.
- The orientation of the lead strips is in general parallel to the x-ray beam axis.

It absorbs oblique scatter beams, allowing the direct beam only to pass through the intespaces

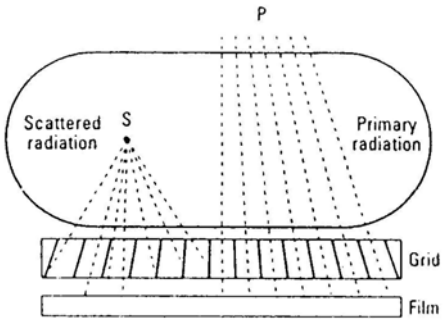


Fig 2.5: Focused grid.

- Few of the scattered rays S can pass through the channels between the strips of lead and reach the film (most of them are traveling obliquely and are relatively soft → will be largely absorbed by the strips of lead).

  *This is shown in **Fig. 2.7***

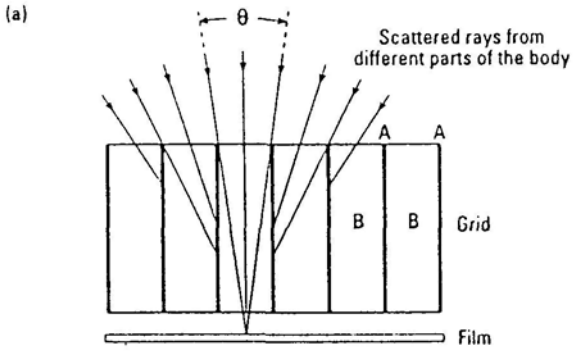


Fig. 2.7 Construction of a grid **A** = the lead strips and **B** = the interspace material

N.B. Aluminum interspace grids:

- Structurally stronger than grids with organic interspacers.
- Needs higher patient exposure (absorbs more 1ry radiation).
- However, it also absorbs more 2ry radiation → ↑ contrast.

Angle of acceptance:

- ***Def.:*** The angle within which scattered rays CAN reach the film through the interspaces *(focused grids have smaller angle of acceptance)*
- It will be seen that the grid has only a small ***angle of acceptance θ*** within which scattered rays can reach a point on the film.

GRID RATIO

$$\textbf{The grid ratio} = \frac{\textit{the depth of the interspace channel}}{\textit{the width of the interspace channel}}$$ ***typically equals 8:1***

The larger the grid ratio, the smaller the angle of acceptance, the more efficient the grid is at absorbing scattered radiation and the greater the contrast in the image.

N.B.: Grids improve IMAGE CONTRAST *(not resolution)*

- With very large fields, especially at a high kV, more scatter is produced, and a high-ratio grid (12:1 or 16:1) is preferable.
- No grid would generally be used with thin parts of the body (or with children) or where there is an air gap.

GRID PATTERN: is the orientation of the lead strips in their longitudinal axis.
It is the pattern of the grid as we see it from a top view. The two basic patterns are ***linear*** and ***crossed***.

CROSSED GRIDS

- Unfortunately, scattered rays traveling obliquely to the primary beam but parallel to the lead strips can pass through the gaps. These rays can be absorbed by the use of crossed grids.
- ***Structure:*** two ordinary stationary grids superimposed with their grid lines at right angles.
- ***Adv.***: More efficient than a single grid at removing scattered radiation, as the pathway for radiation is now a tunnel rather than a channel.
- ***Disadv.:***
  1. Crossed grids need a greater radiographic exposure.
  2. Require very careful centering. If the grids are not at right angles, a coarse interference pattern ***(Moire fringes)*** may be seen on the film.
  3. Grid cut-off can also be a problem (see Section 2.3.2).

FOCUSED & UNFOCUSED "PARALLEL" GRIDS

Focused grids:

- In a focused grid the strips are tilted progressively from the center to the edges of the grid "when viewed in cross-section" so that they all point toward the tube focus, as in **Fig. 2.5.** (*N.B. most grids used in radiology are focused*)
- About 20% of the direct rays impinge on the edges of the lead strips and are attenuated. The rest pass through the gaps between the lead strips.
- Focused grids may be linear or crossed.
- Linear focused grids converge at a line in space (*convergent line*) while crossed focused grids converge at a point (*convergent point*).
- ***Focal distance*** = the perpendicular distance between the grid & convergent line or point.
- The ***Focusing Range*** is wide for low grid ratio & narrow for high grid ratio.
  e.g. 5:1 grid focused at 40 in. → focusing range = 28 – 72 & 16:1 grid focused at 40 in. → focusing range = 38 – 42 in.

Parallel grids:

- Lead strips are parallel when viewed in cross-section.
- Focused at infinity → no convergent line.
- Parallel grids are used effectively with:
  1. Small x-ray fields.
  2. Long target-grid distances.
- It has little use in modern radiology "used in fluoroscopic spot film devices".

- With a linear (i.e. uncrossed) grid, the X-ray tube can be angled ***along the length of the grid*** without 'cutting off' the primary radiation. This can be useful for certain examinations.
- If the tube is angled the other way, or if a focused grid is accidentally placed the wrong way round or upside down on the film, the primary beam will be absorbed, leaving perhaps only one small central area of the film exposed. This is known as ***'grid cut-off'*** **(see Fig. 2.7b)**, and is more restrictive with high-ratio grids.

STATIONARY AND MOVING GRIDS

Grid lines (grid lattice) are shadows of the lead strips of *a stationary grid* superimposed on the radiological image.

- If the line density (number of grid lines per millimeter) is sufficiently high → they may not be noticeable at the normal viewing distance but they nevertheless reduce the definition of fine detail.

Moving grid (Bucky)

- Have typically 5 lines per millimeter.
- During the exposure it moves for a short distance, perpendicular to the grid lines. It can move to and fro (reciprocating) or in a circular fashion (oscillating) → such movement blurs out the grid lines.
- It is important that the grid starts to move BEFORE the exposure starts, moves steadily during the exposure, and DOES NOT STOP moving until after the exposure is over.

Multi-line grid:

- Have 7 or more lines per millimeter together with a high grid ratio.
- Can be used as *a stationary grid* without the lines being visible. It is used when a moving grid cannot be used, and, being thinner, incurs less dose to the patient.

EVALUATION OF GRID PERFORMANCE

The 'Ideal Grid' would absorb all 2ry radiation & no 1ry radiation → so, gives max. film contrast without unnecessary increase in patient exposure. Ideal grid is not present.

Primary Transmission:

- TP is a measurement of the % of 1ry radiation transmitted through a grid.
- Ideal grid will transmit 100% of the 1ry radiation which carries the radiographic image.

$$\textbf{Primary Transmission Tp} = \frac{\textit{Intensity with grid}\ \ Ip}{\textit{Intensity without a grid}\ \ I'p} \ \textit{X 100}$$

- The actual Tp is less than the anticipated "ideal " Tp

$$\textbf{Anticipated Tp} = \frac{\textit{Thickness of interspaces D}}{\textit{Total surface area of the grid}} \ \textit{X 100}$$

$$\textit{"thickness of both interspaces D + lead septa d"}$$

❝ The difference between both values of Tp is due to:

1. Mainly, the 1ry beam absorption by the interspace material.
2. Manufacture imperfect focusing of the lead septa.

- The use of grids necessitates increased radiographic exposure for the same film density, because of the removal of some of the direct rays and most of the scatter.

Contrast Improvement Factor

$$\textbf{Contrast improvement factor} = \frac{\textit{contrast with a grid}}{\textit{contrast without a grid}}$$

*It equals typically between **3 & 5***

- It is the ultimate test for grid performance → measure the ability of the grid to improve contrast.
- Depends on:
  1. Grid ratio (↑ grid ratio → ↑ contrast improvement factor)
  2. The factors affecting the relative amount of scatter produced (& so Contrast), mainly kVp, field size & patient thickness.

SPEED AND SELECTIVITY

- The two tasks of a grid - to transmit primary radiation and absorb scattered radiation - may be judged by its ***SELECTIVITY & SPEED***:

$$\textbf{\textit{Selectivity}} = \frac{\text{fraction of primary radiation transmitted}}{\text{fraction of scattered radiation transmitted}}$$

Typical figures range from ***6 - 12***, depending on the grid ratio and tube kV.

$$\textbf{\textit{Speed or exposure factor}} = \frac{\text{total incident radiation}}{\text{total emergent radiation}} = \frac{\text{exposure necessary with a grid}}{\text{exposure necessary without a grid}}$$

It is also called ***'Bucky factor'***& typically equals ***3 - 5***,

- Bucky factor is a practical measure which indicates how much the exposure factors must be increased when we change from non-grid to a grid technique → so, it also shows how much the patient exposure is increased.
- Bucky factor is a measure of the total quantity of radiation absorbed from an X-ray beam by a grid & so, in part, the ability of the grid to absorb scatter radiation.
- Factors affecting the grid factor:
  1. ***High-ratio grids*** absorb more scatter radiation & have larger bucky factor than low-ratio grids.
  2. ↑↑ ***beam energy*** "i.e. ↑ kV" → ↑ scatter radiation → needs a higher-ratio grids.
- The high bucky factor have desirable & undesirable aspect:
  - ❝ Desirable as regarding the film quality.
  - ❝ Undesirable as regards the exposure factor & patient dose.

Both GRID FACTOR and CONTRAST IMPROVEMENT FACTOR depends on kV → both decrease as kV increases

While, THE GRID RATIO doesn't have anything to do with Kv.

N.B.:
~ 1ry transmission indicates only the amount of 1ry radiation absorbed by a grid.
~ Bucky factor indicates the absorption of both 1ry & 2ry radiation.

2.3.2 EFFECT ON DIRECT RAYS

PRECAUTIONS OF USING GRIDS & GRID CUT-OFF:

(a) The primary disadvantage of grids is that they increase the amount of radiation needed for an exposure & so increase the amount of radiation to the patient.
(b) The grid must be used at a specified distance from the anode.
- *Unfocused grids*, in which the strips are completely parallel, may be used at any focus distance but suffer severely from cut-off.
- The effect can be reduced by using a longer FFD or a grid with a lower grid ratio.

(c) The tube must be accurately centered over the grid.
(d) The grid must not be tilted; otherwise ***CUT-OFF*** of the primary rays will occur.

GRID CUT-OFF:

- Grid cut off occurs due to:
  1. ***Focused grid placed upside down (by mistake)***
  2. ***Lateral decentering (grid angulation)***
  3. ***Focus-grid distance decentering***
  4. ***Combined lateral and focus-grid distance decentering.***

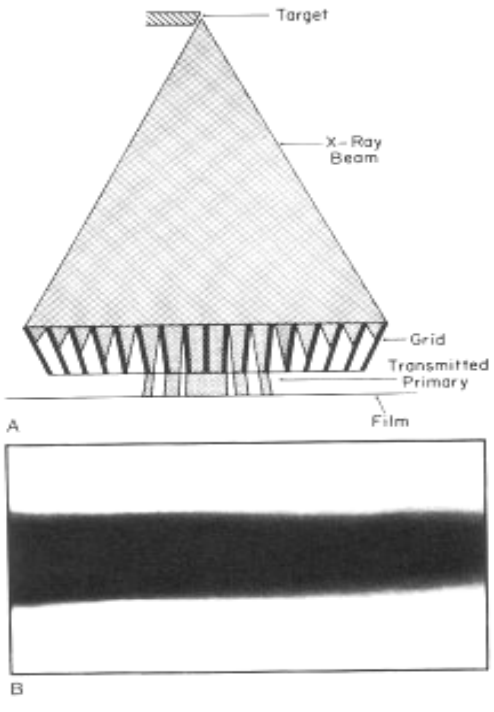


Figure 8–11 Cutoff from an upside down focused grid (*A*) and radiograph resulting from an upside down focused grid (*B*)

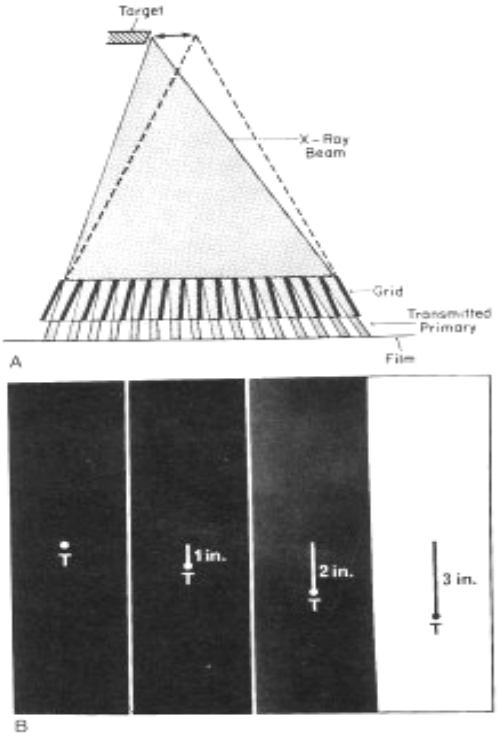


Figure 8–12 Cutoff from lateral decentering (*A*) and series of radiographs resulting from increasing amounts of lateral decentering (*B*)

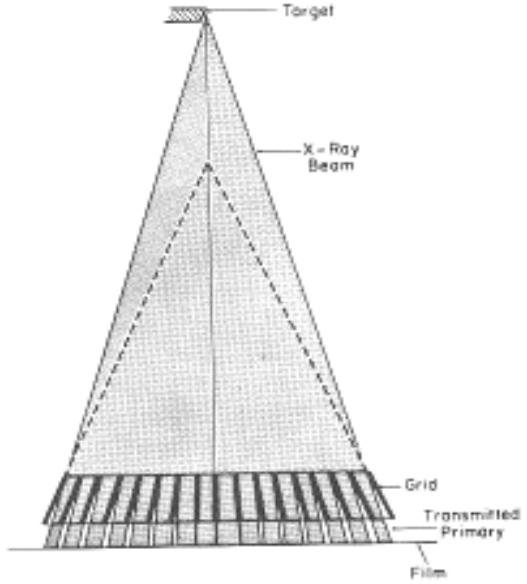


Figure 8–15 Cutoff from far focus-grid distance decentering

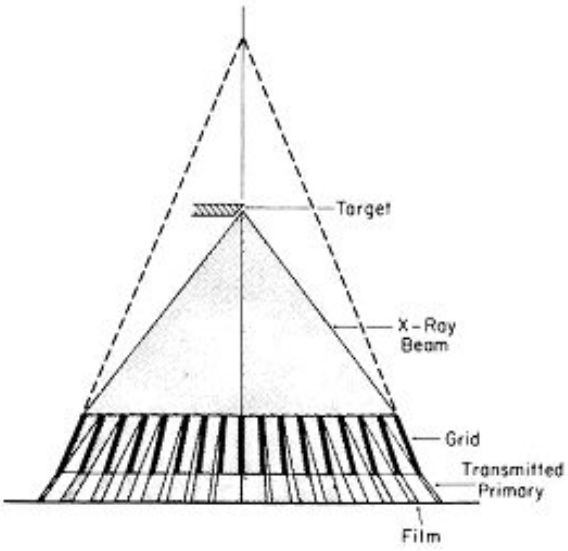


Figure 8–14 Cutoff from near focus-grid distance decentering

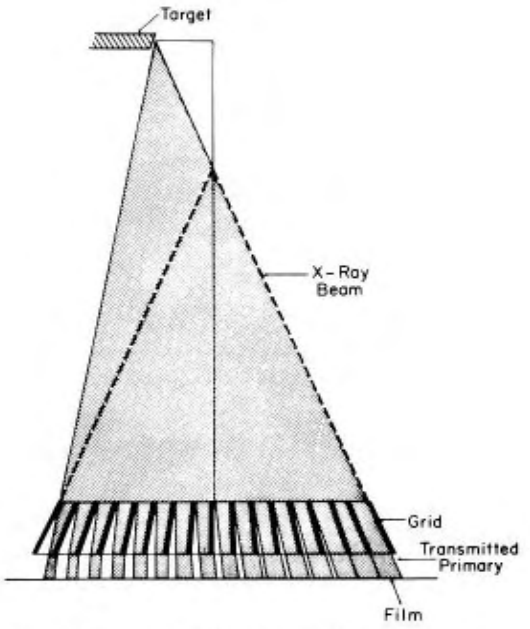


Figure 8–17 Cutoff from combined lateral and far focus-grid distance decentering

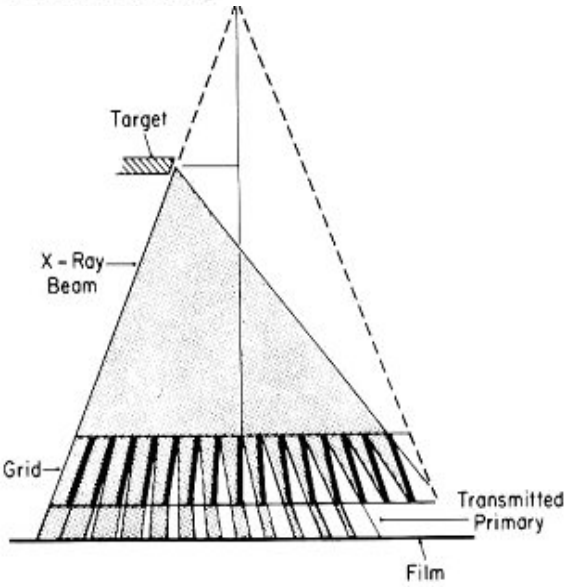


Figure 8–18 Cutoff from combined lateral and near focus-grid distance decentering

Grid-front cassette

- Special X-ray cassette with a grid build into the front of the cassette.
- Used for portable radiography.
- Most are focused with a low grid ratio (4:1 or 8:1) & long focal distance "focusing range"

MOVING SLOT

- An alternative to a grid → consists of two metal plates each with a slot, 5 mm wide, aligned with the beam in front of and behind the patient.
- They are arranged to move steadily across the field during the exposure. With only a slice of the patient being irradiated at any instant, little scatter is produced.
- An increase of exposure time is necessary, but this can be mitigated by employing several slits well spaced apart.

2.4 MAGNIFICATION AND DISTORTION

- Some important aspects of a radiological image arise simply from the fact that *X-rays travel in straight lines*.
- **Figure- 2.8a** .shows how the imago ***I*** of structure ***S*** produced by a diverging X-ray beam is larger than the structure itself.

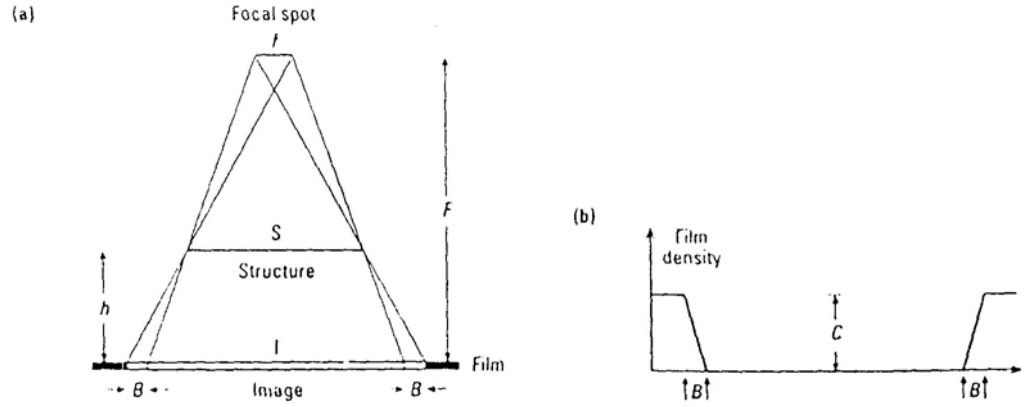


Fig. 2.8 *Magnification and blurring, (a) Formation of magnified image, (b) A plot of film density along a line across the film.*

- If the diagram is redrawn with larger or smaller values for ***F*** and ***h***, it will be seen that magnification is reduced by using a longer FFD ***"F"*** or by decreasing the object-film distance ***"h"***, (It will be shown in Section 2.5 that this also reduces the blurring *B*.)
- *Also to decrease Magnification:*
  - When positioning the patient, the film is placed close to the structures of interest.
  - tissues compression → this will also reduce patient dose.
- On the other hand, advantage is taken of increased magnification in macroradiography (see Section 3.9).

$$\text{The } \textit{magnification } M = \frac{\text{length of the image}}{\text{length of the structure}} = \frac{F}{F - h}$$

DISTORTION

- Distortion = difference between the shape of a structure in the image and in the subject.
- Causes:
  1. It may be due to foreshortening of the shadow of a tilted object, e.g. a tilted circle projects as an ellipse.
  2. It may also be caused by differential magnification of the parts of a structure nearer to and farther away from the film-screen, an effect which is familiar to photographers.
- Distortion can be reduced by using a longer FFD.

2.5 UNSHARPNESS AND BLURRING

In practice, three types of unsharpness combine to ***limit the resolution*** *achievable (see Section 3.6).*

GEOMETRICAL UNSHARPNESS

- The image of a stationary structure produced by the beam from an ideal point source would be perfectly sharp. At the edge of the shadow, the intensity of X-rays would change suddenly from a high to a low value.
- **Figure 2.8a** shows that, in the case of effective focal spot f mm^2, the intensity changes gradually over a distance B, variously called ***the penumbra, blurring or unsharpness***.
- If the diagram is redrawn with larger or smaller values for f, F and h, it will be seen that ***blurring is reduced by:***
  - ✓ using a smaller focal spot;
  - ✓ decreasing the object-film distance; or
  - ✓ using a longer FFD → this also reduces magnification and distortion
- F is usually and conveniently 1 m, but it may be smaller in some techniques, such as fluoroscopy, while 2 m is used with a chest stand.
- ***Geometrical blurring***

$$\text{The geometrical blurring } B(g) = \frac{f\,h}{F}$$

If f = 2 mm, F = 1 m, and h = 100 mm → then $B(g)$ = 0.2 mm.
Usually the geometrical blurring is less than this as f and h are smaller.

- **Figure 2.8b** plots the intensity of X-rays (or film density) along a line across the film. B is the geometrical blurring and C the contrast.

MOVEMENT UNSHARPNESS

- One of the problems in radiography is the imaging of moving structures.
- If, during an exposure of duration ***t*** seconds, the structure moves parallel to the film with an average speed ***v***, the edge of the shadow moves a distance slightly greater than ***vt***.

∴ movement blurring B(m) = vt (approximately).

If v = 4 mm s^{-1} and t = 0.05 s → then *B(m) = 0.2 mm*.

- *N.B.:* Movement strictly perpendicular to the film does not produce blurring.
- Movement blurring may be reduced to a satisfactory degree by:
  1. Immobilization.
  2. Using short exposure time, made possible by a rotating anode tube (see Section 2.7.2) and intensifying screens (see Section 3.4).
- It is, on the other hand, made use of in mechanical tomography (see Section 2.6).

ABSORPTION UNSHARPNESS

- A gradual change in absorption near the edge of a tapered or rounded structure, e.g. a blood vessel, produces absorption blurring.
- This is inherent in the objects being imaged, though the effect can sometimes be reduced by careful patient positioning.

2.6 TOMOGRAPHY

- So far we have considered conventional projection radiography, in which the shadows of structures farther from the film are superimposed on those closer to the film → there is lack of depth.
  This lack of depth resolution is overcome in biplane angiography by taking two crossed projections.
- In *tomography*,
  - × Only structures in a selected slice of the patient, parallel to the film, are imaged sharply.
  - × Those above and below are deliberately blurred → unrecognizable. This blurring is produced by simultaneous movement, during the exposure, of two of the three following: *tube*, *film*, and *patient*.
- In ***linear tomography***, depicted in **Fig. 2.9a**:
  - ✓ The tube T and cassette carrier C are linked by an extensible rod TC which is hinged about a fulcrum or pivot P which, in turn, is attached via a vertical arm to the table top.
  - ✓ During the exposure, the cassette tray moves ***horizontally***, for example from right to left, along rails under the couch top, while the tube stand moves along floor rails in ***the other direction***, from left to right.

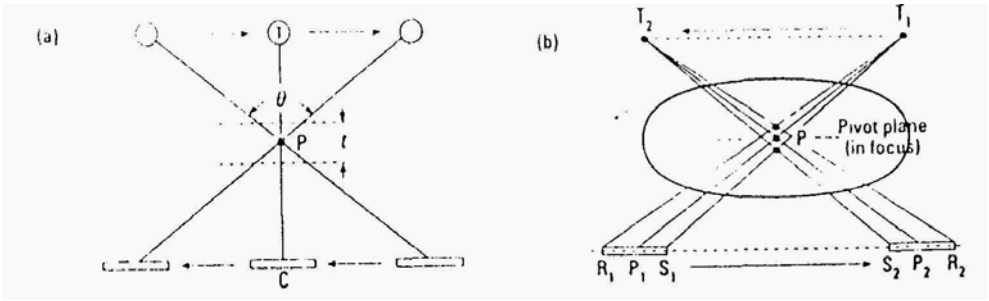


Fig. 2.9 Linear tomography (a) the thickness of cut t is related to swing angle θ. (b) Structures outside the focal plane are blurred.

- **Figure 2.9b** depicts two positions T_1 and T_2 of the focal spot and the corresponding positions of the film. It shows that the plane of interest within the patient is at the level of fulcrum, all points (& levels) above and below are blurred.
  - × Shadow of a structure P at the level of the pivot moves from P_1, to P_2 at the same speed as the cassette → remains stationary on the film → sharp image. This is true of any structure in the plane through P (sometimes called the '***focal plane***').
  - × However, the shadow of a structure R above the pivot moves further, from R_1 to R_2, sweeping across the film, and is blurred out. A structure S below the pivot is similarly blurred.

  The farther the structure from the pivot plane, the greater the movement blurring.
  Structures lying within a slice of thickness t are sufficiently sharp to be recognizable, whereas those lying outside that slice are too blurred and of too low contrast (see below).
- The ***level of cut (focal plane)*** is adjusted by raising or lowering the pivot.

- The ***thickness of cut*** (**t**) is controlled by:
  1. Adjusting the ***tomographic angle θ*** (i.e. the angle of tube swing or the amplitude of tube travel expressed in degrees)
     - ❝ The greater tomographic angle → the thinner the cut, because even structures vertically close to P are blurred.
     - ❝ If θ were zero → **t** would be very large, i.e. a conventional radiograph results.
  2. if the fulcrum (level of cut) is raised → smaller thickness of cut,
     As this increases the movement of the cassette and the tomographic effect.
  3. Decreasing the FFD has a similar effect.

Typically, in tomography θ is around 40° and *t* about 3 mm.

- Since such a thin slice of each structure is being imaged, and the shadows of off-focus anatomy are spread over the film → ∴contrast is low → ∴ a reasonably low kilovoltage must be used, consistent with penetrating the patient.
- The technique has been most useful when imaging structures of ***high inherent contrast***, e.g. bony structures in the inner ear and iodine-filled vessels in pyelography.
- In Tomography, high patient dose is needed
  Since for much of the exposure the beam is passing obliquely through the patient, attenuation is higher and patient dose is greater than in conventional radiography.

Narrow- versus Wide-Angle Tomography:

	Wide-angle Tomography	***Narrow-angle Tomography "Zonography"***
Use	To obtain the max. blurring of obscuring shadows	To view a whole abject "undistorted & sharply defined"
Aim	To enable imaging of an object completely obscured by overlying shadows.	Produce undistorted sharply defined image of an entire structure in focal plane, against a background of slight blurring.
Tomographic angle	Wide (> 10°, usually 35-50°)	Narrow (< 10°)
Exposure time	Long	Short
Effect	~ Considerable unsharpness of focal plane images (i.e. low contrast) ~ Maximum blurring of objects outside focal plane. ~ Less section thickness.	~ Little unsharpness of focal plane images. i.e. retain the natural contrast ~ Minimum blurring of objects outside focal plane. ~ Greater section thickness.
Choice	Best for tissues with high contrast e.g. bone, inner ear	Best for tissues with low contrast e.g. lung, soft tissue
Tomographic motion	Can be done with both linear or circular motion	Done with circular motion.
	Unlikely to cause phantom images	frequently cause phantom images

Blurring:

- The purpose of tomography is to distort the object that might interfere with the radiographic image of structures of interest (in the focal plane).
- ***Width of the Blur*** = the distance over which the image of an object is spread out on film.
- ***Width of blurring is determined by 4 factors:***
  1. ↑ *Amplitude of tube travel* → ↑ width of blur (linear relation)
  2. ↑ *Distance from focal spot* → ↑ blurring. However, the distance inside pt. body is uncontrollable.
  3. *Distance from film:* objects far away from the film are blurred more than objects closer to the film (assuming they are both the same distance from the focal plane)
     So, position patient so that the objects we want to blur are as far from the film.
  4. *Orientation of tube travel*: long & narrow objects which have longitudinal axis oriented in the same direction as the axis of tube travel → not blurred, even though it's outside the focal plane, while maximum blurring is when the long axis of the object is ⊥ direction of tube travel.
     To overcome this problem with linear tomography and increase blurring outside the pivot plane, other tomographic movements may be used:
     - ✓ ***Circular movement,*** which produces the tomographic effect in all directions.
     - ✓ ***Elliptical movement,*** similar to the above but more appropriate to the elongated human body.

       Spiral and hypocycloidal movements, on the principle that the more complex the movement the better!
- Blur margin = the edge of the blurred image.
  - ~ Linear tomography → uniform blurring with gradual fade-off at the blur margin.
  - ~ Circular tomography → non-uniform blurring with sharp blur margin → important in ***phantom image formation***.

Phantom Image Formation:

- Phantom images appear on tomograms, but they don't actually exist.
- It is produced by blurred margins of structures outside the focal plane.
- These unreal images are less dense & less sharp than real image, but still may add difficulty to film interpretation.
- Occur mostly with circular tomography & zonography → object outside focal plane are only minimally blurred.
- Bony trabeculae, teeth, ribs & dye-filled vesels are anatomic parts that are apt to cause phantom images.

QUALITY ASSURANCE

- Commercial test tools are used to check the performance of tomographic equipment for height of cut and slice thickness.
- The simplest test → ***Pinhole camera technique*** (Figure 16-17 Christensen's)
  - ✗ By placing *a lead sheet with a hole 1 mm in diameter* between the fulcrum and the table top (at the level of the focal plane).
  - ✗ ***2 exposures***,
    - ❝ One using the tomographic movement → produce an image of **the swing** *(a straight line of uniform density for linear tomography)*
    - ❝ The other with a vertical beam → **a dense spot** superimposed on swing which should be at the center of the line
- Any elongation of the tomographic image of the hole indicates lack of *coincidence between the movement of the tube and the film cassette*.
- *The of dots produced by the Pin-hole technique provides the following information:*
  1. Tube motion (e.g. linear, circular, etc.).
  2. The angle of swing of tube (exposure angle).
  3. Symmetry of exposure angle → exposed dots have to be equal in length on either side of the central dot.

RADIOGRAPHY WITH FILMS AND SCREENS

X-ray cassette:

- A flat, light-tight box with spring clips.
- Contain ***internal pressure pads*** → keep film between a pair of screens in close contact.
- The ***front of the cassette*** is made of **aluminum (Z = 13)** or **carbon fiber (Z = 6)** → to minimize the attenuation of the beam → reduce the patient exposure.
  Carbon fiber is effective at the **lower kV values** → in mammography & orthopedics.
- The ***cassette back*** incorporates a thin lead sheet (absorb the remnant radiation).

3.1 INTENSIFYING SCREENS

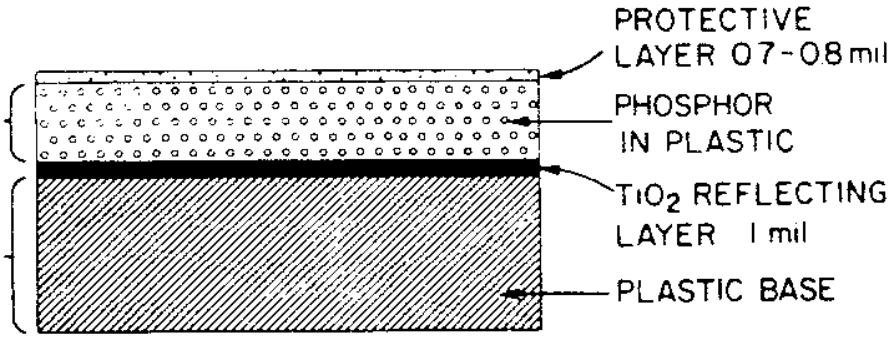
Function

Absorb the energy in the x-ray beam 'penetrated the patient' → convert into a light pattern with the same pattern as original x-ray beam → recorded as latent image on x-ray film.

- They decrease the x-ray dose to the patient, yet still afford a properly exposed x-ray film.
- ↓↓ exposure allows use of short exposure times → necessary to minimize patient motion

Construction

- **An intensifying screen consists of 4 layers:**
  - **A base** 'for support' - polyester "plastic" or cardboard - **0.25 mm thick**.
  - **A phosphor layer:**
    - **0.1-0.5 mm** thick.
    - Dense layer of fine phosphor crystals **(3-10 µm)** bound by a transparent resin.
  - **A reflecting layer** "not in all screens":
    - Thin white reflective layer - between the base & phosphor **(Titanium dioxide TiO_2)**
    - Reflect light directed toward back of screen again toward the film "otherwise lost"
  - Very thin **protective layer** (outermost) → Physical protection to phosphor layer.



- **The most frequently used phosphors are:**
  a) Calcium Tungstate
  b) Various **rare earths**:
  i- Lanthanum oxybromide.
  ii- Lanthanum oxysulfide.
  iii- Gadolinium oxysulfide.
  iv- Yttrium oxysulfide.
  v- Barium lead sulfate.
  vi- Barium fluorochloride.

Matching film and phosphor

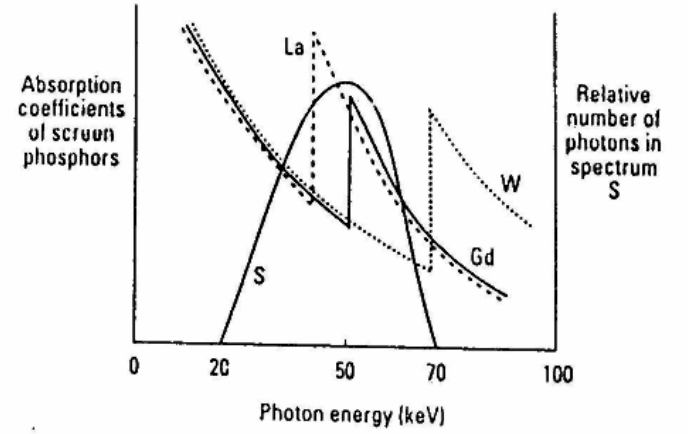
- The **intensity of light** emitted by a screen depends on the phosphor, but its **color** depends on activator.
- **Spectral sensitivity of the film should match Spectral emission of the screen to ensure maximum radiographic effect.**

1- **Calcium tungstate**, which emits a continuous spectrum of **violet and blue light**, and **Lanthanum oxybromide** activated with terbium, which emits a **blue light**
- × Can be used with **ordinary X-ray film** "sensitive only to ultraviolet and blue light".
- × Film doesn't exhibit photosensitivity to red light → Amber red safelight for darkroom.

2- **Gadolinium and lanthanum oxysulfides** activated with terbium → **green light**.
- × Used only with an **orthochromatic film** "its sensitivity include green light".
- × A red safelight is necessary.

To maximize the absorption of X-rays,

- **Phosphor should have a sufficiently high atomic number**
- The **absorption** edge of **tungsten (W, 70 keV)** is less favorably placed in relation to the X-ray spectrum than those of **gadolinium (Gd, 50 keV)** or **lanthanum (La, 39 keV)**.
- **Rare earth screens are also more efficient than tungstate in converting absorbed X-ray energy into emitted light (**conversion efficiency of tungstate is 5% compared to 20% for rare earths, *see later*).



- All these factors make **rare earth screens more sensitive ('faster') than calcium tungstate screens,** so allows:
  - **Lower exposure**.
  - **2-3 times lower patient dose** "for same quality".
  - **Lower kV**.

Afterglow

In afterglow, the screen retains a 'memory' of an exposure → superimposed on the image of a subsequent exposure → must be avoided in intensifying screens.

Intensification factor 'SPEED'

- Measures the reduction in patient dose and tube loading when the screens are used.
- It is the ratio

$$\frac{\text{air kerma necessary to produce D = 1 with film alone}}{\text{air kerma necessary to produce D = 1 with film plus screens}}$$

Typical values are **30-100**

- **Factors ↑↑ IF:**
  1. ↑↑ **kV** → because the K-absorption edges of **silver** and **bromine** in the film are **26 keV** and **13 keV**, respectively, while the K-absorption edge of **tungsten = 70 keV**.
  2. **Heavily filtered x-ray beam** (same reason).
  3. ↑↑ **Thickness of the phosphor** 'coating weight' or using **larger crystals**.
  4. **Rare earth screens** have a larger IF than tungstate.
  5. The use of **a white reflecting layer**, e.g. titanium dioxide.

3.4 USE OF SCREENS

Film exposed directly to X-rays

- **More exposure (mAs) is required if no screens** are used.

  Films exposed with par speed intensifying screens will require an x-ray exposure of approximately 1 mR to produce a density of 1; this value will rise to 30 mR with direct x-ray exposure.
- **At the same density, contrast is always lower for a film exposed to x rays only** than for the same film exposed by light from intensifying screens.
  Intensifying screens are less sensitive than film to lower energy x-rays → ↓ effect of 'lower energy' scattered radiation → ↑ contrast
  Stated another way,
  The gradient "gamma" of x-ray film is greatest when the film is exposed with intensifying screens than with **direct x-ray exposure.**
- **When does direct exposure to X-ray needed?**

  To produces a **sharp image** → used in thin parts and where fine detail is required, e.g. teeth & bone fractures of the extremities.

Film exposed with screens

- ***A film exposed with screens is more sensitive than film exposed alone for 2 reasons:***
  - The screen phosphor layer is thicker → absorbing X-rays > film emulsion.
  - Each X-ray photon absorbed by phosphor produces hundreds of small light photons.

Film and screen	Film only
Absorbed by phosphor, 30	Absorbed by film, 2
Light photons produced, 18000	—
Light photons reaching film, 9000	—
Latent images produced, 90	Latent images produced, 2

- Accordingly, the use of screens **reduces the air kerma or exposure** necessary to produce a properly exposed film
  → reduces **the dose** to the patient
  → reduces **the loading** of the tube and generator
  → allow the use of **shorter exposure time** → reducing movement blurring.
  → allow the use of a **smaller focal spot** → ↓ geometrical blurring.

Front and back screens

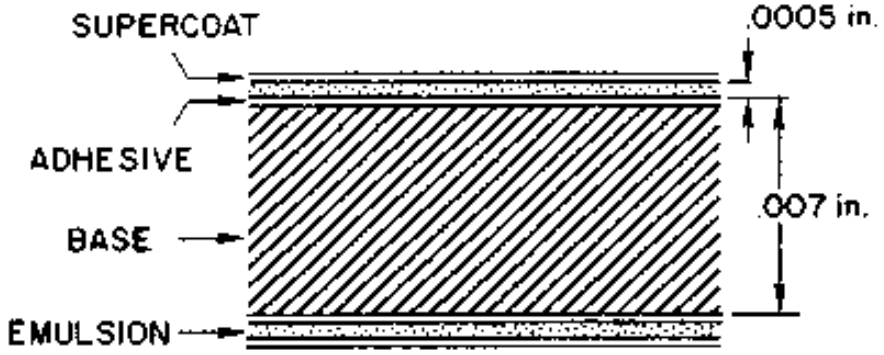
To equalize the densities of the two emulsions, the rear screen coating is **thicker** than that of the front screen since the back screen relies on X-rays which have not been absorbed by the front screen.

Reciprocity law

The density of blackening of a film depends only on the quantity of radiation (or mAs) whatever the particular combination of intensity (mA) and exposure time (s).

- It holds **only for X-rays**, i.e. film exposed without screens. It **does not hold for light**;

3.2 FILMS



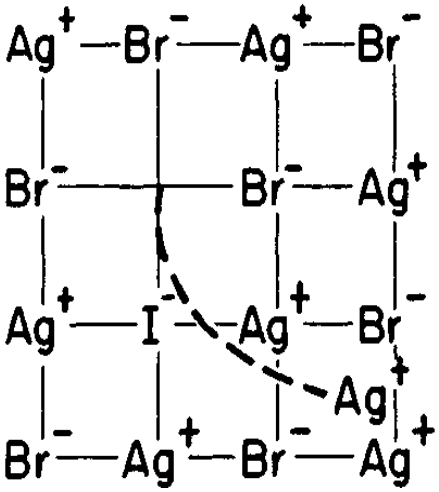
Cross section of a double emulsion x-ray film

- **A film consists of:**
  1- A ***polyester base*** (typically **0.2 mm thick**) → support fragile emulsion.
  2- On which is coated a ***thin photographic emulsion*** (**10 µm thick**).
  - × The emulsion is a suspension of ***fine silver halide crystals*** ***(iodobromide****: 90-99% silver bromide, 1-10% silver iodide)* in gelatine.
  - × Each crystal is about **1 µm** in size and containing a million or more silver atoms.
  - × A photographic emulsion is:
    ...1. Sensitive to X-rays and ultraviolet & visible light.
    ...2. Also, affected by mechanical, electrical & chemical factors.
    All of which have implications for storage and handling.

  3- Thin **transparent antistatic supercoat** → protect against abrasion & curling.
- An X-ray film is usually **double coated** with an emulsion on each side of the base, and is used with a **pair of screens**.
- About a 1/3 of the X-radiation falling on the front screen (nearer the patient) is absorbed
  - About 1/2 the light so produced travels forward and exposes the nearer (front) emulsion 'the rest is absorbed in the screen'.
  - About 1/2 the X-radiation transmitted by the front screen is absorbed by the rear screen → the produced light exposes the rear-facing emulsion.

Exposure to light

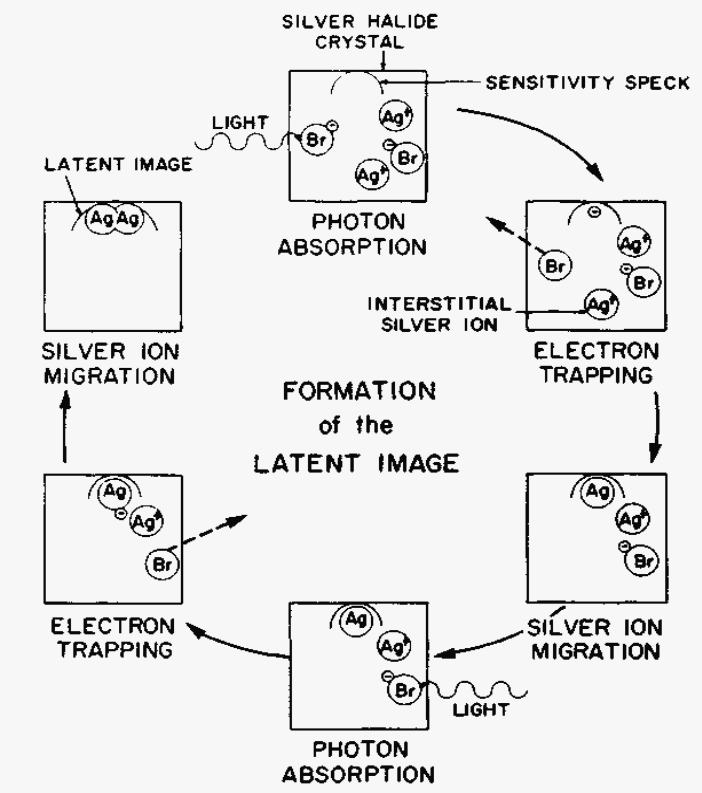
Two features of the silver iodobromide crystal account for the photographic process



1. The small proportion of iodide ions distort the lattice.
There are several types of crystal defects.
- **Point defect** → a silver ion moved out of its normal position in the crystal lattice **"interstitial silver ions"** → can move in the crystal (Fig. 10-4).
- **Dislocation** is a line imperfection in the crystal.

2. The silver halide crystals are manufactured to possess **sensitivity specks**.
- Chemical sensitization is produced by adding a **sulfur-containing compound** to the emulsion → reacts with silver halide to form ***silver sulfide***.
- The silver sulfide is located on the surface of the crystal and is referred to as **the sensitivity speck.**

- **How exposure of sensitized silver iodobromide grains in the film emulsion to light or direct x rays, initiates the formation of atomic silver to form a pattern?**



1. The energy absorbed from a light photon gives an electron in the bromine ion enough energy to escape.

   $Br^- + \text{light photon} \rightarrow Br + \text{electron}$
2. ***AgS sensitivity speck act as an electron trap***.
3. The electron gives the sensitivity speck a negative charge → attracts the mobile interstitial Ag^+ ions in the crystal → form a single silver atom:

   $\mathbf{Ag^+ + electron \rightarrow Ag}$
4. This single atom of silver then acts as an electron trap for a second electron. → get negative charge → causes a second silver ion to migrate to the trap to form a **two-atom silver nucleus**.
5. The negative bromine ions that have lost electrons are converted into neutral bromine atoms → leave the crystal & taken up by the gelatin of the emulsion.

- The submicroscopic speck of **silver metal** form **A LATENT IMAGE** in the film, awaiting development.
- Metallic silver is black.
  It is silver that produces the dark areas seen on a developed radiograph.

Processing

*The invisible pattern of latent images is made visible by **PROCESSING**.*

The film is processed in three stages:

I- Development:

Reduction of the silver ions (addition of an electron) by alkaline solution → black metallic silver: $Ag^+ + \text{electron} \rightarrow Ag$

- ***N.B.:*** The development process is initiated at the site of a latent image speck on the surface of the grain → then, progress to development of the entire grain.
  The unexposed crystals, which carry no latent images, are unaffected by the developer.

- Because, the silver atoms in the latent image accelerate the reduction of the silver ions in the grain → the silver in a grain that does not contain a latent image are reduced at a much slower rate. Thus, **time is a fundamental factor in the developing process.**
- ∴Development should be discontinued when the differential between exposed developed grains and unexposed undeveloped grains is at a maximum.

- If the developer attack unexposed crystals → **Fog formation** or **wholly opaque film**.
  To inhibit this, **Potassium Bromide (Restrainer)** is incorporated in the initial charge of developer (but not in the replenisher since the reduction of silver itself liberates bromine ions into the developer, which also decreases the rate of development).
- The bromide ions released by the reduction of silver ions to silver atoms pass into the developing solution. It is mainly this increase in bromide concentration that limits the life

of developing solutions.

II- Fixation:

- The film is now fixed by an **acid solution of thiosulfate ('hypo')**.
- It dissolves unaffected silver ions → the image becomes stable "unaffected further by light"
- Incomplete fixation → **'milky' radiograph**.

III- Washing:

- After stages (1) and (2) the film is *washed* in water, and finally it is dried by hot air.
- With inadequate washing → retained hypo will **turn brown/yellow**.

Automatic processing:

- *Automatic processors* use a roller feed system to transport the film through different solutions.
- Processor performance is maintained through a comprehensive quality assurance program, described in Section 3.3.

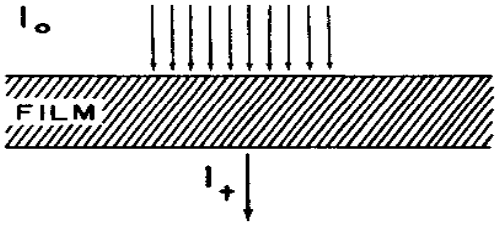
Photographic Characteristics of X-Ray Film

PHOTOGRAPHIC DENSITY

- The measurement of film blackness is called "**photographic density**".
- **The degree of film blackening is:**
  - ✓ **Directly related to the intensity of radiation reaching the film**.
  - ✓ **Directly related to silver grains \ unit area.**
  - ✓ **Inversely related to the light transmission.**
- X-ray image is a **negative image**
  The film is darkest where the **X-rays have been most intense**, and vice versa.
- Photographic density is measured using a **densitometer** as log the ratio of the intensities of the incident to the transmitted light through the film.

$$D = \log \frac{I_0}{I_t}$$

D = density I_0 = incident light on film I_t = transmitted light by the film



$$\text{DENSITY} = \log_{10} \frac{I_0}{I_t}$$

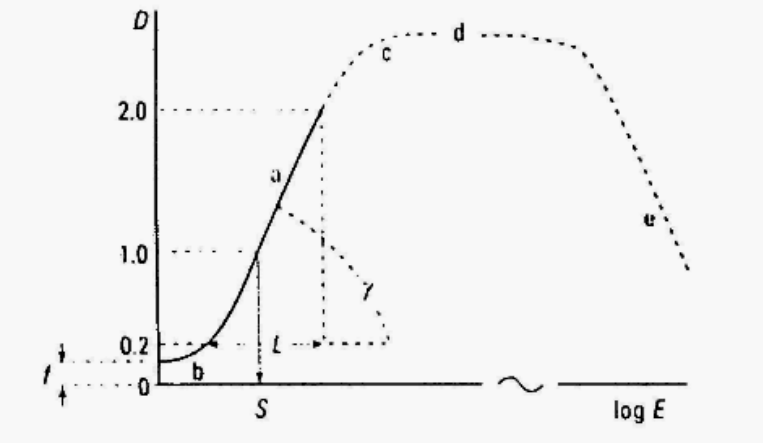
- $\frac{I_0}{t}$ alone measures the **opacity** of the film (the ability of film to stop light).
- Useful densities in diagnostic radiology range from about **0.3** (**50% of light transmitted**) to about **2** (**1% of light transmitted**).
  ∴Density increase of 0.3→ the opacity is doubled.
  → transmitted light is halved.
- The average density of the area of interest on a properly exposed film =

1.0; of the lung field in a chest film **2.0**; while viewing an area of density of **3.0** needs a bright lamp.

- If an unexposed x-ray film is processed, it will demonstrate a density of about **0.12**.
  This density refers to ***base density*** and ***fog***.
  Base density = **0.07**
  Caused by the plastic material & the blue dye used to make film base.
  Fog: "the density resulting from developed unexposed silver grains" = **0.05** *"see later"*
- **Why is density expressed as a logarithm?**
  1. **Logarithms express large differences in numbers on a small scale.**
  2. **The physiologic response of the eye to differences in light intensities is logarithmic.**
  3. **Superimposition of densities is best described on logarithmic base.**
     - **Densities are additive** → either 2 films or 2 emulsions.

3.3 CHARACTERISTIC CURVE

- The relationship between **log air kerma "or log exposure"** and **the density** produced by the exposure → **"characteristic curve"**.



- *The most important parts of the characteristic curve:*

a) The *region of correct exposure:*
- ✓ Straight-line portion.
- ✓ Steepest.
- ✓ The densities within the area of diagnostic interest should lie within this range.
- ✓ Density is proportional to the log exposure.

- **Other features of curve are:**

b) The toe, shallow slope.

c) the shoulder, shallow slope, and

d) saturation density,
In both c & d, the film is too dark to be readable on an ordinary illuminator;

e) reversal or solarization,
- ✓ ↑ E → ↓ D "producing a positive image".
- ✓ Used for ***film copying***, by exposure of reversal films to ultraviolet light.

Four properties of the film-screen combination can be derived from the characteristic curve:

(1) Fog level *f* in Fig. 3.2

- Fog → ↓↓ image contrast.
- Types:
  - Inherent fog has typically **D = 0.12**
  - Additional fog may arise ***during storage*** due to:

✓Temperature & humidity ✓Accidental X-rays exposure. ✓Light exposure.

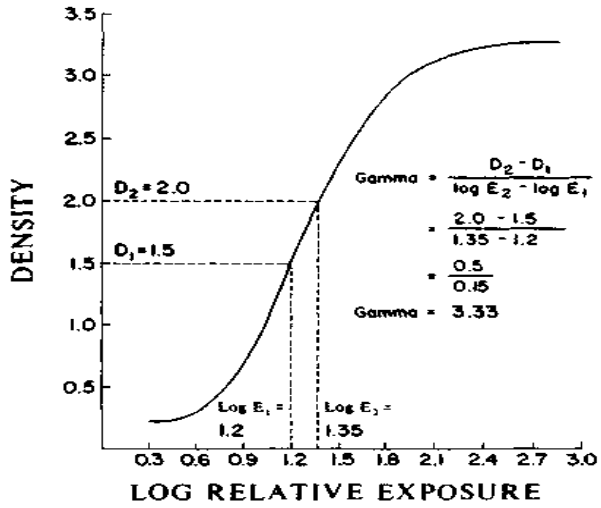
- Assessment → by measuring the density of processed but unexposed film ***(E = 0)***.

(2) Gamma (γ)

= the slope of the straight-line portion of the characteristic curve.

$$Gamma = \frac{D_2 - D_1}{\log E_2 - \log E_1}$$

The steeper slope → ↑ γ → ↑ contrast



- γ generally refers to the average slope between densities **0.25 and 2.0** (or 2.25).
- In Fig. 3.3, film-screen A has a higher ***γ*** than B (has a steeper slope → more 'contrasty').
- γ depends on **the range of crystal sizes** (not their average sizes).

The more uniform the crystals → the higher is γ

(3) Film Speed *I* in Fig. 3.3

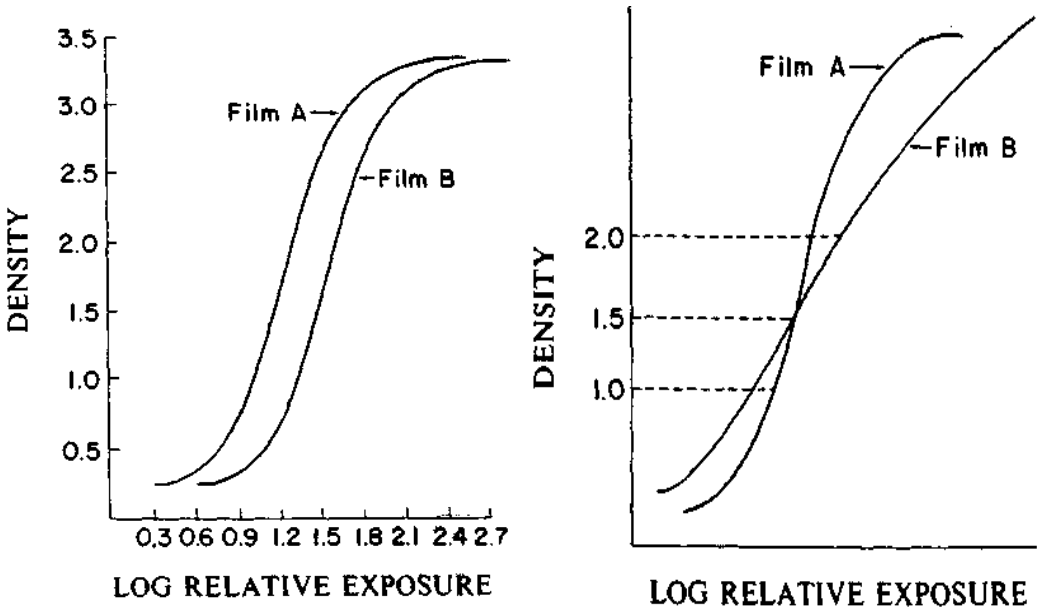
= The reciprocal of the exposure (measured in Roentgen) needed to produce D = 1

$$\text{Speed} = \frac{1}{\text{Exposure "in Roentgens" needed to produce D=1}}$$

- **Factors ↑↑ film speed:**
  - ↑↑ Grain size.
  - Modern emulsions with flat crystals.
  - X-ray photon energy = 30-40 keV.
- **The relative speed** of two films or film-screen combinations is the ratio

$$\frac{\text{exposure needed to produce } D = 1 \text{ on film A}}{\text{exposure needed to produce } D = 1 \text{ on film B}}$$

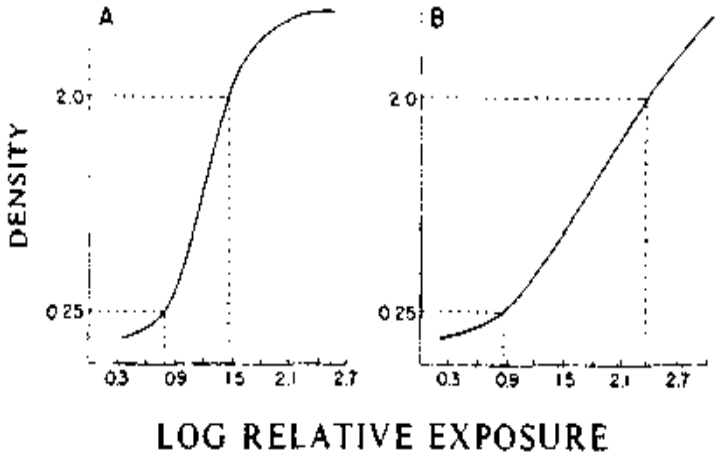
- ↑ Speed "with fixed γ" means that the film needs less exposure to produce same density.
- But with films of different γ → relative speed change with change E وبالتالى D



(4) Film latitude or dynamic range

L in Fig. 3.2.

- L is the range of air kerma E which produce densities D lying in the useful density range → between 0.25 "below which the gradient is too low" and 2.0 "above which the film is too dark for details to be seen using a normal illuminator".
- **Typically the dynamic range is 40:1.**
- Figure 3.3 shows that **film contrast γ *and* latitude are inversely related**.
  - **Film A** has the steeper slope and higher γ. It also has the narrower latitude **L(A)**.



- There are two practical aspects to this concept of film latitude.
  - For the technologist:
    ↑↑ latitude → more room for error in his choice of exposure (mAs).
  - For the radiologist → interested in high contrast "less latitude".
    But if a wide range of subject contrast (such as in the chest) must be recorded → higher latitude can record small changes in film exposures.

Typically, wide latitude is needed in chest radiography and a high γ in mammography.

EXPOSURE LATITUDE

= The range of EXPOSURE FACTORS (kV and mAs) which will give a correct exposure of a subject.

- If the exposure latitude is too small → misjudgment of the machine settings appropriate to individual patients will necessitate repeating radiographs & ↑↑ patient dose.

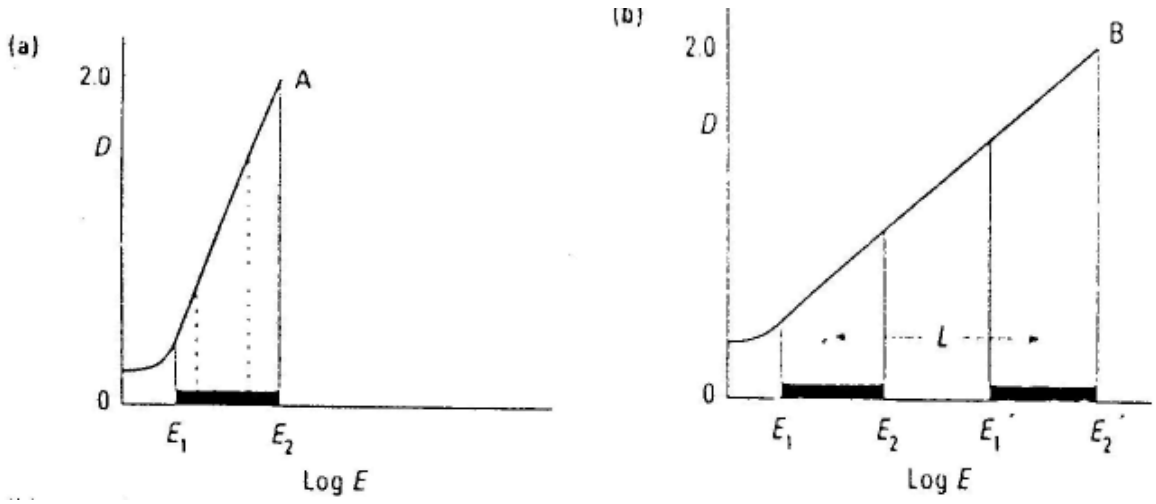


Fig 3.4 Exposure latitude with films of (a) high and (b) low gamma

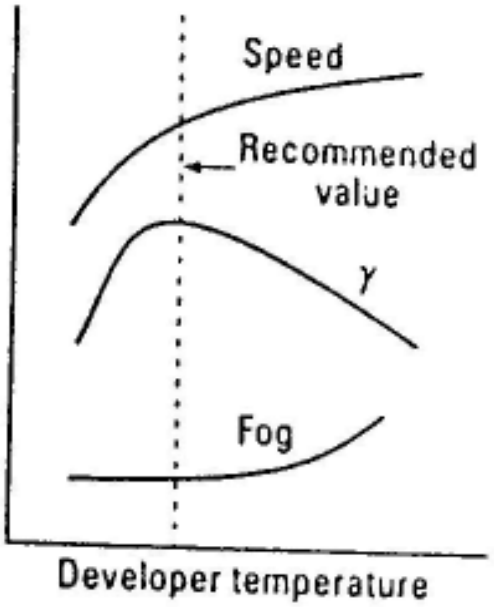
Factors which increase the exposure latitude:

1. ↓ Film γ.
2. ↑ Film latitude.
3. ↓ subject contrast; which in turn depends on:
- ***a)*** Tissue densities.
- ***b)*** Atomic numbers.
- ***c)*** Thicknesses of the structures.
- ***d)*** Tube kV.

If a higher kV is used and the mAs → ↓ subject contrast → ↓ range of air kerma within the image → ↑ latitude of exposure

In conclusion, exposure latitude for a particular radiograph of a patient can be increased by using a higher kV or a film of lower γ.

EFFECT OF DEVELOPING CONDITIONS



- ↑ **Developer temperature** → ↑ chemical reaction rate:
  - ↑ **Speed**.
  - ↑ **Fog level**.
  - ↑ γ initially; but, above the temperature recommended by the manufacturer → ↓ γ due to ↑ fog level.
- Increasing **developer concentration** or **developing time** will have similar effects.
- Developing conditions are optimized to give maximum γ and minimal fog.
- In an automatic processor, the ***temperature*** is controlled thermostatically, ***time*** by roller speed, and ***concentration*** by the speed of the developer replenisher pump, which in turn is controlled by the area of film being processed.

QUALITY ASSURANCE OF PROCESSING UNIT

- Concentration & Temperature of the developer have a significant effect on speed, contrast, and fog → must be controlled rigorously.
- Quality assurance → aims to avoid the additional patient dose and waste of time and materials from having to repeat incorrectly processed films.
- It involves **measuring the density of 3 steps of a step-wedge image "after processing" on a film pre-exposed to light** → using a **sensitometer**.
  - The first step (zero exposure) monitors *fog level;*
  - The second *(D* = 1) monitors *speed.*
  - The difference between the second and third *(D* = 2) monitors *γ.*
- These densities are plotted daily, and a **10-15%** variation in them is acceptable.
- Automatic readers are available, measure **up to 20 steps** → produce a complete characteristic curve.

3.5 RADIOGRAPHIC CONTRAST

I- Objective Contrast:

- **Radiographic contrast**

= the pattern of variations in optical density between various regions on the film.

- Radiographic contrast depends on **subject contrast** and on **film contrast**.
  So, the factors which affect radiographic contrast are:
  - Factor which affect subject contrast (see Section 2.1); plus
  - Factor which affect film **γ** (see Section 3.3).

Radiographic contrast = film γ x subject contrast

Subject Contrast:

- Depends on the differential attenuation of the x-ray beam as it passes through the patient.
- Subject contrast was seen to be affected by:

1. Thickness of the subject.
2. Density and atomic differences of the subject.
3. Radiation energy (kVp).
4. Contrast material.
5. Scatter radiation.

- **Subject contrast controls the relative exposure that reaches the film**
  → so, film directly under a bone receives a low exposure than film under soft tissue areas
- While **kV** controls **subject contrast**, **mAs** determines **exposure** (overall film density)

Film Contrast:

- Film contrast depends on four factors:

1. **Film γ**
2. **Film density**
3. **Screen or direct x-ray exposure**
4. **Film processing**

N.B.:

The greater the film γ, the greater the contrast, the less the exposure latitude

II- Subjective contrast: contrast as seen by the eye is affected by ***viewing conditions***.

- It is reduced by:
  - × **Glare** "very bright low attenuation areas" → should be masked off.
  - × Too high level of **ambient lighting**.
- Film viewing systems should be cleaned regularly & checked for adequate illumination

Speed of Calcium Tungstate Intensifying Screens

- Several factors determine how "fast" or "slow" a calcium tungstate screen will be.
  1) **Thickness of the phosphor layer.**
  2) **Size of the phosphor crystals.**
  3) Presence or absence of **light-absorbing dye** in the phosphor layer.
  4) Phosphor conversion efficiency.

- **The intrinsic conversion efficiency of the phosphor** = The efficiency with which the phosphor converts x rays to light is termed;
  - ***Definition:*** the fraction of absorbed X-ray energy that is converted into light photons.
    - × The intrinsic conversion efficiency of calcium tungstate is about **5%**.
    - × Rare earth phosphors has a higher conversion efficiency (**up to 20%**) → Faster.

The faster screen → ↓↓ x-ray exposure to the patient, but also ↓↓ detail

3.6 SCREEN BLURRING "B"

***Unsharpness U**, or loss of resolution*

- When a film is exposed without screens, a single X-ray produces in effect a point image. When screens are used, a single X-ray absorbed by a fluorescent crystal causes it to emit light in all directions. ***This is illustrated in Fig. 3.6***

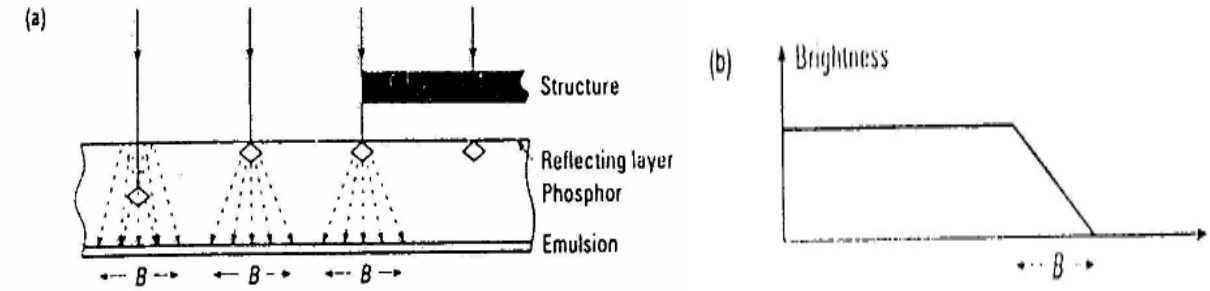


Fig. 3.6 Screen blurring, (a) Cross-section through film and screen, (b) A plot of brightness of phosphor image along a line across the screen.

- Light produced by the crystal & travels in the phosphor coating to reach the film, will be:
  - Absorbed and scattered.
  - Widely diverging → cone of light → recorded on film as a small disk of blackening of diameter *B*.
- Light undercuts the edge of the shadow of a structure → blurring *B* **"typically 0.2 mm"**

The thicker the screen coating or the larger the fluorescent crystals, the greater the blurring

- **Blurring can be reduced by**

(a) Using thinner screens and finer crystals,
(b) Replacing the white reflecting layer by a black absorbing layer,
(c) Incorporating dyes in the binder → absorb diverging light.

All these measures also **reduce the speed of the screen**.

Conversely, any measure taken to increase the intensification factor of the screen increases the unsharpness of the image.

Types of Screen according to speed:

1) **Fast screens**, **IF = 100** → high speed but larger blurring.
2) **detail screens**, **IF = 25** → high definition "less blurring" but slower speed
3) **Par speed screens**, **IF = 50** → screens which compromise between speed & definition.
4) **Ultrafast screens** → used to reduce the patient dose from repeated exposures.

- **Rare earth screens** are more effective than tungstate screens both at **absorbing** X-rays and **converting** the absorbed energy into light:
  1) Produce higher speed screens for the same thickness "& same resolution";
  2) Produce thinner screens "sharper images" for the same speed.
- **Poor film-screen contact**
  → ↑↑ the screen blurring → appears as a region of reduced sharpness and contrast
  - **Causes:** warped cassette or damaged hinges.
  - Checked by **radiographing a perforated metal sheet placed on top of the cassette**;
    → darker image and indistinct pattern of holes.
  - Cassettes should also be tested for **light leakage** → fogging around the edge of the film

Parallax → *another, less important, cause of blurring*

- **The image on the rear emulsion is slightly larger than the front image** due to the diverging nature of the X-ray beam → the edges of shadows less sharp.
- The effect is not noticeable except when the film is viewed **wet and swollen** or when the film is **tilted** relative to the central ray.

Crossover

- In *crossover* → diverging light from the front screen reaches rear emulsion & vice versa
- It **depends on the thickness of the film base** and can account for **25% of blackening**.
- In the newer **tabular or T grain film emulsions** → the crystals are thin and flat with their surfaces aligned parallel to the film base to face the x-ray beam → absorb light more efficiently → ↓ crossover.
- Also, if the base has been **coated on both sides with light-absorbing dye**.

Combination of blurrings:

- A radiographic image may suffer simultaneously from:
  1) Screen blurring *B(s),* just described.
  2) Geometrical or focal spot blurring B(g).
  3) Movement blurring B(m).
- The total blurring *B(t)* perceived is **less than the sum of the individual blurrings**.

= the square root of the sum of the squares of the individual blurrings

$$B(t)^2 = B(g)^2 + B(m)^2 + B(s)^2$$

- For example,
  If *B(g), B(m), and B(s)* = 0.2 mm each → Total blurring = about 0.35 mm (not 0.6 mm).
  - Suppose that *B(s) is* reduced to 0.1 mm by using (slower) detail screens. To compensate, it is necessary to increase the exposure by doubling the exposure time, thus increasing B(m) to 0.4 mm. B(g) remains at 0.2 mm → The total blurring = 0.45 mm.
- **The foregoing illustrates two points:**
  1) The minimum total blurring occurs when the individual blurrings are equal,
  2) Any measure which aims to reduce one of the blurrings generally necessitates an increase in one of the others and in the total blurring.

Asymmetric emulsion films

- **A high-definition front screen is in contact with a high-γ emulsion, and A fast rear screen is in contact with a wide-latitude emulsion.**
- The rear combination may be six times faster than the front.

☒ The combination can simultaneously image the sharp high-contrast structures in the lung and the denser structures of the mediastinum.

Single Coated films:

- Single screens and single-coated films → if **DEFINITION** is more importance & low speed can be tolerated, e.g. in **mammography and bone radiography**.
- **The back screen** is the one used because it produces most of its light nearest to the film, unlike a front screen.

Other uses of single-coated film

- Ordinary photography التصوير الفوتوغرافى uses single coated films with $\gamma = 1$.
- Recording images from cathode ray screens, e.g. in nuclear medicine & digital imaging
- In cineradiography or spot filming with an image intensifier.
- Copying radiographs with reversal film → such film should have $\gamma = -1$.

- These films are all matched to the spectrum of light to which they will be exposed, and formulated for automatic processing.

3.7 QUANTUM MOTTLE OR NOISE

- When a film is exposed with fast screens to a uniform beam of X-rays → **mottled appearance** "density varies a little from one small area to the next" (not uniform blackening as expected).
- In a radiographic exposure, if an average of M photons fall on each square millimeter of a screen *and are absorbed.* Due to the stochastic nature of X-ray attenuation processes, ***the actual number of photons absorbed varies from one square millimeter of the image (or 'pixel') to another***.

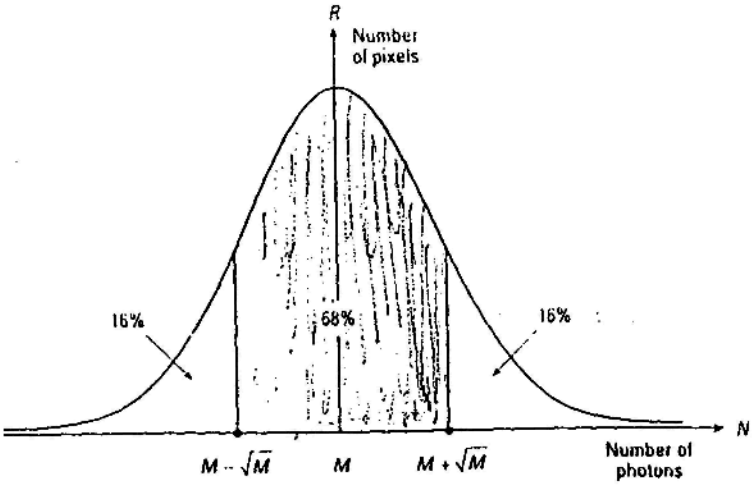


Fig. 3.7 Fluctuation in the number of X-ray photons absorbed in each square millimeter of a phosphor screen.

- About two-thirds (68%) of all pixels absorb between (M - √M) and *(M + √M)* photons. 16% absorb more than *(M + √M)* and 16% absorb less than *(M - √M)*.
- The fluctuation in the number of photons absorbed = **the standard deviation** $\sqrt{M}$.

- This random pattern of photons, called **the 'noise' or quantum mottle**, is superimposed

upon **the 'signal'**, the pattern produced by the structures in the patient.

Noise:

- Obscures the finer detail in the image.
- Noise reduces the visibility of low-contrast shadows, particularly if small in area

- **the relative noise = the ratio of the fluctuation √M of photons absorbed to the average value *M*:**

$$\text{relative noise} = \frac{\sqrt{M}}{M} = \frac{1}{\sqrt{M}}$$

The larger the number of X-ray photons absorbed, the less noisy the image.

- **the signal-to-noise ratio (SNR) = the ratio of signal M to noise √M:**

$$\text{SNR} = \frac{M}{\sqrt{M}} = \sqrt{M}$$

- The SNR should be high to maximize information. If the SNR is low, the image appears 'noisy'.

The larger the number of X-ray photons absorbed, the greater is the SNR

Number of events	Noise	SNR
100	10%	10:1
1000	3%	30:1
10000	1%	100:1
100000	0.3%	300:1

In a typical radiographic exposure → ***M* = 100 000 photons\mm^2**, and the **SNR = 300:1**.

Factors which increase Noise:

As a general rule, measures to reduce noise and increase SNR → increase patient dose.

- **The use of screens increases noise** (for the same density)
  - Fast screen → ↓↓ X-ray dose or exposure (fewer photons / mm^2) → ↓ SNR.
  - Slow or detail screen → better SNR.
- **A rare earth screen is faster than a tungstate screen** → ↑↑ quantum mottle.
- ↑↑ **kV** → fewer and higher-energy protons → ↓ the patient dose but also ↓ SNR.

Other less important forms of noise

✓ Screen is made of individual crystals → *structure mottle.*

✓ The film image is made of individual grains → *'graininess'*, mainly evident when the image must be magnified for viewing, as with cine film.

3.12 Intensifying screens: speed and noise

The IF of a screen depends on the product of the following three factors:

1) ***X-ray absorption,*** the fraction of incident X-ray photons that are absorbed in the screen (tungstate 30%, rare earth 60%);

2) ***Conversion efficiency,*** the fraction of absorbed X-ray energy that is converted into light photons (tungstate 5%, rare earth 20%);
3) ***Screen efficiency,*** the proportion of the light produced in the screen that reaches the film (50%).

FOR SAME FILM DENSITY:

The IF can be increased by increasing X-ray absorption by using thicker screen.

- ↓ Exposure.
- The same number of X-ray photons are absorbed in the screen for the same film density
  → No change in noise (quantum mottle)
  → Worse blurring or resolution will be with the thicker screen.

The IF can also be increased by increasing the conversion or screen efficiency.

- ↓↓ Exposure & patient dose.
- ↓↓ Number of X-ray photons → ↑ Noise.
- **↑↑ Screen efficiency** "e.g. using a reflecting layer"→ ↓↓ resolution, but **↑↑ conversion** efficiency does not affect it.

Table 3.3 Summary of effects on image quality of increasing screen speed

Screen change	Noise	Resolution
X-ray absorption	Same	Same
Density	Same	Same
Screen thickness	Same	Worse
Conversion efficiency	Worse	Same
Screen efficiency	Worse	Worse

3.8 CHOICE OF EXPOSURE FACTORS

The controls of an X-ray set usually include kV and two out of the three factors: mA, exposure time, and mAs (Table 3.2).

- In making a particular radiological examination using film-screen system:

Film dose is approximately proportional to kV^4 x mAs

- As a rule of thumb, since 90^4 in twice 75^4, increasing the tube voltage by 1/4 "15 kV" allows the mAs to be halved when imaging a given subject.

Table 3.2 Examples of exposure factor's

Examination	*Exposure factors*
Barium meal (screening)	90 kV 0.5 mA (up to 5 mA if necessary)
Adult chest X-ray	70 kV 10 mAs comprising a high mA (e.g. 300-500 mA) and a short exposure time of only a few milliseconds (e.g. 0.02 s)
Chest X-ray (high-kV technique)	120 kV 4-5 mAs (high mA & short exposure time)

Kilovoltage

- In general, **as high as possible a kV will be used** so as to
  1) increase the penetration of the beam and reduce patient dose.
  2) increase the latitude of exposure and range of tissues displayed.
  3) reduce the mAs needed → allow shorter exposure times, within the rating of tube.
- But not so high a kV that insufficient contrast results in the area of diagnostic interest.

Milliampere-seconds

- Having chosen the kV for a particular examination, this determines the required mAs, which is then subdivided into
  1) as short as possible an exposure time (to arrest motion) and
  2) a correspondingly high mA - just within the rating of the tube (Section 2.7.3).

Exposure time

- The necessary exposure time can be reduced by selecting
  1) a **higher kV** and
  2) a **larger focal spot**.
- **Focal spot size**, **exposure time** and **screen speed** should be chosen together, to give minimal total blurring → occurs when the separate blurring components are approximately equal.
- The necessary exposure time can also be reduced by ↑ tube rating "allowable mA" using:
  1) a three-phase generator, rather than single phase.
  2) full-wave single-phase rather than self-rectification.
  3) a higher speed and larger-diameter anode disk.

High- Kilovoltage Radiography

- Carried out at **maximum kV** (say, 150 V), the **mAs selected according to the thickness and nature** of the part being radiographed.
- **In consequence:**
  - Subject contrast is low → exposure latitude is wide "wider range of tissue can be imaged on a film" → the choice of mAs less critical "↓ number of repeat exposures";
  - Skin dose is reduced;
  - Efficiency of X-ray production is high, thus reducing the heat loading and allowing very short exposure times;
  - ↑↑ Scattered radiation → grids are less effective & air gap is generally preferred.

Automatic exposure control (AEC)

- The exposure is controlled automatically by placing **3 thin sensor** on top of the cassette to measure the intensity of the X-rays.
- **The sensors "control device" may be either:**
  - **a flat parallel-plate ionization chamber** (see Section 1.8); or
  - **a phosphor**, which converts the X-rays to light, **coupled to a photo-multiplier**, which measures the light.
- 3 sensors are placed at different locations in the X-ray field → allows control of the exposure to one region of interest or an average exposure over two or three areas.
- After selecting the kV → AEC terminate the exposure automatically when the correct mAs has been delivered to the film, irrespective of any misjudgment of the ideal kV (in respect of patient thickness, etc.) or fluctuations in the mains supply.
- The radiologist's preference for 'light' or 'dark' films is accommodated by **a sensitivity or density control**.
- The control device:
  - Should not attenuate the beam very much.
  - Generally larger than the cassette.
  - Must not itself produce an image on the film.
    In some designs of sensor, this last requirement would not be met, and it must be placed behind the cassette, which should then not incorporate the usual heavy metal backing.

QUALITY ASSURANCE

- Reject analysis of all films which are not of diagnostic value should identify which is at fault & actions can be taken accordingly:
  1. Positioning.
  2. Patient movement.
  3. Choice of exposure factors.
  4. Equipment.
  5. Processing.
- To avoid repeat films and unnecessary patient dose; the following parameters should be checked on each tube and generator after each service and whenever there appears to be a lack of consistency of exposure.

KILOVOLTAGE:

- The actual tube kilovoltage should be within ±5% of the set value.
- **The kV** can either be measured:
  - ✓ **Directly** (invasively) by **potential divider** applied across the high tension leads
  - ✓ **Indirectly** (non-invasively) by **a penetrameter** method.
- Penetrameter method:
  - × Employs **2 copper absorbers** of different thicknesses, beneath each of which is a **photodiode**.
  - × The unit is positioned in the middle of the X-ray field, some **50-75 cm** from the tube.
  - × Attached to the tube is a **0.5 mm copper filter** which transmits mainly X-rays near to the peak kiloelectronvolt value.
  - × Tube kV, mA, and exposure time are selected, and an exposure made.
  - × Each detector produces a different current, proportional to the X-ray intensity falling on it. The higher the tube kV, the smaller the ratio of the two currents.
  - × The current ratio is displayed, as **the equivalent kV**, on a digital read-out. The **type of the waveform** (pulsating or constant) can also be displayed.
  - × The kV is checked at several settings of the kV control.
  - × The kV meter itself needs to have the accuracy of its readings checked periodically at a national or secondary standards laboratory.
- In the same meter, the current from **a single diode** may be used to:
  1. Monitor *X-ray output.*
  2. Used to start and stop a built-in digital timer to measure pulse length or check *timer* accuracy.
  3. Displayed on an external storage oscilloscope → showing the *waveform* more precisely, how quickly the X-rays switch on and off, and the exposure time.

THE TOTAL FILTRATION

- Checked by measuring the **kV** (as above) and the **half value layer** (HVL) (see Section 1.4) and referring to a set of published graphs.

THE FOCAL SPOT

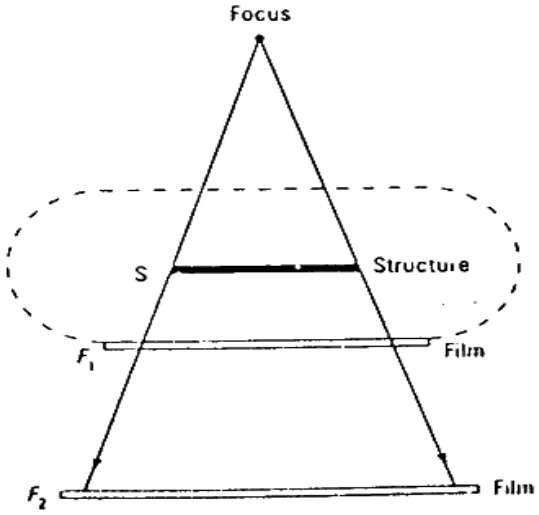
May also be checked when a new tube is installed, as described in Section 2.7.1.

AUTOMATIC EXPOSURE CONTROLS

Checked by measuring the radiation front and back of a water phantom with a dosemeter.

3.9 MACRORADIOGRAPHY

- Where a **magnified image** is required → **the anode-object distance is decreased & the object-film distance is increased**.
- Figure 3.8 shows that the image of a structure S is larger when the film F_2 is away from the patient than when it is at F_1, close to the patient.



This has the following implications for technique:

- ***Focal spot***.
  - ✓ A *very small focal spot* must be used (e.g. 0.1 mm) otherwise geometric blurring would be unacceptable.
  - ✓ ***The heat rating*** is *reduced* as a result of using small focal spot.
- ***Exposure time*** → *increased* to several seconds, to keep within the rating of the focal spot

  ∴ ***Movement blurring*** → *increased*

  ∴ ***Immobilization*** is therefore important.
- ***Patient dose*** → *increased* because of the increased exposure needed.
- ***Contrast***
  - ✓ No grid is needed.
  - ✓ The air gap reduces the scatter reaching the film → reduce the additional exposure needed *(because the use of grids would necessitate ↑ exposure & this didn't happen)*.
- ***Screen blurring*** → *not magnified* although the image of the structure is magnified.

  ∴ The relative effect of screen blurring is reduced.

  ∴ Fast screens may be used, which again helps to reduce additional exposure needed.
- ***Geometrical blurring*** → *increased*, relative to the size of the image.
- ***Quantum mottle*** → *not increased*, since the same number of X-ray photons are absorbed in the screen, for the same film blackening.

3.10 MAMMOGRAPHY

Mammography aims to demonstrate on the same film both:

- ✓ **Microcalcifications** → small "100 μm in size" but of high inherent contrast.
- ✓ **Other tissues** → much lower contrast but large.

N.B. both subject contrast & geometrical unsharpness are important factors in mammography

CONTRAST

- The breast ***does not attenuate*** the beam greatly, allowing the use of the ***low kV*** that is needed to obtain sufficient ***photoelectric absorption*** in order to differentiate between normal and abnormal breast tissues.
- Ideally, **monoenergetic X-rays of about 18-20 keV** would produce optimal contrast and penetration in the case of a small breast.

Tube requirements for mammography:

- **Tube voltage** at **28 kV** (constant potential) → the usual range is 25 – 30 kV.
  At low kV, x-ray output is approximately proportional to the kV^3; in contrast to general radiology with higher kV → x-ray output is proportional to the kV^2
- Relatively **long exposure times** are required to produce enough film blackening at such low kV without exceeding tube rating.
- **Beryllium window**
- **Molybdenum target** (produce more effective spectrum of energies for breast imaging).
- **Molybdenum filter** **(0.03 mm)** → has an absorption edge at **20 keV** → transmits most of the **characteristic radiation (17.9 and 19.5 keV)** but removes most of the continuous spectrum.
  This filter is known as a **K-edge filter**, because the filter **strongly absorbs** the radiation with energy above the k edge of molybdenum & also the low energy photons. While it is **relatively transparent** to the characteristic radiation peaks (17.5 keV & 19.6 keV).

In case of thicker breast, higher-energy radiation is preferred
Better results, with a significant decrease in absorbed dose to the breast tissue, are obtained with:

- **Rhodium target**, giving **20.2** and **22.7** keV characteristic rays.
- **Rhodium or Palladium filter**, having absorption edges at **23** & **24** keV, respectively.

- **Tungsten targets** can be used with a **Rhodium k-edge filter** (k-edge = 23 keV) to remove the high energy photons.

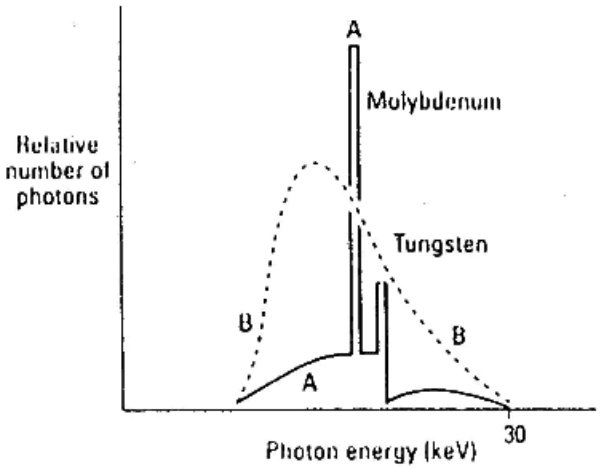


Figure 3.9 compares (A) the spectrum produced in this way by a molybdenum-molybdenum combination with (B) the spectrum that would be produced by operating a tube with a tungsten target at 30 kV and using a 0.5 mm Al filter.

- N.B.: modern mammography tubes allow the selection of both the filter & the target, for example:
  - Mo target with either Mo or Rh filter
  - Rh or W target with a Rh filter.

Other Requirements to increase contrast:

- **Films γ = 3** to overcome the low subject contrast.
- **As gamma & latitude are inversely related → films therefore have low latitude**
  The narrow exposure latitude make **automatic exposure control, carefully controlled processing, and daily quality assurance checks** desirable for consistent films and to avoid repeats.
- The use of a **grid or air gap** → but the exposure and patient dose are increased.
  - × A very fine high-resolution moving grid is the preferred option.
  - × The grid moves continuously during the exposure → to blur the grid lines.
  - × Standard grid ratio for mammography is **4-5**.
  - × Grids increase glandular dose by a factor between **2-3**.
- **Compression** of the breast:
  - ***Importance:*** the main purpose of compression is to **improve image quality**
    - × Vital for immobilization as exposure times are relatively long → so, ↓ movement blurring
    - × Reduce the object-film distance → so reduce geometric blurring;
    - × Equalize tissue thickness.
    - × Compression also reduce patient dose (lower thickness allows reducing exposure).
  - **The Max. Compression** permitted to the breast is a force of **200 N** (=**20 kg force**).

IMAGE DEFINITION

Imaging microcalcifications needs high image definition

- It is necessary to use a **single coated film** to avoid parallax and crossover, together with a **single, rare earth, rear screen**.
- A **vacuum cassette** improves the film-screen contact.
- A **small focal spot** (**0.3 mm** or less) must be used.

  For magnification of suspected lesions (by factors of 1.5 or 2, using an air gap of 15-30 cm) → **0.1 mm** focal spots are used "to limit the geometric unsharpness".
- On account of the small field of view, a **10° target** can be used, or a 0° target with the tube tilted away from the chest wall.
- A **metal (not glass) tube** is often used → ↓↓ extrafocal radiation.
- The small focal spot and the inefficient production of X-rays consequent on the low kV and target atomic number → **problems of tube loading**.

Other requirements:

- **The focal film distance** is commonly **60 cm** → longer FFD would result in problems in achieving sufficiently high exposures.
- **The anode heel effect** is utilized in mammography:
  - The axial ray "produced from the center of the focal spot → more intense beam" is directed to the chest wall "the thickest part of the breast" & the anode side of the beam is not used.
  - MCQ: the axial ray is directed to the center of the x-ray field → "F"
- **A rotating anode** is essential to improve the heat rating → as the small focal spot & the long exposure time significantly increase the heat loading on the tube.
- **The optimum film density** for viewing is **1.5 – 2** assuming optimized ambient viewing conditions.

DOSE

- Breast tissue is relatively sensitive to radiation.
- The requirements of contrast & of sharpness or spatial resolution → ↑↑ patient dose.
- The beam is **tightly collimated** and the collimator is designed to protect the chest wall from irradiation, and the rest of the body is protected by absorbing the remnant radiation immediately behind the cassette.
- Ironically, while the objective of mammography is the early detection of breast tumors → **irradiation of breast tissue is itself carcinogenic**.
- The average dose to glandular tissue in the breast is **2 mGy per mammogram** → carries a risk of inducing fatal cancer of about **20 / million at age 30-50 years** and **10 / million at age 50-65 year** (see Section 6.3).
  This has implications for routine mammography of 'well women' outside recognized breast-screening programs.
- **Mammography equipment is subject to strict Quality Assurance procedures**.
  1. Tube and generator tests for the low kV and filtration.
  2. In addition, image quality and patient dose are crucial factors.
  3. Collimation and field alignment are particularly important.
  - A **mammography phantom** capable of producing an anthropomorphic image, in addition to quantifiable data (for contrast and resolution), is ideal for routine use.
  - The mean glandular dose is also measured periodically, using a special **thin-window ionization chamber** and a **standard Perspex mammographic phantom**.

Dose limits:

- The dose limit for the UK breast screening programme for a standard breast → the mean glandular dose to the breast is **2 mGy**.
- The diagnostic reference level for the breast screening programme for a 55 mm thick compressed breast → the mean glandular dose = **3.5 mGy**.

SILVER RECOVERY

- Silver is an **expensive** and **relatively scarce** material which also causes **pollution** if disposed of in the environment.
- As large amounts of silver are left behind in film processing, it is important to recover as much as possible for recycling.
- **There are a number of ways to reclaim the silver:**
  - **The electrolytic method**,
    - × 90-95% of the silver in fixer can be deposited on a rotating cathode.
    - × The fixer can be reused.
    - × To avoid sulfiding (formation of silver sulfide) the pH must be kept low.
  - **Metallic displacement with iron wool**.
    - × Silver is precipitated as sludge, and needs refining.
    - × The fixer cannot be reused.

Silver may be recovered from *scrap film* by burning or by chemical treatment.

3.11 XERORADIOGRAPHY

- Xeroradiography employs the same principle as a photocopier.
- Instead of a film and screen, the light-tight cassette contains a **rigid aluminum sheet** (A in Fig. 3.10) on which is coated a thin layer (S) of selenium.
- Before exposure to X-rays its surface is sprayed with a uniform positive charge.
- In the dark, this material is an insulator but, when exposed to X rays (or light), electrons are liberated within the material → progressively discharge the positive surface charge.
- The charge remaining at any point on the surface is related to the exposure of X-rays it has received → thus the X-ray pattern is converted into **a pattern of positive charge**.
- Figure 3.10b shows the distribution of charge left after radiographing a stepped structure

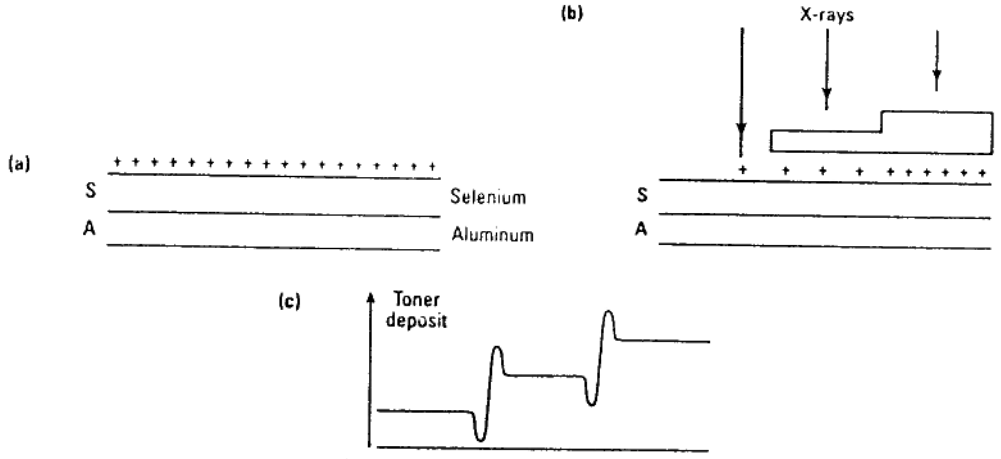


Fig. 3.10 Xeroradiography (a) Cross section through charged selenium plate, (b) Exposure to X-rays with a step-wedge, (c) Plot of density of toner deposit along a line across the plate

- Processing is rapid and 'dry'.
  - The image is developed, in the dark, in a closed development chamber by an aerosol of fine particles of **carbon** or dark blue **thermoplastic toner** material.
  - These are negatively charged and so are attracted to the remaining charge on the plate.
  - The image is then transferred to a paper sheet which is heated to bond the toner particles permanently.
- The selenium plate is reused after cleaning and recharging.
- Figure 3.10c shows the distribution of toner resulting from the exposure of Fig. 3.10b. More toner is accumulated for denser body structures, so the image produced is a **reversal of a normal X-ray film**.
- The image generally has a **very low contrast** as the density of the carbon deposit does not vary greatly over the image, However, the boundaries of structures are **well delineated** by 'edge enhancement'.
- Figure 3.10c shows that the toner piles up along one side of a boundary and is correspondingly depleted along the other side.
  - As a result,
    Structures of about 1 mm in size show a much higher contrast than larger structures.
  - For this reason xeroradiography has sometimes been used in **mammography**, in which case a tungsten anode gives better results than a molybdenum one.
    However, as it generally incurs a ***higher dose*** than with films and screens → no longer favored as an imaging technique.

FLUOROSCOPY

Fluoroscopy is a real time X-ray imaging

✓ Phosphor screen → converts pattern of X-rays into a **similar** pattern of light for real time imaging.

✓ Intensity of light is proportional to the intensity of X-rays & γ= 1.

Direct vision fluoroscopy (early days)

✓ The fluorescent material → **copper-activated zinc cadmium sulfide** → emitted light in **yellow-green spectrum**.

✓ The radiologist's eyes was protected by a sheet of lead glass.

✓ Disadvantages:

~ **High doses**.

~ **Low brightness**, *even with examination carried out in a dark room & with dark-adaptation of eyes by wearing red goggles for 20 to 30 minutes.*
So, was dependent only on the Rods "scotopic" vision & couldn't stimulate the cones "photopic" vision.

✓ The use of direct-vision fluoroscopy is now **BANNED**.

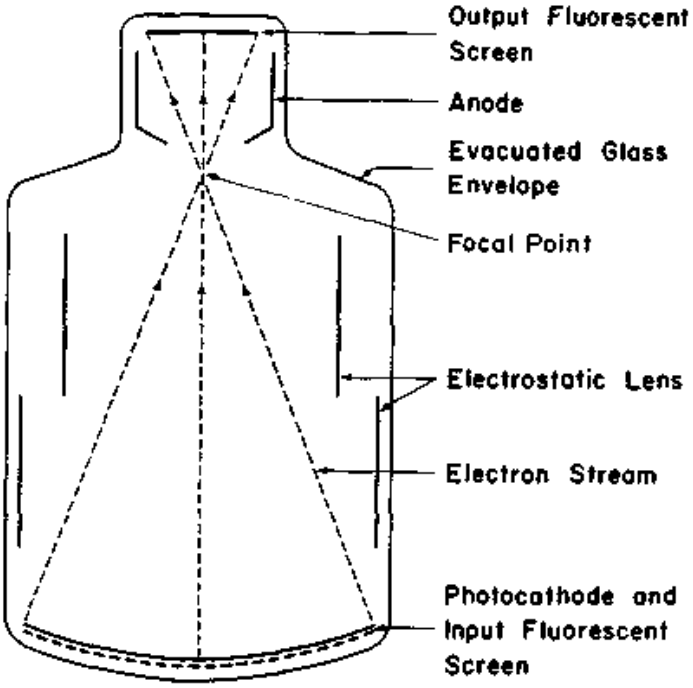
N.B. IRR99 states that **no one can do fluoroscopic examination without image intensifier or similar device**.

4.1.1 THE IMAGE INTENSIFIER:

Used to increase the brightness of the image, while maintaining its proportionality with the X-ray beam intensity

As Fig. 12-3 shows,

- The tube itself is an evacuated glass envelope, a vacuum tube, which contains four basic elements:
  1. input phosphor & photocathode
  2. electrostatic focusing lens
  3. accelerating anode
  4. output phosphor



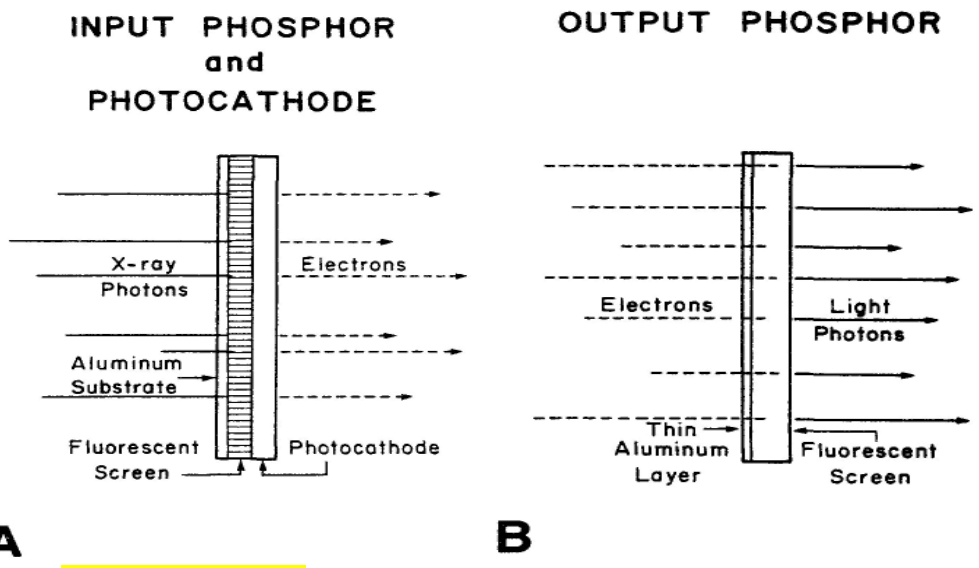
Glass Tube:

- **2 - 4 mm thick**.
- Enclosed in a lead-lined metal container → shielding.

Input Phosphor Screen:

- **230 mm in diameter**, **0.2 mm thick**.
- Coated on the inside of glass tube.
- The input fluorescent phosphor → ***Cesium Iodide (CsI)***.
  → deposited on a **thin aluminum substrate** by a process called "vapor deposition" → tiny needles perpendicular to substrate surface.

- Phosphor absorbs about **60% of the X-ray energy** → converted into light.



- Image quality is **better with CsI screens** than ZnCdS due to:

1- Vertical orientation of the crystals:

- ↓ lateral light diffusion → ↓ blurring & ↑ resolution
  → ↑ screen efficiency → ↓ patient dose.
- The resolution of a CsI image intensifier = **4 line pairs per millimeter** (3 - 5).

2- Greater packing density:

- Since cesium iodide can be vacuum-deposited "requires no inert binder" → ↑ packing density.
- **The packing density of cesium iodide is three times greater than that of zinc-cadmium sulfide** → Phosphor thicknesses have been reduced comparably from approximately **0.3 mm with ZnCd sulfide** to **0.1 mm with CsI**.

3- A more favorable effective atomic number.

- The more appropriate atomic numbers of cesium and iodine give these screens a substantial advantage over those made of zinc-cadmium sulfide.
- Ideally, for maximum photoelectric absorption, the K-absorption edge of a phosphor should be as close to the energy of the x-ray beam as possible, provided the energy of the edge does not exceed that of the beam.

× The absorption edges of **Cesium (at 36 keV)** & **Iodine (at 33 keV)** are favorably placed in relation to the effective energy of the X-ray spectrum "which typically have a **mean energy between 30-40 keV**".

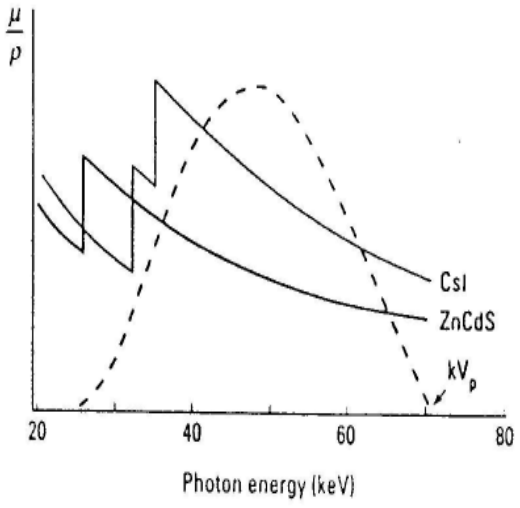


Fig. 4.2 Mass attenuation coefficient of cesium iodide (CsI) and zinc-cadmium sulfide (ZnCdS) versus photon energy with the X-ray spectrum superimposed → shows that the greater part of the spectrum of X-rays leaving the patient lies on the high absorption side of the absorption edge of cesium iodide.

Cesium iodide input screens absorb approximately **2/3 of the incident beam** as opposed to **less than 1/3** for zinc-cadmium sulfide, even though the cesium iodide screen is only one third as thick.

Photocathode

- **Photoemissive metal** "**Cesium-Antimony photoelectric screen**".
- It is coated directly over the phosphor screen → so, the light from the CsI input phosphor passes directly & strike the photocathode → emit **Photoelectrons** in numbers proportional to the brightness of the screen.
- **MCQ:** the max. fluoroscopic tube current is mainly limited by **Patient Dose**

N.B.:

Older tubes had a **thin light transparent barrier** between the input phosphor and the photocathode. Light diffusion in this barrier reduced resolution.

Electrostatic Focusing Lens

- The lens is a series of +ve cylindrical electrodes "usually plated onto the inside surface of the glass envelope".
- These electrodes focus the electron beam as it flows from the photocathode toward the output phosphor "so called **electron lens**".
- **Each point on the input phosphor is focused to a specific point on the opposite side of the output phosphor**.
- **The image on the output phosphor is:**
  1. **Inverted and reversed** due to electron focusing by **point inversion** "all electrons pass through a common focal point on their way to the output phosphor" (Fig. 12-3)
  2. **Reduced in size**, which is one of the principal reasons why it is brighter.
- For undistorted focusing, **all photoelectrons must travel the same distance** → so, **input phosphor is curved** to ensure that electrons emitted at the peripheral regions of the photocathode travel the same distance as those emitted from the central region.

Accelerating Anode

- Located in the neck of the image tube (Fig. 12-3).
- Has a **positive potential of 25 to 35 kV** relative to the photocathode
- Accelerate electrons emitted from the photocathode to a tremendous velocity toward the output screen.

Output Phosphor Screen:

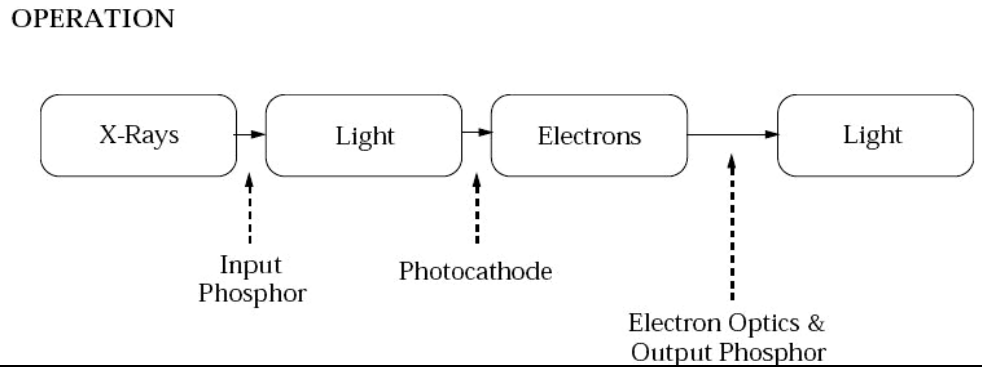
- Typically **25 mm in diameter**.
- The output fluorescent screen of image intensifiers is **silver-activated zinc-cadmium sulfide**, the same material used in first-generation input phosphors
- Output phosphor converts the electron pattern back into one of light.
- **Crystal size and layer thickness are reduced** "since it absorb electrons, not X-rays, need only be a few micrometers thick" → maintain resolution in the minified image.

- The number of light photons from output screen is increased approximately 50-fold than light produced at the input screen due greatly accelerated electrons.

- The phosphor is covered with **Thin Aluminum Film**, through which the accelerated electrons penetrate to fall on the phosphor screen.
  BUT, prevents light from the output phosphor to travel backward to the input photoelectric screen and cause further emission of electrons & ultimately of light. Otherwise, **reduce the image contrast**.
- **The metal housing** provides some shielding against external magnetic fields as well as X-ray protection (protection against X-ray that might penetrate the glass envelop into the detector tube, causing false signals).

In summary:

- A **uniform x-ray beam** passes through and attenuated by the patient → passes through the glass front of the image intensifier tube & enters the **image intensifier tube** → The **input fluorescent screen** absorbs x-ray photons → converts their energy into **light photons** in proportion to the intensity of incident x-ray beam → strike the **photocathode** → emit **photoelectrons** → immediately accelerated away from the photocathode by the high potential difference between it and **the accelerating anode** → as the electrons flow from the cathode toward the anode, they are focused by an **electrostatic lens** → guides them to the **output fluorescent screen** without distorting their geometric configuration → electrons strike the output screen → emits the **light photons** that carry the fluoroscopic image to the eye of the observer.
- In the intensifier tube, the image is carried first by x-ray photons, then by light photons, next by electrons, and finally by light photons.

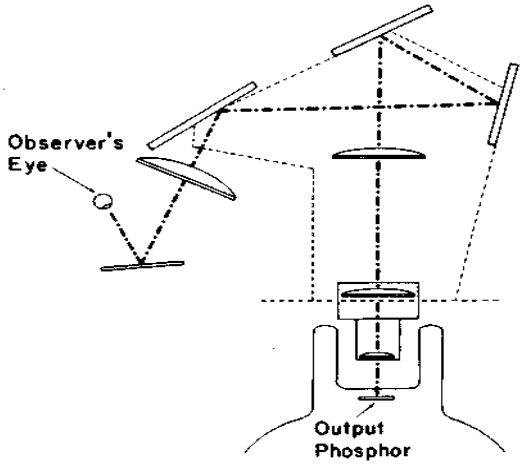


- The output phosphor image is viewed either **directly** through a series of lenses and mirrors, or **indirectly** through closed-circuit television "in modern systems".

Mirror optical system "shown in Figure 12-4"

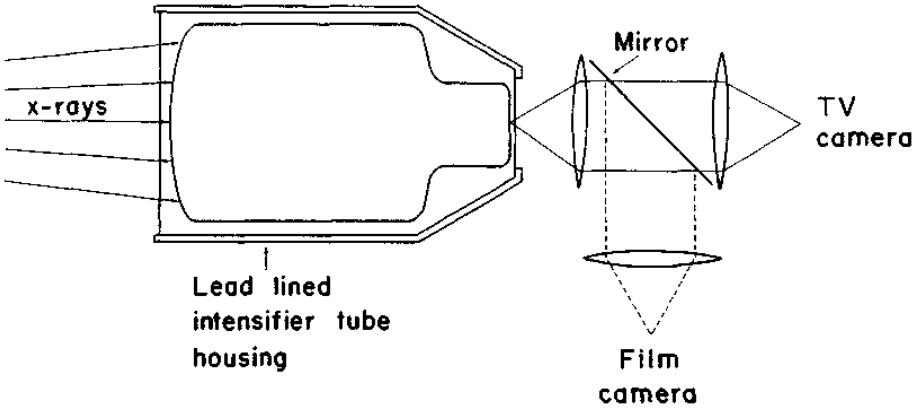
Disadv.:

- Light travels a long distance.
- Small viewing angle → difficult to palpate patient.
- One observer can view the image → a serious disadvantage in training.



RECORDING IMAGE:

- On photospot or cine film.
- From the TV camera signal "image degraded by the television chain" or by directly exposing the film to the output phosphor "better".
- Beam Splitter allows continuous TV viewing while exposing the film → by splitting the light from the **II** output into two paths at the time of film exposure using a 45° semitransparent "partially silvered" mirror positioned in the light beam:
  - 90% of light is reflected to the film camera.
  - 10% pass through the mirror to TV camera "still produce a satisfactory TV image since the exposure level has been increased "
- the image may be coupled to the TV camera by a **fiberoptic bundle**.



***Gain*:**

- The image is intensified, minified & inverted by the electron lens.
- For each X-ray photon absorbed by the input phosphor → about 400 light photons are emitted → producing 400 photoelectrons → which cause the output phosphor to emit nearly 400000 light photons.

- Intensification can be measured in two ways:

Brightness gain	***Conversion factor***
Equals the ratio **brightness of the output phosphor** **brightness of the input phosphor** Also called ***intensification factor***.	is a ratio of the luminance of the output phosphor to the input exposure rate Equals the ratio **brightness of the output phosphor (candela/m2)** **dose rate in air on the input surface of the intensifier (µGy/s)**
not directly measurable	Measured with a photometer and a dosemeter employing a flat circular ionization chamber, respectively
The overall brightness gain is typically 5000-10000	Typical figures are in the range 15-25, but it decreases with age and use.

- The brightness gain of an image intensifier comes from two completely unrelated sources, called **"minification gain"** and **"flux gain"**.

Minification Gain

- Produced by a **reduction in image size**.
- The quantity of the gain depends on the relative areas of the input and output screens.

$$\text{Minification gain} = \left(\frac{d_1}{d_0}\right)^2$$

where d_I is the diameter of input screen, and d_0 is the diameter of output screen

Minification gain increase overall gain by about 100 times

- With a 1-in. output screen, the minification gain is simply the square of the diameter of the input screen; that is, a 9-in. intensifier has a gain of 81.
- The brightness gain from minification **does not improve the statistical quality of the fluoroscopic image** as the same number of light photons make up the image regardless of the size of the output screen.
- Theoretically, brightness can be increased indefinitely by minification, but also the picture becomes **more grainy** → due to magnification of the fluoroscopic crystals in the output screen.

Flux Gain

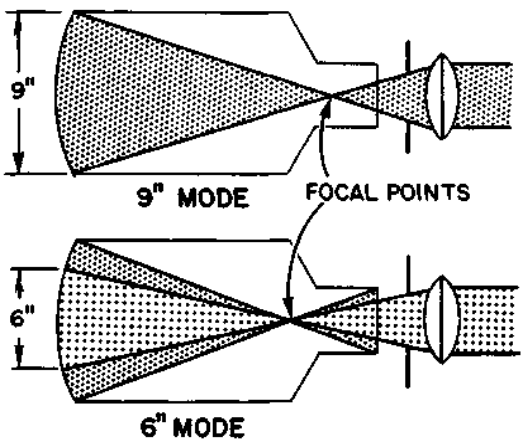
- It is the increase in the number of light photons **due to acceleration of electrons**.
- It increases the brightness by a factor of **approximately 50-100**.
- For each **light photon** from the input screen, as ejecting **one electron** from the photocathode. The electron is accelerated to the opposite end of the tube, gaining enough energy to produce **50 light photon**s at the output screen.

The total brightness gain of an image intensifier is the product of the minification and flux gains:

Brightness gain = minification gain X flux gain

Dual- And Triple-field Intensifiers (Zooming)

- **Image quality increase** as **the size of the input field is decreased**.
- Dual-field or triple-field image intensifiers can be operated in several modes, including a **4.5-in., a 6-in., or 9-in. mode** "or even larger image intensifiers (12- to 16-in.)" → resolve the conflicts between image size and quality
  - **The 9-in. mode** is used when it is necessary to view **large anatomic areas**.
  - When size is unimportant, **the 4.5- or 6-in. mode** is used "better image quality".
- Field size is changed by applying a simple electronic principle: **the higher the voltage on the electrostatic focusing lens, the more the electron beam is focused**; *In figure 12-7*
  - **In the 9-in. mode,** the electrostatic focusing voltage is decreased → the electrons crossover point move close to the output phosphor → smaller final image.
  - **In the 6-in. mode,** the electrostatic focusing voltage is increased → the electrons focus farther away from the output phosphor →



diverge to form larger image on the output phosphor than in the 9-in. mode.
The central part of the input image (6-in in diameter) then fills the whole of the output phosphor.

- **Effect of Zooming (adv. & Disadv.)**
  - **Magnifies** the image.
  - **Improves the sharpness** "resolution"
  - But, makes the image **less bright** "less minification gain" → **exposure factors are automatically increased** to compensate for the decreased brightness → **increases the patient's skin dose** (↑ scatter).

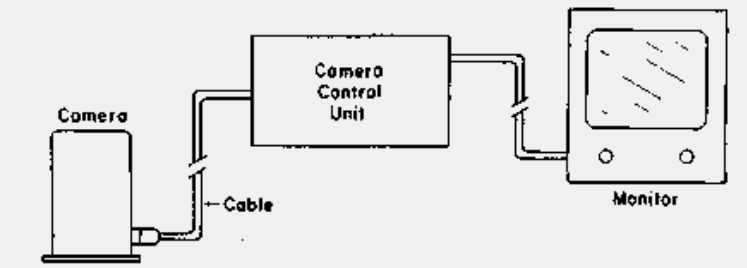
    BUT the X-ray beam is **automatically recollimated** → ↓↓ volume of irradiated tissue → **↓↓ scatter & improve contrast**

Viewing and Recording the Fluoroscopic Image

- The development of the image intensifier allowed displaying the fluoroscopic image on television.
  - **Its small output phosphor simplifies optical coupling,**
  - **Its bright image produces a strong video signal.**

CLOSED-CIRCUIT TELEVISION

- Components of a TV system are a ***camera***, ***camera control unit***, and ***monitor***.

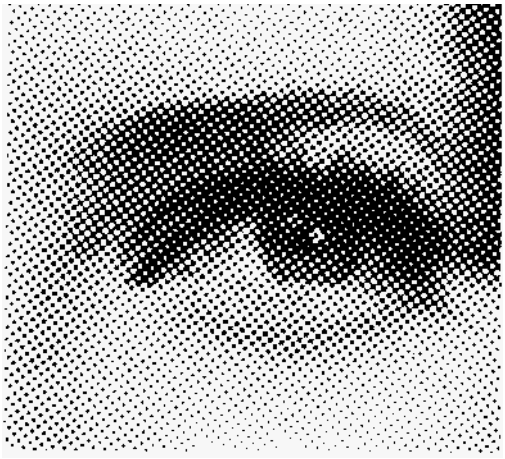


- Fluoroscopic television systems are always **closed-circuit systems**; "i.e. *the video signal is transmitted from one component to the next through cables* rather than through the air, as in broadcast television".
- A **lens system or a fiberoptic system** conveys the fluoroscopic image from **the output phosphor of II** to the video camera → image is converted into a series of electrical pulses called **the video signal** → transmitted through a cable to the camera control unit → amplified → forwarded through another cable to the television monitor → converts the video signal back into the original image for direct viewing.

Nature of the video picture

The television image is made up of a mosaic of hundreds of thousands of tiny dots of different brightness → each contributing a minute bit to the total picture.

- The individual dots are clearly visible at close range & with magnification.
- The lines are close together in a small picture tube and spread apart in a large tube, but in both

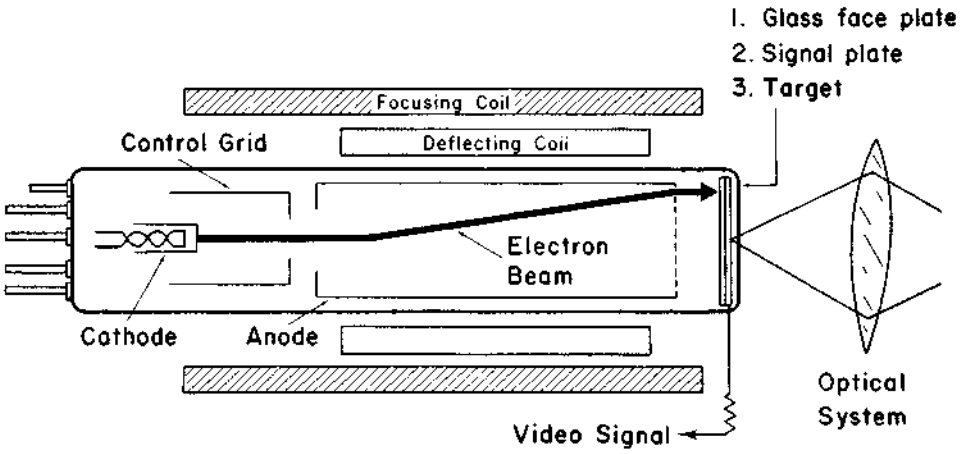


the total number is the same.

- The dots are arranged in a specific pattern along horizontal lines, called **horizontal scan lines.**
- The number of lines varies from one television system to another but, in the United States, most fluoroscopy and all commercial television systems use **525 scan lines**. The UK TV systems uses **625 scan lines**

Television Camera

- **The vidicon camera** is the one usually employed for fluoroscopy "relatively inexpensive, compact unit"
- There are several types of vidicons; one is **the plumbicon**.
- The essential parts of a vidicon camera are shown in Figure 13-3.



- The most important part is the vidicon tube, a small electronic vacuum tube that measures only **1 in. (25 mm) in diameter** and **6 in. in length**.
- The tube is surrounded by **coils**:
  An electromagnetic focusing coil and **2 pairs of electrostatic deflecting coils**
- **The fluoroscopic image from the image intensifier is focused onto the target assembly, which consists of three layers:**
  (1) Glass face plate; (2) Signal plate; (3) Target.

The glass face plate:

- Its only function is to maintain the vacuum in the tube.
- Light merely passes through the face plate on its way to the target.

The signal plate:

- A thin transparent film of **graphite** located on the inner surface of glass face plate.
- It is an electrical conductor with a positive potential of **approximately 25 V**.

The vidicon target:

- **It is functionally the most important element in the tube.**
- It is a thin film of **photoconductive material**, usually **antimony sulfide (Sb_2S_3)** suspended as **globules in a mica matrix**.
  In a plumbicon the photoconductive material is **lead monoxide (PbO)**.
- Each globule is about **0.001 in. in diameter** and is insulated from its neighbors and from the signal plate by the mica matrix.
- The globules behave like tiny **capacitors**, **which converts the light**

pattern focused on it into pattern of electrical resistance (*see later*).

The cathode

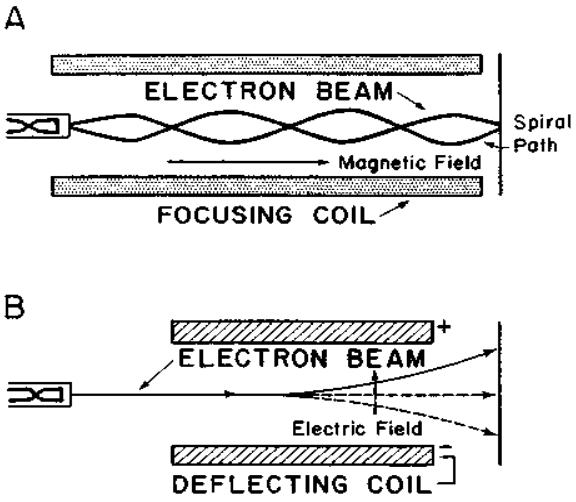
- Located at the opposite end of the vidicon tube from the target.
- Heated indirectly by an **internal electric coil**.
  - The heating coil boils electrons from the cathode (thermionic emission), creating an electron cloud.
  - These electrons are immediately formed into a beam by **The Control Grid**, which also initiates their acceleration toward the target.
- **The cathode-heating coil assembly** with **the control grid** are called "electron gun" because it shoots electrons out of the end of the control grid.

The anode

- The electron beam progresses down the tube → moves beyond the influence of the control grid into the electrostatic field of the anode.
- The anode has a positive potential of **approximately 250 V** relative to the cathode.
  - The anode extends across the target end of the tube as **a fine wire mesh**.
  - The wire mesh and signal plate form a **uniform decelerating field** adjacent to the target.

    The signal plate (+ 25 V) has a potential of 225 V less than that of the wire mesh (+ 250 V), so electrons should flow from the signal plate to the wire mesh.
- The electrons from the cathode are accelerated to **high velocity**, but they are still **low energy electrons** (about 250 eV).
  - Then they coast through the decelerating field → by the time they reach the target, they have been slowed to **near standstill** (**they are now 25-eV electrons**).
  - The decelerating field also performs a second function**: it straightens the final path of the electron beam** → so it strikes the target perpendicularly.

Electromagnetic Focusing Coil



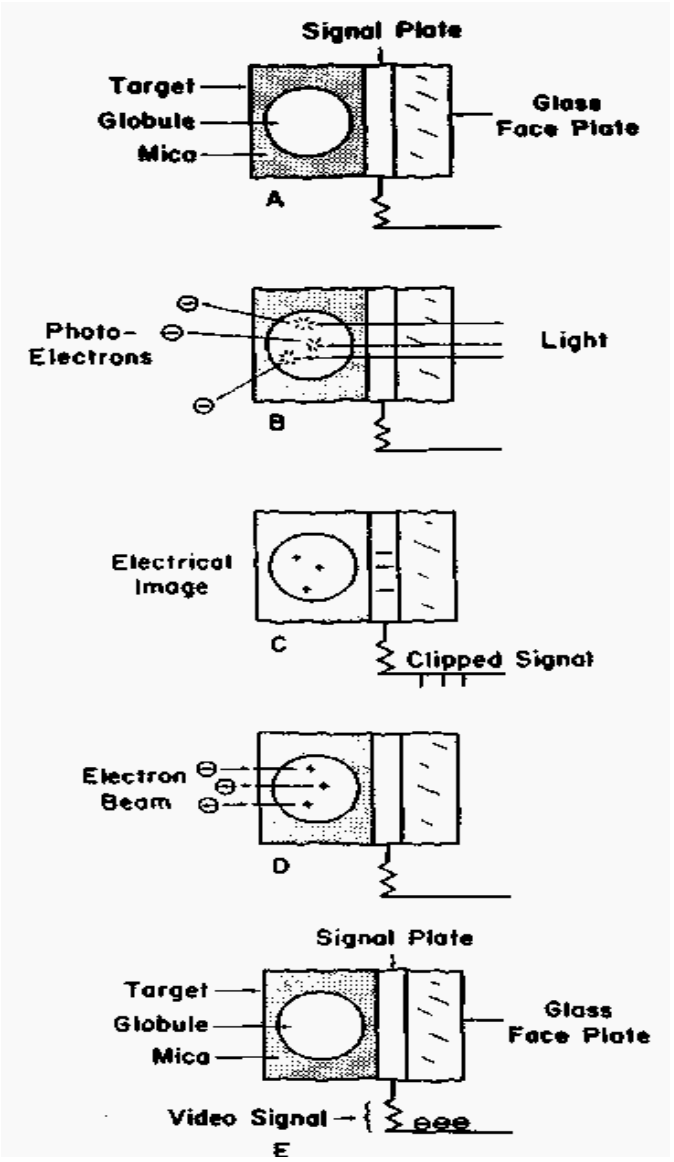
- Wraps around almost the entire length of the vidicon tube → creates a constant magnetic field parallel to the long axis of the tube → keeps electron beam in a narrow bundle essential to scans the fine mosaic of photoconductive globules.
- The electrons progress down the tube in a series of oscillating spirals.

Electrostatic deflecting coils

- The electron beam is steered by variable electrostatic fields produced by two pairs of deflecting coils that wrap around the vidicon tube. "*Time-varying voltages* from a **'sweep generator'**"
- **Vertical deflecting coils** are shown in Figure 13-4B**.**

- By alternating the voltage on the coils, the focused electron beam is moved up and down to scan the target.
- The other pair of coils moves the beam from side to side along a **horizontal** line.
- All four coils, working together, move the electron beam over the target in a repetitive scanning motion.

Video Signal



- When a globule absorbs light, photoelectrons are emitted (Fig. 13-5B).
- The electrons are immediately attracted to the anode and removed from the tube.
- The globule, having lost electrons, becomes positively charged.
- Since the globule is insulated from its surroundings it behaves like ***half of a tiny capacitor***, and draws a current onto the conductive signal plate → this current that flows onto the signal plate is ignored, or clipped, and is not recorded (Fig. 13-5C).
- Similar events occur over the entire surface of the target.
- A brighter area in the light image emits more photoelectrons than a dim area, and produces a stronger charge on the tiny capacitors.
- The result is **a mosaic of charged globules** that store an electrical image that is an exact replica of the light image focused onto the target.
- The electron beam scans the electrical image stored on the target and fills in the holes left by the emitted photoelectrons (i.e. discharging the tiny globule capacitors).
- After the capacitors are fully discharged (no more positive charges are left), no additional electrons can be deposited in the globules.
- *Excess electrons* from the scanning beam drift back to the anode and are removed from the tube.
- When the electrons in the scan beam neutralize the positive charge in the globules, the electrons on the signal plate (Fig. 13-5D) no longer have an electrostatic force to hold them on the plate. They will leave the plate via the resistor.
  - These moving electrons form a current flowing through a resistor → a voltage appears across the resistor which constitutes the video signal (Fig. 13-5E).

It was indicated earlier that the electrons in the electron beam were reduced to low energy electrons before they entered the target. There are two reasons for this.

- The first Reason is that we want no electrons to enter the target after the positive

charge has been neutralized.
  - The second reason is that the electrons should not have sufficient energy to produce *secondary electrons* when they do enter the globules. "high energy secondary electrons would be able to neutralize the positive charge in other globules and degrade the image".

- The globules are not all discharged at the same time.
  - Only a small cluster, a dot, is discharged each instant in time. Then the electron beam moves on to the next dot in an orderly sequence, discharging all the globules on the target.
  - The result is a series of video pulses, all originating from the same signal plate but separated in time.
  - Each pulse corresponds to an exact location on the target.
  - Reassembling these pulses back into a visible image is done by **the camera control unit** and **the television monitor**.

Television Monitor

- The last link in the television chain is the monitor.
  It contains ***the picture tube*** and ***the controls for regulating brightness and contrast***.

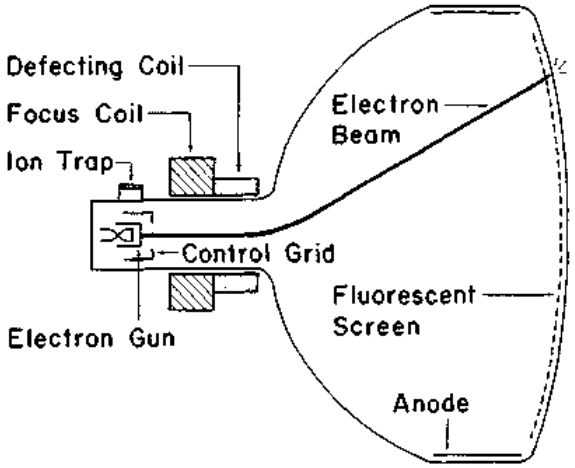


Figure 13-6 Television monitor

- A picture tube is similar to a vidicon camera tube (Fig. 13-6).
  - Both are vacuum tubes and both contain an electron gun, control grid, anode, focusing coil, and deflecting coils.
  - A picture tube, however, is much larger.
- This evacuated glass envelope contains:
  - at the narrow end, ***an electron gun (c)***, which projects a pencil of electrons, shown as a dashed line in the figure,
  - ***A phosphor screen (e)*** coated on the inside of the wide end of the envelope, where the pencil produces a small dot of light.
- The focusing and deflecting coils are wrapped around the neck of the tube, and they control the electron beam in exact synchrony with the camera tube.
- The brightness of the individual dots in the picture is regulated by the control grid → modulate the brightness of spot of light on the monitor screen.
  - The control grid receives the video signal from the camera control unit, and uses

this signal to regulate the number of electrons in the electron beam.
  - To produce a bright area in the television picture, the grid allows a large number of electrons to reach the fluorescent screen. To produce a dark area, the grid cuts off the electron flow almost completely.
- The anode is plated onto the inside surface of the picture tube near the fluorescent screen. It carries a much higher positive potential (10,000 V) than the anode of the camera tube (250 V), so it accelerates the electron beam to a much higher velocity.
- The electrons strike the fluorescent screen at the flared end of the tube, which makes the screen emit a large number of light photons. The generation of light photons over the entire surface of the tube is the visible television image.
- Many secondary electrons are set free by the impact of the electron beam with the screen, and they are attracted to the anode and conducted out of the picture tube.

TELEVISION SCANNING

- The television image is stored as an electrical image on the target of the vidicon tube, and it is scanned along 525 lines by a narrow electron beam **30 times per second**.
- Each scan of the entire target is called a **"frame"**.
- The electron beam scans the target in much *the same manner that we read a page in a book*, only it does not have to turn pages. Instead, as the beam reads, it also erases. As the electron beam discharges the globule capacitors, it erases their image.
- As soon as a line is read and erased, it is ready to record a new image, and it begins immediately.
- Because the electron beam scans the target 30 times each second → our eyes perceive a continuous motion as in a cine film.
- But, the eye can detect individual flashes of light, or flicker, up to **50 pulses per second**. A television monitor only displays 30 frames per second, so an electronic trick, called **interlaced horizontal scanning,** is employed to avoid flicker.
  - Instead of scanning all 525 lines consequently, only the even-numbered lines are scanned in the first half of the frame, and only the odd-numbered lines are scanned during the second half (Fig. 13-7).
  - Each pass of the electron beam over the video target is called **a field**, and consists of $262^{1}/_{2}$ lines.

    ∴ Although only 30 frames are displayed each second, they are displayed in 60 flashes of light (fields), and flicker disappears.

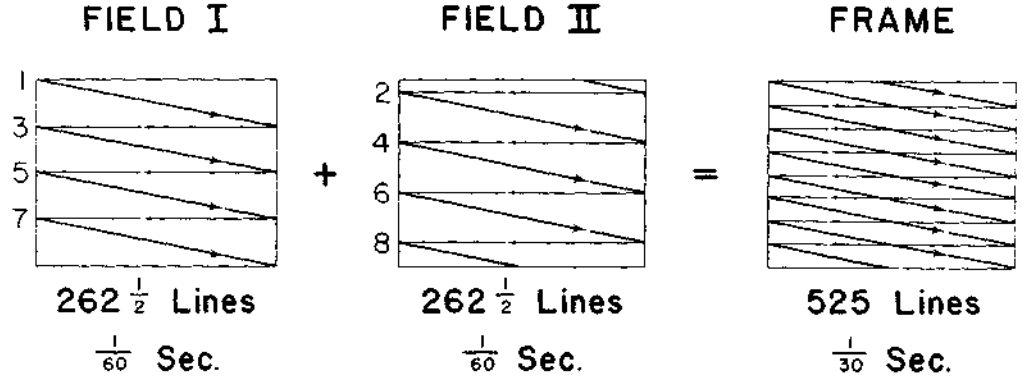


Figure 13-7 Interlaced horizontal scanning

Synchronization

- It is necessary to synchronize the video signal between the camera and monitor to keep them in phase with each other.
- The camera control unit adds synchronization pulses to the video signal at the end of each scan line & scan field **"horizontal and vertical synchronization pulses"**.
- They are generated during the retrace time of the electron beam, while no video signal is being transmitted.
  - First, the picture screen is blackened by a **blanking pulse**, and the synchronization signal is added to the blanking pulse.
  - If the synchronization pulses were added to the video signal while the screen was white → white streaks of noise.

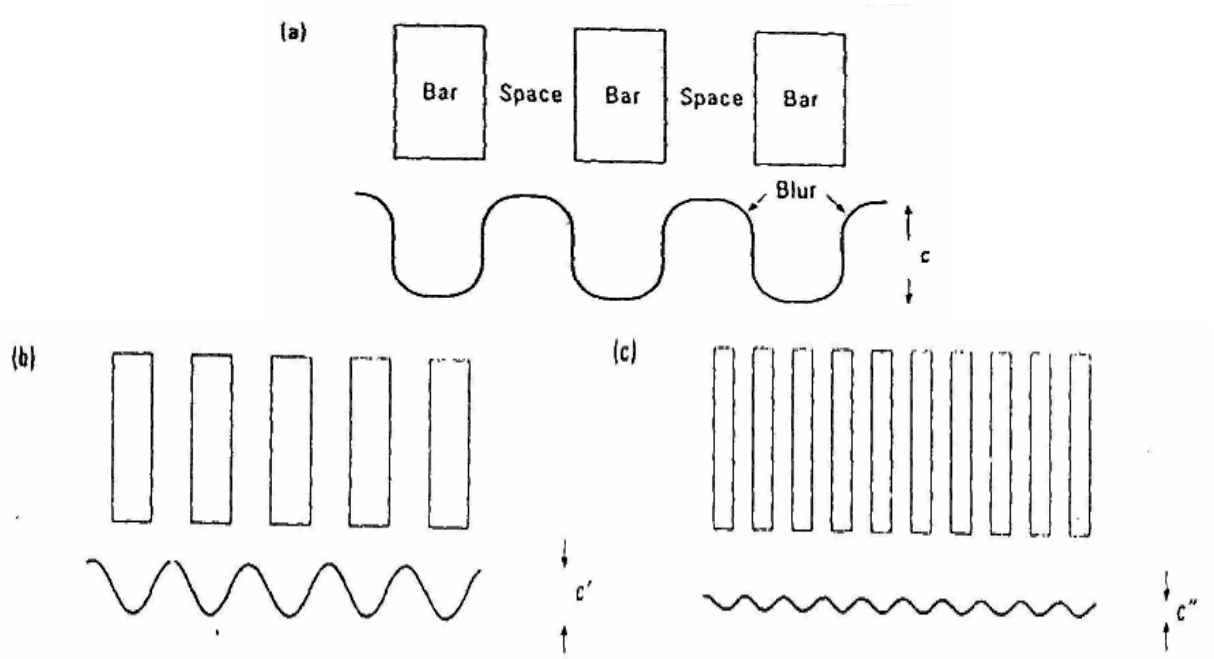
TELEVISION IMAGE QUALITY

I- RESOLUTION

- ***Spatial resolution*** is the ability to detect a single small structure against its background or to distinguish two separate structures close together.
- It is tested by imaging a ***bar 'test tool'*** or ***'resolution grid'*** (Fig. 4.5a).
  - The bars are strips of lead affixed to a Perspex plate.
  - The bars are equally spaced & each space = the width of a bar.
  - A bar and a space together make up a line pair.
  - ***The spatial frequency*** = the number of such ***line pairs per millimeter (lp\mm)***.
- Figure 4.5a also plots the ***brightness of the screen image*** (or the video signal) along a scan line.
  - The higher the spatial frequency → ↑ blurring & ↓ contrast.

  ∴ if the blurring is too large or the bars too narrow and too close together → the blur of the edges of each bar merges with that of the adjacent one → the gap between them cannot be distinguished.
- The effect of blurring is to worsen resolution

  So, the smaller the blurring → the better the resolution.



- The spatial resolution of the system is defined as *the spatial frequency of the finest pattern that can still be resolved*.

Video Signal Frequency (Bandpass)

- **Bandpass "bandwidth"**, is ***the frequency range that the electronic components of the video system must be designed to transmit without distortion***.
- The frequency of the video signal fluctuate from moment to moment, depending on the nature of the television image *"that's why we need to set range for frequencies"*

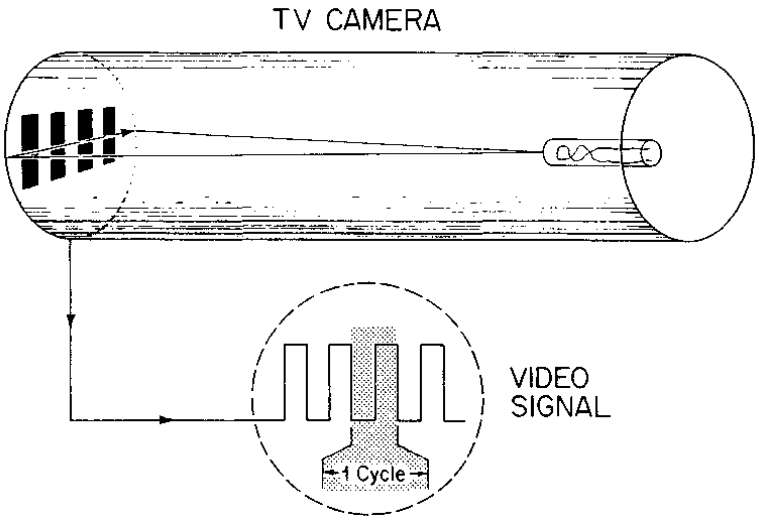


Figure 13-9 The video signal from one scan line of a line pair phantom

- Figure 13-9 shows one scan line of an image containing 4 line pairs (4 lp) → So, video signal for this scan line consists of 4 cycles.
- We can calculate **the frequency** *"number of cycles per second"* of the video signal generated by the four-line-pair image **by multiplying the number of cycles per scan line (four in this case)** by **the number of scan lines per frame** by **the number of frames per second**:

$$\frac{\text{cycles}}{\text{scan line}} \times \frac{\text{scan lines}}{\text{Frame}} \times \frac{\text{frames}}{\text{seconds}} = \text{cycles/sec}$$

$$4 \times 525 \times 30 = 63{,}000$$

- When the number of line pairs in the image changes, the frequency of the video signal also changes.

Resolution of the TV system

The TV system degrades the resolution further due to:

- Mosaic structure of the TV camera image plate.
- The two aspects of the way in which the image is scanned:

1- Line structure

2- Bandwidth

VERTICAL RESOLUTION (depending on the line structure)

- VERTICAL RESOLUTION is determined by the number of vertical scan lines (525 in our illustration) → the test pattern positioned with **the bars horizontal**.
- For a 525-vertical-line system, the maximum line-pair structure that can be resolved on the TV monitor is $262\,^1/_2$ line pairs per TV monitor image.
- *Factors affecting vertical resolution:*
  1. The smaller fields, in magnification mode → ↑↑ resolution.
  2. ↑ monitor size with fixed number of horizontal scan line → ↓ resolution
     ∴ 525-line system displayed on a 6-in. monitor has better resolution than a 13- or 19-in. monitor. So, **the image on a small TV screen will look better than that on a large screen**.
  3. ↑ Scan lines → ↑ vertical resolution.

HORIZONTAL RESOLUTION (depending on the bandpass)

- HORIZONTAL RESOLUTION depends on the bandwidth of the TV monitor electronics → to test it; the test pattern is turned with **the bars vertical**.
- For a 525-line system, lowest and highest frequency signals will be as follows:

$$\frac{\text{cycles}}{\text{scan line}} \times \frac{\text{scan lines}}{\text{frame}} \times \frac{\text{frames}}{\text{second}} = \text{cycles/sec}$$

Minimum:

$$1 \times 525 \times 30 = 15{,}750$$

Maximum:

$$262\tfrac{1}{2} \times 525 \times 30 = 4{,}130{,}000$$

∴ The frequency of the video signal will fluctuate between a minimum of 15,750 Hz and a maximum of 4,130,000 Hz (*i.e. bandpass = 4.1 MHz*).

- **Actually, a somewhat higher bandpass is required, because** about 10% of the scan time is lost in *retracing from one line to another*.
  - This additional 10% increases the required bandpass to approximately 4.5 MHz for a 525-line system.
  - At this bandpass, vertical and horizontal resolutions are equal.

Remember,

✓ **Vertical resolution depends on the number of vertical lines** (such as 525), **whereas horizontal resolution is determined by the bandpass.**

- Most **X-ray TV systems** have a bandpass of 5 MHz with a 525-line system. *Interlacing* is not entirely satisfactory; resolution may be impaired if tissues move between the two halves of a 1/25 s frame.
- **A high-resolution image intensifier (II) TV system** employs 1250 lines, non-interlaced ('progressive') scan, can resolve 2 lp\mm, but requires a bandwidth of at least 25 MHz.
- **Digital photospot imaging** produces high resolution with the normal bandwidth.
- In film-screen radiography, the film can resolve 100 lp\mm whereas a slow ('detail') intensifying screen can only resolve 10 lp\mm, and a fast screen 5 lp\mm.

Resolution of different imaging modalities:	
1. Radiographic film ALONE	100 lp/mm. *(but needs very high dose)*
2. Film-screen with Slow screens	10 lp/mm.
3. Film-screen with Fast screens	5 lp/mm
4. Image intensifier	4-5 lp/mm
5. TV system	1 lp/mm
6. *High resolution non interlaced TV system* (II-TV system)	2 lp/mm
7. Photo spot cut film 100mm	4-5 lp/mm
8. Photo spot cut film 35mm	2 lp/mm
9. CT	1 lp/mm
10. Gamma camera	1-2 lp/cm Very poor resolution!!!
11. Mammography	10-20 lp/mm (or 5-20)

-

- We assumed that a 525-line TV system actually uses all 525 lines to form an image → absolute maximum resolution (*but, we never attain maximum values*).
- In fact, significantly fewer than 525 lines are available for image formation → some lines are lost to prevent the retrace and blanking signals from showing on the TV screen.
- Resolution of **370 lines (185 line pairs)** is typical in a 525-line system.
  N.B. 200 line pairs are typical in the UK 625-lines TV system
- The overall resolution of the imaging system depends on the size of the input image.

↑↑ size of II input image → ↓↓ resolution.

Table 13-1 Resolution of a TV Imaging System for Various-Sized Image Intensifiers

SIZE OF IMAGE INTENSIFIER		*TELEVISION RESOLUTION (lp/mm)*
in.	mm	
4.5	114	1.6
6	152	1.2
9	229	0.8

'Based on a 525-line TV system with a total resolution of 185 lp.

- Even though a resolution of 1.6 lp/mm is a considerable improvement, it falls far short of displaying the entire resolution of cesium iodide image intensifiers.
  → The only way that this resolution can be adequately displayed is with **a film system** such as a 35 mm cine, or spot film cameras.

Resolution of the image intensifier

- The image intensifier itself has a spatial resolution of about 4-5 lp/mm (or better in the magnification mode).
- ***It is principally affected by***
  - *The blurring caused by light spread in the input phosphor*.
  - Less significantly in the much thinner output phosphor.
- Due to defects in the electron lens, the periphery of the image has
  - Worse resolution than the center.
  - Greater magnification → ***'pincushion' distortion***.
- The resolution is always stated in relation to the size of the X-ray image on the face of the intensifier.
- Resolution with 100 mm cut film is nearly as good as that of intensifier itself. but, resolution on 35 mm film is only about half that of intensifier.

CONTRAST

CONTRAST OF IMAGE INTENSIFIER

- Tested using a lead disc ($^1/_4$-in. thickness & its diameter = 10% of the input screen)
- The disc is placed over the center of the input screen → exposed to radiation → brightness is measured at the output phosphor.
- Contrast is ***the brightness ratio of the periphery to the brightness in the center of the output screen*** "representing area under lead disc".

Contrast ratios range from 20:1 to 30:1

- **Two factors tend to diminish contrast in image intensifiers.**

  1- The input screen does not absorb all the photons in the x-ray beam.
  - × Some transmitted through the intensifier tube & few absorbed by output screen.
  - × These transmitted photons contribute to ***the illumination*** of the output phosphor but ***not to image formation*** → produce a background of fog "↓↓ image contrast".

  2- Retrograde light flow from the output screen.
  - × Not all retrograde light photons blocked by the thin layer of aluminum → some penetrate through it → pass back to activate the photocathode to emits photoelectrons
  - × These electrons produce "fog" → ↓↓ image contrast.
- Contrast tends to deteriorate as an image intensifier ages.

Veiling glare

- It is due to scattering of light in the **output window** of the image intensifier, and to a lesser extent in the **TV camera tube** → ↓ contrast of the image.
- It is worse with the ***larger sizes*** of intensifier.

CONTRAST OF TV CAMERA & MONITOR

- Both the camera and monitor affect the contrast of a television image.
  - A vidicon camera → ↓↓ contrast by a factor of approximately 0.8.
    A plumbicon camera → does not cause any decrease in image contrast.

    A Vidicon camera has **γ** = 0.8 while a Plumbicon tube has **γ** = 1.0.
    Remember: ↑ γ → ↑ contrast
  - The monitor enhances contrast by a factor of 2.
- The net result is a definite improvement in contrast > the image intensifier alone.
- Furthermore, both brightness & contrast levels can be regulated with the monitor → the optimum combination can be selected to best show a point of interest.

Dynamic range (latitude) of the television monitor

This is the ratio

$$\frac{\textbf{\textit{maximum acceptable brightness of the TV monitor screen}}}{\textbf{\textit{smallest detectable brightness above black}}}$$

Typically = 1000:1, which is usually expressed as 30 dB, *as explained in Section 7.16.*

The choice of kV and the TV contrast are made so that the range of tissues being imaged fall within the dynamic range.

LAG

Lag of image intensifiers:

- = **persistence of luminescence after x-ray stimulation has been terminated**.
- With old image tubes → lag times were 30 to 40 ms.
  With CsI tubes → lag times are about 1 ms.

Lag of TV camera & monitor:

- An undesirable property of most vidicon tubes is **lag or stickiness**.
  - Lag becomes apparent when the camera is moved rapidly during fluoroscopy (i.e., the image blurs).
  - Lag occurs because it takes a certain amount of time for the image to build up and decay on the vidicon target.
- Plumbicon tubes demonstrate significantly less lag than vidicon tubes.
- The lag of a vidicon is usually not a problem with *routine fluoroscopy*, but may become a problem in *cardiovascular fluoroscopy*.
- In one respect a certain amount of lag is actually advantageous.
  It averages out the statistical fluctuations that occur with low-dose fluoroscopy → minimizes quantum mottle.
  The image generated by a plumbicon tube will show more quantum mottle than a standard vidicon image الحلو ما يكملش.

AUTOMATIC BRIGHTNESS CONTROL

- Problem: ↑↑ X-ray intensity when moving from a high-attenuation to a low-attenuation area "e.g. from the abdomen to the chest" → sudden increase of brightness → the image becomes **chalky**, and all detail is lost.
- Solution: A 'feedback' system to control the brightness of the TV monitor automatically → used in cineradiography & also in fluoroscopy.
- The brightness of the image is monitored either by:
  (a) Measuring the (average) video signal or
  (b) By a sensor 'watching' the brightness of the output phosphor.
  Then sending orders back to the X-ray tube & generator to modulate exposure factors ***(feedback system)***

There are three ways to change the radiation input to the II input phosphor:

1. kVp variability 2. mA variability 3. pulse width variability

kVp Variability

- kVp will vary while mA stays constant.
- *Advantages:*
  - Fast response times.
  - Satisfactory images over a wide dynamic range.

mA Variability

- The best general purpose automatic brightness control system.
- Varies the mA as needed with a convenient kVp control → offers the operator to control of kVp.
- *Advantages:* relatively simple and inexpensive method.
- *Disadvantages:*

- **Slow** response time "changes in mA require change the temperature of the x-ray tube filament".
- The dynamic range of this control is less than the kVp-variable units → operator must choose appropriate kVp.

Combined Control

A number of systems vary both kVp and mA to control brightness → wide dynamic range.

Pulse Width Variability

- *Advantage:* very fast response times - very broad dynamic range - allows the operator to choose the mA and kVp levels best suited for the examination.
- The length of each exposure is controlled with a grid-controlled x-ray tube or a constant potential generator with secondary switching.

AUTOMATIC GAIN CONTROL

- It is a simple and inexpensive way to control image brightness.
- It ***varies the brightness of the TV system by 1) varying the sensitivity of the TV cameras or 2) varying the gain of the TV amplification system***.
- ***Disadvantages***
  - ***It does not change the x-ray dose rate to the patient*** → unnecessary patient exposure.
  - ***Not improve quantum mottle*** and will increase electronic noise.

Noise

- Quantum mottle is noticeable in fluoroscopy > radiography.
- **Noise is due to** the statistical fluctuations in the number of X-ray photons absorbed in the input phosphor → similar fluctuations in the brightness of the image, the density recorded on a spot film and the video signal voltage from the camera tube.
- Noise reduces the perceptibility of a structure having **low contrast**.

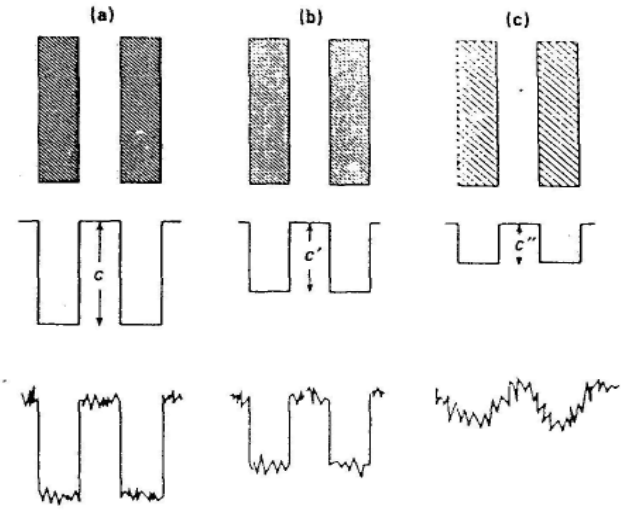
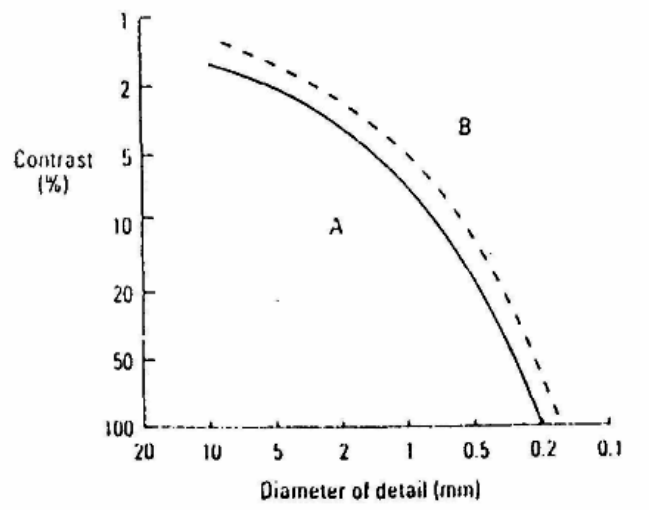


Fig. 4.6 Resolution tests grids (a), (b) and (c) having different inherent contrasts and the corresponding plots of video signal or image brightness along a scan line, showing the effect of noise on perceptibility.

- Figure 4.6 depicts part of each of three resolution grids having (a) high, (b) medium, and (c) low contrast, made perhaps with strips of *lead, aluminum, and Perspex*, respectively.
- The bars can easily be resolved in Fig. 4.6a. They can still be resolved in Fig. 4.6b, *but they would not be if the noise were greater*. In Fig. 4.6c the contrast is

completely obscured & the bars can't be distinguished from spaces between them.

- **Thus the structures cannot be distinguished, if :**
  - The noise is too great.
  - The contrast difference is too small.
  - The structures are too small, or too close together.
- With a typical average dose rate in air of 1-2 μGy s^{-1} on the surface of the image intensifier, during the 1/6 s time constant (lag) of a Vidicon camera tube, an average of 3000 X-ray photons might be absorbed in each square millimeter of the input phosphor.
  - As a result, when trying to see a structure 1 mm^2 in size, the noise is $\sqrt{3000}$, which is 2% of the signal.
  - ***The signal-to-noise ratio (SNR)*** is 50:1.
- For a structure to be detectable, the contrast must be at least 2-5 times the noise relative to signal.
  So, a structure 1 mm in size will be seen against its background provided its contrast is at least 5%.
- The image of a small structure is produced by the absorption of relatively few photons and is noisy, and to see it requires a high contrast.
  Either a high dose rate is used to increase the SNR, or the inherent contrast of the object has to be increased, e.g. by changing the kV or using a contrast medium.



- Fig. 4.7, the solid curve plots on a logarithmic scale the min. contrast needed to see structures of different diameters.
  - Obtained using a special test object (e.g. **Leeds TO 10**) with II.
  - Details having a size and contrast falling in region A can be resolved; those falling in region B cannot.
  - The dashed line shows the improvement in perceptibility produced by ↑ dose rate & ↓ noise.

To summarize:
❝ the contrast resolution (= smallest detectable contrast) improves with larger details;
❝ the spatial resolution improves with higher contrast;
❝ ↑↑ the dose rate → ↓↓ noise & improves the inherent detectability of all structures.

- This relationship (or 'trade-off') between spatial resolution, contrast and noise or dose applies to all forms of imaging (digital, CT, gamma, etc.).
  In film-screen radiography, noise is too small to affect the details.
- The lag in a Vidicon camera tube ***smooths out*** the statistical fluctuations and ***reduces*** noise or mottle.
  A Plumbicon tube shows less lag and less movement blurring but ***more*** noise.
- The noise is worse in the areas of the image where the ***brightness is low***.
  - Improved by ↑ the tube current & X-ray intensity → so, the quality of the image

is ***dose limited or photon limited***
  - But, increase patient dose.
- Full advantage cannot be taken of the brightness gain of an II in the reduction of patient dose.
  - The mA cannot be reduced much below that formerly used in direct vision fluoroscopy → otherwise, increase noise.
  - The real advantage of the image intensifier → the contrast and definition of the image can be seen in ambient lighting and by more than one viewer "due to the brighter image".

Typical doses and dose rates

- *Images with acceptable noise are produced by the following approximate doses and dose rates on the input surface of the image intensifier:*

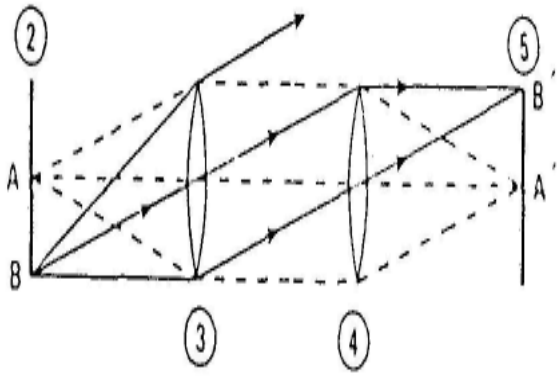
Fluoroscopy	1 μGy\s
Photospot film	1 μGy\frame
Cine	0.1 μGy\frame
Digital	10 μGy\frame

- Due to attenuation by the patient, grid, and couch top, the skin proximal to the tube will receive doses around **300x greater**. See also Section 6.7.

Quantum Sink

- The information in the image also suffers from statistical fluctuations in all the other discrete 'events' occurring in the image chain:
  → Light photons emitted by the input phosphor
  → Photoelectrons emitted by the photocathode
  → Light photons emitted by the output phosphor
  → Electrons constituting the video signal, etc.
- The noise produced in each of the above stages is relatively **low** since the number of light photons and electrons involved is very large.
- **The Quantum Sink** is It is the weakest link in the imaging chain
  - The part of the system where the number of photons or electrons/mm^2 of the image field is lowest → the relative noise the largest and the SNR the lowest.
  - *In an II-TV system,* it lies in the absorption of X-rays in **the input phosphor**.
    In radiography, it lies in the absorption of X-rays in **the intensifying screens**.

Vignetting



- **Vignetting** means that ***the center of the final image is brighter than its edges.***
  - Figure 4.3b shows that all the light from the center A of the output phosphor (2) that is collected by the first lens (3) is collected and focused by the second lens (4) onto the image plane (5) at A'.
  - However, some (perhaps 25%) of the light from the edge B of the phosphor that is collected by the first lens misses the second

lens so that the image at B' is less bright.
- This occurs in the electron lens system also.

DISTORTION

- The electric fields that accurately control electrons in the center of the image are not able to control peripheral electrons to the same degree.
  - Peripheral electrons tend to flare out from an ideal course → do not strike the output phosphor where they ideally should & are not well-focused.
  - The result is unequal magnification → peripheral distortion.
- The amount of distortion is always greater with **large intensifiers** "the further an electron is from the center of the intensifier, the more difficult it is to control".

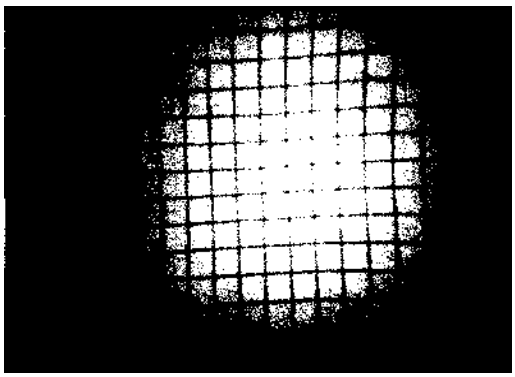


Figure 12-6 Test film of a wire screen (35 mm cine frame) from a 9-in. image intensifier

- Figure 12-6 shows a cine image of a coarse wire screen taken with a 9-in. intensifier. As you can see, the wires curve out at the periphery; this effect is most noticeable at the corners.
- This same effect has been observed in optical lenses and termed the "pincushion effect," and the term is carried over to image tubes. The distortion looked like a pincushion to the guy who named it.
- Generally this distortion does not hamper routine fluoroscopy, but it may make it difficult to evaluate straight lines (for example, in the reduction of a fracture).
- Unequal magnification also causes unequal illumination.
  - The center of the output screen is brighter than the periphery (Fig. 12-6).
  - The peripheral image is displayed over a larger area of the output screen, and thus its brightness gain from minification is less than that in the center.
  - A fall-off in brightness at the periphery of an image is called **vignetting.**
- Unequal focusing has another effect on image quality; that is, resolution is better in the center of the screen.

In summary, the center of the image intensifier screen has better resolution, a brighter image, and less geometric distortion.

FLUOROSCOPIC IMAGE RECORDERS

- There are two modes of recording the fluoroscopic image.

  First, Light Image Recorders
  - The light image from the output phosphor of the image intensifier may be recorded on film with a ***photospot camera*** or ***cine camera***.
  - *Routine spot films* are made directly with x rays.

Second, TV Image Recorders

- It makes use of the electrical signal generated by the TV camera.
- This group includes magnetic tape, magnetic discs, and optical discs.
- The three recorders may employ either analog or digital signals.

LIGHT IMAGE RECORDERS

Conventional Spot Film Recorder

- Spot film devices interpose an x-ray film cassette between the x-ray beam and the image intensifier tube.
- ***The standard $9^1/_2$-in. square cassette*** is now replaced with several sized cassettes.
- During fluoroscopy, the radiologist can at any time move the cassette from its park position (shielded by lead) to a position ready for exposure → But, there is **a delay** before a film moved into position and an exposure made ($^3/_4$ - 1 sec).

  Several factors make this delay necessary:
  - First, Heavy cassette.
  - Some changes at the x-ray factors are required.
    - Fluoroscopy is conducted at about 80-90 kVp and 1-3 mA of tube current.
    - Spot film uses fluoroscopic kVp, but requires much higher mA (300-400 mA)
    - So, time is required to increase x-ray tube filament heating, and the x-ray tube anode rotation speed.
    - A phototimer controls the length of exposure.

Spot "or Photospot" Film Cameras

- Records **the image output of an image intensifier** on a film.
- Produce reduced size images: typically, the film is ***roll film*** of size 70 or 105 mm, or ***cut film*** 100 mm in size.

Recall that the light from the output phosphor of the image intensifier is converted into a parallel beam image by a lens placed close to the output phosphor (refer back to Fig. 12-5). A semitransparent mirror placed in this parallel beam will allow about 10% of the light to travel on to the TV camera, and reflect the remainder to a photospot camera or a cine camera

- Originally, it was confined to *gastrointestinal fluoroscopy* → now used for all fluoroscopic images, including angiography.

  This has been made possible by *the improved resolution of cesium iodide image intensifier tubes*.

  Large input phosphor diameters up to 16 in. allow large areas of the body to be imaged without moving the image intensifier → a single photospot film can cover almost the entire abdomen (this could not be done with a 9-in. tube).

Advantages:

1. Most significant → ***Marked reduction in patient exposure***.
   - The recommended per-frame exposure for photospot film cameras is 100 **µ**R. The exposure for a comparable spot film is 300 **µ**R, three times as much.
   - Generally, the dose to the patient is 3-5 times smaller than with full-size (cassette-loaded) film.

   N.B. 100 mm film requires a greater patient dose than 70 mm.
2. ***For gastroenterology, cameras are more convenient than conventional spot***

films.

- The film does not have to be changed between exposures.
- The delay between initiation and completion of an exposure is shorter.
- Exposure times are shorter (in the 50-ms range) → ↓↓ motion.
- High framing frequency = 12 frames/second.

3. it is possible to record and view the image at the same time → since the camera is recording directly from the output phosphor.

4. The resolution of the resulting films is that of the image intensifier, ***about 4 line pairs per mm*** (a range of 3 to 5 Ip/mm).
Resolution of routine spot films is theoretically greater than that of spot film camera films → but longer exposure times required for spot films may degrade the image because of motion unsharpness.

5. Savings in film costs of greater than 80%.

Disadvantages:

- The little films are a nuisance to process and store.
- It needs practice to feel comfortable looking at angiograms on small format.
- The sharpness or resolution, being that of the image intensifier, is less good.

CINEFLUOROGRAPHY

- Cinefluorography is the process of recording fluoroscopic images on cine film.
- Records from ***the output phosphor of the image intensifier***.
- A beam splitting mirror allows simultaneous cine recording and television viewing, just as with spot film camera recording.
- Two film sizes: ***16 mm*** and ***35 mm***.
- In the United States, 98% of all cine is done on 35 mm film, and 95% of all cine studies involve the heart. Therefore, our major emphasis will be on ***35 mm cardiac cinefluorography***.

Cine Camera

- The basic components of the camera are:
  - Lens.
  - Shutter.
  - Pressure plate.
  - Aperture
  - Pulldown arm.
  - Film transport mechanism.
- Light enters the camera through ***the lens*** and is restricted by ***the aperture***.
- ***The shutter*** is a rotating disc located in front of the aperture with a sector cut out of its periphery.
  As the shutter rotates → it interrupts light flow into the camera.
- While the shutter is closed, ***the pulldown arm*** advances the film to the correct position for the next exposure (Fig. 13-13).
- The x-ray pulses and shutter opening are synchronized.

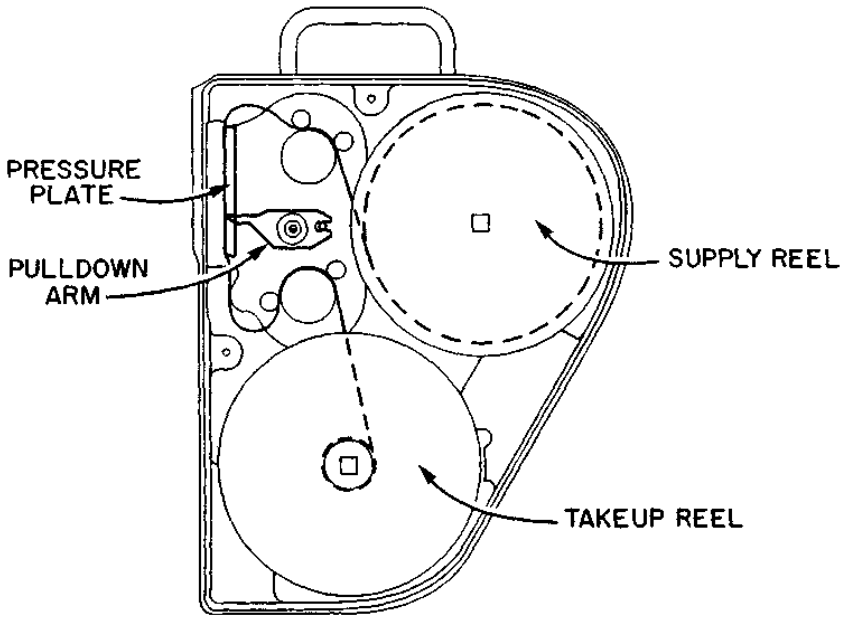


Figure 13-13 Cine camera

- **The framing frequency = 60** "divided or multiplied by a whole number (e.g., $7^1/_2$, 15, 30, 60, or 120)".
- The combination of the framing frequency and shutter opening determines the amount of time available for both the exposure and pulldown.
  For example, with a 180° shutter opening and 60 frames per second, the time available for both the exposure and pulldown is 1/120 sec.

Framing

- Framing is controlled by the lens of the cine camera.
- **Exact framing** means that the entire image (the output phosphor of the II) just fits on the cine film.
- **Over-framing** means that only a portion of the image is recorded on the film → so, some of the output image is not recorded.
  - The film image with overframing is larger than the film image for exact framing, and this increased size is usually desirable.
  - Extremes of overframing are generally avoided because patient exposure in areas not recorded is undesirable.
- Framing characteristics are established when the cine system is installed.

X-Ray Exposure

- The timing and intensity of the x-ray exposure are controlled during cinefluorography by ***two electrical signals*** that originate from within the cine system.
  - One signal coordinates the x-ray exposure with the open time of the camera shutter (*synchronization*).
  - The other maintains a constant level of intensifier illumination by varying the exposure factors for areas of different thickness or density (*automatic brightness control*, mentioned before).

Synchronization

- In old cinefluorographic equipment, ***x rays were generated continuously***

throughout a filming sequence → the patient was needlessly irradiated when the camera shutter was closed.

- *These continuous exposures had two serious disadvantages:*
  - Large patient exposures.
  - Decreased life expectancy of the x-ray tube.
- In all modern cinefluorographic systems → ***the x-ray output is intermittent*** & the synchronized with the open time of the camera shutter.
- The shutter of the camera is timed by ***60 Hz power*** → permits shutter speeds that are fractions or multiples of the number 60 (e.g., 7 $^{1}/_{2}$, 15, 30, 60, and 120 frames exposed per second).
- At low framing frequencies the image flickers because the x rays are pulsed, but flicker does not interfere with monitoring.

TV IMAGE RECORDERS

- The second method of recording the fluoroscopic image involves recording the electrical signal from the TV camera.
- This includes: magnetic tape, magnetic disc, and optional disc recorders.

Video Tape Recorders

- ***The 'write' head of the recorder*** is a small coil which has a narrow gap in its closed iron core.
- The video signal is applied to the 'write' head → translates the video signal into a time-varying magnetic field → the signal is recorded as ***variations in the magnetism*** of the ferrous oxide coating of a plastic tape which travels at a high speed across the narrow gap.
- Switching from the 'write' or recording mode to the 'read' or playback mode → the traveling magnetic tape induces in the coil a voltage signal which, after amplification, reproduces the image on the TV monitor. Alternatively a video disk may be used.
- Contrast and brightness can be varied as with any TV image.
- The **dose** to the patient is less than with cineradiography but the **quality** of the image is worse.
- No processing is needed; instant replay and frame freeze are possible.
- Magnetic tape is low in cost and widely used.

  But it has significant limitations:
  - The rate of data recording is limited by the speed of tape movement.
  - Long time is needed to retrieve a stored image.
  - Not a good permanent recording medium due to tape wear and degradation of the recorded data → so, needs proper storage.
  - Shelf life of magnetic tape is about 2 years.

4.2 DIGITAL IMAGING

❝ The radiological images considered so far are analog images. In particular, *the video signal from the TV camera tube is an analog signal*, a voltage which varies smoothly as the image brightness is scanned in the raster of horizontal lines.

❝ If it is converted to digital form, the image can be enhanced in various ways - and if necessary stored - using a computer, before it is displayed on a video monitor or printed via a laser camera.

4.2.1 EQUIPMENT

Digitizer

- The video signal from the TV camera → applied to an analog-digital converter (ADC) or digitizer.
  This samples the signal at equally spaced intervals (say) 512 times along each of 512 scan lines.
- Figure 4.8 shows how the video signal varies during the time it takes to scan a single line and how it is sampled at regular intervals.

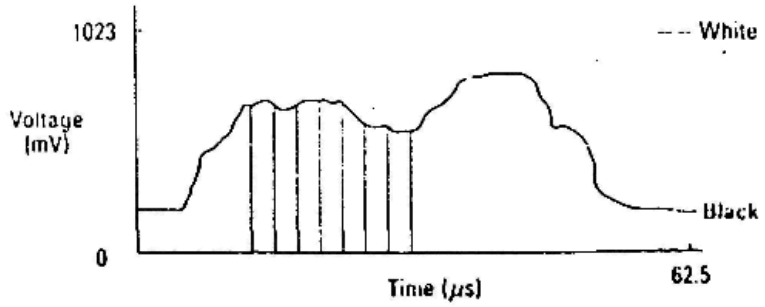


Fig. 4.8 Sampling and digitization of a video signal along a scan line.

- The voltage at each data point, which gives the grey level, is expressed as the nearest 10-bit binary number between **00000 00000 = (0)** & **11111 11111 (= 1023)**

Computer

- The image has in effect been divided into a matrix of 512 x 512 pixels (Fig. 4.9a). Each pixel is roughly a square of side 0.5 mm. This permits a resolution of 1 mm (= two pixels).
- The same diagram can be taken to represent a corresponding 'frame' of 512 x 512 memory locations in the core memory of a computer (microprocessor).

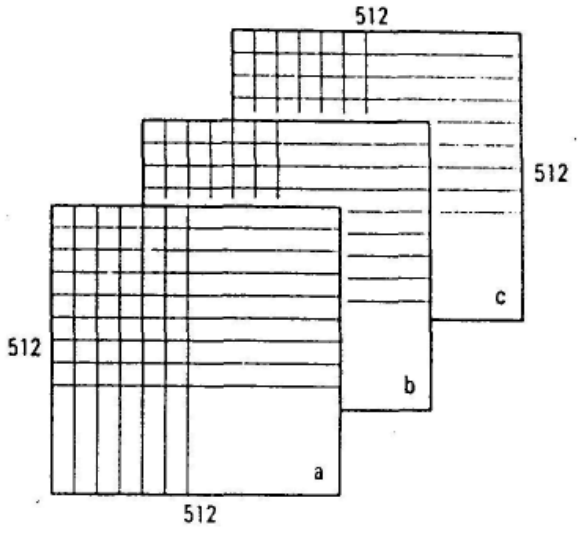


Fig. 4.9 Three successive image frames of a digital image, each a matrix of pixels or memory locations.

- The binary numbers representing the image brightness or 'grey level' of each pixel are stored in a frame of 512 x 512 memory locations.
  - Each location has an 'address', expressed as two binary numbers and is ***'10 bits deep'***. This requires a storage capacity of 10 x 512 x 512 bits = 320 kilobytes (where 1 byte = 8 bits).
  - Thus a 40 megabyte RAM (random access memory) can store 128 separate images.
- If the sampling frequency were to be doubled, to 1024 per scan line → the pixel size would be halved → the matrix size doubled, and → the resolution improved by a factor of 2.
  However, the 40 megabyte *RAM* could then only store 30 separate images.

For further remarks about sampling frequency, see Section 9.2.

Image display

- The image is displayed by reading out of the computer memory the brightness or grey scale values of the pixels in sequence, in synchronism with the electron pencil scanning the monitor (cathode ray tube).
- The data from the computer are converted into an analog voltage signal (by a digital-analog converter, DAC) which modulates the brightness of the spot of light on the screen.

Lost frame hold

A simple application is to store the last image of a fluoroscopic examination *so* that it can continue to be observed on the monitor without continuing to expose the patient ***('freeze frame').***

Digital photospot high-resolution, slow television scan

- A very short exposure at high mA is made, thus freezing movement → the video system is made inoperative ('blanked') during the actual exposure → the camera then scans the image → writes it into the computer memory with a 1024 line progressive (non-interlaced) raster at 6.25 frames /sec "*four times more slowly than normal*" → thus allowing the usual bandwidth to be used.
- The stored image is read out of the memory at the usual 25 frames /sec for flicker-free display on a monitor or is recorded with a laser camera.
- The spatial resolution is typically ***2 lp/mm***, compared with *4 lp/mm* for an ordinary photospot, but with the advantages of digital imaging.

4.2.2 Image Processing, Storage, And Recording

The below methods of processing, storing, and recording a digital image all find general application in CT, gamma imaging, digital ultrasound, and MRI.

Before reading out the stored image from memory, the grey scale numbers in each address can be processed and manipulated in a number of ways.

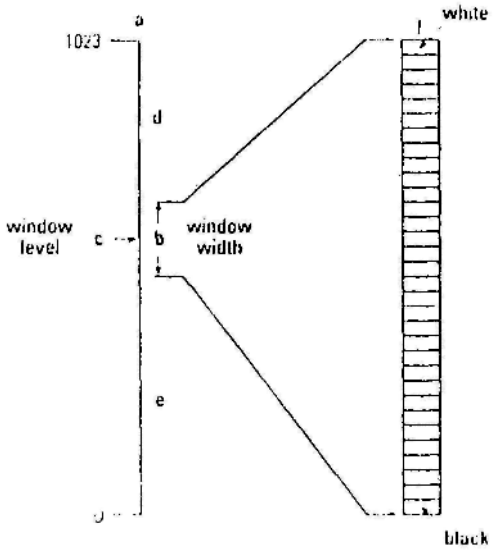


Fig. 4.10 Windowing

Windowing

- Windowing is sometimes called *'grey level mapping'*.
- The digitized image contains more information than can be seen at once on the monitor screen.
- The image stored in a 10-bit computer contains 1024 discrete intensity levels, represented by scale a in Fig. 4.10 → but the eye can only distinguish about 32 gradations of brightness on a TV screen.
- A small range of values b, **the window width**, centered on **the window level** c, is selected for display on the monitor as (say) 32 distinct shades of grey f in the range from black to maximum white.
- Intensities in the range d are not differentiated, being all displayed as white, while those in the range e are all displayed as black.
- It is possible to visualize subject contrast only in the structures or tissues whose image lies within the *window width.*
- The *window level* is the mid-range value of the window, and it and the window width can be independently set at the controls.
  By moving the window level into the image areas d or e, these parts of the image then become differentiated and can be visualized.
- **Value:**
  - It allows the contrast and the average brightness of the image to be optimized within the tissues and region of interest.
  - It allows the speed and γ or latitude of the imaging system to be altered at will, subsequent to a single X-ray exposure → cannot be done in film-screen radiography.
  - This feature can outweigh the poorer resolution of digital compared with film-screen radiography.

Background subtraction

- A technique used to reduce the effect of X-ray scattering and veiling glare.
- Subtraction of the same number from each of the stored pixel values will increase contrast. (This is the opposite of the effect of scatter or fog reducing contrast on a radiograph.)

Noise reduction by frame addition or averaging

- Several successive images of the same subject, stored in memory, are added together and averaged, pixel by pixel.
- ***The useful signals*** are in the same locations in all frames and so will add up.
  The noise varies randomly from frame to frame & therefore partially averaged out.
- As a result, the SNR is improved by a factor = the square root of the number of frames so averaged.
- This is sometimes called 'digital temporal altering'.
- It depends on the patient being immobile while the several images are acquired.

Noise reduction by 'low-pass spatial filtering'

- To the grey scale value of each pixel is added a proportion of the pixel values of the eight surrounding pixels and an average taken → reduces noise but can impair spatial resolution.
- Small bright or dark areas are removed whether they are noise or real images, while leaving the images of larger objects.
- It can be compared to turning up ***the bass control of a hi-fi system***.

Digital filtering is further explained in Section 9.1.

Edge enhancement by 'high-pass spatial filtering'

- Where the pixel values change at an edge or boundary in the image, the gradient can be enhanced mathematically **(*It achieves digitally the edge enhancement feature inherent in xerography - see section 3.11*)**
  ADV. & DISADV.:
  1. Reduce the effect of blurring in the imaging system. → enhance those parts of the image with fine structure detail
  2. But, increases noise.
- It can be compared with turning up ***the treble control of a hi-fi system***.

Data shifting

- The pixel values can be moved horizontally and/or vertically within a frame, and the image can be shifted, inverted, rotated, or even stretched.

Image storage

- A number of separate images can be stored in real time, usually in a solid state memory (RAM).
- ***Access*** to stored images is rapid (microseconds) but the ***storage capacity*** is limited by cost.
- To make the RAM available for further images → the stored data are transferred to

a magnetic disk "medium-term store" → access is reasonably fast (milliseconds), and may be either:

1. A floppy disk, which is portable but has a storage capacity of only about 1 megabyte, or
2. A hard (Winchester) disk able to store several thousand images.

- For long-term storage (archiving), the images are transferred to optical disks which have a capacity of many gigabytes.
  The digital information is burnt by a laser into a specially coated disk "the cheapest form of storage".
  Digital magnetic tape storage is also used, and has a very high storage capacity (optical tape *is* even better), but again access is relatively slow.
- When required, digitally stored images can be played back into the solid state memory and, after any necessary manipulation, displayed on the screen.
- A series of still images tan be presented in rapid sequence ('cine' mode).

CAMERAS

- The image on the monitor screen can be recorded on single-coated photographic film (formulated so that its spectral sensitivity matches the light emitted by the cathode ray tube phosphor), and it can be processed in the normal X-ray film automatic processor.
- *To obtain good images:*
  1. The cathode ray tube must be of a high grade; and
  2. The film correctly exposed.

  This is achieved by **a light sensor** attached to a corner of the screen which feeds back to the modulator grid of the electron gun and controls the brightness of the screen.

Laser Camera:

- A *laser camera* can be connected directly to the digital processor, bypassing the cathode ray tube.
- A helium-neon gas laser (for example) emits a beam of light only 70 μm in diameter → scanned in a raster across a moving film by means of a rotating or oscillating mirror → so records the image.
- The image is recorded by reading out of the memory the brightness or grey scale values of the pixels in sequence, in synchronism with the laser beam scanning the recording film.
- The data from the computer are converted (by a DAC) into an analog voltage signal winch modulates the brightness of the laser beam, it takes a total of 20 s to scan a film, which, on account of the narrow laser beam, can record about 4096 x 4096 pixels, with a resolution of 10 lp\mm.
- The single-coated film is specially formulated for infrared and the automatic processor. A green safelight may be used.

Multiformat Camera

- In a multiforrnat camera (whether conventional or laser) the whole of the screen image can be made to fill either the whole film or just a part of it, in which latter case a number of images may be recorded, reduced in size, side by side.

4.3 COMPUTED TOMOGRAPHY (CT)

In CT scanning:

(a) A transverse slice of the patient "say 10 mm thick" is imaged → avoiding the superposition of adjacent structures.

(b) The slice is defined by a 'sheet' of X-rays, produced by a narrow fan beam rotated around the patient → ↓ scatter.

(c) The slice is subdivided into a **matrix of 512 x 512 volume elements (voxels)**, each **typically 0.5 x 0.5 x 10 mm**. The image is reconstructed by a digital computer as a corresponding **matrix of 512 x 512 picture elements (pixels)**.

(d) The computer allows the use of 'windowing' (see Section 4.2.2) to selectively display a restricted range of tissues.

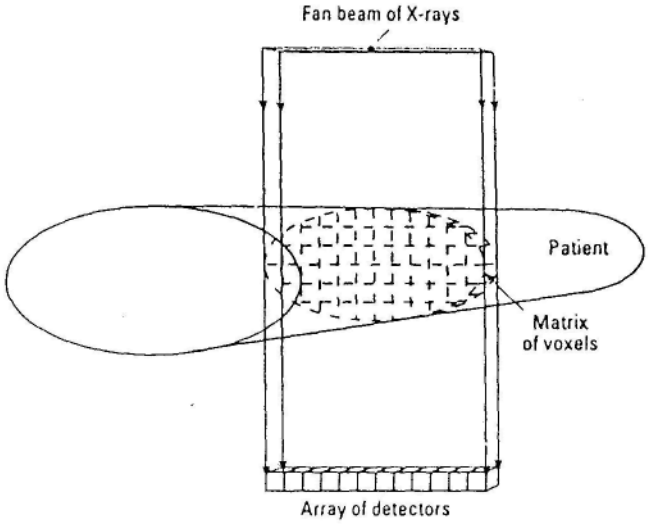


Fig. 4.12 Principle of CT imaging

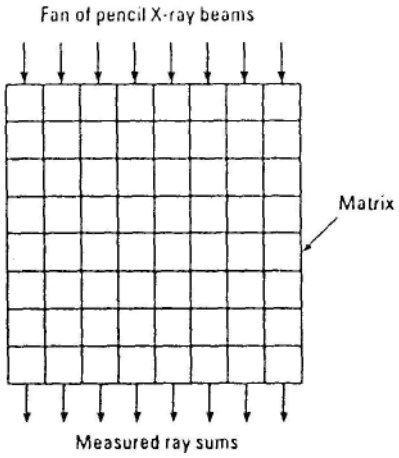


Fig. 4.13 Matrix of tissue voxels, corresponding memory locations in the computer or image pixels.

- From (a), (b), & (d) → **contrast resolution is more** than conventional radiography
  From (c) → **the spatial resolution is less good**

  N.B. **contrast resolution =** the ability to display low contrast structures.
- The image is displayed as a matrix of pixels, each 0.5 x 0.5 mm.
- **The brightness or grey scale value of each pixel in the image = the average linear attenuation coefficient μ of the contents of the corresponding voxel.**

4.3.1 PRINCIPLE OF COMPUTED TOMOGRAPHY IMAGING

CT numbers

- The linear attenuation coefficient μ_t of each tissue pixel is compared with that μ_w of water by the formula:

$$\text{CT number} = 1000 \frac{(\mu_t - \mu_w)}{\mu_w}$$

- **Water is used as the reference material because:**
  1) Its attenuation coefficient is close to those of soft tissues.
  2) It is a reproducible material for machine calibration.
- **The multiplier (1000)** is used to obtain whole numbers.
- The CT number (or ***Hounsfield number***) is defined as
  - -1000 for air.
  - 0 for water.
  - **For tissues CT number is depends on the kV employed**. *for example;*
    - If, at 80 keV the linear attenuation coefficient of typical bone and water are 0.38 and 0.19 cm^{-1}, respectively → the CT number of the bone is +1000.
    - CT number is higher in the case of cortical bone.

Scanning the patient:

- Commonest CT scanner use **rotating anode tube with a 0.6 mm focal spot**.
- It must have a high heat capacity because the examination takes several seconds.
- The tube is mounted with its axis perpendicular to the slice → ↓↓↓ heel effect.
- The X-rays are collimated to leave the tube into **a fan beam** which just covers the body section.
- After emerging from the patient, the transmitted beam passes through **a second collimator set**, accurately aligned with the first; both sets being motorized to set the slice thickness.
- The beam then falls on a curvilinear array of (say) **700 detectors**, individually collimated and all carefully matched in sensitivity → convert the transmitted beam intensity into a proportional signal current.
- **The tube & detectors,** mounted on opposite sides of a ring, rotate smoothly around the patient.

  In the 360° rotation, **X-ray tube is pulsed 300 times**. **Each pulse lasts 2 – 3 ms**, & **the scan can take about 1 s**.

Acquiring the data

- Each time the tube is pulsed, each detector measures **the logarithm of the intensity of the radiation falling upon it** "these are related to the sum of all the CT numbers of the voxels each ray has passed through" → called **Ray Sum**.
- The set of ray sums collected at each position of the tube is called **Projection**.
- Each individual voxel is traversed by an X-ray pencil from several different

directions during the 360° rotation of the ring, **to calculate CT number of voxel**.

- If a pencil beam of width **t** passes obliquely through a pixel of size **t x t**, some of the contents of the pixel will be 'missed' → the computer correct that.

Reconstructing the image

- In principle, if we have **256 x 256 voxels** & **700 (detectors no.) x 300 (pulses no.) ray sums** → enough data for the CT numbers of all the voxels.
- The arithmetic involved can be performed in a sufficiently short time by a computer and by taking various short cuts, e.g. **('filtered back-projection')** → the CT image can be produced in close to real time.
- The CT numbers so computed are stored in the computer memory locations, each of which corresponds to a voxel and therefore to a pixel, as in Fig. 4.13.

Back-projection

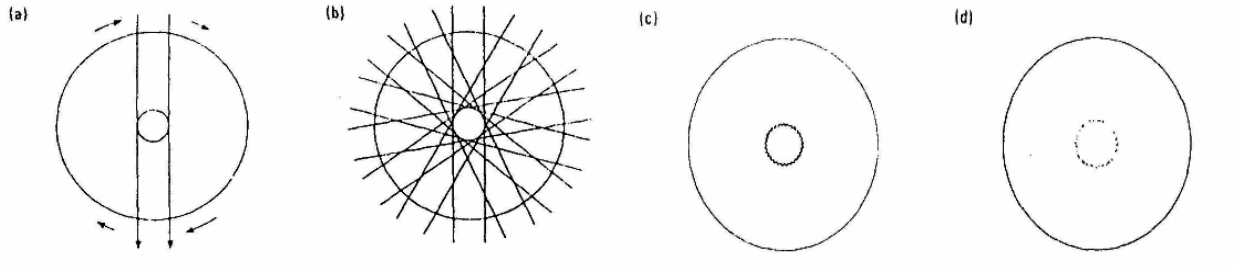
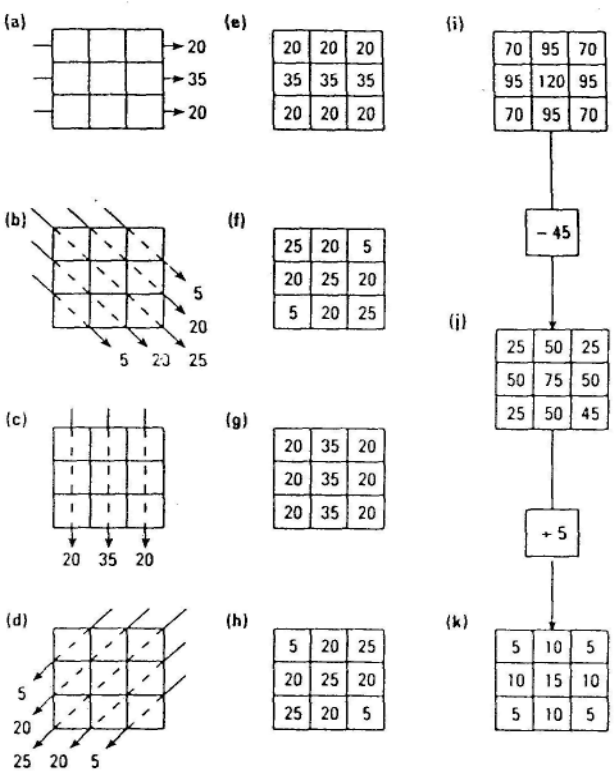


Fig. 4.14 Back-projection: schematic, *(a)* Pencil beam routing around a small dense structure, *(b-d)* image reconstructed with increasing numbers of projections.

- Imagine one voxel, the contents of which have **a higher μ than its surroundings**.
- As depicted in Fig. 4.14a, **an X-ray pencil traverses the voxel and the ray sum is measured**. In principle, a stripe of light could now be projected backward along the direction of the X-ray & its intensity being proportional to the ray sum.
- Repeating this for each of the rays which traverse the voxel in the course of a scan would build up an image of the structure (Fig. 4.14b).
- With a moderate number of stripes the image would be **spiky** (Fig. 4.14c).
  With ↑ number of stripes → **blurring of edges of the image** (Fig. 4.14d).
- The blurring could be removed by **modifying the brightness near the edges of each back-projected beam or stripe** - a process known as **'filtering'**.



- A simplified mathematical example is given in Fig. 4.15, in which an array of 9 pixels is scanned from 4 successive directions producing the ray sums shown.
- The 3 ray sums in Fig. 4.15a are entered (as in Fig. 4.14e) into the memory-locations corresponding to each of the voxels encountered by each ray. Similarly the ray sums shown in Fig. 4.15b-d.
- **Adding** the numbers (Fig. 4.15e-h), results in the totals shown in Fig. 4.15i.
- A little further arithmetic manipulation, involving **background subtraction** and **rescaling**, finally yields Fig. 4.15k. This is a fair representation of the CT numbers of each pixel.

Filtered back-projection

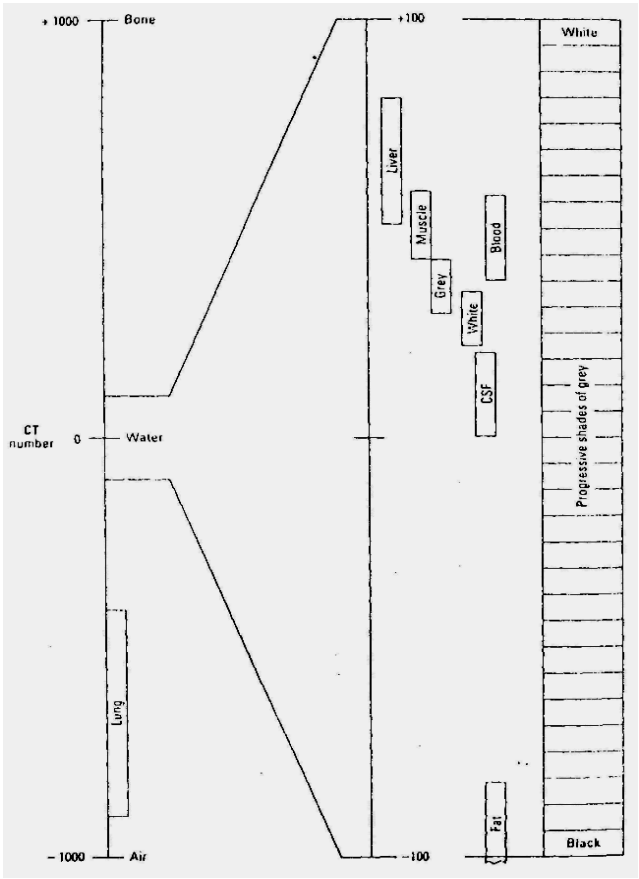
The blurring introduced by the back-projection process can be compensated by a mathematical process carried out by the computer called **'filtering'** → modifies the brightness near the edge of each back-projected beam.

Filtering algorithms *different "filters" can be used*

- **'Bone' algorithm** → enhance fine detail but increase noise.
- **'Soft tissue' filter** → improve contrast by smoothing out noise, but impairs the spatial resolution.

Windowing

- Although ***the scanner*** can distinguish 2000 different CT numbers, BUT ***the eye*** cannot distinguish nearly as many separate shades of grey on the screen.
- **Soft tissues (excluding fat)** only cover a range of about **80 CT numbers**.
- So a window is chosen which just embraces all the tissues of interest, and only these are displayed as shades of grey within the range black to maximum white on the monitor.
- Pixels with CT numbers outside this window are **undifferentiated**, being displayed as either black or white.
- Window level and window width can be set independently at the control panel, for example to differentiate lung tissues.



- They only affect the displayed image; the whole of the data referring to the reconstructed image is retained in the computer.

Partial volume effect

- CT cannot reveal detail within a voxel.
- It measures the average CT number of the contents of each voxel.
- A high-contrast object occupying only part of a voxel will raise the CT number for the corresponding pixel and so appear larger than it is → **e.g. tiny calcifications and small traces of contrast medium**.
- The partial volume effect is **reduced by using thinner slices & smaller pixels**.

Beam-hardening effect

- **The use of a relatively high kV (typically 120 kV constant potential)**:
  - Reduces both **patient dose** and **the hardening of the beam** by the patient.
  - Unfortunately, reduces **efficiency of the detector** and also **the image contrast**.
  - It also **increases scatter**, making necessary the collimation in front of detectors.

- Hardening of the beam as it penetrates the patient results in the CT number of the same kind of tissue decreasing along the ray. However, the image reconstruction process assumes that, to the contrary, the CT number of each kind of tissue is constant along each ray.
- ***Correction:***
  - Using a **'Beam-Hardening Algorithm'** by the computer
  - The use of a **0.5 mm copper filter** mounted on the X-ray tube, which, with the high kV, produces a relatively homogeneous beam.
- Recently, **improved beam-hardening algorithms** have allowed **lighter filtration** → resulting in a **greater tube output** and a **shorter scan time**.

❝ To compensate for ***diminishing patient thickness toward the edges*** of the fan beam → 'Bow Tie" compensating filter is used.

4.3.2 THE COMPUTED TOMOGRAPHY SCANNER

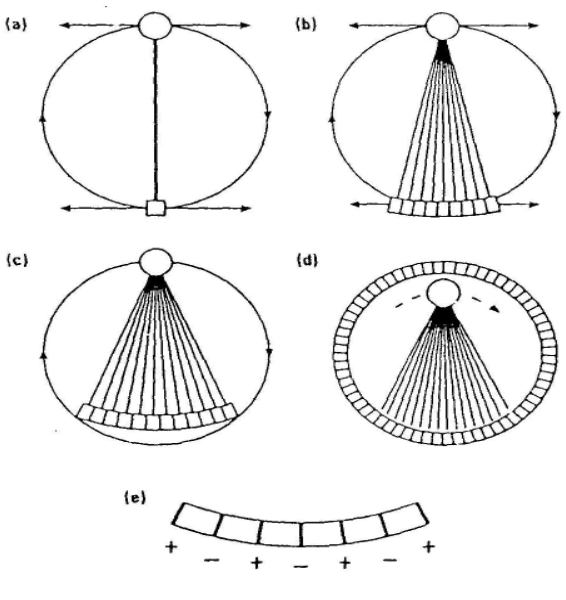
Slip Ring Technology

- If the tube kV is supplied by high-tension cables, the gantry ring has to reverse direction after each 360° rotation.
- Faster continuous rotation of the tube is achieved in modern scanners by mounting a high-voltage generator, operating at high frequency (up to 100 kHz) on the rotating gantry ring itself and supplying it with power through slip-rings.
- Tube can rotate in one direction indefinitely → making ***helical scanning*** possible.

	1st generation	2nd generation	3rd generation Most common	4th generation
Beam	Single pencil	Narrow fan	Wide fan	Wide fan
Translation	180 steps	Less	No	No
Detectors	Single	Small curved array	Large array (100s) rotate opposite tube	Complete ring (1000s) of stationary detectors
Rotation	1° at a time through 360°	Through 360° with less angular steps	Continuous for 360°	Tube alone rotate 360°
Scan time	3-5 min	20 sec	1 sec	1 sec
Adv.			Better predetector collimation	i- avoid ring artifact ii- easy detector calibration
Disadv.			Ring artifact	Higher pt. dose (Tube is close to pt.)

Further increase of scan speed is possible by simultaneous use of **multiple X-ray tubes** or **by inserting the patient into a huge funnel-shaped X-ray tube** in which an electron beam (1000 mA) scans rapidly round a large semicircular target - usually called the *fifth-generation scanner.*

- Multiple stationary detector rings allow multiple slices to be scanned simultaneously.



- A scan time of 50-100 ms → used mainly for cardiac imaging.

DETECTORS

The detectors need to have:

1. **High-detection efficiency**;
2. **Fast response** (short afterglow) to keep up with fast scanning;
3. **Wide dynamic range** - able to cope with both the high-intensity beam either side of the patient and the highly attenuated beam passing through the patient (**intensity ratio 5000:1**);
4. **Linearity** - signal accurately proportional to the X-ray intensity;
5. **Stability** in face of **voltage** and **temperature** fluctuations;
6. **Reliability**;
7. **Small size** to allow close packing, giving better resolution;
8. **Low cost** in view of the large number of detectors used.

SCINTILLATORS

- Originally: sodium iodide (thallium-activated) crystal, coupled to a **photomultiplier** which required a highly stabilized high-voltage power supply.
- Sodium iodide has been superseded by other scintillators such as cesium iodide, calcium fluoride, cadmium tungstate, and bismuth germinate → **shorter afterglow**
- Photomultipliers have been superseded by **silicon photodiodes** → المزايا
  - **Very much smaller**
    ∴ Very close packing can be achieved with crystals of cadmium tungstate or cesium iodide, with a silicon light sensor embedded in each solid state detector.
  - **Do not need high-voltage supply**.
- Detector size typically 1.0 x 15 mm (or 1.0 x 1.5 mm for multiple detector arrays)

IONIZATION CHAMBERS

- ***Features:***
  - **Less sensitive** but **more easily matched for sensitivity**.
  - They are **very stable** → unaffected by voltage fluctuations.
  - Have a **wide linear response** with **no lag**.
  - They are **narrow (and closely packed)**.

To compensate for the lower sensitivity, ionization champers are:

- Filled with a high atomic number gas (xenon) rather than air & at high pressure (25 atm, 2.5 MPa).
- Made relatively deep & thick (e.g. 6 cm).

SCINTILLATORS	IONIZATION CHAMBERS

• Better absorption efficiency than gas detectors because of higher density and higher effective atomic number	
• A small gap between detector elements is necessary to reduce crosstalk between adjacent detectors → reducing geometric efficiency	• Thin metal septa separating individual detectors improves geometric efficiency by reducing dead space between detectors
• Top surface of detector is flat → capable of x-ray detection over a wide range of angles	• Must be positioned in fixed orientation in respect to x-ray source. • The tungsten electrodes, alternately positive and negative (Fig. 4.17e), converge toward the tube (like strips of focused grid) → help to collimate beam and reduce scatter.
• Required for 4th generation scanners: particularly as their sensitivity can be checked continuously by the leading or trailing edge of the X-ray fan beam • But may be used in 3rd generation scanners as well	• Well suited for 3rd generation scanners, where very stable detectors are needed as their sensitivity cannot be checked or calibrated very often. • Cannot be used for 4th generation scanners because those detectors must record x-rays as the source moves over a wide angle

4.3.3 IMAGE QUALITY

Noise:

- This can be tested by imaging a **water phantom**.
  - The CT numbers of the pixels will not be all the same, due to statistical variations in the number of X-ray photons absorbed in each voxel → the image is not uniform but appears mottled or grainy.
  - The computer can be asked to compute the mean CT number and also the standard deviation or noise.
- **The quantum noise** is a fundamental limit to the quality of the CT image since it both **1) reduces contrast resolution of small objects** and

2) worsens the spatial resolution of low-contrast objects.

- **Noise may be reduced by:**

1. Increasing the number of photons absorbed in each voxel, by increasing the slice thickness or the pixel size.

Improving contrast resolution in this way → impair spatial resolution

2. Increasing either the mA or the scan time.

Both of these involve increasing the patient dose.

To minimize patient dose the radiologist must accept the noisiest picture consistent with good diagnosis.

- **Other factors increasing noise:**
  - Zoom enlargement; "spreads available ray sum information over pixel matrix"
  - Narrower window width "each grey level covers a smaller range of CT numbers, i.e. derived from the absorption of fewer X-ray photons in each voxel"
  - Reducing the scan time or reducing the slice thickness, unless the mA is increased proportionally.
  - Deficiency of photons →; occurring with:
    - × Thicker patients.
    - × High-attenuation materials such as bone or prostheses in the slice.

Spatial resolution of high-contrast objects

High-contrast spatial resolution is good, being determined by Pixel Size.

- In CT terms 'high contrast' is between water and Perspex (about 12%).
- Spatial resolution may be tested with BAR PHANTOM having a range of different line pairs per millimeter.
  - As CT scanning smooths out the detail within each voxel → detail within a voxel is not imaged → ∴ 2 pixels are needed to define a line pair

∴ Resolution is about 1 lp\mm → much poorer than film-screen radiography.

High-resolution imaging

❝ By increasing matrix size or reducing field of view → decreasing pixel size.

❝ **Below a certain pixel size, spatial resolution is further limited by:**

1) Size of the focal spot.
2) Collimators.
3) Number and size of detectors.
4) Spacing between detectors.
5) Patient movement.

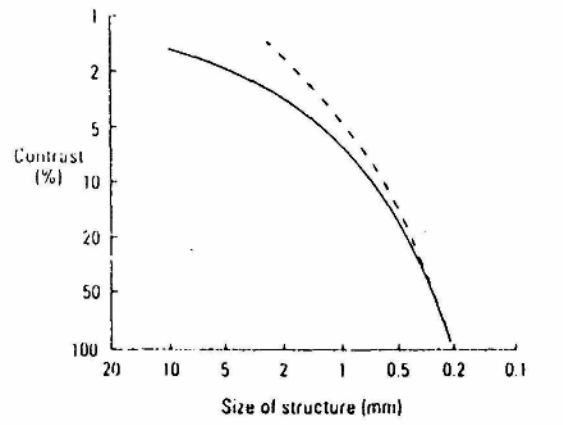
Spatial resolution of low-contrast objects

Low-contrast spatial resolution is less good and is limited by the NOISE.

- The larger the structure → the greater the number of pixels over which the

noise is averaged → **the better the SNR**.

- A low-contrast structure may need to be **5-10 mm in diameter** to be resolved.
- Low-contrast spatial resolution is assessed by imaging a slice though **a Perspex phantom with water-filled holes of different diameters and different depths** → providing different levels of contrast.
  - A graph is plotted **"Detail-contrast diagram"** showing the minimum contrast needed to see structures of different diameters.
  - The solid curve in Fig. 4.18 shows how **the spatial resolution depends on the contrast of the image**.
  - The dashed curve shows the improvement in low-contrast perceptibility produced by **increasing the mA**, or **dose per slice**, and so reducing the noise.



Contrast resolution

'The ability to detect small differences in the attenuation coefficient of adjacent structures'

`Contrast resolution is tied to the SNR`

- The contrast between a structure and its surroundings is ONLY detectable if it is → **3-5 times greater than the noise** in the image.

`The more pixels a structure occupy → ↓ noise → better contrast resolution.`

With a structure **10 mm in diameter**, differences of **4-5 CT numbers "0.5% difference in attenuation coefficient"** can be detected → at least **10 times better** than can be achieved in film-screen radiography.

- ***In CT, soft tissue contrast is superior to that in plain film radiography because:***
  - Not obscured by overlying bone.
  - Smaller Scatter.
  - Windowing allows quite small differences of CT number to be selected from the full range and displayed over the whole grey scale.

Resolution compromise (trade-off)

- Although a spatial resolution of 1 lp mm^{-1} and a contrast resolution of 0.5% are quoted for CT → they cannot be achieved at the same time, as Fig. 4.18 makes clear.
- It is not possible to achieve excellent spatial and contrast resolution simultaneously, except by delivering an unacceptable dose to the patient.
- **In fact**: Well-established relationship among Noise (N), pixel dimensions (Δ), slice thickness (T), and radiation dose (D):

$$D \propto \frac{1}{T.N^2.\Delta^3}$$

$$\left(\begin{matrix}\text{slice}\\ \text{thickness}\end{matrix}\right) \times \left(\begin{matrix}\text{relative}\\ \text{noise}\end{matrix}\right)^2 \times \left(\begin{matrix}\text{pixel}\\ \text{size}\end{matrix}\right)^3 \propto \frac{1}{\text{dose}}$$

or alternatively,

$$\left(\begin{matrix}\text{slice}\\ \text{thickness}\end{matrix}\right) \times \left(\begin{matrix}\text{minimum}\\ \text{detectable}\\ \text{contrast}\end{matrix}\right)^2 \times \left(\begin{matrix}\text{minimum}\\ \text{detectable}\\ \text{size}\end{matrix}\right)^3 \propto \frac{1}{\text{dose}}$$

Accordingly,

- To improve contrast delectability by a factor of 2 involves increasing the dose by a factor of 4.
- To improve spatial resolution by a factor of 2 involves increasing the dose by a factor of 8.
- To halve the slice thickness without impairing image quality involves increasing the dose by a factor of 2.

In conclusion:

Compared with x-ray radiography, CT has significantly worse spatial resolution and significantly better contrast resolution

- Limiting spatial resolution for screen-film radiography is about **7 lp/mm**; for CT it is about **1 lp/mm**
- Contrast resolution of screen-film radiography is about **5%**; for CT it is about **0.5%**

Dose

- **The distribution of absorbed dose in the body section imaged is much more uniform than in conventional radiography**.
  - **With a single radiograph of the skull,** if the entry skin dose is **100%**, the exit skin dose might be **0.1%** and the central dose **3%**;
  - **In CT,** the skin dose is more or less uniform all round. The central dose in the

head is about **100%**, and in abdominal CT typically **60%**, of the skin dose.

- Due to scatter from one slice into adjacent slices, **the dose increases with the number of slices, but not proportionally**.
- Although the detector collimators are set to the nominal slice thickness, the actual X-ray beams overlap, as their width is much greater, being determined by the collimation near the tube.
- effective dose is directly proportional to the tube current and total scan length (product of the slice thickness and total number of slices)

The CT dose index (CTDI):

- For calculating spread of dose outside a nominal slice.
- It is the integral of **the dose along the axis of the patient from a single slice *divided by* the nominal thickness of the slice**.
- It can be measured by inserting a **10 cm long, thin cylindrical ionization chamber dosemeter along the axis of a cylindrical Perspex phantom** and imaging one slice through its middle.
- Organ doses from CT examinations estimated by **multiplying CTDI by the appropriate conversion factors**.
- Typical effective doses are in the range **5-10 mSv per examination**.
- Although CT scans account for **only 2% of X-ray examinations**, they contribute **more than 20% of the radiation dose** delivered to the UK population by medical X-rays.

ARTEFACTS

I- Motion artefacts

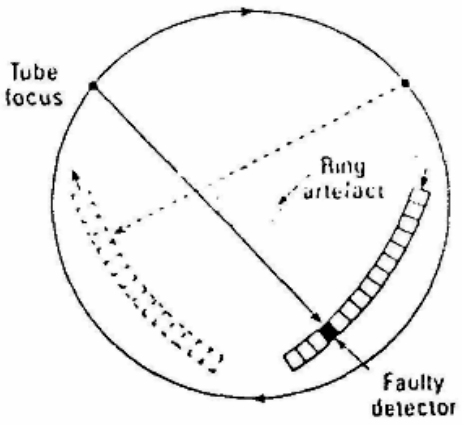
- Cardiac motion produces **streak artefacts** (black and white bands).
- The reconstruction process is misled by a moving structure occupying different voxels during the scan.
- Mechanical misalignment and movement of the patient have similar effects.

II- High-attenuation objects

- Neurosurgical clips, dental amalgam, Small areas of bone or contrast medium etc., give rise to **star artefacts** which may obscure the area of interest.
- The effect is accentuated by motion.

III- Defector malfunction

- In a third-generation scanner even a small imbalance in the sensitivity of the scintillation detectors can produce **ring artefacts**.
- **Cause:** the X-ray pencil associated with each detector traces out a ***'data ring'*** - a ring of tissue which is 'seen' by that detector alone.
- This ring can be seen on the image as an artefact if that detector malfunctions.
- The problem is ***reduced by*** frequent recalibration of



the detectors, between patients, and is ***less noticeable*** with gas detectors, which are more easily matched.

IV- Beam hardening

- The reconstruction process assumes a homogeneous X-ray beam, with the result that CT numbers are lower in the center of the patient (known as **'cupping'**).
- This is corrected to some extent by a ***"beam-hardening algorithm"***.

V- Geometrical artefacts

Because of the diverging beam → **CT slices are narrower at the center than at the edge** → overlap at the edges or an unscanned region at the center.

VI- Aliasing

- A sharp and high contrast boundary (as at a bone edge) may produce a number of **parallel streaks** nearby in the image, for reasons explained in Section 9.2.
- Similarly, at the boundary between the lung and diaphragm, spurious increased density may appear in the base of the lung.

VII- Partial volume or volume averaging artefacts

Quality Assurance: ***summary***

Each department should have a quality control protocol using appropriate test objects to verify the performance of their scanners.

The topics, already mentioned in this chapter include:

1. ***Noise*** - the standard deviation of the computed pixel values for the image of a water phantom, or other reference material;
2. ***Reproducibility*** – the consistency of mean CT number for reference material;
3. ***Uniformity*** - the variation of mean CT number over different areas of the scan field for the reference material;
4. ***Sensitivity*** - the smallest detectable object for a series of various materials (different contrasts) (see Fig. 4.18);
5. ***Contrast scale*** - the differences between the mean CT numbers for various test materials;
6. ***Resolution*** - the spatial resolution at a high contrast level;
7. ***Alignment*** - the presence or absence of streak artefacts in the scan of, for example, a high-contrast pin;
8. ***Slice thickness and spacing***;
9. ***Light beam alignment*** for patient positioning;
10. ***Dose measurements*** - CTDI and dose profile.

4.3.4 OTHER TECHNIQUES

Zoom reconstruction

- An area of interest can be delineated and displayed in an enlarged format.
- The computed data normally used to set the grey level of one pixel on the monitor is shared between several contiguous pixels.

∴ Noise is increased but resolution is effectively improved.

Scanning in other planes

Longitudinal scan

- If the tube and detectors are held stationary and the couch is moved steadily along its length during the exposure → a digital image can be obtained similar to a conventional (anteroposterior, lateral, or oblique) radiographic projection.
- Performed at the beginning of an examination, in either the anteroposterior or lateral plane → allows correct positioning & selection of subsequent axial images.
- These scout scans are produced with less patient dose than normal radiograph.

Multiplanar imaging (sagittal, coronal, and oblique sections)

- A section can be taken through the three-dimensional array of CT numbers acquired with a series of separate contiguous slices and reconstructed as an image in any plane through the patient.
- The image so obtained has a characteristic appearance

→ The pixels are rectangular, the longer side = the slice thickness.

This problem has been overcome by **spiral scanning**.

SPIRAL (HELICAL) SCANNING

- The couch moves continuously at a steady speed while the tube and detectors make a number of revolutions around the patient.
- The tube receives its power supply through slip-rings, and the detectors send their signals by radio.
- Suppose, for example, that the tube makes a complete rotation each second, the couch moves 10 mm /sec, and the collimated slice thickness is 10 mm.
  - In this case the pitch is 1:1.
  - A block of anatomy 300 mm long will be covered in 30 s, a long breath hold.
- The data are ***acquired*** in the form of a continuous ribbon of contiguous slices.
- The data are ***reconstructed*** as a series of vertical slices, in this case 10 mm thick.
- Interpolation allows slices to be imaged at any level and with any incrementation. For example, a series of overlapping slices, each 10 mm thick at increments of *2* mm, could be reconstructed through a volume of interest.
- Note that the slice thickness cannot be changed retrospectively.

Compared with sequential CT scanning, in which the tube reverses and the patient couch is indexed between slices with separate breath holds, spiral scanning has the following advantages and

disadvantages:

Advantages:

1. It is **faster** → allowing a greater number of patients and also the use of a smaller volume of contrast medium.
   (A ***double-helical scanner*** with two rows of detectors is even faster.)
2. It **overcomes the problem of slice-to-slice misregistration**, particularly in the region of the diaphragm, caused by variations in inspiration between the separate breath holds needed in sequential scanning.
3. It **reduces partial volume artefacts** since the reconstructed slices can be incremented in small steps.
4. Because of the volume acquisition of data, **resolution in the axial direction is good**, and reformatting into other planes is improved.

Disadvantages:

1. **No cooling periods between slices** → high heat loading of the tube.
2. Even though a high-capacity tube and sensitive detectors are used → a **lower mA must be employed** → ↓ ***patient dose*** but ↑ ***noise***, particularly with thicker patients.
3. There is some **loss of spatial resolution** due to the interpolation process.
4. **A high-speed computer** with a large data store is necessary.

Pitch

- ***Def.:*** **the distance (millimeters)** moved by the table during one rotation of the tube divided by **the slice thickness (millimeters)**
- Increasing the pitch, by increasing the table speed, is like stretching the spring;
  - سرعه Speeds up scanning.
  - جرعه Reduces dose,
  - BUT resolution may be lost "greater interpolation needed".
- Above a pitch of **2:1** there are gaps in the volume being scanned, and artefacts may arise.

Two-dimensional reformatting

- Imaginary, mathematical, parallel 'rays' may be sent in any chosen direction through the three-dimensional array of CT data in the computer memory, and projected on to a selected image plane.
- As each ray encounters the CT numbers in the voxels it passes through, it may first reject the high numbers corresponding to bone if it is required to remove bone from the image. Then:
  (a) In shaded surface display (SSD)
  - **Any CT number** so encountered in any voxel along each ray is recorded in a corresponding pixel in the image plane, provided it exceeds a set threshold value.
  - The image is displayed as if illuminated by an imaginary light source.
  - Particularly useful in plastic surgery.

(b) In maximum intensity projection (MIP)

- **The highest CT number** so encountered in any voxel along each ray is recorded in a corresponding pixel in the image plane.
- **Calcified lesions and contrast media** can be distinguished.
- Used particularly in **CT angiography** and **arthrography**.

Three-dimensional reformatting

- Multiple projections may be made in this way, around an axis of rotation, and displayed in a cine loop as a rotating three-dimensional representation of anatomy, either as a shaded surface image or a volume rendered (see-through) display.
- These software manipulations are very computer-hungry and may be time-consuming.

Cine computed tomography scanning

A ***continuously rotating scanner*** can also be used with the couch stationary to take a sequence of images of a single slice, e.g. to study the passage of contrast medium through the slice and to allow the best image to be selected for interpretation.

GAMMA IMAGING

5.1 RADIOACTIVITY

Stable nuclei

- Nearly all the nuclides extant in the world are stable.
- Apart from the nucleus of ordinary hydrogen, which consists of a single proton;
  - **All the stable lighter nuclei** contain nearly **equal numbers of protons and neutrons**.
    For example, the nucleus of a *helium atom* (alpha particle) is a very stable combination of two neutrons and two protons.
  - **The heavier nuclei** contain **a greater proportion of neutrons**.

Isotopes

Isotopes of an element are nuclides which	
Similar in	**Different in**
The number of protons. Atomic number. Position in the periodic table. Chemical and metabolic properties.	The number of neutrons. Mass number. Density Other physical properties

- **The nuclei of all carbon atoms contain six protons**.
  - 99% of stable carbon nuclei are **carbon-12** (^{12}C) with six neutrons;
  - 1% is **carbon-13** (^{13}C) with seven neutrons.
  - **Carbon-11** (^{11}C) with only 5 neutrons "neutron deficit", and **carbon-14** (^{14}C) with 8 neutrons "neutron excess" → both artificially produced, unstable & radioactive
  - All 4 nuclides are isotopes of carbon.

Radionuclides

Unstable nuclei, having a neutron excess or deficit, are radioactive → 'decay' to become stable nuclei, with the emission of any combination of alpha, beta, and gamma radiation.

Production of radionuclides:

- **Natural radionuclides:** few, sufficiently long lived, e.g. uranium, radium, and radon.
- **Radionuclides in medical imaging** → produced artificially, in the following ways:

Radionuclides produced by additional neutron forced into a stable nucleus:

- Nucleus has a neutron excess → unstable.
- In a ***nuclear reactor***,
- e.g. with **Molybdenum (Mo)**:
  $$^{98}Mo + n \rightarrow {}^{99}Mo$$
- Same atomic number.
- Mass number increased by 1.
- Radionuclides produced have same chemical properties "an isotope" → cannot be made ***'carrier-free'***.

Radionuclides produced by additional proton forced into a stable nucleus → knocking out a neutron:

- Nucleus has a *neutron deficit* → unstable.
- In a ***cyclotron*** which accelerates positively charged ions: e.g. protons or alpha particles.
- e.g. with **Boron (B)**:
  $$^{11}B + p \rightarrow {}^{11}C + n$$
- Atomic number increased by 1.
- Same mass number.
- Can be obtained ***carrier-free***.
- **Short lived** → only possible to use them near to the cyclotron.

Radioactive fission products may be extracted from the spent fuel rods of nuclear reactors.

Radionuclides are obtained from generators (Section 5.5)

5.2 RADIOACTIVE DECAY

Nuclides with a neutron excess:

β⁻ Decay

- Neutron change into a proton & an electron → the electron is ejected from the nucleus with high energy **"-ve beta particle"**

$$n \rightarrow p + \beta^-$$

- For example,

Iodine-131 (^{131}I, Z= 53) → Xenon-131 (^{131}Xe, Z= 54).

- Same mass number.
- Atomic number increased by 1 العالى يعلى.
- The daughter nucleus mostly produced with excess energy → immediate loss with the emission of one or more **γ** photons → daughter nucleus in ***ground state'***.

Isomeric transition (IT)

- In isomeric transformation: **γ** ray is not emitted immediately, but after appreciable time from emission of β particle.
- For example,

$$^{99}_{42}Mo \xrightarrow[67\ h]{\beta^-,\gamma} {}^{99m}_{43}Tc \xrightarrow[6\ h]{\gamma} {}^{99}_{43}Tc \xrightarrow[0.2\ Ma]{\beta^-,\gamma} \text{Stable nuclide}$$

  - The daughter nucleus technetium-99 (^{99}Tc) remains in the excited state for **6 hours**.
  - It is said to be metastable, and is written technetium-99m (^{99m}Tc).
  - Technetium-99m decays to the ground state ^{99}Tc, with the emission of a **γ**-ray of energy **140 keV**.
  - Isomeric transition here result in **γ** rays only "no β ray emission"
  - ^{99}Tc & ^{99m}Tc are said to be ***ISOMERS***:
    Def. of isomers: nuclei having different energy states but otherwise indistinguishable as regards A number, Z number and other properties.
- Another isomeric transformation used in nuclear imaging occurs when ***rubidium-81 (^{81}Rb)*** decays to ***kryplon-81 (^{81}Kr)***

$$^{81}Rb \rightarrow {}^{81m}Kr \rightarrow {}^{81}Kr$$

Nuclides with a neutron deficit:

β⁺ Decay

- A proton change into a neutron and a positive electron → the latter is ejected from the nucleus with high energy **"+ve β particle"**.

$$p \rightarrow n + \beta^+$$

- For example,

Carbon-11 (^{11}C, Z= 6) → Boron-11 (^{11}B, Z= 5).

- Same Mass and charge.
- The atomic number decreased by 1 الناقص يوطى.
- The daughter nucleus, if excited → loses excess energy by the emission of gamma photons till reaches the ground state.

K-electron capture (EC)

- The nucleus capturing an extra-nuclear electron from the nearest (K) shell → increase its number of neutrons relative to the number of protons.

$$p + e \rightarrow n$$

- Same Mass and charge.

- The atomic number decreased by 1 يوطى برضه الناقص.
- The daughter nuclide will emit **characteristic X-rays** when the hole so created in the K-shell is filled by an electron from an outer shell ± **gamma rays** if still excited.
- **Iodine-123 (^{123}I)** decays by electron capture and emits **160 keV gamma** and **28 keV X-rays**, but **no β-particles**.

Gamma Rays:

- Gamma rays have identical properties to X-rays.
- The gamma rays emitted during radioactive decay have at most a **line spectrum** which is **characteristic of the nuclide** which emits them.
- For example, ^{131}**I** emits mostly **360 keV gamma rays**.

Internal conversion (IC)

The γ rays emitted by nuclei → photoelectrically absorbed in its K-shell → emit both **photoelectrons** and **characteristic X-rays**, usually of fairly low energy.

Beta rays

- Have a **continuous spectrum** of energies up to a **maximum E_{max}** which is **characteristic of the radionuclide**.
- Their average energy is about $E_{max}/3$.
- When positive and negative beta particles travel through a material → excitation & ionization of atoms "track of the particle is dotted with ion pairs" → till the loss of the whole initial energy → stop "end of its range".
- **The range of beta particles** is greater with **↑↑ initial energy** of β particle & **↓↓ density** of the material "inversely proportional".
- The most energetic beta rays have a range of about **2 mm** in tissue.

Positron emitters

- Positron (= positive electrons) is **antimatter** → very brief existence.
- **FATE:** When a +ve beta particle comes to the end of its range → it combines with a -ve electron → **the charges** neutralize each other, and **the masses** of the two electrons are wholly converted into two photons of annihilation radiation (each of 511 keV) & travel in opposite directions
- ***According to Einstein's formula***

$$E = mc^2$$

- Positron emitters are used in positron emission tomography (PET) imaging.

RADIOACTIVE DECAY

Radioactive disintegration is a stochastic process.

Activity:

= The rate of disintegration = **the number of nuclei disintegrating per second**

- ✓ The SI unit is **Becquerel (Bq)** = 1 disintegration per second → Bq is a very low activity.
- ✓ **The natural radioactive content of the human body** = **2 kBq (2000 Bq)**.
- ✓ The activity of radionuclide administrations in imaging are measured in Megabecquerels (1 MBq = 10^6Bq) and the activity of radionuclide generators in Gegabecquerels (1 GBq = 10^9 Bq)

- ✓ The older unit is **the Curie "Ci"** → **(1 mCi = 37 MBq)**

- **Counts** = number of **β** or **γ** rays enter a detector
- **The count rate** = number of counts per second, **cps**
- ***Count rate*** is measured by a detector is **less than** the ***activity*** because the greater proportion of the rays usually miss the detector "undetected".
- However,

Count rate **α** activity **α** number or mass of radioactive atoms in sample

The fundamental law of radioactive decay states that:

The activity of a radioactive sample decreases by equal fractions (%) in equal time intervals.
→ **The Exponential Law**

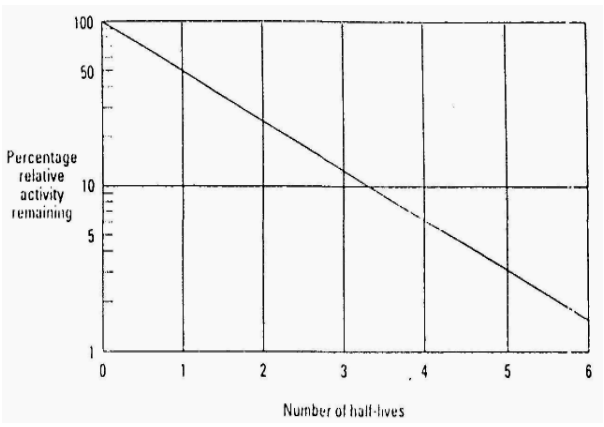
Physical Half-Life:

- **The half-life ($t_{1/2}$) of a radionuclide**
  = the time taken for its activity to decay to 1/2 of its original value.
- For example,
  2 successive half-lives reduce the activity of a radionuclide by a factor of 2 x 2 = 4.
  10 half-lives reduce the activity by a factor of 2^{10} = 1000.
- This half-life is more properly called the physical half-life.
  - ✓ **Characteristic** for the radionuclide.
  - ✓ **Unaffected** by any agency such as heat, pressure, electricity, or chemical reactions.
  - ✓ Examples for the physical half-lives:

Nuclide	Half-life
Krypton -81m	13 s
Rubidium -62	1 min
Nitrogen -13	10 min
Carbon -11	20 min
Gallium -68	68 min
Fluorine -18	112 min
Technetium -99m	6 h
Iodine -123	13 h
Molybdenum-99	67 h
Indium -111	67 h
Thallium -201	73 h
Gallium -67	78 h
Xenon -133	5 days
Iodine -131	8 days
Technetium-99	200 000 years

Exponential Decay:

- Activity of a radioactive sample never falls to Zero.
- The graph of activity versus time, both being plotted on linear scales → **exponential curve**.
- If, the activity is plotted on a logarithmic scale, → **straight-line** (Fig. 5.1).
- Such graphs are useful in calculating:
  1. **The activity** of prepared sample at a particular time; and
  2. **Time** necessary to store radionuclide waste.



Effective Half-Life:

- For imaging: **the pharmaceutical is 'labeled' with the radionuclide** forming **the radiopharmaceutical**
- The metabolic properties of the pharmaceutical ensure that it concentrates in the tissues or organ of interest.
- The pharmaceutical alone is eliminated from the tissues, organ, and whole body by metabolic processes & excretion → biological half-life **"t_{biol}"**
- The radionuclide activity alone decays with its physical half-life **"t_{phys}"**.
- The activity of the radiopharmaceutical administered in body decreases due to the simultaneous effects of:
  - **a)** Radioactive decay
  - **b)** Metabolic turnover and excretion.

  The activity can be regarded as having an effective half-life **"t_{eff}"**
- The effective half-life is shorter than either the biological or physical half-lives.

$$1 / t_{eff} = 1 / t_{boil} + 1 / t_{phys}$$

- **The effective half-life depends on:**
  - **a)** The radiopharmaceutical.
  - **b)** The organ involved.
  - **c)** Personal variations.
  - **d)** Health state of the organ.

5.3 GAMMA IMAGING

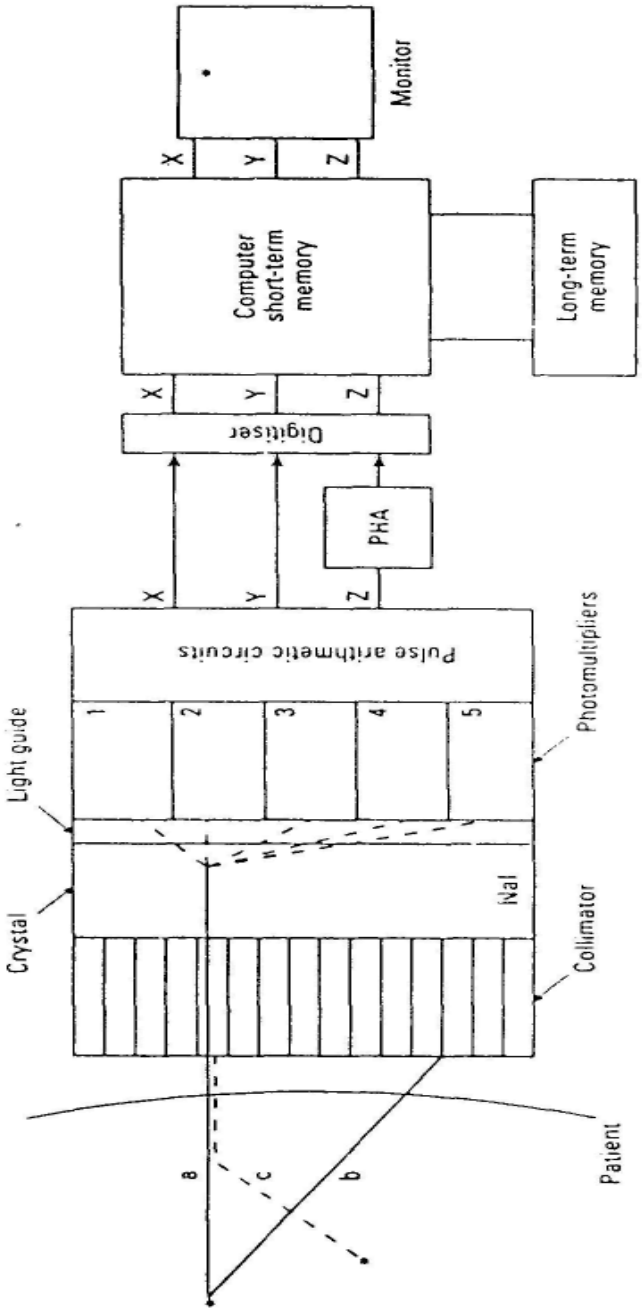
- The patient is given an appropriate radiopharmaceutical, usually by intravenous injection.
  (a) The function of the pharmaceutical is to concentrate in the organ or tissues of interest.
  (b) The role of the radionuclide is to signal the location of the radiopharmaceutical by the emission of gamma rays.
- The radionuclide most commonly used, ^{99m}**Tc**, emits **140 keV gamma rays**.
- γ-rays are collected by a gamma camera → image of the radioactive distribution on a monitor screen.
- Since gamma rays cannot be focused → **Multihole collimator** is used.
- A gamma camera has **heavy lead shielding** → attenuate background gamma radiation.

The Multihole Collimator

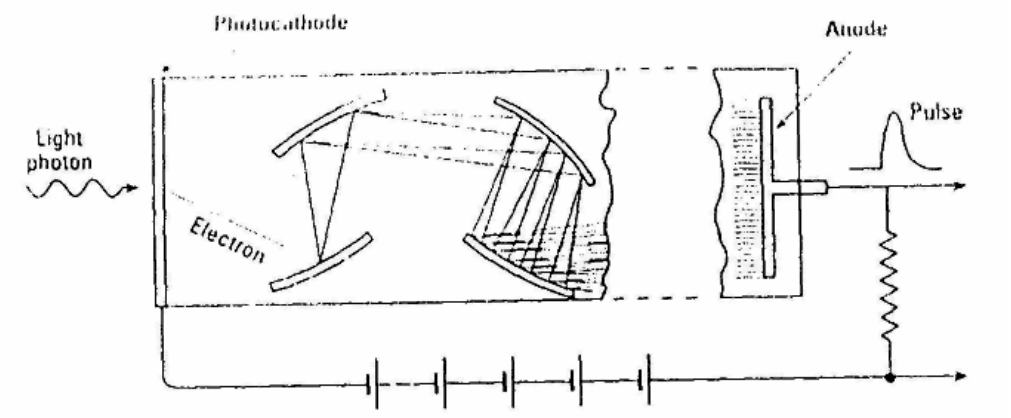
- This consists of:
  1. **Lead disk:** **25 mm thick** and **400 mm in diameter**.
  2. It is drilled with **20000** **circular or hexagonal holes**, each **2.5 mm in diameter**.
  3. They are **separated by septa** **0.3 mm thick** which absorb the rays attempting to pass through them obliquely.
     (The half value layer (HVL) of lead for ^{99m}Tc gamma rays is 0.3 mm.)
- Each hole only accepts gamma rays from a narrow channel, thus locating any radioactive source along its line of sight.
- For example, in Fig. 5.2:
  Ray "a" is accepted by the collimator, and ***Ray "b"*** rejected.
  Ray "c" can be scattered in the body and then pass through the collimator → rejected later by energy discrimination because it have less energy (in 'pulse height analyzer').

The crystal

- Instead of a large number of tiny detectors, behind the collimator there lies **a single large phosphor crystal** → **500 mm in diameter** and **9 - 12 mm thick**.
- It is made of **SODIUM IODIDE** (activated with a trace of thallium).
  NaI have a high atomic number (Z = 53) and density → it absorbs about **90% of ^{99}mTc gamma rays**, principally by the photoelectric process; but **only 30% of ^{131}I γ rays**.
- It is **fragile, hygroscopic** and **easily damaged by temperature changes**.
  To protect → it is encapsulated in an **aluminum cylinder** with one flat Pyrex face.
- ***Mechanism:***
  - The crystal absorbs **γ photon** (photon ***a***) → flash of light "dashed lines".
  - The flash contains say **5000 light photons** → travel in all directions and last less than a microsecond → about **4000** emerge from the farther flat surface.
  - The distribution of light leaving the face of the crystal depends upon which collimator hole the gamma ray passed through.
  - Light photons are **measured by up to 91 matched photomultipliers**, closely packed in a hexagonal array.
  - **A flat transparent plate** **"light guide"** maximizes transfer of light from the crystal to the photomultipliers.



Photomultipliers



- Each photomultiplier (Fig. 5.3) consists of:
  - An evacuated glass envelope.
  - **Photocathode** coated with a material which absorbs light and emits photoelectrons: **one electron per 5 or 10 light photons**.
- Electrons are accelerated toward a **positive anode**.
- *En route* electrons impinge on a series of **dynodes** "connected to progressively increasing positive potentials".
  - When each electron strikes a dynode it **knocks out 3-4 electrons** → accelerated to strike the next dynode.
  - After 10 stages, the electrons have been multiplied by a factor $4^{10} \approx 10^6$ مليون مره.
  - Thus **each initial flash of light** produces **a pulse of charge or voltage** large enough to be measured electronically.
- **The amplification factor** is very sensitive to changes in the overall voltage across the PMT **(about 1 kV)** → has to be highly stabilized.

Pulse arithmetic (position logic)

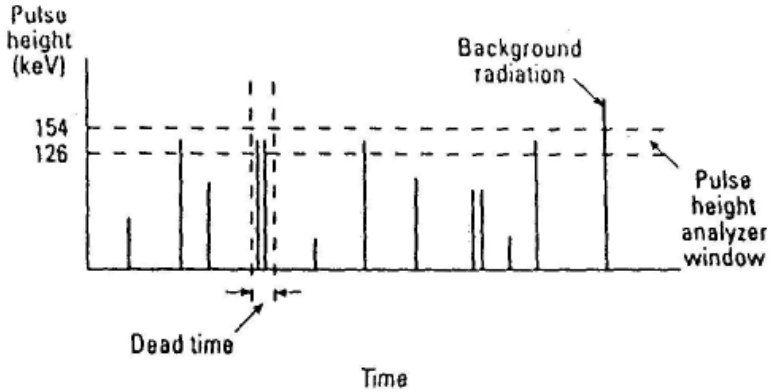
- In Fig. 5.2, the light pulse illuminates differentially the array of photomultiplier tubes. It produces the largest electrical pulse in photomultiplier (No. *2)* nearest to the collimator hole through which ***γ ray "a***" passed - and smaller pulses in adjacent photomultipliers.
- ***The 'pulse arithmetic circuit'*** is a microprocessor chip, which combines the pulses from all the photomultipliers according to certain equations → yields three voltage pulses (X, *Y,* Z) which are proportional to:
  1. **The horizontal "X" and vertical "Y" coordinates of the light flash in the crystal** → the hole through which the gamma ray has passed → and so the position in the body of the radioactive atom that has emitted it *(X, Y).*
  2. **The photon energy of the original gamma ray (Z)**.
     - ✓ The pulses from all the photomultipliers are summed → measuring all the light produced by the gamma ray in the phosphor crystal.
     - ✓ The size or 'height' of the Z-pulse (in volts) is proportional to the **γ** ray energy absorbed (in keV).
     - ✓ **The pulse height is generally stated in kiloelectronvolts**.

Pulse height spectrum:

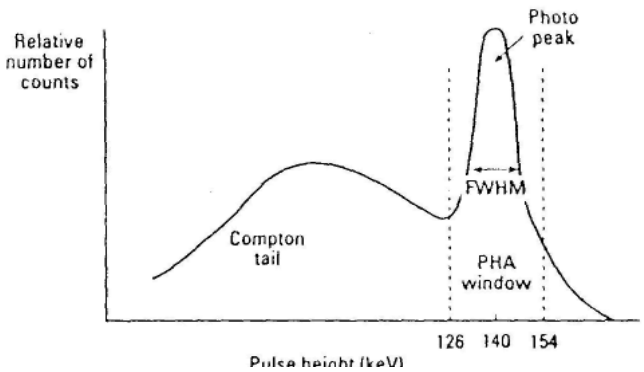
- **The account so far ignores two facts:**
  1. **Scattered Gamma rays** → gamma rays originated outside the line of sight of the collimator can enter a collimator hole.

     Scattered rays will have **reduced energy** (***ray "c"*** in Fig. 5.2);
  2. Gamma rays may lose energy through **Compton interactions** in the crystal before being absorbed photoelectrically → **pulses of reduced height**.

∴ Z-pulses vary in height.



- For ^{99m}Tc, Fig. 5.4 illustrates a sequence of such pulses; it plots the height (kiloelectronvolts) of pulses coming in succession from a photomultiplier coupled to a phosphor crystal against time.



- Figure 5.5 plots the relative number of pulses having various heights or energies, in a given period of time.

(***FWHM***, full width at half maximum. ***PHA***, pulse height analyzer.)

- This pulse height spectrum is made up of:

  Photopeak: on the right,
  - Comprising pulses produced by complete photoelectric absorption in the crystal of gamma ray photons which have come from within the patient without suffering Compton scattering.
  - They **vary in height**, within a 'window' shown by horizontal dashed lines in Fig. 5.4.
    This range of energies in the photopeak is due to statistical fluctuations in both:
    1. Number of **light photons produced in the crystal** by each gamma ray photon and
    2. Number of **electrons produced in the photomultiplier** by each light photon.

    This also causes **the short tail on the right**.

  Tail, on the left,
  Containing **pulses of lower energy**

  → produced by γ rays suffered Compton interactions in the patient or the crystal.

  Subsidiary 'iodine escape peak'
  - At 30 keV below the photopeak.
  - Due to some of the K-characteristic rays from iodine escaping from the crystal.
- Only pulses in the photopeak are of use in locating the source of the radioactivity in the patient, → A **pulse height analyzer** is used to reject those in the Compton tail

Pulse height analyzer:

- **The Z-pulses** enter a pulse height analyzer → reject pulses which are **(a) lower** than a preset value or **(b) higher** than another preset value.
- It allows only pulses which lie within a window of, say, **±10% of the photopeak energy**.
- Any high-energy background radiation is also rejected.
- The pulses so selected are referred to as **'counts'**.

- In the case of ^{99m}**Tc** the window might be set **at 126-154 keV, centered on 140 keV**.
  - ✓ Because a 140 keV photon will lose only 10 keV of energy even when scattered through 45° → some scattered photons may 'pass through' the window & produce counts → degrade the image.
- For ^{67}***Ga*** or ^{111}***In*** → 2 or 3 windows must be used → each selecting one γ ray energy.

- **The X-, Y-, and Z-pulses** are next applied:

1. Directly to a **monitor** for visual interpretation "in older machines", or
2. Newer systems → **analog-to-digital converters (ADCs)** into a computer, enables:
   - ✓ Dynamic and gated studies.
   - ✓ Image processing.

The monitor

- *The X- and Y-pulses* steer the electron beam in the monitor tube.
- If and only if the Z-pulse has passed through the window of the pulse height analyzer → ***a pinpoint of light*** appear momentarily on the screen at the X- and Y-coordinates corresponding to **the heights** of the X-and Y-pulses and **the positions** of the radioactive atom emitting each gamma ray.
- Thousands of such dots, equally bright, make up the image.
- **Two types of monitor** are used:
  1. **Long persistence screen:**
     - × Each dot of light persists for a sufficiently long time for a visual image to build up of the radioactivity in the patient.
     - × The image quality is not good enough for diagnosis → only helpful for positioning the patient and making sure that the activity has been taken up.
  2. **Short persistence screen: of high quality;**
     - × Each dot *quickly dies away* but can be captured on film, using a film camera.
- **Types of film camera:**
  1. **Polaroid film camera:**
     - ✓ **Adv.:** high speed – high resolution - processed very quickly.
     - ✓ **Disadv:** expensive - low contrast - limited dynamic range.
  2. **Multiformat film camera:**
     - ✓ Employs **single-coated cut transparency film**, formulated for X-ray automatic processor.
     - ✓ A number of images can be recorded in sequence side by side on a single film.
- If the film is **exposed for too long**, it will be **saturated**;
  if **for too short time**, the image will be **underexposed, faint, and grainy**.
- Typically***, a total of 0.5 million counts is acquired for each image, taking about 5 min.***

The computer

- After digitization with an ADC → the X-, Y- and Z-pulses pass to a computer → records each Z-pulse as a count in a memory location corresponding to the X- and Y-coordinates.
- As the pulses arrive at random, the counts build up in each location → stored as a digital image in a 128 x 128 matrix.
- When complete, it is scanned by a television raster and **displayed on a monitor screen as a 128 x 128 matrix of 3mm pixels**.
- **The brightness of each pixel** depends on the number of counts stored in the corresponding memory location, i.e. to the number of gamma rays which have emanated from the corresponding area of the patient and to the activity therein.
- **If counts were acquired for too long**, the memory locations would become full
  → more or less uniformly bright monitor screen me.
  If they were acquired for too short time → grainy image.

Typically, a total of 0.5 or 1 million counts are acquired for each image frame

- **Stored image can be manipulated and improved, as described in Chapter 4:** Background suppression - Blurring reduction - Contrast enhancement by windowing - Noise reduction by averaging - Pixel interpolation "to increase matrix" – Extraction of Quantitative data – Image subtraction or addition for two radionuclides.

Dynamic imaging

- **The function** of kidney, lungs, heart, etc., can be studied by acquiring **a series of separate images (frames)** in suitably rapid succession. The images can be retrieved from the computer store in sequence and either ***(a)*** recorded side by side on a single film in a multiformat camera or ***(b)*** repeatedly displayed *seriatim* on the screen as a cine loop.
- **Areas of interest (e.g. kidneys)** can be defined by cursors → and the total counts therein measured on each frame and displayed as a function of time (e.g. a renogram).
- **An area of interest can be defined between the kidneys** → used for **background subtraction**.
- **In multiple-gated cardiac studies:**
  - ✓ Separate frames, each lasting 40 ms, are acquired at 20–30 different points in each cardiac cycle. Each sequence is initiated by the R-wave from an ECG.
  - ✓ At each such point, several hundred successive images are added, pixel by pixel, to improve statistics and reduce noise.
  - ✓ The images → multiformat mode or cine loop of the pulsating heart.
  - ✓ Quantitative data about heart function can be extracted.

COLLIMATORS:

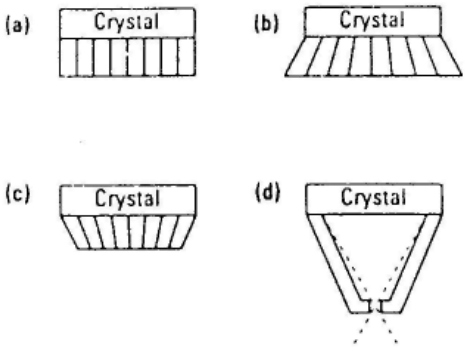


Fig. 5.6 **Types of collimator**

(a) Parallel hole, (b) divergent hole, (c) convergent, hole, and (d) pinhole.

	Parallel hole	***Divergent hole***	***Convergent hole***	***Pinhole***
Camera	400 mm	smaller camera e.g. mobile γ camera		
FOV	Same at all distances	Large	Small	
holes		Holes diverge toward pt.	Holes converge toward pt.	
Image	Same size	Minified	Magnified	Magnified & inverted
Usage		Imaging large	Children	Superficial small

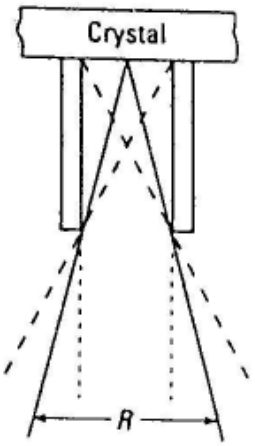
		organs e.g. lung		organs e.g. Thyroid
Characteristics	Sensitivity is same at any distance	Both FOV & sensitivity vary with distance. Both have geometrical blurring.		
	Resolution ↓ with ↑ collimator-object distance		Resolution ↓ toward edge	

The sensitivity "efficiency" of collimator

- Measures **the proportion of gamma rays, falling on collimator from all directions that pass through the holes**.
- It is only a fraction of a percent.
- **The sensitivity is greater with: The more holes - the wider & shorter they are.**
- ↑ Sensitivity → ↓ radionuclide needed to be administered → ↓ patient dose.

Spatial resolution:

Def.: **the ability of the system to produce distinct images of 2 small radioactive sources close together.**



- Figure 5.7 illustrates one of the holes in a collimator, lying between the crystal and the surface of the patient.
  - γ rays originating between the inner dotted lines → 'illuminate' the whole of the 'visible' crystal surface → produce a maximum signal.
  - γ rays originating outside the outer dashed lines → cut off by the lead septa → produce no signal.
  - γ rays originating from any points along the solid lines illuminate exactly half of the crystal face.
- ***R*** is the spatial resolution of the collimator; **↑ R → ↓ resolution**
- ***Factors affecting the spatial resolution:***
  - ↑ Distance from collimator face → ↑ ***R*** i.e. worse resolution.
    ∴ Resolution is best close to the collimator.
  - Wider or shorter holes → ↑↑ sensitivity but ↓↓ spatial resolution.
    ∴ The better the resolution, the less the sensitivity & a compromise must be made.
    This is a major limitation to the performance of a gamma camera.

Types of collimator:

Low energy collimators	▪ have thin septa (0.3 mm) & more holes. ▪ can be used with gamma rays of up to 150 keV, e.g. with ^{99m}Tc
Medium-energy	▪ for use up to 400 keV, e.g. with ^{111}In, ^{67}Ga, and ^{131}I. ▪ have thicker septa (1.4 mm) and consequently fewer holes ▪ lower sensitivity.
General purpose	▪ have **20000 holes** each **2.5 mm** diameter. ▪ Resolution (@ 10 cm from the face) = **9 mm**. ▪ Sensitivity =**150 cps/MBq**.
high-resolution	▪ have more and smaller holes. ▪ lower sensitivity → ↑ amount of radioactivity and the imaging times.
high-sensitivity	▪ have fewer and larger holes.

	▪ poorer resolution. ▪ used in dynamic imaging where short exposure times are necessary.

Types of gamma camera:

- **General-purpose 400 mm camera** → optimized for ^{99m}Tc.
- **A mobile gamma camera** → for cardiac imaging "easy to position, used ICUs" ***250 mm*** field - 5 mm thick crystal → good resolution with 80 keV γ rays from ^{201}T1.
- **A large field of view (500 mm) camera** → bone and gallium imaging.
- **A scanning gamma camera**

  The head translates along the patient → ↑↑ image matrix from 128 x 128 to 128 x 512.

5.4 CHARACTERISTICS AND QUALITY ASSURANCE OF THE GAMMA IMAGE

Uniformity of field

- Tested by a **flood field phantom** consists of a flat sealed dish, larger than the field of view (FOV), filled with ^{99m}Tc or its longer lived analog cotalt-57 (^{57}Co).

Should give a uniform image, with and without the collimator in place

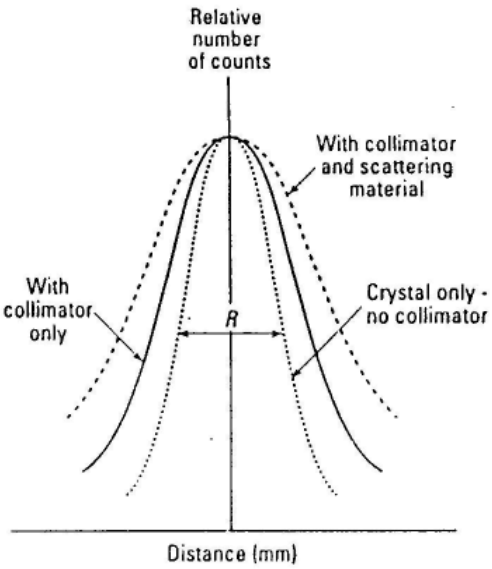
- A **defective photomultiplier** → seen as a **dark area** in the image.
- A **cracked crystal** → a **linear defect**.
- **Slight differences in the performance of individual photomultipliers** → **Non-uniformity** due to:
  - ✓ Is assessed by instructing the computer to compute a histogram of the counts in individual pixels. (A sufficiently long exposure is necessary to reduce noise).
  - ✓ It calculates the mean & standard deviation → typically the **uniformity is 1 - 2%**.
- Modern gamma cameras can be instructed to compensate subsequent images automatically for minor non-uniformities of the field.

Spatial resolution:

See before

Intrinsic resolution:

- Refers to **THE CAMERA** (crystal, photomultipliers, and position logic circuits) **in the absence of the collimator and patient**.
- When a single γ photon is absorbed at a point in the crystal, the 4000 or so photons of emerging light only eject a total of 400 or so electrons from the photocathodes of all the photomultipliers.
  - × In Fig. 5.2, photomultipliers Nos. 1 and 3 should receive equal numbers of photons and produce identical pulses.
  - × BUT, because of **the small numbers of light photons and electrons** involved → significant **statistical variations** in the relative numbers and the heights of the pulses produced → errors in the X and Y coordinates assigned to the event → **blurring**
- Intrinsic resolution can be improved by using a **THINNER CRYSTAL** but with consequent **reduction in sensitivity** (just as with intensifying screens).



System resolution:

- Total blurring due to **Intrinsic blurring**, **Collimator** & **Scattering of γ rays in the patient** (according to the same formula as for radiographic blurrings).
- Resolution worsens **the farther the activity from the collimator**. Consequently it is worse for fat patients than for thin.

Testing the resolution:

Resolution can be tested by imaging a line source

- The computer is instructed to plot the counts along **a line of pixels at right angles to a thin tube filled with ^{99m}Tc**. The graph (Fig. 5.8) is called **"line spread function"**.
- **The line source can be placed:**
  - ✓ **Against the face of the collimator in air (solid curve).**
    The spread of the curve measured halfway up, called the ***'full width to half maximum' or FWHM*** corresponds to **R** in Fig. 5.7, and is **typically 5 mm**.
  - ✓ **Against the crystal face after removing the collimator (dotted curve).**
    The FWHM of this curve measures **intrinsic resolution**, typically **1 - 2 mm**.
  - ✓ **At 10 cm deep in a scattering medium while using the collimator (dashed curve).**
    (This depth is chosen, as organs being imaged typically lie 5-10 cm deep)
    The FWHM of this curve measures **system resolution**, typically **10 mm**.

Resolution is not improved by using smaller pixel size than 3 mm in a 128 x 128 matrix.

Alternatively, spatial resolution can be tested with a bar test pattern:

- It is made of either; strips of lead placed on a flood field phantom or evenly spaced parallel line sources.
- It is placed against the face of the crystal.
- This measures **the intrinsic resolution** → **typically 3-6 lp \ cm**.
- In practice **the overall system resolution** is **worse than 1 lp \ cm**.

So, the value of γ imaging lies in evaluating function rather than anatomy

Linearity

Linearity (**i.e. lack of distortion**) can also be checked by **imaging a line source**.

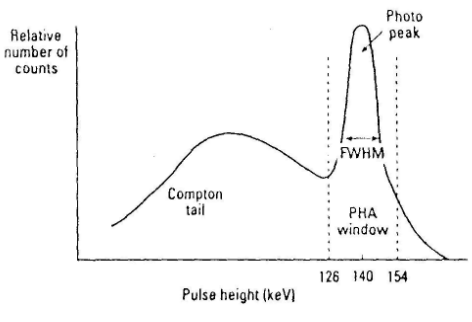
Energy resolution

Def.: **the ability to distinguish between separate gamma rays of different energies.**

- ***Importance:***

Better **energy resolution** → better **scatter rejection** & better **spatial resolution**

- Calculated from **FWHM of the photopeak divided by the energy of the photon** & **expressed as a percentage**
  Typically 12% of the peak energy



- The pulse height analyzer - in a sophisticated form called **Multichannel Analyzer** - can be used to plot the photopeak (see Fig. 5.5).
- Setting a **narrower pulse height analyzer window** → **improves the energy resolution** but **reduces the sensitivity and increases imaging time**.
- **The energy resolution is better for high-energy gamma photons** because they each produce more light photons → it is therefore **better with ^{99m}Tc than with ^{201}T1**.

Temporal resolution: dead time and lost counts

- **Flash of light produced by a gamma photon in the crystal has a decay time of 0.2 µs**
- About 95% of the light has been emitted in **1 µs**, at which point the pulse is cut off electronically. For that period the counting circuit does not recognize other pulses, and is said to be 'dead'.
- Due to the stochastic nature of radioactive decay, counts arrive at **irregular intervals**.
  If 2 gamma photon enters the camera during the dead time (indicated by vertical dashed lines in the figure) → the two flashes of light overlap, and they are treated as one.
  → if the combined pulse is too large, it will be rejected by the pulse height analyzer.

Lost counts:

At high count rates a significant proportion of the gamma photons is missed → underestimated count rate

- Typically there is **20% loss at 40000 cps** and more at higher count rates

Effect on resolution:

- If two Compton-scattered photons (60 and 80 keV) enter the system within 1 µs of each other → recorded as a single photon (140 keV) → pass through the pulse height analyzer & produce a spurious image in a false location → **deterioration of the spatial resolution**
- Obvious at the high count rates **in cardiac imaging**.

Sensitivity

- This is measured with a **small version of the flood field phantom**.
- Expressed as **Total counts per second per megabequerel of activity**.
- **The crystal efficiency** is rather high, & **the collimator** **determines overall efficiency**.

Up to a point, using **thicker** crystal ***increases sensitivity*** but ***poorer resolution***; more importantly, so does using a collimator with **larger** holes.

Noise: Quantum Mottle

- Using **shorter exposure** → the flood field phantom shows a characteristic mottled appearance "because **the counts fluctuate from pixel to pixel**".
- The computer can be instructed to draw a histogram of counts per pixel and to calculate the mean and standard deviation.
  & dividing the mean by the standard deviation gives **the signal-to-noise ratio**.
- **Noise in gamma imaging is high** because of the inherently small signal from a limited amount of radioactivity.

Noise could be reduced by using **more radionuclide** → BUT, ↑↑ patient dose.

- The activity is distributed through the body and typically only ***20%*** concentrated in the organ of interest.
- **The gamma rays are emitted isotopically** and only a small fraction passes through the collimator holes (cannot be made too wide otherwise resolution is lost).
- The gamma rays could be collected for any length of time without further dose to the patient → but imaging time is limited by **ability of the patient to stay still** & **workload**. The imaging time must be shorter still for dynamic studies, especially cardiac imaging.
- **The total counts acquired per image are further subdivided among the 128 x 128 pixels → only about 100 counts per pixel → ∴ pixel to pixel noise = 10%.**
- More important is the number of counts acquired over the blur size **R** about 1000, with a noise of 3% → ∴ **hot spots and cold spots of about 10%** can detected against the background activity in the body.

  This **"Contrast Resolution"** can only be improved at the expense of either increased patient dose or worsened spatial resolution.

- Noise is the principal factor in determining the quality of gamma images.

Gamma imaging is therefore said to be noise limited or dose limited.

- The count rate is maximized and the patient dose minimized by a judicious choice of radiopharmaceutical.

5.5 RADIOPHARMACEUTICALS

Desirable properties of a radionuclide for imaging are:

1. A ***physical half-life of a few hours***, similar to the time from preparation to injection.
   If the half-life is too short, much more activity must be prepared than is actually injected.
2. ***Decay to a stable daughter*** or one with a very long half-life (e.g. 200 000 yrs for ^{99}Tc).
3. Emit ***γ rays*** (which produce the image) but ***no α or β particles*** or very low-energy photons (which have a high linear energy transfer "LET", & only deposit dose in patient)

Decay by isomeric transition or electron capture is preferred.

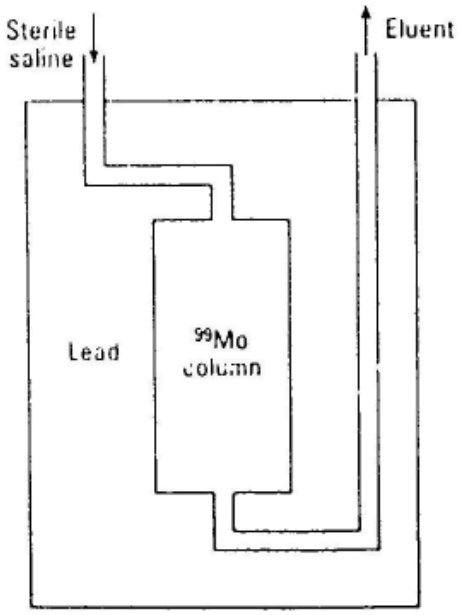
4. Emit gamma rays of energy ***50-300 keV*** (**ideally 150 keV**)
   → high enough to exit the patient but low enough to be easily collimated and easily measured, being largely absorbed in the collimator septa and the crystal.
5. Ideally ***emit monoenergetic gamma rays*** so that scatter can be eliminated by energy discrimination with the pulse height analyzer.
6. Be ***easily and firmly attached to the pharmaceutical*** at room temperature & not affect its metabolism.
7. Be readily ***available*** on the hospital site.
8. Have a ***high specific activity***.

In addition, the radiopharmaceutical should:

1. ***localize*** largely and quickly in the 'target';
2. be ***eliminated*** from the body with an **effective half-life similar to the duration of the examination** → patient dose;
3. have a ***low toxicity***;
4. form a ***stable product*** both in *vitro* and *in vivo*
5. be readily ***available and cheap*** per patient dose.

Technetium generator:

- ^{99m}Tc is used in 90% of radionuclide imaging as it fulfills most of the above criteria:
  1. With its **gamma energy of 140 keV** → easily collimated and easily absorbed in thin crystal → good spatial resolution.
  2. With its **short half-life** and **pure gamma emission** → a reasonably large activity can be administered → reducing noise.
- ^{99m}Tc is supplied in a generator shielded with lead, Fig. 5.9
- The generator contains an **alumina exchange column** on which has been absorbed a compound of **the parent ^{99}Mo** (produced in **nuclear reactor** & it's **half-life = 67 h**).



- **At the time of arrival, the activity of the 'daughter' ^{99m}Tc has built up to its maximum, equal to that of the parent ^{99}Mo.**
- The daughter is decaying as quickly as it is being formed by the decay of its parent → ***transient equilibrium with the parent***.
- The daughter and parent decay together with **the half-life of the parent, 67 h** (Fig. 5.10).

- **The technetium is washed off (eluted)** as **sodium pertechnetate** with sterile saline solution → flows under pressure from a reservoir through the column into **a rubber–capped sterile container**.
  - Elution takes few minutes → leaves behind Molybdenum "firmly attached to column"
  - **The eluent** decays with its own **half-life of 6 h**.
  - **The ^{99m}Tc in the column** regrows with the same half-life of 6 h.
- **After 24 h** → the activity has grown again to a new maximum (equilibrium) value. (After 6 h it has reached 50% of the maximum; after 12 h, 75% and so on.)
- Figure 5.10 plots the activity of ^{99}Mo (dashed line) and ^{99m}Tc (solid line) against time, following the first elution (1) at time 0.

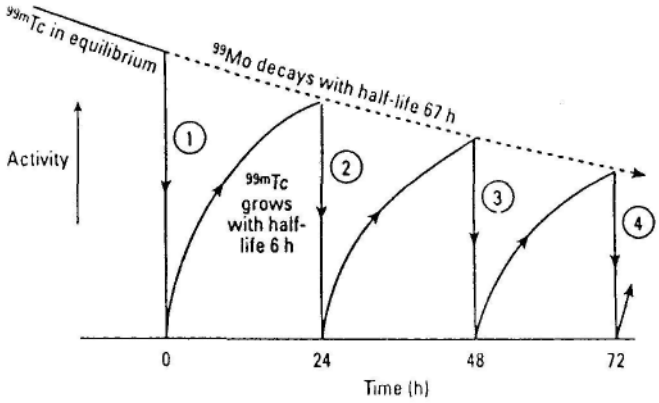


Fig. 5.10 Decay of activity of ^{99}Mo and growth and regrowth of activity of ^{99m}Tc in a generator which is eluted daily.

- **Elution can be made daily** (& if necessary, the column can be eluted twice daily) - though it will be seen that the strength of successive eluents (2, 3, . . .) diminishes in line with the decay of ^{99}Mo
  → **after a week**, the generator is replaced and the old one is returned for recycling.

Uses of Technetium-99m

- **Sodium pertechnetate-99m** "have similarity to iodide and chloride ions":
  1. Thyroid (trapped but not fully metabolized).
  2. Gastric emptying studies (mixed with bran porridge)
  3. Gastric mucosa (localization of Meckel's diverticulum)
  4. Testicular imaging.
  5. Salivary glands.
  6. Cerebral blood flow.
- **Technetium can easily be labelled to a wide variety of useful compounds:**
  1. **Hexamethyl propylene amine oxime (HMPAO)** → **cerebral** imaging;
  2. **Dimercaptosuccinic acid (DMSA)** - **Mercaptoacetyletriglycine (MAG3)** → **renal** study
  3. **Iminodiacetic acid (HIDA)** → **biliary** studies;
  4. **Human serum albumin (HSA) colloidal particles**, 0.5 μm in size, phagocytosed in reticulo-endothelial cells → imaging of **liver, spleen and red bone marrow**;
  5. **HSA Macroaggregates** - 15-100 μm microspheres → temporarily block a small fraction of the capillaries in **lung perfusion** imaging;
  6. **Diethylene Triamine Pentacetic Acid (DTPA) aerosol** (5 μm particles) →

lung ventilation studies

7. **Diphosphonates** → **bone** imaging, being taken up in sites of bone repair;
8. **Autologous red cells** → **cardiac** function;
9. **Heat–damaged autologous red cells** → imaging the **spleen**;
10. **Sestamibi or tetrofosmin** → **cardiac perfusion** imaging.

Other radionuclides and their uses

Iodine	• Avidly trapped and metabolized by the thyroid, which was the organ first imaged. • *Iodine-131* (^{131}I) the first radionuclide used for imaging: ‣ Cheap. ‣ highly reactive. ‣ excellent label. ‣ It is produced in a reactor and has a long shelf life (half-life 8 days). ***Disadv.:*** emits beta rays as well as rather energetic (mainly 364 keV) γ rays. • ^{131}I has largely been replaced by iodine-123 (^{123}I): ‣ more expensive. ‣ cyclotron produced. ‣ has a half-life of 13 h. ‣ decays by electron capture, emitting 159 keV gamma rays. • ^{123}I is more expensive than, but otherwise superior to ^{125}I which have: ‣ long half-life (60 days). ‣ low photon energy (around 30 keV). • Iodine may be labeled to hippuran for renal studies, being cleared by both glomerular nitration and tubular secretion.
Xenon-133 (^{133}Xe)	• Reactor produced. • Half-life = 5.2 days. • Emits beta rays and rather low-energy (81 keV) gamma rays. • It is an inert gas, although somewhat soluble in blood and fat. • Used, with rebreathing, in lung ventilation imaging.
Krypton-81m (^{8lm}Kr)	• Another inert gas. • Generator produced → the generator is eluted with compressed air. • Half-life = 13 s. • Emits 190 keV gamma rays. • The patient inhales the ***air-^{81m}Kr*** mixture in pulmonary ventilation studies. • The short life of the parent (***^{81}Rb, 4.7 h***) presents transport difficulties and means it must be used the day it is delivered
Gallium-67 (^{67}Ga)	• Cyclotron produced. • Half-life = 78 h. • Decays by electron capture, emitting gamma rays of three main energies. • Gallium citrate is used to detect tumors and abscesses as it binds to plasma proteins.
Indium-111 (^{111}In)	• Cyclotron produced. • Half-life = 67 h. • Decays by electron capture, emitting 173 and 247 keV gamma rays. • used to label white blood cells and platelets for locating abscesses and thromboses, respectively.
Indium-113m (^{113m}In)	• sometimes used instead of ^{111}In. • Generator produced. • Half-life = 100 min.

	• Emits only gamma rays, but they have a high energy (390 keV).
Thallium-201 (^{201}Th)	• Cyclotron produced. • Half-life = 73 h. • Decays by electron capture, emitting 80 keV X-rays. • As an analog of potassium → used as Thallous chloride in myocardial perfusion imaging, where its half-life is well suited to repeated imaging over a few hours

Preparation of radiopharmaceuticals

- By **simple mixing** at room temperature:
  Radionuclide (e.g. ^{99m}Tc) + Pharmaceutical (e.g. MDP) + other necessary chemicals
- **Shielded syringes** transfer the components between sterile vials.
- Manipulations **under sterile conditions** in a 'workstation' → **glove box** or **laminar downflow cabinet**.
- Room is under a **positive pressure of filtered sterile air**.
- **Impervious surfaces:** continuous floors- gloss-painted walls- Formica-topped benches.
- **Entry** is via an air lock and changing room.
- **The pharmacy** must meet the conditions of both the Medicines Act and the Ionising Radiations Regulations in the UK.

Quality control includes testing for:

1. **Radionuclide purity:**
   Testing for contamination with **^{99}Mo**, which give unnecessary dose to the patient
   By measuring γ radiation after blocking off the gamma rays from ^{99m}Tc with **6mm lead**;
2. **Radiochemical purity:**
   Testing for **free pertechnetate** in a labeled compound by **chromatography**;
3. **Chemical purity:**
   Spot colour test for **alumina**, "which would interfere with labeling";
4. **Sterility testing and pyrogens testing:** → available only retrospectively;
5. **Response of the radionuclide calibrator: (see Section 5.6).**

5.6 DOSE TO THE PATIENT

Dose to an organ

- **The absorbed dose delivered to an organ** by the activity it has taken up increases in proportion to:
  1. **the activity** administered to the patient and **the fraction** taken up by the organ;
  2. **the effective half-life** of the activity in the organ;
  3. **the energy (MeV) of beta and gamma radiation** emitted in each disintegration;
  4. Also depends on **how much of that energy escapes from the organ** & not contribute to the absorbed dose.
     - × All the energy of a **beta ray** is deposited inside the organ and none escapes.
     - × Some of the energy of **a gamma ray** is deposited in the organ and some leaves it, → depending on the size of the organ and how energetic the gamma ray is.
  5. **the additional dose** from activity in surrounding tissues.

Effective dose to the body

- Unlike imaging with X-rays, the dose delivered by a radionuclide examination is **unaffected by the number of images taken**
- After an intravenous injection most tissues may receive some dose, but **the target organ and the organs of excretion generally receive the highest doses**.

- The distribution of a dose is non-uniform and specific to the examination, but an average dose to the body as a whole can be calculated → ***the effective dose (ED)***, "Section 6.3"

Typical activities and doses

- **Most investigations** deliver an ED of **1 mSv or less** → no greater than the variation, from place to place and individual to individual, in the annual dose of natural radiation.
- Some, **such as bone or static brain imaging**, deliver doses in the region of **5 mSv**.
- Few examinations, such as **tumor or abscess imaging with ^{67}Ga**, deliver higher doses → undertaken only when other imaging modalities are inappropriate (Table 5.2).

Table 5.2 Typical activities and doses

Site	*Agent*	*Activity (MBq)*	*Effective dose (mSv)*
Bone	^{99m}Tc phosphonate	600	5
Lung ventilation	^{99m}T DTPA aerosol	80	0.6
	^{81m}Kr gas	6000	0.1
Lung perfusion	^{99m}T HA Macroaggregates	100	1
Kidney	^{99m}T DTPA gluconate	80	1
	^{99m}T MAG3	100	1
Tumor	^{67}GaGa^{3+}	150	18

- In order to minimize patient dose, patients should drink a good deal of water and empty the bladder frequently to reduce the dose to the gonads and pelvic bone marrow.
- The activity of each administration of radiopharmaceutical is kept within the limits set by ***the Administration of Radioactive Substances Advisory Committee (ARSAC)*** of the UK Department of Health (Section 6.6), and checked & recorded before administration.
- The phial is placed in the "well' of a large re-entrant ionization chamber, know as:

  The radionuclide or dose calibrator

  - × **The ionization current** produced by the gamma rays is:
    - ✓ Proportional to **the activity** of the sample.
    - ✓ Depends on **the gamma energy** and **half-life** of the radionuclide.
  - × The radionuclide is entered on the control panel and the activity in **MBq** is displayed on a digital read-out.
- The accuracy of the radionuclide calibrator must be checked regularly using **a reasonably long-lived source, such as ^{57}Co**.
- The calibrator can also be used with a lead sleeve to check for the higher-energy gamma rays from molybdenum impurity.

5.7 PRECAUTIONS TAKEN IN THE HANDLING OF RADIONUCLIDES

- When handling radionuclides, in addition to the hazard from ***external*** radiation there is also a potential hazard from ***internal*** radiation due to *accidental ingestion or inhalation of the radionuclide or its entry through wounds*.
- Generally, the risk from contamination is greater than that from external radiation.
  It is therefore important to avoid contamination of the environment, the workplace, and persons, and to control any spread of radioactive materials.

Segregation

- A nuclear medicine facility must have separate areas for:
  (a) Preparation and storage of radioactive materials.
  (b) Injection of patients.
  (c) Patients to wait.
  (d) Imaging.
  (e) Temporary storage of radioactive waste.
- Patients containing radioactivity are a source of external radiation → should be spaced apart in the waiting area.
- Departmental layout should make use of ***the "inverse square law"*** to reduce the effect of background radiation from other patients and sources, particularly in the imaging areas.

Personal protection

- Use should be made of distance, shielding, and time.
- Staff should only enter areas where there is radioactivity when it is strictly necessary; all procedures must be carried out expeditiously and efficiently.
- Departmental local rules must be followed.
- ***Some general guidance follows.***
  1. Radionuclides are contained in ***shielded*** generators or in bottles in lead pots.
  2. Where feasible, bottles and syringes are handled with ***long-handled forceps*** (tongs).
  3. Manipulations, such as the labeling of pharmaceuticals and the loading of syringes, are carried out with the ***arms behind a lead barrier*** which protects the body and face, and over a tray, lined with ***absorbent paper***, to catch any drips.
  4. Syringes are protected by ***heavy metal or lead glass sleeves*** (which can reduce radiation doses by 75%) → & transported in special containers or on a kidney dish.
  5. Before injection, syringes are vented into swabs or closed containers and not into the atmosphere.
  6. Lead-rubber aprons are ***ineffective*** against the high-energy gamma rays of ^{99m}Tc.
  7. To avoid accidental ingestion → waterproof (double-latex) surgical gloves are worn when handing radionuclides.
  Cuts and abrasions must be covered first.
  8. There must be no eating, drinking, or facial contact.
  9. Hands and work surfaces are routinely monitored for radioactive contamination.
  10. The air in Radiopharmacies may also be sampled and monitored.
  11. Staff will be monitored for ***external*** radiation doses to the body and possibly the hands. They may also be monitored for ***internal*** contamination.
  12. Swabs are taken from the workstation to monitor for radioactive and bacterial contamination.
  13. Hands should be washed regularly at special wash basins. Where necessary, and particularly after spills, decontamination may be carried out. This normally involves the use of water, mild detergents, and swabs, which are then sealed in plastic bags and disposed of as ***radioactive waste*** in marked bins.
  14. Any use of a nail brush should be gentle; if contamination is obstinate, special detergent solutions may be necessary.

Patient protection

- Every radionuclide should be checked for activity before administration, using a radionuclide ***('well') calibrator***.
- The patient's identity must he checked against the investigation to be made and the activity to be administered, and this must be recorded.
- Particular care should be taken to avoid contamination during oral administrations.
- Special circumstances apply for pregnant patients and those with babies they are breast-feeding.

Dealing with a radioactive spill

In the case of a radioactive spill, vomiting, incontinence, etc.:

1. Clear the area of non-essential persons.
2. Wearing gloves, aprons, and overshoes.
3. Mop the floor with absorbent pads and seal the swabs in designated plastic bags. If necessary, continue with wet swabs.
4. Continue until monitoring shows the activity to be at a satisfactorily low level.
5. If necessary, cordon off the area or cover it with impervious sheeting until sufficient decay has occurred.
6. Contaminated materials are treated as waste.

Disposal of radioactive waste*:*

These follow the two principles of:

Containment and decay; and
Dilution by dispersal to the environment.

- Special rules and authorizations cover the accumulation, storage, and disposal of radioactive waste.
- Every hospital is subject to strict limitations on the amount which can be disposed of by each of the following routes.
  - ***Gaseous waste*** can be vented to the atmosphere:
    In lung ventilation studies, ^{133}Xe and ^{99m}Tc aerosols should be exhausted to the exterior of the building; this is not necessary with the very short-lived ^{81m}Kr.
  - ***Aqueous liquid waste*** → well diluted with water → disposed of via designated sinks or sluices with drains running direct to the foul drain.
  - ***Solid waste*** *(swabs, syringes, bottles, etc.)* → placed in designated sacks for disposal by incineration or, if suitably diluted with ordinary waste, to waste disposal sites.
  - **Old generators** are kept in a secure shielded store until they are returned to the manufacturer.
  - ***Contaminated clothing and bedding*** is appropriately bagged and stored in a secure protected area until sufficiently decayed for release to the laundry.
- Records must be kept, for inspection, of all deliveries, stocks, administration, stored waste, and disposals of waste.

Radiation Hazards & Protection

IONIZING RADIATION INTERACTION WITH TISSUE

- Absorption of radiation energy in tissue → biological damage (radiation hazards)
- If X-ray passes through tissues unabsorbed, no biological effect will take place.

When radiation absorption takes place:

- Chemical changes (immediate)
- Subsequent molecular damage (seconds or minutes)
- Biological damage (hours to decades)

Examples of radiation induced damage:

1. **Skin and hands** (occurring to radiologists)
2. **Leukemias** → seen in patients treated with radiation for ankylosing spondylitis.
3. **Radiation accidents (Hiroshima, Chernobyl)**

❝ The current estimates of radiation risk mostly derived from the outcomes of nuclear explosions (esp. 90 000 survivors in Hiroshima & Nagasaki)

Types of medical radiation

- Particles (beta particles, neutrons)
- Electromagnetic radiations (X and Gamma rays)

Principle sources of radiation in medicine:

1. X-ray
2. Nuclear medicine
3. Radiotherapy (including β-emitters, X-rays & others).

Effect of particulates radiation:

- When electrons or β-particles pass through tissue → repeated ionizations & excitations till particle completely loose its energy & comes to rest.
- The particles have **very tortuous path** in the tissue (very light → easily deflected by the negatively charged orbital electrons of tissue atoms).
- **The total range of interactions is very short** (several millimeters)

∴ Electrons & particles radiations are easily deflected by a shield of several millimeters of perspex.

Effect of X and Gamma rays

*They **do not have a maximum depth of penetration** because:*

- They undergo progressive attenuation as they go deeper in tissue
- Their intensity (energy) decreases all the time (as they get attenuated), but never falls to zero → never give up all their energy completely (unlike electrons).

IONIZATION

- Ionization is the causes of majority of radiation **immediate chemical changes**.
- **Proteins (e.g. enzymes)** and **nucleic acids (mainly DNA)** are most sensitive for ionization (critical tissues)
- Damage occurs in 2 ways:
  - Direct rupture of a covalent bond of a molecule
  - Indirectly ***"more common"***, by interaction between the molecules and the free radicals (that are produced during ionization of tissue water)

Those changes occur in microseconds or less after exposure

How indirect damage happens:

- **Ionization of water molecule:**

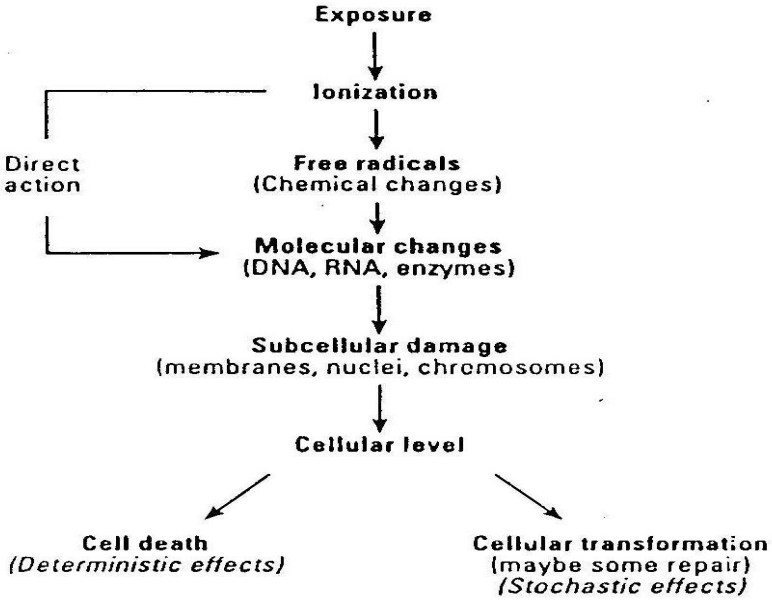
$$H_2O + \text{radiation} \Longrightarrow H_2O^+ + e^-$$

This results in a positively charged water ion & a free electron.

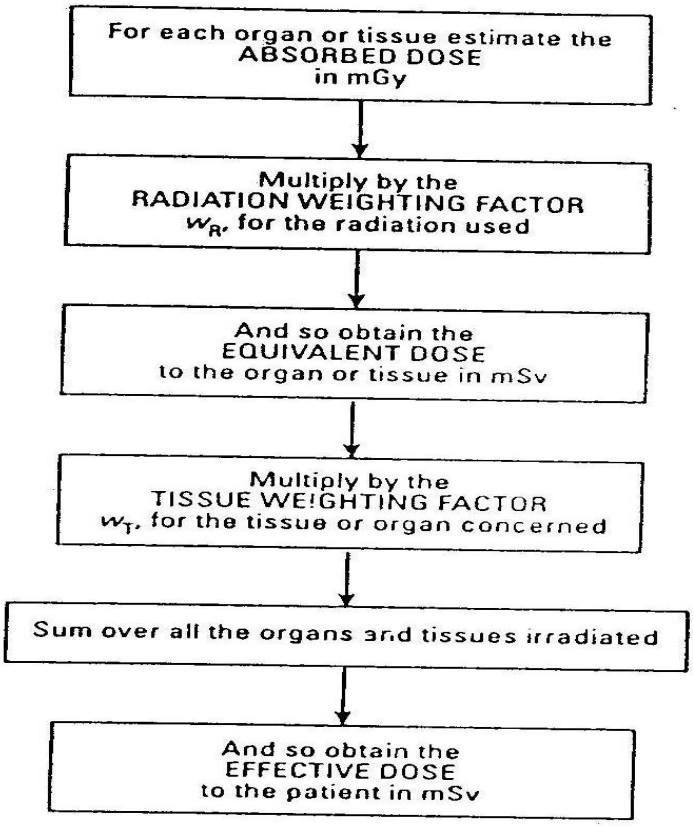
$$H_2O^+ \text{ decomposes} \Longrightarrow H^+ + OH^\cdot$$

H_2O^+ *decomposes* into hydrogen ion H^+ and hydroxyl free radical $OH^\cdot$

- **The OH is highly reactive and powerful OXIDIZING agent to tissues** → chemical modifications in organic molecules of the tissues.
- **Damages occur at a variety of levels:**
  - **Molecular level (**DNA, RNA and enzymes) **or**
  - **Subcellular level (**cell membrane, nuclei, chromosomes) **or**
  - **Cellular level (**cell division inhibition, cell death & malignant transformation**)**
- *Cell repair may occur (if enough time for recovery left between irradiation events)*



RADIATION QUANTITIES AND UNITS



- ☒ For each tissue estimate the **ABSORBED DOSE** (in **mGy**) given to each tissue or organ
- ☒ Then multiply it by *Radiation Weighting Factor* (specific for each radiation), to obtain the **EQUIVALENT DOSE** in **mSv**.
- ☒ Multiply it by Tissue weighting factor to obtain **WEIGHTED EQUIVALENT DOSE**
- ☒ Sum the WEIGHTED EQUIVALENT DOSE of all exposed tissues, to obtain the **EFFECTIVE DOSE** in **mSv**.

- Equivalent dose for tissue or organ takes in account of the TYPE of radiation to determine radiation quantity.
- ***Radiation weighting factor*** is indication of **the effectiveness of radiation type, compared with that of electrons in inducing cancer at low doses and low dose rates**.
  - In X- & Gamma rays, **RWF = 1** (both absorbed by 2ry electrons production).
    ∴ In most medical applications, **Absorbed dose = Equivalent dose**
  - In high energy neutrons and alpha particles (Heavy particles), **RW Factor = 20**
    → as their energy is completely deposited in much shorter range.
  - In low energy neutrons, **RW Factor = 5**.
- **1Sv = 1 J/kg** (unit of equivalent and absorbed doses)
- If a person is uniformly irradiated, by X or Gamma rays,
  the whole body absorbed dose = Equivalent dose.
  This occurs in occupational exposures & usually expressed in μSv.

EFFECTIVE DOSE

- Used to compare the risk from one procedure to the other.
- Effective (whole body) dose is calculated to give effective risk (undependent on uniformity of exposure of whole body)
- It is calculated by

The sum of (each organ equivalent dose X its organ weighted factor wt)

Table 6.3a ICRP (1991) tissue weighting factors

Tissue	W_T *for each tissue*	ΣW_T
Gonads	0.20	0.20
Colon, lung, red bone marrow, stomach	0.12	0.48
Bladder, breast, liver, esophagus, thyroid	0.05	0.25
Bone, skin	0.01	0.02
Remainder - each *of* 5 organs / tissues	0.01	0.05
Total		1.00

ICRP = International Commission on Radiological Protection.

SOMATIC AND GENETIC EFFECTS OF IONIZING RADIATION

GENETIC:

- Occurs in ***the offspring of the exposed person*** (due to affection of germinal cells)
- Difficult to assess.
- Statistically, frequency of occurrence of **genetic effect** in case of irradiated parents is no much different compared with case of non irradiated parents.
- The risk of **hereditary ill-health** in subsequent children without irradiation is **70000 cases \ a million**
  → The risk increase only by **10 extra cases** in parents exposed to **1 mGy**.

SOMATIC:

- Occurs in ***exposed person***
- Divided into: Deterministic effects & Stochastic effects

DETERMINISTIC EFFECTS

They can be measured according to dose, individually considered.

- Occurs on **high doses** (e.g. radiation accidents) → unlikely in diagnostic radiology.
- **Threshold dose** applies here. However, may be different from person to another

Examples:

Effect	***Threshold***
CATARACT *One of the highest deterministic risks.*	5 Sv *CT can give very high eye doses.*
SKIN DAMAGE (erythema and dry desquamation)	4 Sv Seen in interventional radiology
BONE MARROW CELL LOSS (aplastic anaemia, not leukaemia)	
GONADS	1 Sv → measurable effect. 4 Sv → sterility
MYXOEDEMA (due to affection of thyroid, leading to malfunction)	

- In general, **thresholds are greater than 500 mSv** (not common in radiology practice)
- Biological changes can't be identified in **less than 50 mSv**.
- **The amount of radiation damage & Severity of the effect increases with radiation dose** (beyond the threshold),

Also with:

1. The volume of tissue irradiated.
2. The rate at which dose is given.

- Dividing the dose on several events, will eliminate deterministic effect i.e. **NON CUMULATIVE** (except in **the lens**, as it has no repair mechanism, so cataract effect is CUMULATIVE)
- A dose given to a single organ (exceeding the threshold), will cause certain effects, but if the SAME dose given to the whole body, effect is different, the effects might not occur.

- **Lethal Dose:** the dose that will cause 50% of the irradiated persons to die in 30 days from exposure. (MCQ)

LD50/30 = 5 Sv whole body dose.

10 Sv whole body dose → 100% lethal to humans.

STOCHASTIC EFFECTS (STATISTICAL)

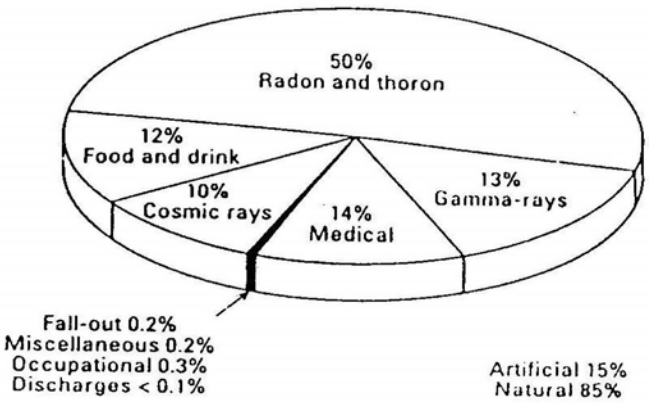
- Of real concern regarding **diagnostic radiology**
- **Probability of occurrence** increases with dose (MCQ) → not severity.
- **No threshold dose**, thus, cancer may be induced even with small radiation doses
- Cancer occurrence takes a **latent period** to occur, ranging from few years (e.g. Leukemia) to up to 40 years in some solid tumors "may be not expressed within lifetime of recipients".
- **Basal cell carcinoma** is an example of stochastic effects.
- **Children are more sensitive than adults** "**3 times more sensitive** → as they have longer years to live, increasing the probability of occurrence of cancer).

Probability coefficient for tissue at risk

- The total risk of inducing a determinant effect in UK population of all age & both sexes which exposed to whole body irradiation of low doses at low dose rate = **7% per *Sv* whole body equivalent dose = 70 / million /1 mSv**.
- Each individual organ has probability coefficient for cancer induction → *Table 6.1*

Population exposure in UK

Natural background radiation in UK (annual per caput value for all radiation sources) = **2.6 mSv** *(MCQ)*



The amount of background radiation depends on the place, amount of natural resources, what the food is & local geology.

- **2.2 mSv comes from natural radiation**
  - Radon gas is the largest contributor 1.3 mSv (but can range from negligible to 50 mSv/year)
    - × Radioactive gas, results from the decay of uranium.
    - × Emits alpha-particles.
  - Gamma rays from the ground and buildings 350 µSv
  - Food and drinks (from natural long lived Radionuclides "mostly ^{40}K") 300 µSv
  - Cosmic radiation (frequent air travelers double their overall dose) 260 µSv
- **Only 0.4 from artificial sources** (including medical)
  - Medical radiation is the largest share of the artificial radiaton (0.37 mSv)
  - Medical radiation is about **14% of the total background radiation** (*MCQ*)

In MCQ, take care:
Background radiation = 2.6 mSv
Natural Background radiation = 2.2 mSv
Man-made "Artificial" Background radiation = 0.4 mSv

RADIATION PROTECTION PRINCIPLES

- Proposed by ***international commission of radiological protection (ICRP)***.
- Composed of 3 fundamental principles: Justification – Optimization – Limitations.

JUSTIFICATION

- The benefit of radiological exposure should be greater than risk
- Means that any medical practice must be justified both as general procedure & as regards the individual patient

IR(ME)R 6- Justification of Individual Medical Exposures

No person shall carry out a medical exposure unless -

(a) It has been justified by the practitioner as showing a sufficient net benefit over risks, as regarding:
- ***i.*** Objective of exposure.
- ***ii.*** Total potential diagnostic & therapeutic benefits.
- ***iii.*** The individual detriment that the exposure may cause.
- ***iv.*** The efficacy, benefits & risk of alternative techniques "having less exposure".

(b) It has been authorized by the practitioner *(or by operator according to the practitioner guidelines)*.

(c) In the case of a person voluntarily participating in medical or biomedical exposure → approved by a Local Research Ethics Committee; and

(d) In the case of exposures for medico-legal purposes → it complies with the employer's procedures for such exposures.

(e) In the case of a female of childbearing age:
- ***i.*** Has he enquired whether she is pregnant or breastfeeding.
- ***ii.*** The practitioner shall justify the urgency of exposure.
- ***iii.*** Special care is essential for examinations involving the abdominal & pelvic areas.

(f) The practitioner takes account of any data supplied by the referrer to avoid unnecessary exposure.

- Regarding Justification of exposures:
  1. Some exposures are easier to justify than others.
  2. some are unjustified (e.g. Mammography screening in 20-30 years old well women)

- ***When does a radiological procedure considered unjustified?***
  1. If harm from the exposure exceeds its benefit.
  2. If the patient undergoes the same radiological examination recently for the same condition in another hospital → every effort must be done to get the films & reports.
  3. If the diagnosis can be made using other technique (e.g. MRI).
  4. If the procedure won't contribute to the patients management (e.g. Coccydynia)

- ***Special cases:***
  - Introducing radiopharmaceutical to a ***breast feeding woman*** (breast feeding may need to be interrupted or stopped).
  - Female patients in the reproductive period of life "pregnant or might be pregnant"
    - Applies to radiographic examination of any area between the knee & diaphragm and to Radionuclide injection.
    - This justification follows the "28 day rule" → based on the principle that there is little or no risk to live born child from irradiation during the first 3 weeks of gestation (i.e. before first missed period), except from high-dose procedures (Ba enema & Pelviabdominal CT).
    - Within the first 3 weeks of the gestation, the dose equivalent to a fetus not to exceed 5 mSv.
      The risk of inducing cancer with this dose is 1/1000, which is same as the natural prevalence of malignancy < 10 years.

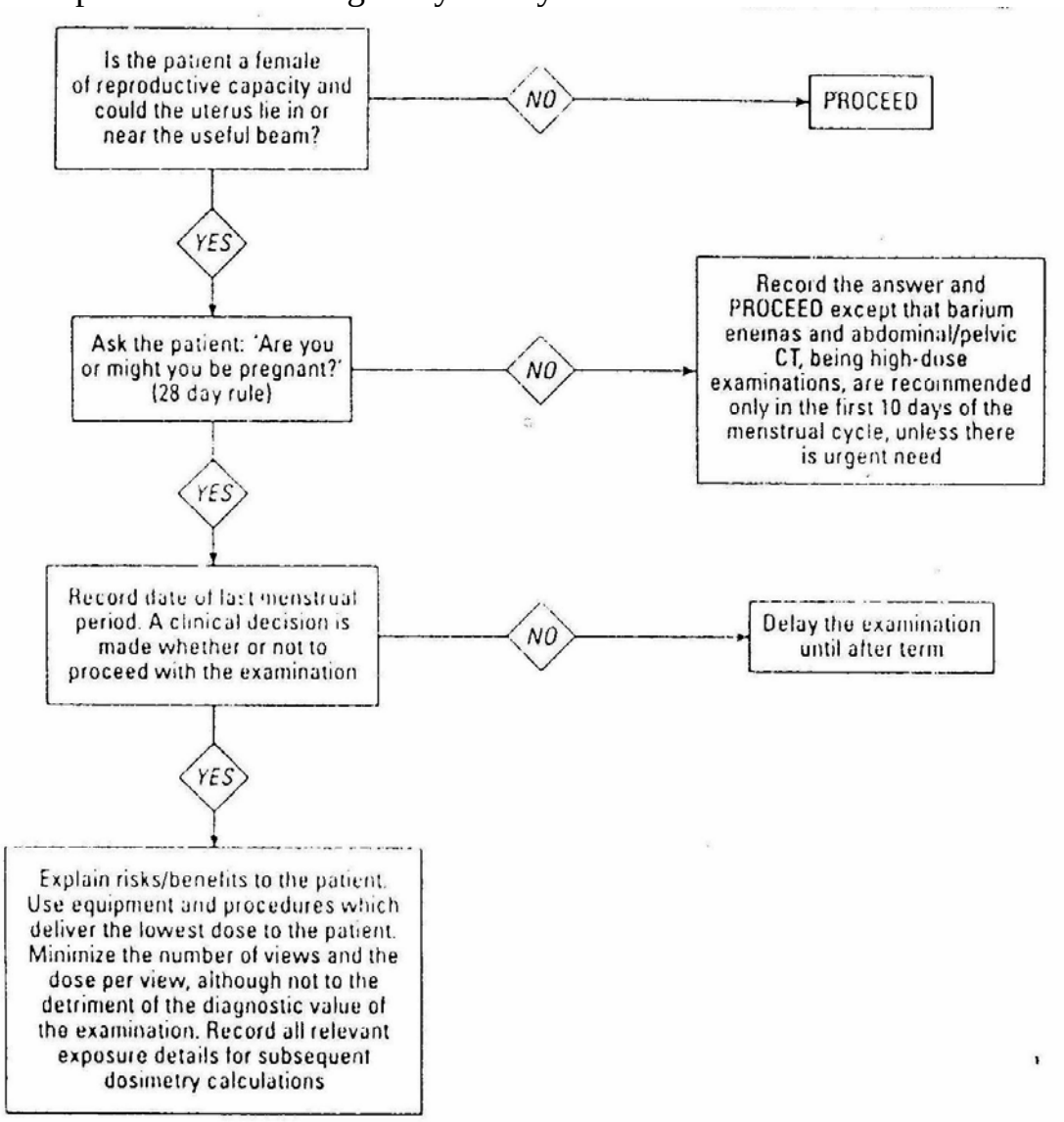


Fig. 6.5 Radiation protection of patients who are or might be pregnant.

OPTIMIZATION

- ***For staff and visitors,***
  Effective Dose should be AS LOW AS REASONBALY PRACTICABLE (ALARP)
- ***For Patients,***
  Radiological exposure should be **as low as compatible with diagnostic information** → *achieved by*:
  - **Reducing number of images (films taken)**
  - **Reduce absorbed dose for every exposure**
  - **Quality assurance system** → *including periodic measurement of the patient dose***.**

Table 6.4 gives guide for Practical measures for the reduction of patient dose

Table 6.4 Practical measures for the reduction of patient dose

(A) Some dose-saving equipment

1. *Fast screen-film combinations (e.g. rare earth)*
2. *Low attenuation (e.g. carbon fiber) materials for cassette fronts, antiscatter grid interspacing, table tops.*
3. *Constant potential generators with appropriate kilovoltage*
4. *Appropriate beam filtration (minimum 2.5 mm Al for general radiography)*
5. *Specialized equipment for mammography and pediatrics*
6. *Pulsed and frame-hold (image storage) fluoroscopy equipment.*
7. *Digital radiography equipment.*
8. *Dose-area product meter to monitor patient exposure.*

(B) Some dose-saving techniques

1. *Use smallest possible field size and good collimation.*
2. *Collimate to exclude radiosensitive organs (gonads, breasts, eyes).*
3. *When gonads lie outside the primary beam, make distance between the edge of the field and the gonads as large as possible.*
4. *Shield breasts, eyes, and gonads unless the area of interest would be masked. Dose to ovary can be halved and that to testes reduced by a factor of 20.*
5. *Use largest practicable focus to skin distance: never less than 30 cm, especially in mobile radiography.*
6. *Position the patient carefully. Reduce the dose to the female breast and, in skull radiography, to the eye by postero-anterior projection. Minimize the gap between patient and film-screen.*
7. *Use compression of patient where possible.*
8. *Use non-grid techniques when examining children and small adults.*
9. *Keep film reject rate due to all causes down to 5%. Check the factors before exposure. Quality assurance, particularly of automatic processors, is important*
10. *In fluoroscopy use the minimal field size and minimal screening time essential for good diagnosis.*
11. *Use zoom or small field techniques, which require a higher dose rate, with discretion*

(C) High-risk examinations

1. *Keep pediatric radiation doses to an absolute minimum consistent with adequate diagnosis as children up to the age of 10 years are believed to be 3-4 times more radiosensitive than adults.*
2. *In pelvimetry: use MRI or CT scanography where possible; otherwise use fast rare earth screens and carbon fiber components*
3. *Mammography is not generally performed on women younger than 50 years unless there is a family history of breast cancer or the patient has related symptoms.*
4. *In CT scanning, take the minimum number of slices, position the patient to avoid the eyes and other critical organs; reduce milliamperage if appropriate, e.g. for the chest*
5. *Patients who are or might be pregnant; see Fig. 6.5.*
6. *Interventional radiology needs care to avoid skin reactions; use pulsed and frame-hold systems: minimize screening times*

***IR(ME)R 7- Optimization**:*

- ***In relation to all medical exposures except radiotherapeutic procedures,***

the practitioner and the operator, shall ensure that doses arising from the exposure are kept as low as reasonably practicable (ALARP)

- ***In relation to exposures for radiotherapeutic purposes:***, ***the practitioner*** shall ensure that:
  - ***i.*** Exposures of target volumes are individually planned.
  - ***ii.*** Dose to non-target volumes shall is as low as reasonably practicable (ALARP)
- ***for each medical exposure,*** the operator shall select equipment and methods to ensure that:
  - ***i.*** Dose of IR to the individual undergoing the exposure is ALARP.
  - ***ii.*** Dose is consistent with the intended diagnostic or therapeutic purpose.
  - ***iii.*** special attention to -
    (a) quality assurance;
    (b) assessment of patient dose or administered activity; and
    (c) adherence to diagnostic reference levels.
- ***For each medical or biomedical research programme,*** the employer's procedures shall provide that -
  1. the individuals concerned participate voluntarily.
  2. the individuals are informed in advance about the risks of exposure;
  3. ***if volunteers have no direct medical benefit from the exposure*** → the dose constraint set down in the employer's procedures is adhered to.
  4. ***if volunteers are patients expected to receive a diagnostic or therapeutic benefit*** → individual target levels of doses are planned by the practitioner.

- ***In the case of patients undergoing treatment or diagnosis with radioactive***

medicinal products, the employer's procedures shall provide written instructions and information to the patient, to consent to the treatment or diagnostic procedure; The instructions and information referred to shall -

1. set out the risks associated with ionising radiation; and
2. specify how doses resulting from the patient's exposure can be restricted as far as reasonably possible so as to protect persons in contact with the patient;
3. be provided to the patient prior to the patient leaving the hospital.

- ***the practitioner and the operator shall pay special attention to -***
  - ***a)*** the need to keep doses arising from medico-legal exposures as low as reasonably practicable;
  - ***b)*** medical exposures of children;
  - ***c)*** medical exposures for health screening programme;
  - ***d)*** medical exposures involving high doses to the patient;
  - ***e)*** females in whom pregnancy cannot be excluded and who are undergoing a medical exposure, in particular if abdominal and pelvic regions are involved, taking into account the exposure of both the expectant mother and the unborn child; and
  - ***f)*** females who are breastfeeding and who are undergoing exposures in nuclear medicine, taking into account the exposure of both the female and the child.
- The employer shall take steps to ensure that a clinical evaluation of the outcome of each medical exposure is recorded, including factors relevant to patient dose.
- ***In the case of fluoroscopy -***

  (a) no person shall carry out an examination without an image intensification or equivalent technique.

  (b) the operator shall ensure that examinations without devices to control the dose rate are limited to justified circumstances; and

IRR (1999), 8- Restriction of exposure

- It's the duty of the Employer to take all necessary steps to restrict the exposure of his employees and other persons to ionising radiation.
- ***Steps for restriction of IR exposure: -***
  - ***(1)*** Engineering controls and design features.
  - ***(2)*** The use of safety features and warning devices.
  - ***(3)*** Systems of work.
  - ***(4)*** Provide employees with personal protective equipment (including respiratory protective equipment) & ensure its adequate maintenance & regular testing.
  - ***(5)*** Using dose constraints.
  - ***(6)*** Taking steps to ensure that PPE & system of work are properly used or applied by employee.

- Radiation employer shall ensure, that -

(a) For pregnant employee,
→ after her employer has been notified of the pregnancy → the equivalent dose to the foetus is unlikely to exceed 1mSv during the remainder of the pregnancy; and

(b) For breastfeeding employee,
→ exposure is restricted to prevent bodily contamination.

- Every employer shall ensure that an investigation is carried out when the effective dose of ionising radiation received by any of his employees for the first time in any calendar year exceeds ***15mSv*** or as specified in writing in local rules.

LIMITATION

- Legal dose limits for workers & members of public should ensure:
  1. No deterministic effects.
  2. Reasonably low probability of stochastic effect.
- Limitation of patient dose → limits are not appropriate for patient dose, however Reference values indicate levels above which exposure should be reviewed (section 6.7)

See table 6.5 - Dose limits for staff & visitors.

Table 6.5 Current UK dose limits (1985 Regulations)

	Dose limit (mSv)		
	Staff "classified"	***Trainees aged 16-18 years***	***Public, visitors***
Whole body	20	6	1
Eyes	150	50	15
Extremities and other organs	500	150	50

The annual (whole body) dose limits for workers = 20 mSv.

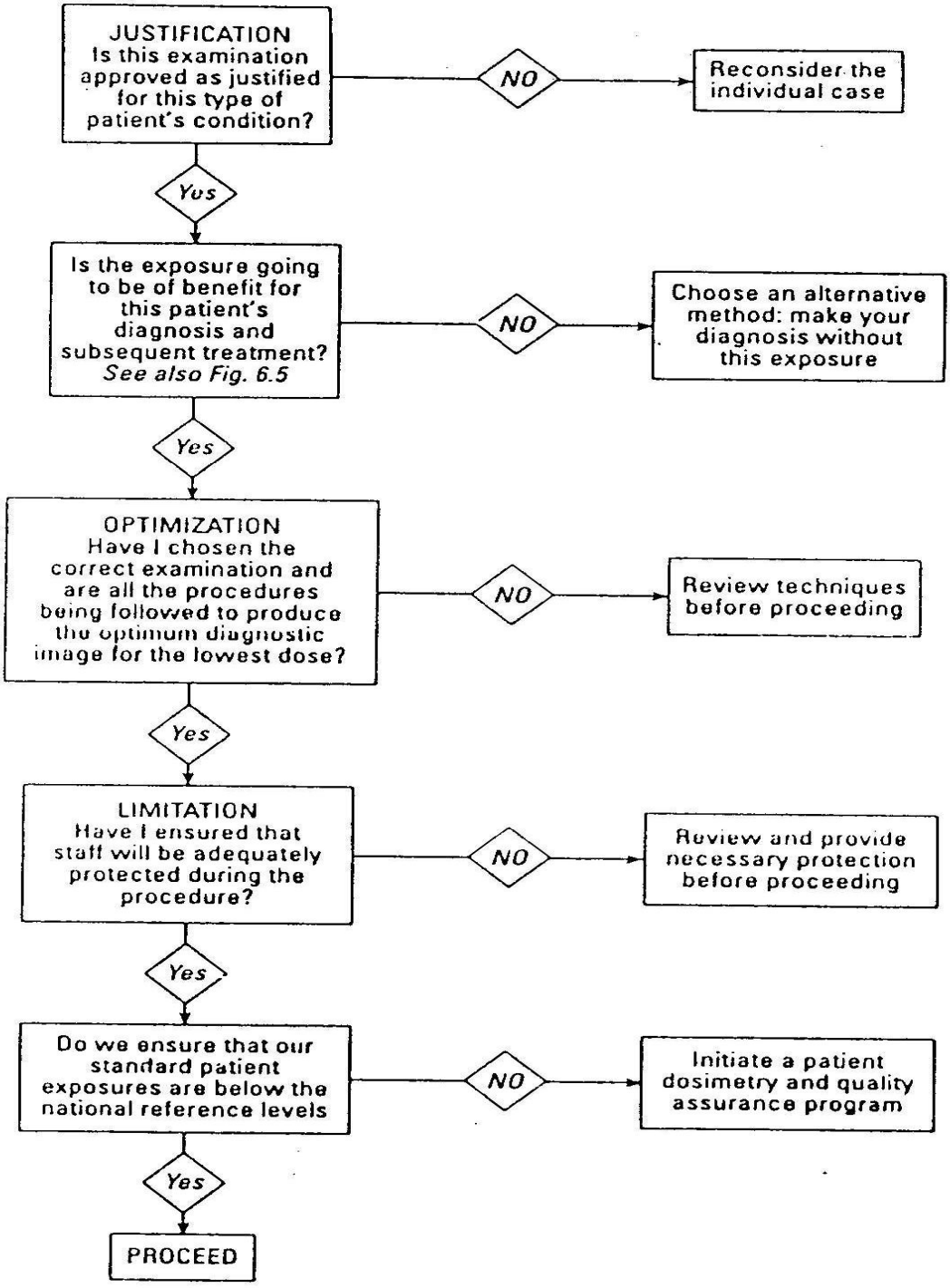


Fig. 6.4 Radiation protection principles applied to medical diagnostic procedures.

Dose limitation

Regulation 11 (IRR 1999) –

- Every employer shall ensure that his employees are not exposed to ionising radiation exceeding any dose limit in any calendar year.

SCHEDULE 4-Regulation 11

DOSE LIMITS Part 1

Employees of 18 years of age or above

- Effective dose limit is **20 mSv** in any calendar year.
- Equivalent dose limit in a calendar year,
  a) for the lens of the eye is 150 mSv;
  b) for the skin is 500 mSv "applied to the dose averaged over 1cm^2 regardless of the area exposed";
  c) for the hands, forearms, feet and ankles is 500 mSv.

Trainees aged under 18 years

- Effective dose limit is **6 mSv** in any calendar year.
- Equivalent dose limit in a calendar year,
  d) for the lens of the eye is 50 mSv;
  e) for the skin is 150 mSv "applied to the dose averaged over 1cm^2 regardless of the area exposed";
  f) for the hands, forearms, feet and ankles is 150 mSv.

Women of reproductive capacity

Equivalent dose limit from external radiation for the abdomen of a woman employee of reproductive capacity → 13 mSv in any consecutive period of three months.

Other persons

Any person other than an employee or trainee including any person below the age of 16→ Effective dose limit is 1 mSv in any calendar year.

Any person (not being a comforter or carer) who may be exposed to ionising radiation resulting from the medical exposure of another → the effective dose limit on is 5 mSv in any period of 5 consecutive calendar years.

& for both:

- Equivalent dose limit in a calendar year,
  g) for the lens of the eye is 15 mSv;
  h) for the skin is 50 mSv "applied to the dose averaged over 1cm^2 regardless of the area exposed";
  i) for the hands, forearms, feet and ankles is 50 mSv.

Occupational exposure of fertile woman

Female staff shouldn't be exposed to more than 1mSv per month

Occupational exposure of pregnant woman

- From declaration of pregnancy, a female staff shouldn't receive more than 1 mSv through out the remainder of pregnancy time.
- This would mean a max. dose to fetus = 0.6 mSv.

Reg. 11(2)

Where an employer is able to demonstrate in respect of any employee that the dose limit specified above ***is impracticable*** *(**20 mSv** in any calendar year for any employee of 18 years of age or above)* having regard to the nature of the work undertaken by the employee, the employer may apply the dose limits set out Part II of Schedule4 in respect of that employee.

Schedule 4-PART II

For employees of 18 years or above:

- Effective dose limit is **100 mSv** in any 5 consecutive calendar years.
- Maximum effective dose of **50 mSv** in any single calendar year
- Equivalent dose limit in a calendar year,
  - for the lens of the eye is 150 mSv;
  - for the skin is 500 mSv "applied to the dose averaged over 1cm^2 regardless of the area exposed";
  - for the hands, forearms, feet and ankles is 500 mSv.

Women of reproductive capacity

Equivalent dose limit from external radiation for the abdomen of a woman employee of reproductive capacity → **13 mSv** in any consecutive period of three months.

For employees under 18 years: it is not allowed to use this system of dose limits

However, the employer shall not put this system into effect unless he do the following provisions: -

1. Consult the RPA.
2. Consult & inform in writing any employees who are affected;
3. Inform in writing the approved dosimetry service; and
4. Give notice to the Executive at least 28 days before the decision is put into effect giving the reasons for the decision.
   - If the Executive is not satisfied that it is impracticable for that employee → require the employer to apply the dose limit specified in Part 1.
   - Any person who is aggrieved by the decision of the Executive may appeal to the Secretary of State.

Other important precautions

- Employer shall review the decision to use this system of dose limitation at appropriate intervals → ***at least once every five years***.
  if as a result of a review, an employer proposes to revert to a system of annual dose limitation → he shall do the pervious provisions again
- The employer shall record the reasons for that decision → keep for 50 years.
- If > 20 mSv given in a year → employer must undertake investigations & notify HSE.

N.B.: Dose limits for Fluoroscopy

- ***For staff working in fluoroscopy, the D.I.L. "dose investigation level" is:***
  - 6 mSv a year effective dose
  - 300 μSv a month under-apron dose
  - 5500 μSv a month over-apron dose
  - Hand dose of 7.5 mSv a month
- ***For pregnant staff:***
  - 1 mSv during declared term,
  - 125 μSv a month under-apron
  - 1500 μSv a month over-apron

Note

- ***Dose limits are not like a speed limit.***
  Doses must be as low as is reasonably practicable (ALARP)
- **Dose constraints used in design**
  - **e.g. 0.3 mSv for members of public,**
  - **5 mSv for comforters and carers (1mSv if pregnant)**
- **Foetus limit: 1 mSv from notification of pregnancy by employee**
- **Need formal investigation levels for staff**
- **Do not apply to medical exposures**

- **In practice, staff members generally receive doses less than 3 mSv/year**
  Even interventional radiologists SHOULD NOT exceed 30% of the occupational dose limit/year

See figure 6.6 page 162 for the dose distribution among personnel in radiodiagnosis department.

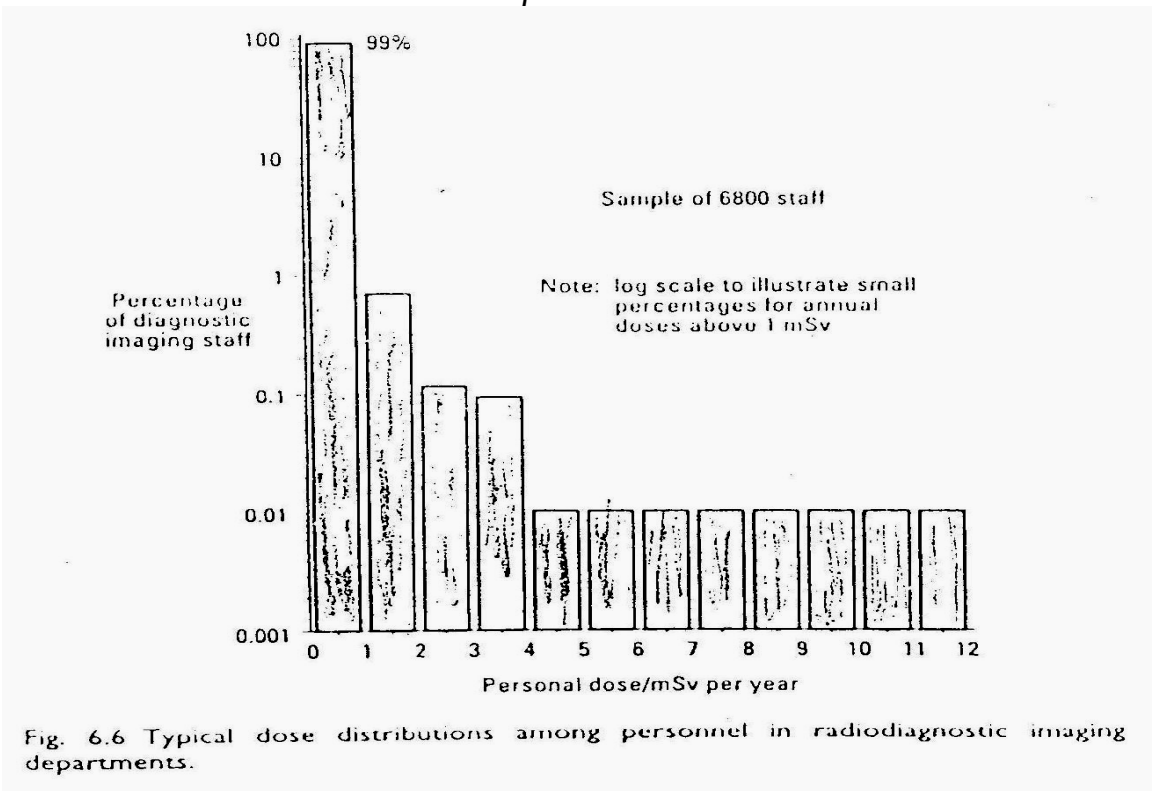


Fig. 6.6 Typical dose distributions among personnel in radiodiagnostic imaging departments.

- Staff who likely to exceed 30% of any annual dose limits for workers is considered "CLASSIFIED" (e.g. > 6 mSv whole body dose) → ***Health & Radiation monitoring is statutory***.
  - They must subject to regular medical surveillance by an appointed doctor.
  - Monitored by dosimetry services 'approved' by HSE.
  - Their records are kept centrally in the Central Index of Dose Information operated by HSE for 50 years.
  -

IRR (1999); 20- Designation of classified persons:

Def: any employees who are likely to receive:

1. Effective dose > ***6mSv per year;*** or
2. Equivalent dose > 3/10 of any relevant dose limit.

- The employer is responsible for such designation & shall inform those employees that they have been so designated.
- The employee designated as a classified person must be:-
  1. aged 18 years or over; and
  2. fit for the work with ionising radiation as certified by an appointed doctor or employment medical adviser in his health record.
- The employer may cease to treat an employee as a classified person ***only at the end of a calendar year*** except if -
  1. An appointed doctor or employment medical adviser so requires; or
  2. The employee is no longer employed by the same employer or will work in a position which is not likely to result in significant exposure.
- Differences between classified and other staff working in controlled areas are outlined in *table 6.6 page 166 Farr book*

Table 6.6 Differences between classified and other staff working in controlled areas

	Classified	***Not classified***
Annual effective dose limit	20 mSv	6 mSv
Personal monitoring	Required	Preferable
Follow 'system of work'	Preferable	Required
Medical surveillance	Required	Not required
Radiation passbook	Required for 'outside' work	

.

IRR(1999); 24- Medical surveillance

- ***Who needs medical surveillance:***

1. Classified persons.
2. Employee received over-exposure but not classified persons.
3. Employee seen fit to work in IR *under conditions* set by the appointed doctor or employment medical adviser.

- The employer shall ensure that each of his employees (mentioned above) is under adequate medical surveillance (at least once yearly) by an appointed doctor or employment medical adviser → to determine the fitness of each employee for the work with ionising radiation.

- ***PARTICULARS TO BE CONTAINED IN A HEALTH RECORD:***
  1. The employee's → full name; sex; date of birth; address; and National Insurance number;
  2. The date in which the employee's designated as a classified person in present employment;
  3. The nature of the employee's employment;
  4. In the case of a female employee, a statement as to whether she is likely to receive in any consecutive period of three months an equivalent dose of ionising radiation for the abdomen exceeding 13 mSv;
  5. The date of last medical examination;
  6. The type of the last medical examination;
  7. A statement by the appointed doctor or employment medical adviser made as a result of the last medical examination → classifying the employee as fit, fit subject to conditions (which should be specified) or unfit;
  8. The name and signature of the appointed doctor or employment medical adviser in relation to each medical examination;
  9. The name and address of the approved dosimetry service for maintaining the dose record.
- ***The employer shall ensure that:***
  a) A health record for his employees is made and maintained.
  b) That health record is kept until the person attained the age of 75 years & for at least 50 years from the date of the last entry made in it.
- The employer shall ensure that there is a valid entry in the health record of each classified employees made by an appointed doctor or employment medical adviser
- An entry in the health record shall be valid for 12 months from the date it was made or until cancelled by an appointed doctor or employment medical adviser by a further entry.
- if the appointed doctor or employment medical adviser has certified that employee should not be engaged in work with ionising radiation ***"unfit"*** or should only work under conditions he has specified in the health record ***"fit under conditions"***
  ∴ The employer shall not permit that employee to be engaged in the work with ionising radiation except in accordance with this conditions.
- If an appointed doctor or employment medical adviser requires to inspect any workplace, the employer shall permit him to do so.
- The employer shall make available to the appointed doctor or employment medical adviser:
  1. The summary of the dose record kept by the employer.
  2. Other records as the appointed doctor or employment medical adviser may require.
- If an employee is aggrieved by a decision recorded in the health record by an appointed doctor or employment medical adviser:
  1. Apply to the Executive in writing within 3 months of the date on which he was notified of the decision to be reviewed in accordance with a procedure approved by the Health and Safety Commission.
  2. The result of that review shall be notified to the employee and entered in his health record.

21- Dose assessment and recording:

- Assessment & recording of all doses of ionising radiation received by employees designated as a classified person:
  - Is the duty of every radiation employer.
  - Done through arrangements with an approved dosimetry service.
  - The employer shall provide the approved dosimetry service with such necessary information concerning classified employees.
- Duties of approved dosimetry service regarding this is:
  1. The making of systematic assessments of the doses using suitable individual measurement for appropriate periods.
  2. The making and maintenance of dose records for each classified person.
     - Keep the records until the classified person attained the age of 75 years & for at least 50 years;
     - To provide the employer with:
       - ***a)*** Summaries of the dose records at appropriate intervals.
       - ***b)*** Copies of the dose record of any of his employees when required;
       - ***c) Copy of "Termination record"*** → a record of the information concerning the dose assessment of a classified person who ceases to be an employee of the employer → + send that record to the Executive;
       - ***d)*** A current radiation passbook for outside workers.
     - To provide the Executive with:
       - ***a)*** Termination record.
       - ***b)*** summaries of all current dose records of the year → within 3 months of the end of each calendar year;
       - ***c)*** copies of any dose records when required
     - Make an entry in the dose record and retain the summary of the information used to estimate that dose in case of loss of dosimeter;

- An employer shall ensure that each ***outside worker*** employed by him is provided with a current individual radiation passbook.

  & ensure that the particulars entered in the radiation passbook are kept up-to-date as long as this outside employee works for him.

- ***PARTICULARS TO BE ENTERED IN THE RADIATION PASSBOOK (Schedule 6):***
  1. Individual serial number of the passbook.
  2. A statement that the passbook has been approved by the Executive.
  3. Date of issue of the passbook.
  4. The name, telephone number and mark of endorsement of the issuing approved dosimetry service.
  5. The name, address, telephone and telex/fax number of the employer.
  6. Full name, date of birth, gender and national insurance number of the outside worker to whom the passbook has been issued.
  7. Date of the last medical review and the relevant classification in the health record → fit, fit subject to conditions (which shall be specified) or unfit.

8. The relevant dose limits.

9. The cumulative dose assessment in mSv for the year to date for the outside worker, external (whole body, organ or tissue) and/or internal as appropriate and the date of the end of the last assessment period.

10. In respect of services performed by the outside worker -

(a) the name and address of the employer responsible for the controlled area;

(b) the period covered by the performance of the services;

(c) estimated dose information, which shall be -

(i) whole body effective dose in mSv;

(ii) the equivalent dose in mSv to organs and tissues in case of non-uniform exposure; and

(iii) an estimate of the activity taken in or the committed dose in case of internal contamination,.

❝ The employer shall keep a copy of the summary of the dose record received from the approved dosimetry service for at least 2 years from the end of the calendar year to which the summary relates.

❝ The employer shall make available to the classified person at request -

1. a copy of the dose summary record of 2 years preceding the request; and

2. a copy of the dose record of that person; and

3. a copy of termination record.

HSE Nov. 01:

There has been a number of reported cases where employees have failed to take good care of their dosemeters. Many of these cases involve employees in the Health Services, some of whom have been senior clinicians.

"Non-Classified employees who have been provided with a dosemeter by their employer to ensure compliance with regulation18 IRR99 have a duty to look after that dosemeter and return it for processing as required. Provided the employer has informed the employees of that duty and is exercising the appropriate level of supervision, employees who persistently fail to wear, look after or return their dosemeters promptly are liable to enforcement action by inspectors up to and including prosecution under Section 7 of the HSW Act 1974. Employers may find statement of this fact useful when dealing with 'errant' staff."

<u>22- Estimated doses and special entries</u>

In case of loss or damage of a dosemeter used to make any individual measurement under regulation 21 (i.e. not practicable to assess the dose received by a classified person over any period)

- Employer shall make an adequate investigation of:

1. The circumstances of the case.

2. A view to estimate the dose received by that person during that period.

- ***If there is adequate information to estimate the dose received***, Employer shall:
  - ***a)*** Send to the approved dosimetry service a summary of the information used to estimate that dose.
  - ***b)*** Arrange for the approved dosimetry service to enter ***the estimated dose*** in the dose record of that person.
    → mentioned in the dose record as estimated dose.
  - ***c)*** The employer shall not enter the estimated dose in the dose record except after the consent of ***the Executive*** if:
    i. Recorded cumulative effective dose ≥ 20 mSv in one calendar year.
    ii. Recorded cumulative equivalent dose ≥ any relevant dose limit in one calendar year
- ***if there is inadequate information to estimate the dose received***, Employer shall arrange for the approved dosimetry service to enter ***a notional dose*** in the dose record ***"i.e. proportion of the total annual dose limit for the relevant period"***
  → mentioned in the dose record as a national dose.
- In either case, ***the*** employer shall
  - ***a)*** Inform the classified person of the entry (either estimated or national dose).
  - ***b)*** Make available at the request of the classified person → a copy of the summary sent to the approved dosimetry service.
  - ***c)*** Make a report of any investigation → keep a copy for 2 years from the date it was made.

Objections on the estimated dose:

- If employer think the dose received by the classified person is > or < the relevant entry in the dose record → he shall make ***adequate investigation***.
  But under 2 conditions:
  1. before 12 month in case of classified person subject only to an annual dose limit.
  2. before 5 yrs in any other case.
- If investigations confirms the belief of the employer, he shall:
  1. Send to the approved dosimetry service a summary of the information used to estimate that dose.
  2. Arrange for the approved dosimetry service to enter ***the estimated dose*** in the dose record of that person.
  → mentioned in the dose record as special entry.
  3. Notify the classified person of the change.
  4. Make a report of the investigation → keep a copy for 2 yrs.
- If the classified person is aggrieved by this decision → apply to review this decision in writing to the Executive "within 3 months of the date on which he was notified of the decision".
- If the Executive concludes that -
  (a) The investigation was inadequate; or
  (b) estimated dose is not reasonable,
  The Executive shall direct the employer to re-instate the original entry in the dose record.

OTHER PROTECTION MEASURES:

- Radiologists and almost all radiology workers ARE NOT CLASSIFIED normally
- According to ***LOCAL RULES***, they however supposed to wear personal dosemeters when entering a controlled area

N.B. it is not an absolute necessity, this is preferred but not must, but local rules in most places states so, note that the answer of the question:

Radiologist SHOULD wear a dosemeter when entering fluoroscopy room.

The answer is **FALSE**, because it is not SHOULD, although we all wear them in that case, but still not absolute necessity, if the word used in the question USUALY, so the answer is **TRUE**.

- *Perhaps that example shows you the degree of sterility of the examination system!!*

About personal monitors:

1. Personal dosimeters are worn on the trunk, under the lead apron.
2. Additional monitors MAY BE worn on the forehead or neckband to monitor eye exposure, or fingers to monitor hand doses.
3. Body monitors are usually worn for **4 weeks**
4. Commonest personal monitoring dosimeters are film badges or TLD.
5. Electronic dosimeters are used in high dose areas when an indication in needed to monitor at the same time of exposure (ex. Interventional procedures by pregnant radiologist)

IRR(1999); 9-Personal protective equipment:

- Any personal protective equipment shall comply with the Personal Protective Equipment (EC Directive) Regulations 1992.
- Every radiation employer shall provide appropriate accommodation for personal protective equipment when it is not being worn.

STATUTORY RESPONSIBILITIES AND ORGANIZATIONAL ARRANGEMENTS FOR RADIATION PROTECTION:

- ***IRR1999*** aims to Protection of staff and members of public.
- ***IR(ME)R2000*** aims to Protection of patients.

ARRANGEMENTS FOR THE MANAGEMENT OF RADIATION PROTECTION

IRR(1999); 13- Radiation protection adviser

MATTERS IN RESPECT OF WHICH A RADIATION PROTECTION ADVISER MUST BE CONSULTED BY A RADIATION EMPLOYER

1. Advising to the observance of the Regulations
2. The implementation of requirements as to controlled and supervised areas.
3. For new or modified sources of ionising radiation → prior plans for installations and the acceptance into service "in relation to any engineering controls, design features, safety features and warning devices provided to restrict exposure to ionising radiation".
4. Regular checking of systems of work provided to restrict exposure to ionising radiation.
5. The regular calibration of equipment provided for monitoring IR levels and the regular checking that such equipment is serviceable and correctly used.
6. The periodic examination and testing of engineering controls, design features, safety features and warning devices.
7. Incidents where more than 6 mSv has been received.

- ***R.P.A. need not be appointed if only:***
  - Very, small amounts of radioactive material (below specified levels)
  - Very low dose (< 1μSv/h @ 10 cm) x-ray units of a design approved by HSE
  - VDUs with < 1μSv/h @ 10 cm
  - < 30 kV and < 1μSv/h @ 10 cm.

- There should be a radiation protection advisor (RPA) in every radiological facility.
- RPA must have qualification approved by HSE (e.g. RPA2000 certificate).
- The radiation employer shall appoint the radiation protection adviser in writing and shall include the advice needed.
- The radiation employer shall provide RPA with adequate information and facilities.

14- Information, instruction and training

- Every employer shall ensure that -
  - ***(1) his employees*** are given appropriate training, information and instruction in the field of radiation protection regarding:-
    - ***(a)*** the risks to health by exposure to ionising radiation;
    - ***(b)*** the precautions; and
    - ***(c)*** the importance of complying with the medical, technical and administrative requirements of these Regulations;

(2) ***other persons*** concerned with the work with ionising radiation are given adequate information to ensure their health and safety; and

(3) ***female employees***:

- Informed of the risk of ionising radiation to the fetus & a nursing infant.
- Informed of the importance of informing the employer in writing as soon as possible
  - ***(a)*** after becoming aware of their pregnancy; or
  - ***(b)*** if they are breast feeding.

IRMER(11) Training for patient protection:

- No practitioner or operator shall carry out a medical exposure or any practical aspect without having been adequately trained (certificate issued by an institute shall be sufficient proof).
- A person can participate in practical aspects of the procedure as part of practical training only under the supervision of adequately trained person.
- The employer shall keep an up-to-date training record of all practitioners and operators engaged by him to carry out medical exposures or any practical aspect of such exposures available for inspection by the appropriate authority
- Records should show the dates on which training was completed and the nature of the training.
- Practitioner or operator employed by other employer → shall supply such records to the new employer upon request.

PROTECTION OF STAFF & MEMBERS OF THE PUBLIC:

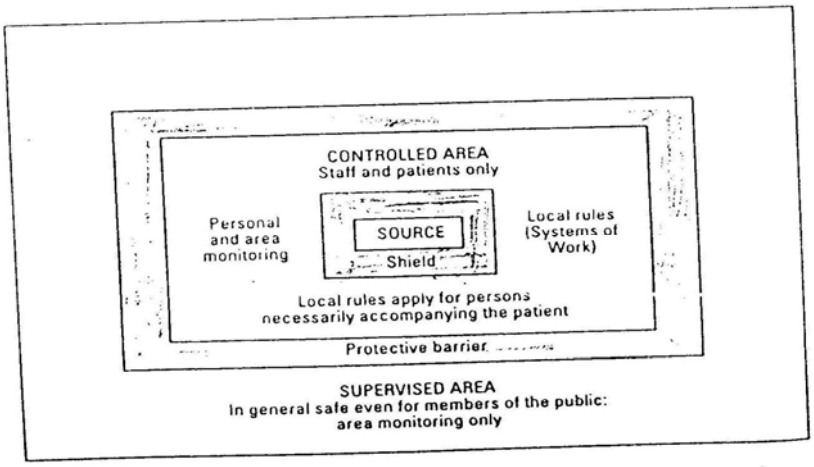
“ Legislation is enacted to ensure that individual doses are as low as reasonably practicable (ALARP)
& that people are unlikely to exceed a proportion of the dose limits.

CONTROLLED AREAS:

- Required as a further control when ***inherent shielding*** of the source (X-ray ***tube*** and radiopharmaceutical ***syringes***) is not enough → the area around the shielded source is designated as a controlled area.
- Controlled areas have ***physical boundaries*** that are able to prevent radiation penetration (above specific level).
- Controlled area should be ***clearly defined boundaries***.
  This is simple to achieve in an x-ray room but more difficult with mobile X-ray set → where the controlled area is determined by eye as extending for 2 meters around tube.
- Every diagnostic X-ray tube produces a large amount of radiation exposure
  ∴ has to be contained within a controlled area.
- In nuclear medicine, area is defined controlled, wherever:
  - A generator is located, or
  - There is a syringe containing radiopharmaceutical.

- Controlled area should have restricted access (to radiation workers & others who work under "written system of work")
- ***"Written system of work"*** organize work within controlled area to ensure that radiology workers can't receive dose > 30% of any dose limit.
- Personal protection should take place within controlled area (e.g. 2.5 mm lead screens, lead rubber aprons and gloves, lead glasses, etc.)

N.B. ***in practice, radiology and nuclear medicine staff receives doses below the public dose limit.***



PART IV
DESIGNATED AREAS
IRR(1999); 16- Designation of controlled or supervised areas

- Every employer shall designate as ***a controlled area*** any area in which -
  1. Any person who enters or works in the area should follow special procedures to restrict significant exposure to ionising radiation in that area or prevent radiation accidents.
  2. Any person working is likely to receive:
     - Effective dose > 6 mSv / year.
     - Equivalent dose > 3/10 of any relevant dose limit (Schedule 4) "for an employee aged 18 years or above".

- also ACOP says if
  - > 7.5 µSv/h averaged over 8 h working day
  - > 75 µSv/h to hands averaged over 8 h working day
  - contamination risk
  - need to keep non-radiation workers out
- or > 7.5 µSv/h averaged over 1 minute and
  - site radiography, or
  - employees untrained in radiation protection enter area (unless radioactivity is dispersed inside a person)

- This area should be under complete control of the employer before starting activities which require that area to be designated as a controlled area.
- An employer shall designate as ***a supervised area*** any area which, not designated as a controlled area :-

1. where it is necessary to keep the conditions of the area under review to determine if the area should be designated as a controlled area; or
2. Any person working is likely to receive:
   - Effective dose > 1 mSv / year.
   - Equivalent dose > 1/10 of any relevant dose limit (Schedule 4) "for an employee aged 18 years or above".

- ***Any Controlled or Supervised Area should be (as a duty of the employer):***
  - i. Adequately described in local rules. "*N.B.* not in the 'System of work'…MCQ"
  - ii. Physical demarcation *of the controlled area*, with suitable warning signs.
  - iii. Display suitable & sufficient signs in suitable positions indicating:
    - The area is a controlled 'or supervised' area.
    - The nature of the radiation sources in the area.
    - The risks arising from such sources.
  - iv. Non-classified workers can only enter under written system of work.
- Employer must demonstrate by personal dose monitoring or other means that dose is restricted.

17- Local rules and radiation protection supervisors:

Def.: Local interpretation of the legislations that specify the procedures needed to ensure working safely in designated area.

- Local rules ***must*** include:
  - Description of controlled areas.
  - System of work within controlled areas, which includes:
    1. Restricting access to it.
    2. Specify the need for lead protection.
    3. Staff monitoring.
  - Dose investigation levels.
  - RPS name.
  - Work instruction for unclassified workers.
  - Back up contingency plan for the department, in case of radiation accidents.
- Local rules ***can*** also include:
  - management and supervision of work
  - testing and maintenance of safety features
  - radiation and contamination monitoring
  - testing of monitors
  - personal dosimetry
  - arrangements for pregnant and breast feeding staff
  - risk assessments
  - programme to review ALARA
  - RPA contact.
- Every radiation employer shall provide Local Rules for any controlled or supervised area → according to the radiation risk & nature of operations performed.
- It should be set down in writing.
- New employee get to read local rules & sign to say they have understood.

- The radiation employer shall ensure:
  1. Observation مراقبة of Local rules.
  2. Local rules are followed by employees and other persons who may be affected.
  3. Appoint ***radiation protection supervisors (RPS)*** to ensure Local rules compliance with the Regulations.
     & mention the names of RPSs in the local rules.

- Local rules are A LEGAL DOCUMENT.
  Policed by RPS & Enforced by HSE inspector.

Radiation Protection Supervisor:

- Must be appointed "*for the purpose of securing compliance of local rules with these Regulations*".
- Name must be in Local Rules
- It is recommended that RPS
  - know & understand regulations and local rules
  - command sufficient authority
  - understand necessary precautions
  - know what to do in an emergency

Requirements of Designated areas

IRR(1999); 19- Monitoring of designated areas

- Every employer shall monitor the levels of ionising radiation in the controlled & supervised areas through suitable and sufficient equipment.
- The monitoring equipments shall be -
  a. adequately tested – by a qualified person – before its first use.
  b. properly maintained
  c. adequately tested and examined at appropriate intervals.
- The employer shall make suitable records of the results of the monitoring and of the tests → authorised by a qualified person → & keep the records for at least 2 years.

Employee allowed to enter or remain in Controlled area:

The employer shall not permit any employee to enter or remain in such an area except:-

1. ***An outside worker*** → is a classified person who is:
   - ***i.*** Received training required.
   - ***ii.*** Certified fit for the work with ionising radiation.
   - ***iii.*** Subject to individual dose assessment.
   - ***iv.*** Provided with personal protective equipment and trained to use them.
   - ***v.*** Have a radiation passbook issued by approved dosimetry service "which contain their personal details & up-to-date radiation doses" before they enter Controlled area.

- The employer shall ensure that ***the classified outside worker is:***
  - Subject to arrangements for estimating the dose of IR he receives whilst in the controlled area.
  - An estimate of the dose received by that worker in that controlled area must be entered into his radiation passbook.
  - the radiation passbook is made available to that worker upon request

2. ***If not an outside worker:***
   - ***i.*** **Is a classified person.**
   - ***ii.*** **If not being a classified person** → Not permitted to enters or remains in the area, unless the employer can demonstrate, by personal dose monitoring, that the doses are restricted as follows: -
     - ❝ *in case of employee ≥ 18 years or over* → not receive in any calendar year a cumulative dose of IR which require him to be a classified person; or
     - ❝ *In case of any other person* → not receive in any calendar year a dose > any relevant dose limit.
     - ❝ The employer shall keep the results of the monitoring or measurements by personal dose monitoring for this non-classified persons for ***2 years***.
     - ❝ Employer shall make that results available to that person on request.

- ***If there is a significant risk of the spread of radioactive contamination from a controlled area:***

The employer shall make adequate arrangements to restrict the spread of such contamination:

1. provide suitable & sufficient washing and changing facilities for persons who enter or leave any controlled or supervised area;
2. maintenance of such washing and changing facilities;
3. prohibit eating, drinking or smoking within controlled area → ↓↓ probability of ingestion of a radioactive substance; and
4. monitoring contamination of persons, articles or goods leaving a controlled area.

IRR(1999); 35- Approval of dosimetry services:

- Occurs in accordance with criteria specified by the Executive.
- Approval is by a certificate in writing.
- The purposes of these services are specified in the certificate.
- The Executive may carry out a re-assessment of any approval.

LEGAL LIABILITIES

- Definition of employer: ***anyone who uses ionizing radiation in a self-employed capacity, with their own equipment.***

Duties of Employer *(IRMER2000)*

(1) The employer shall put *written procedures* *"System of work"* for medical exposures & ensure that the practitioner and operator are complied with.

SCHEDULE 1

Employer's Procedures

The written procedures for medical exposures shall include -

(a) identify the individual to be exposed to ionising radiation;

(b) identify individuals entitled to act as referrer or practitioner or operator (i.e. identify competent staff for specific task);

(c) procedures to be observed in the case of medico-legal exposures;

(d) procedures established by the employer for biomedical and medical research programmes "i.e. no direct medical benefit for the individual";

(e) procedures for the use of diagnostic reference levels established by the employer for radiodiagnostic examinations;
(f) assessment of patient dose and administered activity;
(g) procedures for the carrying out and recording of an evaluation for each medical exposure including factors relevant to patient dose; & review if they are consistently exceeded & take appropriate actions.
(h) procedures for making enquiries of females of childbearing age to establish whether the individual is or may be pregnant or breastfeeding;
(i) procedures to ensure that quality assurance programmes are followed;
(j) procedures for giving information and written instructions for patients undergoing treatment or diagnosis with radioactive material;
(k) Procedures to ensure that the probability and magnitude of accidental or unintended doses to patients from radiological practices are reduced so far as reasonably practicable.

(2) Write protocols for every **standard** radiological examination practice for each equipment.
(3) ***The employer shall establish -***
- ***a)*** Referral criteria, including radiation doses, and ensure that these are available to the referrer;
- ***b)*** Quality assurance programmes;
- ***c)*** diagnostic reference levels for radiodiagnostic examinations regard to European diagnostic reference levels where available;
- ***d)*** Dose constraints for biomedical and medical research programmes.

(4) The employer shall take steps to ensure that:
- ***a)*** no practitioner or operator shall carry out a medical exposure or any practical aspect without having been adequately trained; and
- ***b)*** practitioners or operators undertakes continuing training for new techniques.

(5) ***In case of radiation overexposure incident:***
- ***i.*** Make an immediate preliminary investigation of the incident.
- ***ii.*** Notify the appropriate authority.
- ***iii.*** Arrange for a detailed investigation of the circumstances of the exposure.
- ***iv.*** Arrange for an assessment of the dose received.

(6) If diagnostic reference levels are exceeded → undertake appropriate reviews and ensure that corrective action is taken.

Other duties of Employer:

1. clinical audit in accordance with national procedures ***must*** be performed.
2. Ensure a medical physics expert in areas specified
3. All employers using ionizing radiation in controlled areas should (i.e. required by law) to appoint RPA to provide advice on practical means of complying the legislations.
4. Keep an equipment inventory
5. Limit the amount of equipments.
6. Legislation lays ***"Duty of care"*** on Employers → responsibility for ensuring that regulations are followed (through Radiation Protection Committee).
7. Local rules are produced by or on behalf of the employer.
8. Ensuring the requirements to comply the RSA93.

- The employer is on the top of the organization tree "but legal liabilities may be shared with other individuals" *see Table 6.7*

Responsibilities for radiation safety

Radiation Employer:

- Authorisation of practice.
- Notification of specified work.
- Prior risk assessment.

IRR(1999); 5-Authorisation of specified practices

- A radiation employer shall not carry out the following practices, except in with a prior authorisation by the Executive in writing, -
  (a) the use of electrical equipment intended to produce x-rays -
  (b) the use of accelerators, except electron microscopes.
- This authorisation may be granted subject to conditions and with or without limit of time and may be revoked in writing at any time.
- If the radiation employer attempt to makes a material change to the circumstances relating to that authorisation → that change shall also be notified to the Executive.

IRR(1999); 6- Notification of specified work

- A radiation employer shall not for the first time carry out work with ionising radiation unless at least 28 days before commencing that work he has notified the Executive of his intention to carry out that work.

SCHEDULE 1 - Regulations 6(1) and 13(3)

WORK NOT REQUIRED TO BE NOTIFIED UNDER REGULATION 6

(a) where the concentration of activity per unit mass of a radioactive substance does not exceed the concentration specified in ***column 2 of Part I of Schedule 8***;

(b) where the quantity of radioactive substance involved does not exceed the quantity specified in ***column 3 of Part I of Schedule 8***;

(c) where apparatus contains radioactive substances in a quantity exceeding the values specified but -

- the apparatus is of a type approved by the Executive;
- the apparatus is constructed in the form of a sealed source;
- the apparatus does not under normal operating conditions cause a dose rate of more than 1μSv\h at a distance of 0.1m from any accessible surface; and
- conditions for the disposal of the apparatus have been specified by the appropriate Agency;

(d) the operation of any electrical apparatus (except those for next point) provided that -

- the apparatus is of a type approved by the Executive; and

- the apparatus does not under normal operating conditions cause a dose rate of more than 1µSv\h at a distance of 0.1m from any accessible surface;

(e) the operation of -

- any cathode ray tube intended for the display of visual images; or
- any other electrical apparatus operating at a potential difference not exceeding 30kV,

  → provided that the operation of the tube or apparatus does not under normal operating conditions cause a dose rate of more than 1µSv\h at a distance of 0.1m from any accessible surface;

(f) where the work involves material contaminated with radioactive substances resulting from authorised releases which the appropriate Agency has declared not to be subject to further control.

- The Employer should provide the Executive with the particulars specified in Schedule 2

SCHEDULE 2 - Regulation 6(2)

PARTICULARS TO BE PROVIDED IN A NOTIFICATION UNDER REGULATION 6(2)

a) The employer contacts: name, address, telephone or fax number or email address;

b) the address of the premises where or from where the work activity is to be carried out and a telephone or fax number or email address at such premises;

c) whether or not any source is to be used at premises other than the address given; and

d) the nature of the business of the employer;

e) the category of the sources of ionising radiation:

- ***(i)*** sealed source;
- ***(ii)*** unsealed radioactive substance;
- ***(iii)*** electrical equipment;
- ***(iv)*** an atmosphere containing the short-lived daughters of radon 222;

f) dates of notification and commencement of the work activity.

- The Executive may require that radiation employer provide additional particulars of that work → Schedule 3.

SCHEDULE 3 - Regulation 6(3)

ADDITIONAL PARTICULARS THAT THE EXECUTIVE MAY REQUIRE

(a) a description of the work with ionising radiation;

(b) sources of IR " type of electrical equipment or nature of RAS used";

(c) the quantities of any radioactive substance involved in the work;

(d) the identity of any person engaged in the work;

(e) the date of commencement & the duration over which the work is carried on;

(f) the location and description of any premises at which the work is carried out;

(g) the date of termination of the work;

(h) further information on any of the particulars listed in Schedule 2.

- If a radiation employer makes any change that would affect the particulars so notified → he shall notify the Executive.

IRR(1999); 7- Prior risk assessment etc.

- Before a radiation employer commences a new activity involving work with ionising radiation, he shall make a suitable and sufficient assessment of the risk to any employee and other person for the purpose of identifying the measures he needs to take to restrict the exposure.
- *An assessment should* -
  - ***(a)*** identify all hazards; and
  - ***(b)*** evaluate the nature and magnitude of the risks to employees and other persons arising from those hazards.
- If the assessment shows that a radiation risk to employees or other persons exists from an identifiable radiation accident, the radiation employer shall take all reasonably practicable steps to -
  - ***(a)*** prevent any accident;
  - ***(b)*** limit the consequences of any such accident which does occur; and
  - ***(c)*** provide employees with the information, instruction and training, and equipments necessary, to restrict their exposure to ionising radiation.
  - ***(d)*** prepare ***a contingency plan*** designed to secure the restriction of exposure to ionising radiation and the health and safety of persons who may be affected by such accident

    & he shall ensure that:
    - " a copy of the contingency plan is identified in the local rules;
    - " any employee under his control who may be involved in the plan has been given suitable and sufficient instructions and where appropriate issued with suitable dosemeters or other devices; and
    - " Rehearsals of the arrangements in the plan at suitable intervals.

- ***Duties of employee:***

I- responsibilities for radiation safety:

(1) Not expose himself or any other person to IR greater than necessary for the purposes of his work.

(2) Shall exercise reasonable care while carrying out his work.

(3) If a personal protective equipment is provided to him, he shall:

(a) Make full and proper use of personal protective equipment.

(b) Report the employer for any defect in personal protective equipment.

(c) Ensure personal protective equipment is returned after use to the accommodation provided for it.

(4) Shall notify his employer of any overexposure, radiation accident or RA substance leakage.

(5) Report equipment defects.

II- Extra-duties for classified persons:

(1) Not to misuse the radiation passbook or falsify any information in it

(2) Comply with the local rules, dose measurements & assessment for classified workers.

(3) Subject to medical surveillance:

- When required by his employer.
- At the cost of the employer & during working hours.
- Shall provide the appointed doctor or employment medical adviser with such information concerning his health

- ***Duties of the Referrer:***

Supply the practitioner with sufficient medical data relevant to the medical exposure to enable the practitioner to decide on whether there is a sufficient net benefit.

- ***Duties of Practitioner & Operator:***

Practitioner	***Operator***
(1) Responsible for the justification of a medical exposure ***(2)*** Not necessarily a medic – could be a radiographer if specialized in certain procedures.	***(1)*** Responsible for each and every practical aspect which he carries out. ***(2)*** In fluoroscopy, ensure AEC used unless other method justified.
(3) Both shall comply with the employer's procedures. ***(4)*** Must cooperate with other specialists & staff involved in the exposure. ***(5)*** Undergo continuing education or training.	

Medical Physics Experts:

- Employer shall ensure that a medical physics expert is involved in every exposure.
- Medical physics experts must have a science degree & experienced in the application of physics to the diagnostic & therapeutic uses of ionising radiation.
- ***Duties of medical physics expert:***
  a) Give advice on radiation protection concerning medical exposure.
  b) ***closely involved*** in every radiotherapeutic practice other than standardised therapeutic nuclear medicine practices;
  c) ***available*** in standardised therapeutic nuclear medicine practices and in diagnostic nuclear medicine practices;
  d) In all other radiological practices → he shall be ***involved*** for consultation on optimisation, including patient dosimetry and quality assurance.

- Any new work or change in work with ionizing radiation should be notified to HSE 28 days before starting.
- Responsibilities of HSE:
  2. Enforcing IRR.
  3. Have the power to prosecute the employer or individual workers under civil or criminal law.

RADIOACTIVE SUBSTANCES ACT 93 (RSA93)

i. This is a legal document that ***organizes*** acquisition, storage, and safe disposal of any radioactive substance. This act controls radioactive substances in the environment

ii. The requirements to comply with this Act are the responsibility of the ***EMPLOYER***.

IRR 1999 - PART VI

ARRANGEMENTS FOR THE CONTROL OF RADIOACTIVE SUBSTANCES, ARTICLES AND EQUIPMENT

27- Sealed sources and articles containing or embodying radioactive substances:

The radiation employer shall ensure that:

- The radioactive substance used as a source of ionising radiation is in the form of a sealed source.
- the design, construction and maintenance of any article containing a radioactive substance, *including its bonding, immediate container or other mechanical protection*, is such as to prevent the leakage of any radioactive substance -
  (a) in the case of a sealed source → so far as is practicable; or
  (b) in the case of any other article → so far as is reasonably practicable.
- Suitable tests are carried out at suitable intervals to detect leakage of radioactive substances from any article → & make a suitable record of each test & keep for at least ***2 years*** after the article is disposed of or until a further record is made following a subsequent test to that article.

28- Accounting for radioactive substances:

- Every radiation employer shall take steps to ***account for and keep records*** of the quantity and location of radioactive substances involved in work with ionising radiation.
- Shall keep the records for at least 2 years from the date on which they were made and for at least 2 years from the date of disposal of that radioactive substance.

29- Keeping and moving of radioactive substances:

- Every radiation employer shall ensure that any radioactive substance not in use or being moved, transported or disposed of -
  3. is kept in a suitable receptacle; and
  4. is kept in a suitable store.
  5. suitably labelled.

30- Notification of certain occurrences:

In the following 2 cases:

- If a radioactive substance is ***released into the atmosphere*** as a gas, aerosol or dust; or ***spilled*** (in quantity exceeds the quantity in column 4 of Schedule 8).
- If a radioactive substance is lost or stolen "in quantity exceeds the quantity in column 5 of Schedule 8"

In both cases, a radiation employer shall:

1) Notify ***the Executive***.

2) Make an immediate investigation → make a report & keep it for at least 50 years (if the problem happened) or for at least 2 years (if investigation shows that the problem didn't actually occur).

<u>31- Duties of manufacturers etc. of articles for use in work with ionising radiation</u>

- In the case of articles for use at work with ionising radiation shall be designed and constructed to restrict the exposure of employees and other persons to ionising radiation as far as reasonably practicable.
- Where a person erects or installs an article for use in work with ionising radiation, he shall -

1) Undertake a critical examination to ensure that -
   - the safety features and warning devices operate correctly; and
   - there is sufficient protection for persons from exposure to ionising radiation;
2) Consult with the radiation protection adviser about the nature and extent of any critical examination and the results of that examination; and
3) Provide the radiation employer with adequate information about proper use, testing and maintenance of the article.

PROTECTION OF PATIENTS *(IRMER2000)*

IRNER2000 is concerned with appropriate use of radiation procedures on patients by properly trained staff

- The regulation outline:
  1. The core of knowledge = the theoretical knowledge that staff should have (*see table 6.8*).
  2. It specify the need of practical instruction for all staff.

Table 6.8 Core of knowledge in the POPUMET regulations

1. Nature of ionizing radiation and its interaction with tissue.
2. Genetic and somatic effects of ionizing radiation and how to assess their risks
3. The ranges of radiation dose that are given to a patient with a particular procedure, the principal factors which affect the dose and the methods of measuring such doses.
4. The principles of quality assurance and quality control applied to both equipment and techniques.
5. The principles of dose limitation and the various means of dose reduction to the patient including protection of the gonads.
6. The specific requirements of women who are, or who may be, pregnant and also of children.
7. If applicable, the precautions necessary for handling sealed and unsealed sources.
8. The organizational arrangements for advice in radiation protection and how to deal with a suspected case of overexposure.
9. Statutory responsibilities.
10. In respect of the individual diagnostic and therapeutic procedures which the person intends to use, the clinical value of those procedures in relation to other available techniques used for the same or similar purposes.
11. The importance of utilizing existing radiological information - films and/or reports - about a patient

- Staff individuals can be divided into:
  1. ***individuals clinically directing the exposures*** e.g. Radiologist**:**
     - Staff members who carry the clinical responsibility.
  2. ***Staff physically directing the exposure*** e.g. Radiographer**:**
     - Those who directly irradiate patients.
     - if not well-trained → can't work except under supervision of well-trained person (till he complete his training)
- Regulation 4 of POPUMET is fundamental to patient protection, it requires:
  Every medical exposure to be carried out under the direction of a person who is clinically directing the exposure.
  a) ensure that only accepted diagnostic practices are used.
  b) Ensure selection of procedures ŵ fulfill Justification & Optimization principles:
     - ***i.*** Ensure patient dose is ALARP.
     - ***ii.*** Ensure examination is consistent with requirements for diagnosis.
     - ***iii.*** Ensure particular care of pregnant patients.

REFFERRALS:

- The radiologist takes responsibility for clinical direction (So, the request from the clinician is only a request of opinion, the radiologist is having the right to refuse, accept, or tail out a study according to the clinical situation)
- The request form – properly filled by clinician – is a legal document.
- There should be locally agreed referral criteria set by the employer.
  The RCR handbook *"Making the best use of radiology department"* may be used as a basis for referral practice.

Sharing responsibilities:

i. Other (non radiologist) medical staff as orthopaedicians, cardiac catheterizators may take responsibility of directing for procedure (physically, or clinically) like in case of C-arm fluoroscopy in Operation Room, or Cathlab.

ii. Any radiographer who continues with a procedure knowing that it is inappropriate, is equally culpable (blamable) in law (i.e. responsible in front of law).

Legal liability (IRR99)

- IRR 1999 regulates the responsibility of each, the employer as well as the person who is physically (tech) or clinically (radiologist) directing the study. *(Employer, Practitioner and Operator)*
  1. responsible for enforcing persons clinically or physically directing examinations lies on secretary of State Of Health (who uses health department inspectorate).
  2. There is no umbrella of an employer ??!!

Table 6.7 Legal liability and inspection

	LEGISLATION			
	IRR8S	***IRR[POPUMET] 88***	***M(ARS)R 78***	***RSA93***
Area	X-rays and nuclear medicine	X-rays and nuclear medicine	Nuclear medicine	Nuclear medicine
Liability	Employer and employee	Employer and practitioner	Employer and practitioner	Employer
Inspection	HSE	HSE and Government Health Departments	Departments of Health and of the Environment	Departments of the Environment

Legal liability (M[ARS] regulations)

- Use of radiopharmaceuticals (diagnostic and therapeutic purpose) is regulated by the M[ARS] in addition to POPUMET.
- *Procedure should be performed UNDER SUPERVISION OF an ARSAC certificate holder.(MCQ)*
- Injection may be performed by other staff, but under supervision of ARSAC holder. (Administration of Radioactive Substance Advisory Committee)
- Maximum dose to the patient is defined in the certificate.
- Everyone who is involved in a procedure (ARSAC holder clinician, or injector, the one physically conducting the procedure) need to be trained under IRR[POPUMET]
- Employer is responsible to ensure that clinicians are holding ARSAC.
- ***Regarding the ARSAC certificates "Department of Health"***
  1. Must be held by the person clinically supervising procedures using RAS.
  2. Authorize certain procedures to be performed by it's holder.
  3. Define max. dose to patients (max. activity to be administrated).
  4. Issued to individual clinicians- for specific procedures- (including research) using specific equipment.
  5. Valid for 5 years (& only 2 years for research purposes).
  6. Needs to be signed by RPA.
- Responsibilities of ARSAC certificate holder:
  1. Gives clinical supervision to procedures using RAS.
  2. Instructing & supervising the person physically directing patients.
  3. Responsible for discharging radioactive patients from hospital:
     - Depending on max. activity remaining in the body.
     - Gives specific behavioral instruction or advice to patient (e.g. stop lactation).
     - RPA should be able to give further advice.

*IRR 32.*EQUIPMENT USED FOR RADIODIAGNOSIS AND TREATMENT:

*"**Radiation equipment**"* means equipment which delivers ionising radiation to the person undergoing a medical exposure and equipment which directly controls the extent of the exposure.

(1) Every employer who controls any equipment which is used for medical exposure shall ensure that such equipment is *of such design or construction* and is so *installed and maintained* to be capable of ***restricting the exposure to ionising radiation*** of any person undergoing a medical exposure "diagnostic, therapeutic or research" *to a compatible extent.*

- This includes the use of equipments which directly affects the dose to the patient, e.g. film processors, intensifying screens, radionuclide dose calibrators, etc.

(2) An employer who controls any radiation equipment "installed after the date of these Regulations" shall ensure that it is provided with suitable means for informing its user of ***the quantity of radiation*** produced during a radiological procedure.

(3) Every employer shall make arrangements to provide a suitable ***quality assurance programme*** for the equipment → to ensure it remains capable of restricting exposure.

(4) the quality assurance programme shall provide: -

(a) adequate testing of ***New equipments*** before its first use for clinical purposes by an RPA appointed by the employer.

(b) adequate testing of the performance of the equipment at appropriate intervals and after any major maintenance procedure.

(c) measurements at suitable intervals to enable the assessment of doses to persons undergoing medical exposures.

(5) Every employer shall take all steps to monitor & prevent the failure of any equipment which could result in an exposure to ionising radiation greater than intended and to limit the consequences of such failure.

- *To monitor equipment malfunctions* "what is accepted to occur from time to time".
  - ❝ There must be systems to detect and to correct for malfunctions.
  - ❝ There should be ***a log*** for the recording of faults and defects for each X-ray unit.
  - ❝ Deterioration in performance does not necessarily mean that equipment should be withdrawn from use → it may mean that certain procedures should no longer be carried out using that equipment.
  - ❝ The equipment should be properly justified for the new uses.

(6) Where a radiation employer suspects or has been informed that an incident may have occurred in which a person while undergoing a medical exposure was exposed to ionising radiation to an extent much greater than intended, *as the result of a malfunction of, or defect in, radiation equipment* under his control حادث نتيجة عيب بالجهاز, he shall:

i. Make an immediate investigation of the suspected incident.

ii. If that investigation shows that an incident has occurred:

- Employer shall notify the Executive.
- Make or arrange for a detailed investigation of the circumstances of the exposure and an assessment of the dose received.

iii. A radiation employer shall make a report of that investigation and shall -

- ***Immediate investigation report***→ keep that report for at least 2 years.
- ***Detailed investigation report***→ keep that report for at least 50 years.

IRMER 10- Equipment:

- The employer shall draw up, keep up-to-date and preserve at each radiological installation an inventory of equipment at that installation.
- Employer shall furnish the inventory to the appropriate authority when requested,.
- The inventory shall contain the following information -
  - ❝ name of manufacturer,
  - ❝ model number,
  - ❝ serial number or other unique identifier,
  - ❝ year of manufacture, and
  - ❝ year of installation.
- The employer shall ensure that equipment at each radiological installation is limited to the amount necessary for the proper carrying out of medical exposures at that installation عدد محدود.

Radiation Accidents & Overexposures:

Investigation and notification of overexposure

IRR 25

(1) If a radiation employer suspects or has been informed that any person received an overexposure:

1. Employer shall make an immediate investigation to determine whether there are circumstances which show beyond reasonable doubt that no overexposure could have occurred and
2. Employer shall as soon as practicable notify the suspected overexposure to -
   - ***(i)*** the Executive;
   - ***(ii)*** other employer → in case of an employee of other employer; and
   - ***(iii)*** in the case of his own employee → the appointed doctor or employment medical adviser;
   - ***(iv)*** Notify the affected person as soon as practicable.
3. Arrange for detailed investigation of the circumstances of the exposure and
   - ❝ An assessment of the dose received.
   - ❝ Determine the measures required to prevent a recurrence of such overexposure.
4. and shall notify the results of that investigation and assessment to the persons and authorities mentioned above "as in immediate investigation" and
5. shall notify that employee of the results of the investigation and assessment.

(2) A radiation employer shall make a report of that investigation and shall -

(a) in immediate investigation → keep report for at least 2 years; and

(b) in detailed investigation → keep report until the exposed person attains the age of 75 years & at least for 50 years.

(3) Where the person who received the overexposure is an employee who has a dose record, his employer shall arrange for the assessment of the dose received to be entered into that dose record.

Dose limitation for overexposed employees

IRR 26.

- The employer shall ensure that - during the remainder of the dose limitation period - an employee subjected to an overexposure does not receive a dose of ionising radiation greater than the proportion of any dose limit = the proportion of the ***remaining part of the dose limitation period*** to the ***whole of that period***.
- The employer shall inform an employee who subjected to an overexposure of the dose limit for the remainder of the relevant dose limitation period.

Dosimetry for accidents etc.

IRR23

- If any accident takes place which is likely to result in a person receiving an effective dose of ionising radiation exceeding 6mSv or an equivalent dose greater than three-tenths of any relevant dose limit, ***the employer shall*** -

a) Arrange for dose assessment:

in the case of a classified person → arrange for a dose assessment to be made by the ***approved dosimetry service***;

in the case of an employee to whom a dosemeter has been issued → arrange for dosemeter examination & assessment of the dose received by the ***approved dosimetry service*** as soon as possible;
in any other case → arrange for dose assessment by an appropriate means as soon as possible under advice of the ***radiation protection adviser***.

b) Inform each person for whom a dose assessment has been made of the result of that assessment; and

c) Keep a record of the assessment until the person to whom the record relates attained the age of 75 years & for at least 50 years from the date of the accident.

Patient Overexposures:

- The legislation has been designed to reduce the potential for errors in radiation administration to patients.
- ***Causes:***
  a) *Human errors*, if serious → investigated by the Department of Health.
  b) *Equipment fault.*
- If the overexposure is greater than ***three times the dose*** that was intended, the following action is necessary:

1. *The Manager "i.e. Employer"* and ***RPS*** should be informed.
2. The equipment should be withdrawn from use (in consultation with the ***RPA***).
→ returned into use only once the fault has been investigated and rectified.
3. Details of the malfunction should be properly recorded, including:
- Circumstances.
- Equipment settings.
- Patient details.
- Who was present, etc.

4. The dose received by the patient should be estimated by an ***RPA***.
5. The ***RPA*** will provide advice on further action according to the circumstances.
6. ***Inform:***
- ***The patient.***
- ***The hospital management***, through the manager responsible for the equipment → to establish external reporting mechanisms.
- ***The Department of Health*** → to issue national hazard warning notices.
- ***The HSE*** should be informed in case of high-dose procedures *(Table 6.9a)*.

N.B.
Patient Doses Much Greater Than Intended:
- x 20 - extremities, skull, chest, etc.
- x 10 - lumbar spine, abdomen, pelvis, mammography and other examinations not referred to elsewhere,
- x 3 - fluoroscopy, digital radiography, C.T

Table 6.9a Ranges of effective dose		
Effective dose	***Range (mSv)***	***Procedure***
High	***5-50***	Barium enema, gallium scan, CT scans
Medium	***0.5-5***	Intravenous urography Barium meal Lumbar spine Abdomen, Pelvis Thoracic spine ^{99m}Tc scans of brain, bone, kidney, liver, Lung perfusion Thyroid imaging
Low	***0.05-0.5***	Chest, Dental, Skull

Notification Levels

Type of diagnostic examination	Guideline multiplying factor
Barium enemas/meals, IVU, angiography and any other such procedure involving fluoroscopy (including digital radiology) and CT	X 3
Nuclear medicine: intended E > 5 mSv, e.g. ^{201}Tl (myocardial imaging)	X 3
Lumbar spine, abdomen, pelvis, mammography,	X 10
Nuclear medicine: intended E ≤ 5 mSv but > 0.5 mSv, e.g. ^{99m}Tc (MAA lung imaging)	X 10
Extremities, skull, chest, dental and other simple examinations such as elbow, knee, and shoulder	X 20
Nuclear medicine: intended E ≤ 0.5 mSv, e.g. ^{51}**Cr** (EDTA) GFR measurement	X 20
Type of treatment	**Guideline multiplying factor**
Beam therapy, brachytherapy	1.1 (whole course) 1.2 or 1.2 (any fraction)
Radionuclide therapy, eg ^{131}**I**	1.2 (any administration)

PATIENT RECORDS

- A record should made of:
  1. The type of examination.
  2. Radionuclide and activity administered.
  3. Number of X-ray films and screening times.
  4. Exposure factors
  5. Equipment used, film cassette size, and focus-skin distance.
  6. Completed request form, signed by a medical practitioner **"legal document"**.
- The information kept in the patient's notes.
- The Department of Health recommends that films and other records be kept for a minimum of **6 years**.
- This information may be needed for:
  a) Possible future litigation.
  b) Calculation of 'total patient dose'.

PATIENT DOSIMETRY

- Measuring the dose to a patient is an important part of any medical exposure because:
  - The dose can be used to predict the occurrence of adverse health effects.
  - Used, by comparison with a **reference value (or DRL)**, as an index to check that the procedure had been optimised.
- Measuring **the absorbed dose** the patient receives is actually very difficult.
- Instead, the following indices can be recorded to estimate patient dose during screen-film radiography or fluoroscopy:

Entrance skin dose (ESD):

- **The dose at the patient's skin surface** where the x-ray beam enters the body.
- It consists of the dose due to **the primary (unscattered) beam** + the dose due to **backscattered radiation** from the patient.
- **It can be measured using:**
  - **TLDs:** most common, must be accurately calibrated, placed on the skin surface of the patient.
  - **Ionization chambers:** measure air kerma rate.
- Measured in units of **mGy**.
- For a more complete estimation of the risk from the exposure → **the field size** should also be recorded with the ESD.

Dose-Area Product (DAP)

- A measure of the **total x-ray energy absorbed** by the patient.
- It is measured in units of **mGy cm^2**
- It is measured using a **DAP meter**,
  - Parallel-plate ionisation chamber filled with air.
  - Sits just below the diaphragms/collimator in the x-ray tube.
  - The current recorded by the DAP meter depends on both ***the intensity and the area of the beam*** (hence "*dose-area product*").
- It is important to record the DAP during fluoroscopy → because non-standard field-sizes are often used & beam direction changes during the examination.

- Naturally, if neither of these measurements can be made on a patient → the dose delivered to the patient can be estimated **indirectly** from knowledge of the:

1. Beam parameters (eg kVp, mAs & HVL),
2. Beam orientations (eg AP, PA, lateral views etc)
3. Field sizes for each view
4. Focus-Skin distance for each view
5. Patient size/thickness for each view

- **For routine screen-film investigations** where standard procedures are followed (ie kVp, HVL and FSD are constant) → it is often enough to record **the mAs** as a measure of the patient dose during the procedure.
  In fluoroscopy, → the **beam-on time** is the parameter which is often recorded.
  In CT studies → the **"CT Dose Index" (CTDI)** is parameter of patient dose.
  In nuclear medicine studies → the **injected activity in MBq**

Patient Doses from Common Procedures

Various national surveys have been conducted in the UK of patient doses as a result of common x-ray procedures. A list of typical patient doses is given below (please learn it!)

Typical effective doses, equivalent periods of natural background radiation and lifetime fatal cancer risks from diagnostic medical exposures

Diagnostic procedure	Typical effective doses (mSv)	Equivalent period of natural background radiation[1]	Lifetime additional risk of fatal cancer per examination[2]
X-ray examinations:			
Limbs and joints (except hip)	< 0.01	< 1.5 days	1 in a few million
Teeth (single bitewing)	< 0.01	< 1.5 days	1 in a few million
Teeth (panoramic)	0.01	1.5 days	1 in 2 million
Chest (single PA film)	0.02 **– 0.2**	3 days	1 in a million
Skull	0.07	11 days	1 in 300,000
Cervical spine (neck)	0.08	2 weeks	1 in 200,000
Hip	0.3	7 weeks	1 in 67,000
Thoracic spine	0.7	4 months	1 in 30,000
Pelvis	0.7	4 months	1 in 30,000
Abdomen	0.7	4 months	1 in 30,000
Lumbar spine	1.3	7 months	1 in 15,000
Barium swallow	1.5	8 months	1 in 13,000
IVU	2.5 **- 5**	14 months	1 in 8000
Barium meal	3 **- 5**	16 months	1 in 6700
Barium follow	3 - 5	16 months	1 in 6700
Barium enema	7 **- 9**	3.2 years	1 in 3000
CT head	2	1 year	1 in 10,000

CT chest	8		3.6 years	1 in 2500
CT abdomen/pelvis	**8 -** 10		4.5 years	1 in 2000

Nuclear medicine studies:

Lung ventilation (Kr-81m)	6000 MBq	0.1	2.4 weeks	1 in 200,000
Lung perfusion (Tc-99m)		1	6 months	1 in 20,000
Kidney scan (Tc-99m)		1	6 months	1 in 20,000
Thyroid scan (Tc-99m)		1	6 months	1 in 20,000
Bone scan (Tc-99m)		4	2 years	1 in 5000
Dynamic cardiac (Tc-99m)	800 MBq	6	2.7 years	1 in 3300
Myocardial perfusion (Tl-201)		18	8 years	1 in 1100
Abscess imaging (Ga-67)	150 MBq	18	8 years	1 in 1100

	Procedure	Effective dose
Fluoroscopy	Skin absorbed dose rate	20 mGy\min
	Effective dose rate	1 mSv\min

- ***For X-ray,*** Quality assurance has a major role to play in reducing patient dose → as there is a large range in effective dose delivered by different examinations.
  There is also a wide variation in the absorbed dose delivered by the same X-ray examination carried out in different departments.
- ***For nuclear medicine,*** there is less variation in dose → as the maximum activities of radionuclides are determined by the ARSAC.
  Children should be given proportionally less radionuclide, and even so their effective doses may be higher than for adults → needs greater care.

Regarding the differences between The Entrance Surface Dose (ESD) values for a given X-ray examination:

- It's up to **100% higher in some radiology departments than in others**. (Fig. 6.8)
- The distributions are typical skew.
- About **25% of hospitals giving unnecessarily high doses**.

- The reference level in UK for both film radiography (Table 6.10a) and fluoroscopy is **75th percentile value for the dose**:
  - Patient entrance surface dose should fall below the 75 percentile values for the examination *"made on a standard-sized (70 kg) patient or standard phantom"*.
  - **Values above the 75th percentile** → the equipment and departmental techniques should be investigated with a view to ***reducing dose*** while ensuring good image quality (see Table 6.4).
  - **If values below the 10th percentile** → the ***image quality*** should be reviewed.

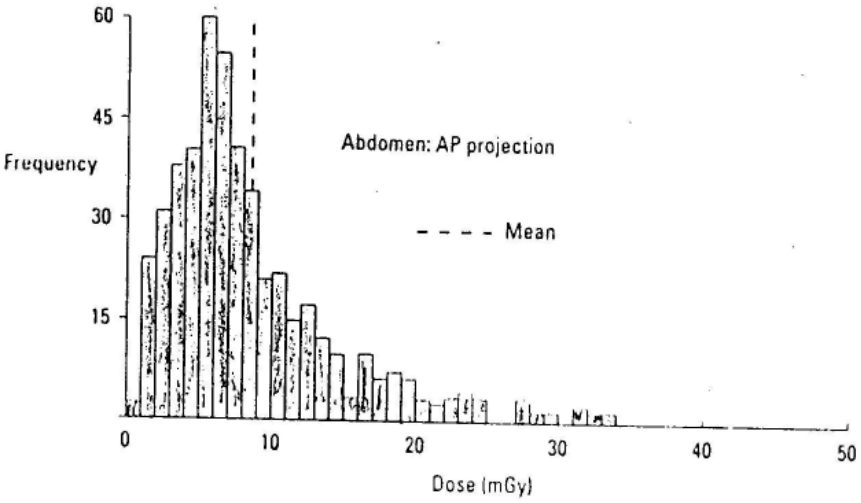


Fig. 6.8 - Histogram of the entrance surface dose per radiograph

Table 6.10a Reference values of entrance surface dose

Site	View	Reference dose (mGy)	
		75th percentile	10th percentile
Lumbar spine	AP	10	4
	Lat	30	10
	LSJ	40	
Abdomen	AP	10	5
Pelvis	AP	10	4
Chest	PA	0.3	0.1
	Lat	1.5	
Skull	AP	5.0	2.0
	PA	5.0	
	Lat	3.0	

Table 6. 10b Reference values of the dose - area product

Examination	Reference dose (Gy cm^2) 75th percentile
Lumbar spine	15
Barium enema	60
Barium meal	25
Intravenous urography	40
Abdomen	8
Pelvis	5

6.8 PRACTICAL REDUCTION OF DOSE TO STAFF AHD VISITORS

- The practical radiation protection techniques is primarily concerned with **dose optimisation**, ie techniques which will minimise the dose received.
- Members of staff are constantly exposed to ionising radiation → even procedures which expose staff to small dose-rates are capable of generating substantial cumulative doses over a period of many years.

So, there is a need to **keep dose-rates as low as possible** in the workplace.

- Staff working with x-rays can be exposed to three different sources of radiation:

× Direct beam. **× Leakage radiation.** **× Scatter radiation.**

Scatter & leakage radiations are collectively known as **"secondary radiation"**

- **In nuclear medicine,** there are 2 principal sources - **the radionuclide before injection** and **the patient after injection** (see Section 5.7).

SOURCES OF X-RAY EXPOSURE

Primary "Direct" beam

- **No-one other than the patient** should be exposed to the direct beam.
- Special care is needed in fluoroscopy, overcouch or C-arm tube & mobile radiography.

Leakage radiation

- Leakage radiation is emitted in all directions from the tube housing.
- leakage has a higher average energy (& HVL) than the primary beam because of **the selective absorption of low energy photons in the housing**.
- The leakage radiation measured at a distance of **1 m** from the focus for **1 hour** must not be more than **1 mSv**, and is typically < 0.1 mSv.

To Protect:

1. The tube housing incorporates lead shielding → defines the useful beam and absorbs the majority of the off-axis photons.
2. The cones, diaphragm, and the housing of the light beam diaphragm.
3. The housing of the image intensifier has a lead equivalent of **2.5 mm**.

Scattered radiation

- X-rays are scattered in ***all directions*** when the X-ray beam strikes any object, including the patient "a source of scattered rays"
- At the x-ray energies used in planar radiography (25-50keV):
  - Because the intensity of the beam is greatest where it enters the body (and most of the forward scatter will be absorbed in the body)

→ ∴ intensity of **backscatter** from patient is higher than in any other direction.

  - **The average energy (or HVL) of scattered radiation is about the same as the primary beam** (remember, low energy x-rays lose vary little energy during Compton scattering), and the intensity or dose-rate due to scatter increases with the size of the primary beam.

Typically, the dose-rate due to scattered radiation at 1m from a patient is **~ 0.1% of the ESD**.

To Protect:

1. Radiologist & radiographer should be as far away from patient as practicable.
2. **During fluoroscopy** → procedures involving lateral views, staffs are advised to stand at the exit side of the patient rather than the side where the beam enters the body
3. Lead-rubber aprons and curtains, glass screens, etc., should be used.
4. When injecting contrast in CT:
   a) High kV techniques → high side scatter.
   b) Avoid the area close to the aperture → highest scatter.

REDUCTION OF EXPOSURE

Distance

- **The inverse square law** affords the cheapest form of protection.

  The dose rate from a small ("point") source will decrease with the square of the distance from it.

- One large step away usually reduces the dose rate *four times*.
- ***Precautions:***
  - X-ray rooms must be **adequately large**.
  - **No one should stay in the X-ray room** or expose to X-ray unnecessarily:
    - Near the patient in ward radiography.
    - During CT warm-up procedures.
  - **Keep as far as possible from the X-ray source**, except if necessary:
    - In ward radiography, the exposure switch has a cable which allows the operator to stand at least 2 m from the patient.
    - In fixed equipment → radiographer is not leaving the protective cubicle containing control panel during exposure.
  - **In nuclear medicine:**
    - Once patients have been injected they become sources of exposure to staff.
    - Waiting areas are designed to avoid unnecessary exposure to others.
    - Staff should be able to position and then image the patient with the gamma camera without being unnecessarily exposed.
  - **Undercouch fluoroscopy** units are preferred to overcouch units.

    In overcouch unit,
    - Staff are closer to the x-ray tube.
    - Staff experiences a higher intensity of scattered radiation because of the increased incidence of backscatter from the patient.

Speed and time

- The dose delivered to any individual = dose-rate x time
- **Fast recording media** and **short screening times** → ↓↓ patient & staff dose.
- ↓↓ time of exposure in interventional procedures & time spend close to nuclear medicine patients after being injected.
- In fluoroscopy there is a **timer with a maximum setting of 10 min.** (exposing the same part of the patient for long times → skin erythema).

Shielding by barriers

- The shielding material, its thickness and its geometry with respect to the source are all dependent on *the energy of the x-rays*, *the intensity of the beams*, *their*

orientation within the room, *the expected workload* and *the level of occupancy of rooms adjacent to the x-ray room*.

- Shielding is most often used to:

1. Absorb leakage radiation from the x-ray tube.
2. Absorb scattered radiation from the patient.
3. Absorb primary radiation that has passed through the patient (this shielding is incorporated into the walls and doors of the x-ray room).

- Structural shielding is designed to **reduce the dose-rate in an area adjacent to the x-ray room to an acceptable level**.

Acceptable level depends on what the adjacent area is used for. Clearly, **frequently occupied areas** by other staff and/or the general public will require ***greater control*** of the radiation dose-rate than those that act as store rooms etc.

- **Protective barriers** should be used when an exposure is made.
  If this is not practicable, distance and protective clothing should be used.
- **The protective screen around the control panel** **protects against scatter only** → the primary beam must never point toward it.
- The panel is usually made of **plywood incorporating 2.5 mm of lead**, which **reduce the exposure to the public dose limit**, without protective clothing.
- It includes a lead glass window giving a clear view of the patient.

Protective clothing

- Lead aprons should be worn by anybody who must enter an x-ray room while the beam is on
- Protective clothing **does not** protect against **the direct beam** but **only attenuated or scattered** radiation by the patient.
- When palpating, a **glove** is worn of **at least 0.25 mm** and preferably **0.35 mm** lead equivalent.
  When injecting, the hands must be outside the direct beam.
- **Standard body aprons:**
  - Cover **75% of the red bone marrow**.
  - Not less than **0.25 mm** lead equivalent (which **typically transmits only 10% of 90° scatter at standard operating kVp "about 100 kVp"**).
  - In interventional radiology, aprons should cover as large an area as possible and have **a front of 0.35 or 0.5 mm** lead equivalent.
  - Aprons are provided in all X-ray rooms and with each mobile set.
  - They must be stored carefully without folding, e.g. draped over a thick rail, to avoid cracking.
    They are examined periodically using X-rays to check for cracks.
- **Thyroid protection shields** → recommended to be worn during fluoroscopic procedures.
- **Lead glass spectacles** may be worn during some interventional procedures, or a *pull-down lead glass window* may be used.
- **Large drapes** of **0.5 mm lead equivalent** are used in fluoroscopy
- **In gamma imaging** → **thin lead protection "adequate for X-rays", is**

insufficient.

→ In this case, distance and time are important factors for staff dose reduction when the patient is the source.

Warning lights and signs

- ***On the X-ray control panel***
  - A light comes on when the set is switched on.
  - Another light comes on when the tube is energized, and stays on long enough to be noticed, even if the exposure is brief.
- ***On each tube housing,*** in case of double tube controlled by a single control panel → yellow or amber lights come on when the tube is selected.
- ***At the entrance to the X-ray room:***
  - A **warning sign** to indicate a 'controlled area' due to X-rays.
  - A **warning light** which comes on during fluoroscopy and when the tube is 'prepared' for radiography.
- ***In nuclear medicine,*** **warning signs alone are adequate**.
  Warning lights are ***not helpful*** as the hazard is effectively present all the time.

Protection of the public

- X-ray rooms are shielded "walls, windows & doors" to **reduce the dose in surrounding areas < the levels for 'other persons',** i.e. **0.1 mSv per week** under normal workloads.

- The walls which the primary beam can be directed against = **"primary barriers"**, while the walls which only protect against scatter and leakage radiation are called **"secondary barriers"**.

The primary barriers must be more absorbing than secondary barriers.

- For 2ry barriers → **2.5 mm** lead equivalent is satisfactory.
- For 1ry barriers "subject to direct beam" → need greater protection.
  - The protection needed is first calculated in terms of lead.
  - Then realized as an equivalent combination of other materials.
  - The following are approximately equal in their protective power for diagnostic X-rays:

120 mm of concrete = 12 mm of barium plaster = 1 mm of lead

- Radiopharmacies are similarly protected, and consideration has to be given to visitors in nuclear medicine waiting areas.

Supporting children during radiography

- *Restraining and supporting devices* → hold children during radiography.
- If this is not practicable, children may be supported by an *accompanying adult* **"Comforter & Carer"** → but not by a pregnant woman.
  - individuals who (other than as part of their profession → not a nurse) knowingly and willingly incur an exposure to ionising radiation to support another person who is undergoing a medical exposure
  - Must be aware of the risk of exposure to IR.
  - He or she is given instructions how to do so

- Positioned outside the beam.
- Wears a protective apron or shielded by a barrier.

- A direct-reading radiation monitor may provide reassurance.

6.9 PERSONAL DOSIMETRY SYSTEMS

- Radiation dosimeter = any device which is capable of measuring absorbed dose.
- ***In particular the ideal dosimeter must be able to;***

1. Record doses of different types of radiation (eg x-rays, β particles, positrons etc)
2. Record doses over a wide range of radiation energies (i.e. its response should be the same when measuring **20** keV γ-rays as it should for measuring **511** keV γ-rays طاقه كبيره او صغيره).
3. Record doses over a wide range of values (ie it should be able to measure very small and very large doses accurately جرعه كبيره او وصغيره).
4. Measure doses independent of environmental conditions (temperature, pressure & humidity).
5. Additionally an ideal dosimeter would also be *small, lightweight, robust and cheap.*

Three different personal dosimetry systems will be described. Their relative advantages or disadvantages are summarized in Table 6.11.

6.9.1 FILM BADGES

- Most used in diagnostic radiology.
- عباره عن film without screens - same size as a dental film.
- It is double coated:
  - ❝ One emulsion is slow → unaffected by normal occupational doses;
  - ❝ The other emulsion is fast → used to assess normal occupational doses.
- High (accidental and emergency) doses:
  1. Completely blacken the fast emulsion → radiation dose cannot be assessed.
  2. The slow emulsion → lesser blackening → allows assessment of high dose.
- Monitoring films are placed in a plastic cassette or ***'badge'*** which:
  - Pinned to the clothing.
  - Carry an identification of the wearer.
  - Most importantly → incorporates plastic and metal filters to differentiate the radiations received (Fig. 6.9a).
- ***CALIBRATION:***
  - Each month, films from a single manufacturing batch → similar sensitivities
  - Stamped with identifying serial numbers (seen through the open window).
  - A proportion of these are retained in the laboratory as calibration films.
  - Calibration is by exposure known doses of gamma rays from a long half-life radioactive source, e.g. the ***662 keV gamma rays from*** ^{137}Cs.
- ***PROCESSING:***
  - Dosemeters are worn for a month → returned to approved dosimetry laboratory
  - Then, the films are all processed under carefully controlled conditions.
    - ❝ The densities of ***the calibration films*** are measured, and a graph is plotted of *density of blackening under a lead filter* versus *dose*.
    - ❝ The densities of the ***badge films*** are then measured → the received doses are read from the appropriate calibration curve.

MECHANISM:

- The operation of the dosimeter is based on **the photochemical reaction**, i.e. radiation reacts with the film emulsion which darkens according to dose when developed.
- The emulsion contains high atomic number elements "than tissue or air" → ∴ the optical density of the film caused by a given dose of radiation will increase at low energies due to an increase in the number of photoelectric events.

  ∴ The film dosemeter is *energy-dependent*.

  For example, diagnostic X-rays produce about 10 times the blackening as the same absorbed dose of gamma rays from diagnostic radionuclides.

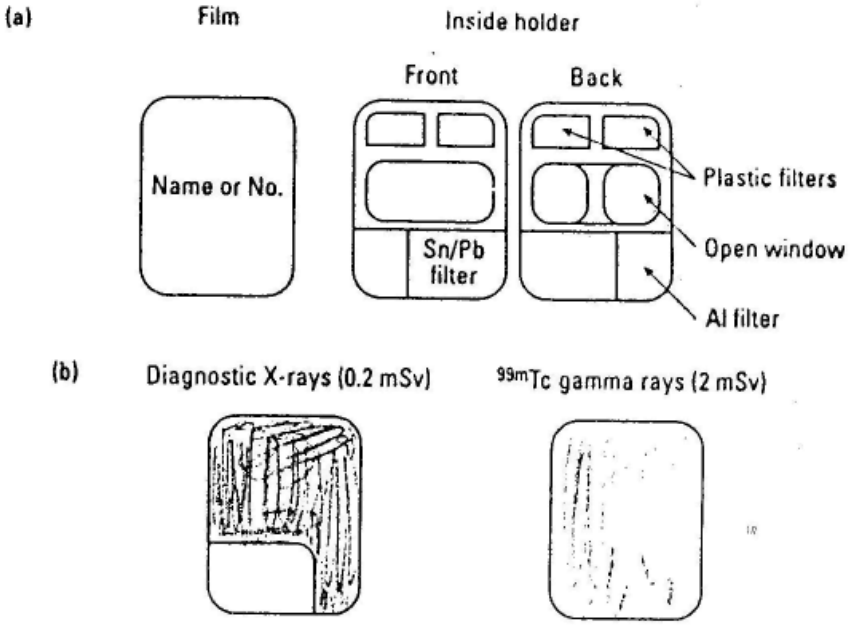


Fig. 6.9 (a) Personal dosimetry film badge, (b) Exposed films.

- Film badge is usually exposed to ***mixed radiations***

  To identify the various energy components, the film is sandwiched between at least three pairs *of* ***filters****:* (a) 'thick plastic', (b) aluminum, and (c) tin with a thin lead foil (Fig. 6.9a).

	High energy	***Medium energy***	***Low energy***
Thick plastic	Not attenuated	Not attenuated	Somewhat attenuated
Aluminum	Not attenuated	Somewhat attenuated	Totally attenuated
Tin with thin lead	Somewhat attenuated	Heavily attenuated	Totally attenuated

- The film badge can also measure *other kinds of ionizing radiations.*
  - To asses the dose of beta rays of various energies → one or more thin plastic filters + the thick one + open window (no filter).
  - To asses the dose from slow neutrons → an additional filter of cadmium.
- ***interpretation of the badge film:***
  - By measuring the optical densities of the film under each filter it is possible to estimate the energy and type of radiation which was responsible for the dose + suitable corrections for the energy dependence.
  - Because ***the characteristic curve of the film is only linear over a limited range of doses*** → film badges are only

able to measure doses from ~0.2 – 1000 mSv "suitable for diagnostic radiology".

1. Pattern of shadows of the three filters → indicate ***type(s)*** of radiation (Fig. 6.9b).
2. The densities under each filter *using the relative speed of the film to radiations of different energies, and the calibration curve* → ***Dose*** of mixed radiations.
3. *A sharp edge* to the shadows of the filters → a single exposure to direct rays from one direction;
   A blurred edge → scattered rays or multiple small exposures from different directions.
   Spots of intense blackening → a radioactive spill (MCQ).

- *Adv.:* small, lightweight and cheap and forms a permanent dose record.
- *Disadv.*
  - ***Used only once.***
  - ***affected by excessive temperature and humidity.***
  - ***Lower threshold for hard gamma radiation is 0.15 mSv.***

6.9.2 THERMOLUMINESCENT DOSEMETERS

- More expensive, so less common in radiology than film badges.
- *Adv.:* particularly useful for measuring extremity doses.
- TLDs depend on the principle of *luminescence* & *thermoluminescence*.
- Different forms and materials, اهمهم → a small chip of ***lithium fluoride*** (3 x 3 mm) mounted in a plastic holder + carries identifying details & pinned to the wearer.
- *In other forms, TL dosimeters are also used to:*
  1. Measure patient dose in radiological procedures.
  2. Mounted in rings to measure staff finger doses.
  3. Mounted in sachets, placed on the forehead to estimate eye doses.
- The badges are worn for a prescribed period → then, returned to the approved dosimetry laboratory for processing.

MECHANISM:

- When X- or gamma rays fall on thermoluminescent (TL) material "lithium fluoride" → absorbed → atomic electrons are raised to higher energy levels → the electrons stay indefinitely in their excited state (in 'electron traps'), and the material retains a 'memory' of the radiation exposure.
- The greater the dose absorbed, the more electrons are 'trapped'.
- TLDs show a linear response over a wide range of doses, unlike film badges.
- LiF has an effective atomic number very close to that of soft tissue → the dose recorded by a TLD is very close to the soft tissue dose over a wide range of radiation energies.
- TLDs can measure doses across a range of ~0.1 – 2000 mSv.
- The response "*signal per unit dose*" of TLDs shows small variation with energy as compared to film badges.

PROCESSING:

- The device which heats the chips & measures light output = "*TLD reader*".
- The chip of TL material is inserted in a light-tight chamber → its temperature is raised to 300-400°C at a carefully controlled rate → the trapped electrons leave

the traps and fall to their ground state & emit photons of light.

- Light is collected and measured by a photoelectric device → (***'glow curve'***) is drawn → the dose is digitized and stored in a computer, together with the glow curve.
- The total light energy emitted under the curve is proportional to the dose of X- or gamma rays originally absorbed.
- The chip is then annealed "overheated 400-500°C" to remove any residual stored energy from previous exposure → return to original & can be reused.
- Calibration is performed as with film dosemeters.

6.9.3 DIRECT-READING ELECTRONIC DOSEMETERS

- Based on Geiger-Muller tubes or single silicon diodes.
- Provide effective alarms and immediate dose readings.
- Used in areas with real risks of high exposures.
- However, these devices have a *very poor response to photon energies below* around ***80 keV*** → Unable to detect low-energy gamma radiation and diagnostic X-rays.

The Siemens electronic personal dosemeter (EPD) overcomes that problem with a linear response ***to below 20 keV*** → suitable for radiodiagnostic staff.

Dose range → Flat response between 20 keV to 10 MeV





- The EPD has achieved approval as a ***legal personal dosemeter*** in the UK, Norway, Italy and Germany.
- The EPD was developed by Siemens & the UK National Radiological Protection Board (NRPB).
- It uses *two silicon photodiodes* to overcome the energy response limitations of a single detector.
- ***The read-out display gives:***
  1. The personal equivalent dose to the body and skin.
  2. Indicate dose rates with or without an alarm feature.
  3. The stored doses → record the values in an individual dose record.
     - The information includes the time when significant dose rates were recorded, which can help in tracing potential incidents.
- The sensitivity is 50-200 times greater than that of a TLD, highly appropriate for:
  1. Measuring doses in diagnostic-imaging (low individual doses).
  2. Detect the proposed limits on a *proportional monthly basis* (0.15 mSv) for pregnant workers "difficult to assure with either films or a TLD".

- A major advantage of such a direct reading dosemeter:
  Immediate dose measurement → allow appropriate steps to reduce exposure.
- A disadvantage is its initial cost (about £300)
  But as its life is expected to be 10 years → the effective monthly cost = TLD or commercial film systems.
- The EPD is calibrated for 'life' when manufactured, but an annual check may be needed to comply with legal approval.
- The battery only needs to be replaced every 12 months, at which time a calibration check is recommended.

Table 6.1 1 Personal dosimetry systems: advantages and disadvantages

Advantages	*Disadvantages*
film badges	
‣ Relatively cheap	‣ Requires dark room and wet processing
‣ Permanent record of the exposure	‣ ***Lower threshold for hard gamma radiation is 0.15 mSv***
‣ Wide range of dose (0.2-1000 mSv)	‣ Is affected by heat, humidity & chemicals
‣ Identifies type and energy of exposure	
‣ Easy to identify individual dosemeters	
Thermoluminescent (TL) personal dosemeters	
‣ Chips can be reused	‣ Requires a high capital outlay
‣ Wide range of dose (0.1-2000 mSv)	‣ No permanent record (other than glow curves)
‣ Direct reading of personal dose	‣ ***Cannot distinguish radioactive contamination***
‣ ***Energy independent within ±10%***	‣ Requires a filtered badge to provide energy discrimination
‣ Compact → suitable for finger dosimetry	
Siemens electronic personal dosemeter (EPD)	
‣ Direct reading and cumulative record storage (up to 16 Sv)	‣ Initial cost
‣ ***Flat response:*** 20 keV to 10 MeV.	‣ ***Linear response to dose***
‣ Can be 'zeroed' by user without deleting cumulative record	‣ Is quite heavy, but weighs less than a hospital 'bleep'
‣ Measures personal dose at depth and at the skin directly, to 1 μSv	‣ Battery should be renewed each year
‣ Audible warning of high dose rates	

RADIATION DETECTORS:

- Detectors may be classified by the type of information produced:
  - ***Counters*** e.g. Geiger-Mueller (GM) detectors***:***
    Detectors that indicate the no. of interactions occurring in the detector.
  - ***Spectrometers*** e.g. NaI scintillation detectors***:***
    Detectors yield information about the energy distribution of incident radiation.
  - ***Dosimeters:***
    Detectors that indicate the net amount of energy deposited in the detector by multiple interactions.
- The *efficiency (sensitivity)* of a detector is a measure of its ability to detect radiation

Gas-filled detectors

Types of gas-filled detectors

- *Three types of gas-filled detectors in common use:*
  - Ionization chambers
  - Proportional counters
  - Geiger-Mueller (GM) counters
- Type determined primarily by the voltage applied between the two electrodes
- Ionization chambers have wider range of physical shape (parallel plates, concentric cylinders, etc.)
- Proportional counters and GM counters must have thin wire anode

IONIZATION CHAMBERS:

- An ionisation chamber consists of two electrodes separated by air and electronic circuit to measure and display the dose.
- ***Principle:***
  - X-rays and gamma rays → ionisation when interact with air → the ion pairs created will recombine very quickly but this can be prevented by applying a voltage between two electrodes.
  - The charge is collected by the electrodes to produce an electric current.
  - The number of ion pairs & current is proportional to the dose of radiation "absorbed dose".
- The electrodes can be flat rectangular plates or consist of a single central wire surrounded by a cylinder.
- Effective atomic number of air is very close to soft tissue → ∴ the dose recorded by an ionisation chamber is very close to the soft tissue dose over a wide range of radiation energies.
- Ionisation chambers are capable of measuring doses over a wide range of values down to as low as 0.1μSv/hr.
- ***Use:***
  1. Portable dose rate meters for dose surveys within the hospital.
  2. The detectors in most x-ray machine phototimers.
  3. Dose-area product (DAP) meters → allow assessment of patient doses.

- *N.B.:*
  - Air-filled Ionization Chambers can be used to measure exposure (***def.***: charge per unit mass of air "C \ kg").
  - Are not suitable for detection of individual particles "produce small current not sufficient to be measured"
  - Suitable for radiation dosimetry because the response in air is close to the response of absorbed dose in soft tissue "mean atomic number of air (Z= 7.6) is very close to that of soft tissue (Z= 7.4)"
  - Ionization chambers don't require highly stabilized voltage supply "output is independent of voltage".
    Only voltage high enough to prevent recombination of ions, but not so high to cause amplification by acceleration of electrons & further ionizations"

GEIGER-MULLER TUBE:

- GM counters must contain gases with specific properties
  Gas amplification produces billions of ion pairs after an interaction – signal from detector requires little amplification
- It detects individual ionization events as electric pulses which can be counted, but *the pulse size is independent of energy*.
- In general, GM survey meters are inefficient detectors of x-rays and gamma rays.
- Sometimes, used in dose measurements.
- It have got a central wire (anode)
- Quenching agent (alcohol or bromide) is added to the counting gas (argon/helium) to prevent the discharge continuing before another pulse is detected.
- It has a long ***dead time*** of about 300 microsecond (i.e. two interactions must be separated by a finite amount of time if they are to produce distinct signals) → during dead time, no more detections can be made.

SCINTILLATION DETECTORS: ***(Tolan)***

- Scintillation detectors consist of a scintillator and a PMT, that converts the light into an electrical signal
- Amount of ***light*** emitted after an interaction of a photon with the detector & the ***size of the electronic pulse*** depends on the energy absorbed.
- If the detector is used with *pulse height measurement electronics*, it can measure the photon energy → can be used to discriminate between different isotopes.
- The sensitivity increases with detector size.
- Very thin detectors can be used to produce contamination monitors sensitive to beta particles (thicker detector wouldn't be suitable, because β-particles will be absorbed in first few millimeters)
- Detectors are usually *inorganic* crystals. However, *organic* scintillators are available including liquids used in assay of very low energy β-emitting nuclides (e.g. tritium).

Statutory Requirements and Non-Statutory Recommendations

1- Medicines (Administration of Radioactive Substances) Regulations 1978
2- Radioactive Substances Act 1993

1- Medicines (Administration of Radioactive Substances) Reg. 1978:

"**No person shall administer** to a human being (otherwise than to himself) **any radioactive medicinal product** unless he is **doctor or dentist holding a certificate issued by the Health Minister** or a **person acting in accordance with the directions of such** a doctor or dentist." .

- In order to assist ministers in the awarding of certificates the ***Administration of Radioactive Substances Advisory Committee*** **(ARSAC)** was established.
- ARSAC comprises 20 members with a range of professional backgrounds (however, the chairperson is always a clinician) and the certificates they award are referred to as **"ARSAC certificates"**.
- ARSAC certificates can be issued for diagnostic, therapeutic and research procedures. Written applications must be supported by the **local RPA**, **radiopharmacist** and **MPE**.

COVERS:

- Nuclear medicine scanning
- Nuclear medicine therapy
- Some pathology test, e.g.
  - C-14 urea breath test
  - Co-57 Schilling test
- Brachytherapy

✓interstitial ✓intracavity ✓surface applicators ✓neutron activation.

ARSAC Certificates:

- A certificate is awarded if the applicant can demonstrate they have the appropriate training, experience and local scientific support, and is usually only granted to a consultant
- Specific to
  - Practitioner
  - Site (i.e. hospital)
  - Radio-pharmaceutical.
  - Proposed use
- Valid for 5 years (or 2 years only for research)
- Applicants assessed against "core curriculum".

2- Radioactive Substances Act 1993 "RSA93":

- The Radioactive Substances Act (RSA) mainly concerns nuclear medicine departments.

The main points of the RSA are summarized below;

- Its main function is to control the spread of radioactivity in the environment.
- It is enforced by the **Environment Agency (EA)**.
- It is concerned with **the storage & use of radioactive materials**. It also deals with **the accumulation and disposal of radioactive waste**.
- All users of radioactive materials (ie each NHS Trust) must be registered with the Environment Agency.
- Registration to keep & use RAS: limits activity & number of sources.
- Clear and legible records of all radioactive materials held on the premises must be produced and maintained.
- Those users who wish to accumulate and dispose of radioactive waste require authorisation to do so from the EA.
- There are legal limits on the amount of radioactive waste that can be accumulated and disposed of each month from the department (this is specified by the Environment Agency).
- The user must hold up to date records of all waste disposals.
- Lost RAS or radioactive waste must be reported to police & EA.

Part Exemptions:

- RS (Hospitals) Exemption Order 1990
  - if disposals small (e.g. < 1 GBq Tc-99m per month to drains, or 500 MBq other radionuclide)
- RS (Smoke Detector) Exemption Order 1980
- etc.

ABBREVIATIONS:

ICRP	International commission on Radiation Protection.
HSE	Health & Safety executive
IRR 99	Ionising Radiation Regulations 1999
IR (POPUMET)R 88	Ionising Radiation (Protection of Patients Undergoing Medical Examination or Treatment) Regulations
M[ARS]R 78	The Medicines (Administration of Radioactive Substances) Regulations 1978
RSA 93	Radioactive Substances Act 1993
IRMER 2000	Ionising Radiation (Medical Exposure) Regulations 2000
RPS	Radiation Protection Supervisor.
HSE	Health & Service Executive.
RPA	Radiation Protection Adviser.
ACOP	Approved Code OF Practice

HSE Nov. 01:
There has been a number of reported cases where employees have failed to take good care of their dosemeters. Many of these cases involve employees in the Health Services, some of whom have been senior clinicians.

"Non-Classified employees who have been provided with a dosemeter by their employer to ensure compliance with regulation18 IRR99 have a duty to look after that dosemeter and return it for processing as required. Provided the employer has informed the employees of that duty and is exercising the appropriate level of supervision, employees who persistently fail to wear, look after or return their dosemeters promptly are liable to enforcement action by inspectors up to and including prosecution under Section 7 of the HSW Act 1974. Employers may find statement of this fact useful when dealing with 'errant' staff."

22- Estimated doses and special entries

In case of loss or damage of a dosemeter used to make any individual measurement under regulation 21 (i.e. not practicable to assess the dose received by a classified person over any period)

- Employer shall make an adequate investigation of:
  1. The circumstances of the case.
  2. A view to estimate the dose received by that person during that period.

  - ***If there is adequate information to estimate the dose received***, Employer shall:
    a) Send to the approved dosimetry service a summary of the information used to estimate that dose.
    b) Arrange for the approved dosimetry service to enter ***the estimated dose*** in the dose record of that person.
    → mentioned in the dose record as estimated dose.
    c) The employer shall not enter the estimated dose in the dose record except after the consent of ***the Executive*** if:
      i. Recorded cumulative effective dose ≥ 20 mSv in one calendar year.
      ii. Recorded cumulative equivalent dose ≥ any relevant dose limit in one calendar year
  - ***if there is inadequate information to estimate the dose received***, Employer shall arrange for the approved dosimetry service to enter ***a notional dose*** in the dose record ***"i.e. proportion of the total annual dose limit for the relevant period"***
    → mentioned in the dose record as a national dose.
  - In either case, ***the*** employer shall
    a) Inform the classified person of the entry (either estimated or national dose).
    b) Make available at the request of the classified person → a copy of the summary sent to the approved dosimetry service.
    c) Make a report of any investigation → keep a copy for 2 years from the date it was made.

Objections on the estimated dose:

- If employer think the dose received by the classified person is > or < the relevant entry in the dose record → he shall make ***adequate investigation***.
  But under 2 conditions:
  1. before 12 month in case of classified person subject only to an annual dose limit.
  2. before 5 yrs in any other case.
- If investigations confirms the belief of the employer, he shall:
  1. Send to the approved dosimetry service a summary of the information used to estimate that dose.
  2. Arrange for the approved dosimetry service to enter ***the estimated dose*** in the dose record of that person.
  → mentioned in the dose record as special entry.
  3. Notify the classified person of the change.
  4. Make a report of the investigation → keep a copy for 2 yrs.
- If the classified person is aggrieved by this decision → apply to review this decision in writing to the Executive "within 3 months of the date on which he was notified of the decision".
- If the Executive concludes that -
  (a) The investigation was inadequate; or
  (b) estimated dose is not reasonable,
  The Executive shall direct the employer to re-instate the original entry in the dose record.

OTHER PROTECTION MEASURES:

- Radiologists and almost all radiology workers ARE NOT CLASSIFIED normally
- According to ***LOCAL RULES***, they however supposed to wear personal dosemeters when entering a controlled area

N.B. it is not an absolute necessity, this is preferred but not must, but local rules in most places states so, note that the answer of the question:

Radiologist SHOULD wear a dosemeter when entering fluoroscopy room.

The answer is **FALSE**, because it is not SHOULD, although we all wear them in that case, but still not absolute necessity, if the word used in the question USUALY, so the answer is **TRUE**.

- *Perhaps that example shows you the degree of sterility of the examination system!!*

About personal monitors:

1. Personal dosimeters are worn on the trunk, under the lead apron.
2. Additional monitors MAY BE worn on the forehead or neckband to monitor eye exposure, or fingers to monitor hand doses.
3. Body monitors are usually worn for **4 weeks**
4. Commonest personal monitoring dosimeters are film badges or TLD.

5. Electronic dosimeters are used in high dose areas when an indication in needed to monitor at the same time of exposure (ex. Interventional procedures by pregnant radiologist)

IRR(1999); 9-Personal protective equipment:

- Any personal protective equipment shall comply with the Personal Protective Equipment (EC Directive) Regulations 1992.
- Every radiation employer shall provide appropriate accommodation for personal protective equipment when it is not being worn.

STATUTORY RESPONSIBILITIES AND ORGANIZATIONAL ARRANGEMENTS FOR RADIATION PROTECTION:

- ***IRR1999*** aims to Protection of staff and members of public.
- ***IR(ME)R2000*** aims to Protection of patients.

ARRANGEMENTS FOR THE MANAGEMENT OF RADIATION PROTECTION

IRR(1999); 13- Radiation protection adviser

MATTERS IN RESPECT OF WHICH A RADIATION PROTECTION ADVISER MUST BE CONSULTED BY A RADIATION EMPLOYER

1. Advising to the observance of the Regulations
2. The implementation of requirements as to controlled and supervised areas.
3. For new or modified sources of ionising radiation → prior plans for installations and the acceptance into service "in relation to any engineering controls, design features, safety features and warning devices provided to restrict exposure to ionising radiation".
4. Regular checking of systems of work provided to restrict exposure to ionising radiation.
5. The regular calibration of equipment provided for monitoring IR levels and the regular checking that such equipment is serviceable and correctly used.
6. The periodic examination and testing of engineering controls, design features, safety features and warning devices.
7. Incidents where more than 6 mSv has been received.

- ***R.P.A. need not be appointed if only:***
  - Very, small amounts of radioactive material (below specified levels)
  - Very low dose (< 1μSv/h @ 10 cm) x-ray units of a design approved by HSE
  - VDUs with < 1μSv/h @ 10 cm
  - < 30 kV and < 1μSv/h @ 10 cm.
- There should be a radiation protection advisor (RPA) in every radiological facility.
- RPA must have qualification approved by HSE (e.g. RPA2000 certificate).
- The radiation employer shall appoint the radiation protection adviser in writing and shall include the advice needed.
- The radiation employer shall provide RPA with adequate information and facilities.

14- Information, instruction and training

- Every employer shall ensure that -
  - ***(1) his employees*** are given appropriate training, information and instruction in the field of radiation protection regarding:-
    - ***(a)*** the risks to health by exposure to ionising radiation;
    - ***(b)*** the precautions; and
    - ***(c)*** the importance of complying with the medical, technical and administrative requirements of these Regulations;

(2) ***other persons*** concerned with the work with ionising radiation are given adequate information to ensure their health and safety; and

(3) ***female employees***:

- Informed of the risk of ionising radiation to the fetus & a nursing infant.
- Informed of the importance of informing the employer in writing as soon as possible
  - ***(a)*** after becoming aware of their pregnancy; or
  - ***(b)*** if they are breast feeding.

IRMER(11) Training for patient protection:

- No practitioner or operator shall carry out a medical exposure or any practical aspect without having been adequately trained (certificate issued by an institute shall be sufficient proof).
- A person can participate in practical aspects of the procedure as part of practical training only under the supervision of adequately trained person.
- The employer shall keep an up-to-date training record of all practitioners and operators engaged by him to carry out medical exposures or any practical aspect of such exposures available for inspection by the appropriate authority
- Records should show the dates on which training was completed and the nature of the training.
- Practitioner or operator employed by other employer → shall supply such records to the new employer upon request.

PROTECTION OF STAFF & MEMBERS OF THE PUBLIC:

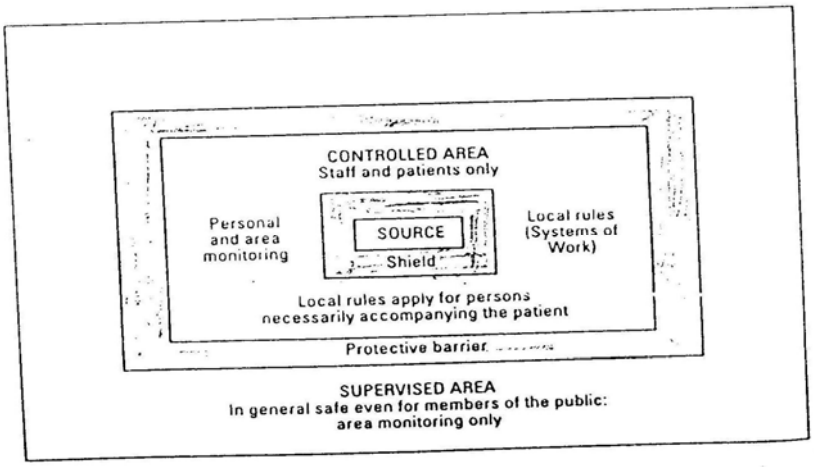
❝ **Legislation is enacted to ensure that individual doses are as low as reasonably practicable (ALARP)**
& that people are unlikely to exceed a proportion of the dose limits.

CONTROLLED AREAS:

- Required as a further control when ***inherent shielding*** of the source (X-ray ***tube*** and radiopharmaceutical ***syringes***) is not enough → the area around the shielded source is designated as a controlled area.
- Controlled areas have ***physical boundaries*** that are able to prevent radiation penetration (above specific level).
- Controlled area should be ***clearly defined boundaries***.
  This is simple to achieve in an x-ray room but more difficult with mobile X-ray set → where the controlled area is determined by eye as extending for 2 meters around tube.
- Every diagnostic X-ray tube produces a large amount of radiation exposure
  ∴ has to be contained within a controlled area.
- In nuclear medicine, area is defined controlled, wherever:
  - A generator is located, or
  - There is a syringe containing radiopharmaceutical.

- Controlled area should have restricted access (to radiation workers & others who work under "written system of work")
- ***"Written system of work"*** organize work within controlled area to ensure that radiology workers can't receive dose > 30% of any dose limit.
- Personal protection should take place within controlled area (e.g. 2.5 mm lead screens, lead rubber aprons and gloves, lead glasses, etc.)

N.B. ***in practice, radiology and nuclear medicine staff receives doses below the public dose limit.***



PART IV
DESIGNATED AREAS
IRR(1999); 16- Designation of controlled or supervised areas

- Every employer shall designate as ***a controlled area*** any area in which -
  1. Any person who enters or works in the area should follow special procedures to restrict significant exposure to ionising radiation in that area or prevent radiation accidents.
  2. Any person working is likely to receive:
     - Effective dose > 6 mSv / year.
     - Equivalent dose > 3/10 of any relevant dose limit (Schedule 4) "for an employee aged 18 years or above".

- also ACOP says if
  - > 7.5 µSv/h averaged over 8 h working day
  - > 75 µSv/h to hands averaged over 8 h working day
  - contamination risk
  - need to keep non-radiation workers out
- or > 7.5 µSv/h averaged over 1 minute and
  - site radiography, or
  - employees untrained in radiation protection enter area (unless radioactivity is dispersed inside a person)

- This area should be under complete control of the employer before starting activities which require that area to be designated as a controlled area.
- An employer shall designate as ***a supervised area*** any area which, not designated as a controlled area :-

1. where it is necessary to keep the conditions of the area under review to determine if the area should be designated as a controlled area; or
2. Any person working is likely to receive:
   - Effective dose > 1 mSv / year.
   - Equivalent dose > 1/10 of any relevant dose limit (Schedule 4) "for an employee aged 18 years or above".

- ***Any Controlled or Supervised Area should be (as a duty of the employer):***
  - i. Adequately described in local rules. "*N.B.* not in the 'System of work'…MCQ"
  - ii. Physical demarcation *of the controlled area*, with suitable warning signs.
  - iii. Display suitable & sufficient signs in suitable positions indicating:
    - The area is a controlled 'or supervised' area.
    - The nature of the radiation sources in the area.
    - The risks arising from such sources.
  - iv. Non-classified workers can only enter under written system of work.
- Employer must demonstrate by personal dose monitoring or other means that dose is restricted.

17- Local rules and radiation protection supervisors:

Def.: Local interpretation of the legislations that specify the procedures needed to ensure working safely in designated area.

- Local rules ***must*** include:
  - Description of controlled areas.
  - System of work within controlled areas, which includes:
    1. Restricting access to it.
    2. Specify the need for lead protection.
    3. Staff monitoring.
  - Dose investigation levels.
  - RPS name.
  - Work instruction for unclassified workers.
  - Back up contingency plan for the department, in case of radiation accidents.
- Local rules ***can*** also include:
  - management and supervision of work
  - testing and maintenance of safety features
  - radiation and contamination monitoring
  - testing of monitors
  - personal dosimetry
  - arrangements for pregnant and breast feeding staff
  - risk assessments
  - programme to review ALARA
  - RPA contact.
- Every radiation employer shall provide Local Rules for any controlled or supervised area → according to the radiation risk & nature of operations performed.
- It should be set down in writing.
- New employee get to read local rules & sign to say they have understood.

- The radiation employer shall ensure:
  1. Observation مراقبة of Local rules.
  2. Local rules are followed by employees and other persons who may be affected.
  3. Appoint ***radiation protection supervisors (RPS)*** to ensure Local rules compliance with the Regulations.
     & mention the names of RPSs in the local rules.

- Local rules are A LEGAL DOCUMENT.
  Policed by RPS & Enforced by HSE inspector.

Radiation Protection Supervisor:

- Must be appointed "*for the purpose of securing compliance of local rules with these Regulations*".
- Name must be in Local Rules
- It is recommended that RPS
  - know & understand regulations and local rules
  - command sufficient authority
  - understand necessary precautions
  - know what to do in an emergency

Requirements of Designated areas

IRR(1999); 19- Monitoring of designated areas

- Every employer shall monitor the levels of ionising radiation in the controlled & supervised areas through suitable and sufficient equipment.
- The monitoring equipments shall be -
  a. adequately tested – by a qualified person – before its first use.
  b. properly maintained
  c. adequately tested and examined at appropriate intervals.
- The employer shall make suitable records of the results of the monitoring and of the tests → authorised by a qualified person → & keep the records for at least 2 years.

Employee allowed to enter or remain in Controlled area:

The employer shall not permit any employee to enter or remain in such an area except:-

1. ***An outside worker*** → is a classified person who is:
   - ***i.*** Received training required.
   - ***ii.*** Certified fit for the work with ionising radiation.
   - ***iii.*** Subject to individual dose assessment.
   - ***iv.*** Provided with personal protective equipment and trained to use them.
   - ***v.*** Have a radiation passbook issued by approved dosimetry service "which contain their personal details & up-to-date radiation doses" before they enter Controlled area.

- The employer shall ensure that ***the classified outside worker is:***
  - Subject to arrangements for estimating the dose of IR he receives whilst in the controlled area.
  - An estimate of the dose received by that worker in that controlled area must be entered into his radiation passbook.
  - the radiation passbook is made available to that worker upon request

2. ***If not an outside worker:***
   - ***i.*** **Is a classified person.**
   - ***ii.*** **If not being a classified person** → Not permitted to enters or remains in the area, unless the employer can demonstrate, by personal dose monitoring, that the doses are restricted as follows: -
     - *in case of employee ≥ 18 years or over* → not receive in any calendar year a cumulative dose of IR which require him to be a classified person; or
     - *In case of any other person* → not receive in any calendar year a dose > any relevant dose limit.
     - The employer shall keep the results of the monitoring or measurements by personal dose monitoring for this non-classified persons for ***2 years***.
     - Employer shall make that results available to that person on request.

- ***If there is a significant risk of the spread of radioactive contamination from a controlled area:***

The employer shall make adequate arrangements to restrict the spread of such contamination:

1. provide suitable & sufficient washing and changing facilities for persons who enter or leave any controlled or supervised area;
2. maintenance of such washing and changing facilities;
3. prohibit eating, drinking or smoking within controlled area → ↓↓ probability of ingestion of a radioactive substance; and
4. monitoring contamination of persons, articles or goods leaving a controlled area.

IRR(1999); 35- Approval of dosimetry services:

- Occurs in accordance with criteria specified by the Executive.
- Approval is by a certificate in writing.
- The purposes of these services are specified in the certificate.
- The Executive may carry out a re-assessment of any approval.

LEGAL LIABILITIES

- Definition of employer: ***anyone who uses ionizing radiation in a self-employed capacity, with their own equipment.***

Duties of Employer *(IRMER2000)*

(1) The employer shall put *written procedures* *"System of work"* for medical exposures & ensure that the practitioner and operator are complied with.

SCHEDULE 1

Employer's Procedures

The written procedures for medical exposures shall include -

(a) identify the individual to be exposed to ionising radiation;
(b) identify individuals entitled to act as referrer or practitioner or operator (i.e. identify competent staff for specific task);
(c) procedures to be observed in the case of medico-legal exposures;
(d) procedures established by the employer for biomedical and medical research programmes "i.e. no direct medical benefit for the individual";

(e) procedures for the use of diagnostic reference levels established by the employer for radiodiagnostic examinations;
(f) assessment of patient dose and administered activity;
(g) procedures for the carrying out and recording of an evaluation for each medical exposure including factors relevant to patient dose; & review if they are consistently exceeded & take appropriate actions.
(h) procedures for making enquiries of females of childbearing age to establish whether the individual is or may be pregnant or breastfeeding;
(i) procedures to ensure that quality assurance programmes are followed;
(j) procedures for giving information and written instructions for patients undergoing treatment or diagnosis with radioactive material;
(k) Procedures to ensure that the probability and magnitude of accidental or unintended doses to patients from radiological practices are reduced so far as reasonably practicable.

(2) Write protocols for every **standard** radiological examination practice for each equipment.
(3) ***The employer shall establish -***
- ***a)*** Referral criteria, including radiation doses, and ensure that these are available to the referrer;
- ***b)*** Quality assurance programmes;
- ***c)*** diagnostic reference levels for radiodiagnostic examinations regard to European diagnostic reference levels where available;
- ***d)*** Dose constraints for biomedical and medical research programmes.

(4) The employer shall take steps to ensure that:
- ***a)*** no practitioner or operator shall carry out a medical exposure or any practical aspect without having been adequately trained; and
- ***b)*** practitioners or operators undertakes continuing training for new techniques.

(5) ***In case of radiation overexposure incident:***
- ***i.*** Make an immediate preliminary investigation of the incident.
- ***ii.*** Notify the appropriate authority.
- ***iii.*** Arrange for a detailed investigation of the circumstances of the exposure.
- ***iv.*** Arrange for an assessment of the dose received.

(6) If diagnostic reference levels are exceeded → undertake appropriate reviews and ensure that corrective action is taken.

Other duties of Employer:

1. clinical audit in accordance with national procedures ***must*** be performed.
2. Ensure a medical physics expert in areas specified
3. All employers using ionizing radiation in controlled areas should (i.e. required by law) to appoint RPA to provide advice on practical means of complying the legislations.
4. Keep an equipment inventory
5. Limit the amount of equipments.
6. Legislation lays ***"Duty of care"*** on Employers → responsibility for ensuring that regulations are followed (through Radiation Protection Committee).
7. Local rules are produced by or on behalf of the employer.
8. Ensuring the requirements to comply the RSA93.

- The employer is on the top of the organization tree "but legal liabilities may be shared with other individuals" *see Table 6.7*

Responsibilities for radiation safety

Radiation Employer:

- Authorisation of practice.
- Notification of specified work.
- Prior risk assessment.

IRR(1999); 5-Authorisation of specified practices

- A radiation employer shall not carry out the following practices, except in with a prior authorisation by the Executive in writing, -
  (a) the use of electrical equipment intended to produce x-rays -
  (b) the use of accelerators, except electron microscopes.
- This authorisation may be granted subject to conditions and with or without limit of time and may be revoked in writing at any time.
- If the radiation employer attempt to makes a material change to the circumstances relating to that authorisation → that change shall also be notified to the Executive.

IRR(1999); 6- Notification of specified work

- A radiation employer shall not for the first time carry out work with ionising radiation unless at least 28 days before commencing that work he has notified the Executive of his intention to carry out that work.

SCHEDULE 1 - Regulations 6(1) and 13(3)

WORK NOT REQUIRED TO BE NOTIFIED UNDER REGULATION 6

(a) where the concentration of activity per unit mass of a radioactive substance does not exceed the concentration specified in ***column 2 of Part I of Schedule 8***;

(b) where the quantity of radioactive substance involved does not exceed the quantity specified in ***column 3 of Part I of Schedule 8***;

(c) where apparatus contains radioactive substances in a quantity exceeding the values specified but -

- the apparatus is of a type approved by the Executive;
- the apparatus is constructed in the form of a sealed source;
- the apparatus does not under normal operating conditions cause a dose rate of more than 1μSv\h at a distance of 0.1m from any accessible surface; and
- conditions for the disposal of the apparatus have been specified by the appropriate Agency;

(d) the operation of any electrical apparatus (except those for next point) provided that -

- the apparatus is of a type approved by the Executive; and

- the apparatus does not under normal operating conditions cause a dose rate of more than 1µSv\h at a distance of 0.1m from any accessible surface;

(e) the operation of -

- any cathode ray tube intended for the display of visual images; or
- any other electrical apparatus operating at a potential difference not exceeding 30kV,

→ provided that the operation of the tube or apparatus does not under normal operating conditions cause a dose rate of more than 1µSv\h at a distance of 0.1m from any accessible surface;

(f) where the work involves material contaminated with radioactive substances resulting from authorised releases which the appropriate Agency has declared not to be subject to further control.

- The Employer should provide the Executive with the particulars specified in Schedule 2

SCHEDULE 2 - Regulation 6(2)

PARTICULARS TO BE PROVIDED IN A NOTIFICATION UNDER REGULATION 6(2)

a) The employer contacts: name, address, telephone or fax number or email address;

b) the address of the premises where or from where the work activity is to be carried out and a telephone or fax number or email address at such premises;

c) whether or not any source is to be used at premises other than the address given; and

d) the nature of the business of the employer;

e) the category of the sources of ionising radiation:

- ***(i)*** sealed source;
- ***(ii)*** unsealed radioactive substance;
- ***(iii)*** electrical equipment;
- ***(iv)*** an atmosphere containing the short-lived daughters of radon 222;

f) dates of notification and commencement of the work activity.

- The Executive may require that radiation employer provide additional particulars of that work → Schedule 3.

SCHEDULE 3 - Regulation 6(3)

ADDITIONAL PARTICULARS THAT THE EXECUTIVE MAY REQUIRE

(a) a description of the work with ionising radiation;

(b) sources of IR " type of electrical equipment or nature of RAS used";

(c) the quantities of any radioactive substance involved in the work;

(d) the identity of any person engaged in the work;

(e) the date of commencement & the duration over which the work is carried on;

(f) the location and description of any premises at which the work is carried out;

(g) the date of termination of the work;

(h) further information on any of the particulars listed in Schedule 2.

- If a radiation employer makes any change that would affect the particulars so notified → he shall notify the Executive.

IRR(1999); 7- Prior risk assessment etc.

- Before a radiation employer commences a new activity involving work with ionising radiation, he shall make a suitable and sufficient assessment of the risk to any employee and other person for the purpose of identifying the measures he needs to take to restrict the exposure.
- *An assessment should* -
  - ***(a)*** identify all hazards; and
  - ***(b)*** evaluate the nature and magnitude of the risks to employees and other persons arising from those hazards.
- If the assessment shows that a radiation risk to employees or other persons exists from an identifiable radiation accident, the radiation employer shall take all reasonably practicable steps to -
  - ***(a)*** prevent any accident;
  - ***(b)*** limit the consequences of any such accident which does occur; and
  - ***(c)*** provide employees with the information, instruction and training, and equipments necessary, to restrict their exposure to ionising radiation.
  - ***(d)*** prepare ***a contingency plan*** designed to secure the restriction of exposure to ionising radiation and the health and safety of persons who may be affected by such accident

    & he shall ensure that:
    - " a copy of the contingency plan is identified in the local rules;
    - " any employee under his control who may be involved in the plan has been given suitable and sufficient instructions and where appropriate issued with suitable dosemeters or other devices; and
    - " Rehearsals of the arrangements in the plan at suitable intervals.

- ***Duties of employee:***

I- responsibilities for radiation safety:

(1) Not expose himself or any other person to IR greater than necessary for the purposes of his work.

(2) Shall exercise reasonable care while carrying out his work.

(3) If a personal protective equipment is provided to him, he shall:

(a) Make full and proper use of personal protective equipment.

(b) Report the employer for any defect in personal protective equipment.

(c) Ensure personal protective equipment is returned after use to the accommodation provided for it.

(4) Shall notify his employer of any overexposure, radiation accident or RA substance leakage.

(5) Report equipment defects.

II- Extra-duties for classified persons:

(1) Not to misuse the radiation passbook or falsify any information in it

(2) Comply with the local rules, dose measurements & assessment for classified workers.

(3) Subject to medical surveillance:

- When required by his employer.
- At the cost of the employer & during working hours.
- Shall provide the appointed doctor or employment medical adviser with such information concerning his health

- ***Duties of the Referrer:***

  Supply the practitioner with sufficient medical data relevant to the medical exposure to enable the practitioner to decide on whether there is a sufficient net benefit.

- ***Duties of Practitioner & Operator:***

Practitioner	***Operator***
(1) Responsible for the justification of a medical exposure ***(2)*** Not necessarily a medic – could be a radiographer if specialized in certain procedures.	***(1)*** Responsible for each and every practical aspect which he carries out. ***(2)*** In fluoroscopy, ensure AEC used unless other method justified.
(3) Both shall comply with the employer's procedures. ***(4)*** Must cooperate with other specialists & staff involved in the exposure. ***(5)*** Undergo continuing education or training.	

Medical Physics Experts:

- Employer shall ensure that a medical physics expert is involved in every exposure.
- Medical physics experts must have a science degree & experienced in the application of physics to the diagnostic & therapeutic uses of ionising radiation.
- ***Duties of medical physics expert:***
  a) Give advice on radiation protection concerning medical exposure.
  b) ***closely involved*** in every radiotherapeutic practice other than standardised therapeutic nuclear medicine practices;
  c) ***available*** in standardised therapeutic nuclear medicine practices and in diagnostic nuclear medicine practices;
  d) In all other radiological practices → he shall be ***involved*** for consultation on optimisation, including patient dosimetry and quality assurance.

- Any new work or change in work with ionizing radiation should be notified to HSE 28 days before starting.
- Responsibilities of HSE:
  1. Enforcing IRR.
  2. Have the power to prosecute the employer or individual workers under civil or criminal law.

RADIOACTIVE SUBSTANCES ACT 93 (RSA93)

i. This is a legal document that ***organizes*** acquisition, storage, and safe disposal of any radioactive substance. This act controls radioactive substances in the environment

ii. The requirements to comply with this Act are the responsibility of the ***EMPLOYER***.

IRR 1999 - PART VI

ARRANGEMENTS FOR THE CONTROL OF RADIOACTIVE SUBSTANCES, ARTICLES AND EQUIPMENT

27- Sealed sources and articles containing or embodying radioactive substances:

The radiation employer shall ensure that:

- The radioactive substance used as a source of ionising radiation is in the form of a sealed source.
- the design, construction and maintenance of any article containing a radioactive substance, *including its bonding, immediate container or other mechanical protection*, is such as to prevent the leakage of any radioactive substance -
  (a) in the case of a sealed source → so far as is practicable; or
  (b) in the case of any other article → so far as is reasonably practicable.
- Suitable tests are carried out at suitable intervals to detect leakage of radioactive substances from any article → & make a suitable record of each test & keep for at least ***2 years*** after the article is disposed of or until a further record is made following a subsequent test to that article.

28- Accounting for radioactive substances:

- Every radiation employer shall take steps to ***account for and keep records*** of the quantity and location of radioactive substances involved in work with ionising radiation.
- Shall keep the records for at least 2 years from the date on which they were made and for at least 2 years from the date of disposal of that radioactive substance.

29- Keeping and moving of radioactive substances:

- Every radiation employer shall ensure that any radioactive substance not in use or being moved, transported or disposed of -
  1. is kept in a suitable receptacle; and
  2. is kept in a suitable store.
  3. suitably labelled.

30- Notification of certain occurrences:

In the following 2 cases:

- If a radioactive substance is ***released into the atmosphere*** as a gas, aerosol or dust; or ***spilled*** (in quantity exceeds the quantity in column 4 of Schedule 8).
- If a radioactive substance is lost or stolen "in quantity exceeds the quantity in column 5 of Schedule 8"

In both cases, a radiation employer shall:

1) Notify ***the Executive***.

2) Make an immediate investigation → make a report & keep it for at least 50 years (if the problem happened) or for at least 2 years (if investigation shows that the problem didn't actually occur).

<u>31- Duties of manufacturers etc. of articles for use in work with ionising radiation</u>

- In the case of articles for use at work with ionising radiation shall be designed and constructed to restrict the exposure of employees and other persons to ionising radiation as far as reasonably practicable.
- Where a person erects or installs an article for use in work with ionising radiation, he shall -

1) Undertake a critical examination to ensure that -
   - the safety features and warning devices operate correctly; and
   - there is sufficient protection for persons from exposure to ionising radiation;
2) Consult with the radiation protection adviser about the nature and extent of any critical examination and the results of that examination; and
3) Provide the radiation employer with adequate information about proper use, testing and maintenance of the article.

PROTECTION OF PATIENTS *(IRMER2000)*

IRNER2000 is concerned with appropriate use of radiation procedures on patients by properly trained staff

- The regulation outline:
  1. The core of knowledge = the theoretical knowledge that staff should have (*see table 6.8*).
  2. It specify the need of practical instruction for all staff.

Table 6.8 Core of knowledge in the POPUMET regulations

1. Nature of ionizing radiation and its interaction with tissue.
2. Genetic and somatic effects of ionizing radiation and how to assess their risks
3. The ranges of radiation dose that are given to a patient with a particular procedure, the principal factors which affect the dose and the methods of measuring such doses.
4. The principles of quality assurance and quality control applied to both equipment and techniques.
5. The principles of dose limitation and the various means of dose reduction to the patient including protection of the gonads.
6. The specific requirements of women who are, or who may be, pregnant and also of children.
7. If applicable, the precautions necessary for handling sealed and unsealed sources.
8. The organizational arrangements for advice in radiation protection and how to deal with a suspected case of overexposure.
9. Statutory responsibilities.
10. In respect of the individual diagnostic and therapeutic procedures which the person intends to use, the clinical value of those procedures in relation to other available techniques used for the same or similar purposes.
11. The importance of utilizing existing radiological information - films and/or reports - about a patient

- Staff individuals can be divided into:
  1. ***individuals clinically directing the exposures*** e.g. Radiologist**:**
     - Staff members who carry the clinical responsibility.
  2. ***Staff physically directing the exposure*** e.g. Radiographer**:**
     - Those who directly irradiate patients.
     - if not well-trained → can't work except under supervision of well-trained person (till he complete his training)
- Regulation 4 of POPUMET is fundamental to patient protection, it requires:
  Every medical exposure to be carried out under the direction of a person who is clinically directing the exposure.
  a) ensure that only accepted diagnostic practices are used.
  b) Ensure selection of procedures ŵ fulfill Justification & Optimization principles:
     - ***i.*** Ensure patient dose is ALARP.
     - ***ii.*** Ensure examination is consistent with requirements for diagnosis.
     - ***iii.*** Ensure particular care of pregnant patients.

REFFERRALS:

- The radiologist takes responsibility for clinical direction (So, the request from the clinician is only a request of opinion, the radiologist is having the right to refuse, accept, or tail out a study according to the clinical situation)
- The request form – properly filled by clinician – is a legal document.
- There should be locally agreed referral criteria set by the employer.
  The RCR handbook *"Making the best use of radiology department"* may be used as a basis for referral practice.

Sharing responsibilities:

i. Other (non radiologist) medical staff as orthopaedicians, cardiac catheterizators may take responsibility of directing for procedure (physically, or clinically) like in case of C-arm fluoroscopy in Operation Room, or Cathlab.

ii. Any radiographer who continues with a procedure knowing that it is inappropriate, is equally culpable (blamable) in law (i.e. responsible in front of law).

Legal liability (IRR99)

- IRR 1999 regulates the responsibility of each, the employer as well as the person who is physically (tech) or clinically (radiologist) directing the study. *(Employer, Practitioner and Operator)*
  1. responsible for enforcing persons clinically or physically directing examinations lies on secretary of State Of Health (who uses health department inspectorate).
  2. There is no umbrella of an employer ??!!

Table 6.7 Legal liability and inspection

	LEGISLATION			
	IRR8S	***IRR[POPUMET] 88***	***M(ARS)R 78***	***RSA93***
Area	X-rays and nuclear medicine	X-rays and nuclear medicine	Nuclear medicine	Nuclear medicine
Liability	Employer and employee	Employer and practitioner	Employer and practitioner	Employer
Inspection	HSE	HSE and Government Health Departments	Departments of Health and of the Environment	Departments of the Environment

Legal liability (M[ARS] regulations)

- Use of radiopharmaceuticals (diagnostic and therapeutic purpose) is regulated by the M[ARS] in addition to POPUMET.
- *Procedure should be performed UNDER SUPERVISION OF an ARSAC certificate holder.(MCQ)*
- Injection may be performed by other staff, but under supervision of ARSAC holder. (Administration of Radioactive Substance Advisory Committee)
- Maximum dose to the patient is defined in the certificate.
- Everyone who is involved in a procedure (ARSAC holder clinician, or injector, the one physically conducting the procedure) need to be trained under IRR[POPUMET]
- Employer is responsible to ensure that clinicians are holding ARSAC.
- ***Regarding the ARSAC certificates "Department of Health"***
  1. Must be held by the person clinically supervising procedures using RAS.
  2. Authorize certain procedures to be performed by it's holder.
  3. Define max. dose to patients (max. activity to be administrated).
  4. Issued to individual clinicians- for specific procedures- (including research) using specific equipment.
  5. Valid for 5 years (& only 2 years for research purposes).
  6. Needs to be signed by RPA.
- Responsibilities of ARSAC certificate holder:
  1. Gives clinical supervision to procedures using RAS.
  2. Instructing & supervising the person physically directing patients.
  3. Responsible for discharging radioactive patients from hospital:
     - Depending on max. activity remaining in the body.
     - Gives specific behavioral instruction or advice to patient (e.g. stop lactation).
     - RPA should be able to give further advice.

*IRR 32.*EQUIPMENT USED FOR RADIODIAGNOSIS AND TREATMENT:

*"**Radiation equipment**"* means equipment which delivers ionising radiation to the person undergoing a medical exposure and equipment which directly controls the extent of the exposure.

(1) Every employer who controls any equipment which is used for medical exposure shall ensure that such equipment is *of such design or construction* and is so *installed and maintained* to be capable of ***restricting the exposure to ionising radiation*** of any person undergoing a medical exposure "diagnostic, therapeutic or research" *to a compatible extent.*

- This includes the use of equipments which directly affects the dose to the patient, e.g. film processors, intensifying screens, radionuclide dose calibrators, etc.

(2) An employer who controls any radiation equipment "installed after the date of these Regulations" shall ensure that it is provided with suitable means for informing its user of ***the quantity of radiation*** produced during a radiological procedure.

(3) Every employer shall make arrangements to provide a suitable ***quality assurance programme*** for the equipment → to ensure it remains capable of restricting exposure.

(4) the quality assurance programme shall provide: -

(a) adequate testing of ***New equipments*** before its first use for clinical purposes by an RPA appointed by the employer.

(b) adequate testing of the performance of the equipment at appropriate intervals and after any major maintenance procedure.

(c) measurements at suitable intervals to enable the assessment of doses to persons undergoing medical exposures.

(5) Every employer shall take all steps to monitor & prevent the failure of any equipment which could result in an exposure to ionising radiation greater than intended and to limit the consequences of such failure.

- *To monitor equipment malfunctions* "what is accepted to occur from time to time".
  - ❝ There must be systems to detect and to correct for malfunctions.
  - ❝ There should be ***a log*** for recording of faults and defects for each X-ray unit.
  - ❝ Deterioration in performance does not necessarily mean that equipment should be withdrawn from use → it may mean that certain procedures should no longer be carried out using that equipment.
  - ❝ The equipment should be properly justified for the new uses.

(6) Where a radiation employer suspects or has been informed that an incident may have occurred in which a person while undergoing a medical exposure was exposed to ionising radiation to an extent much greater than intended, *as the result of a malfunction of, or defect in, radiation equipment* under his control حادث نتيجة عيب بالجهاز, he shall:

i. Make an immediate investigation of the suspected incident.

ii. If that investigation shows that an incident has occurred:

- Employer shall notify the Executive.
- Make or arrange for a detailed investigation of the circumstances of the exposure and an assessment of the dose received.

iii. A radiation employer shall make a report of that investigation and shall -

- ***Immediate investigation report***→ keep that report for at least 2 years.
- ***Detailed investigation report***→ keep that report for at least 50 years.

IRMER 10- Equipment:

- The employer shall draw up, keep up-to-date and preserve at each radiological installation an inventory of equipment at that installation.
- Employer shall furnish the inventory to the appropriate authority when requested,.
- The inventory shall contain the following information -
  - ❝ name of manufacturer,
  - ❝ model number,
  - ❝ serial number or other unique identifier,
  - ❝ year of manufacture, and
  - ❝ year of installation.
- The employer shall ensure that equipment at each radiological installation is limited to the amount necessary for the proper carrying out of medical exposures at that installation عدد محدود.