THE PHYSICS OF RADIOLOGY & IMAGING

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Foreword
S Arumugam

2nd Edition

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CHAPTER

Radiation Detection and Measurements

Chapter Outline

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PRINCIPLES OF RADIATION DETECTION

Ionization

Radiation exposure causes an ionization in matter which involves removal of electrons from neutral atoms or molecules, resulting in positive and negative ions. The positive and negative ions are called *ion pairs*, which can be collected by applying an electric field, that gives rise to *current or pulse.* Total charge collected is proportional to radiation intensity. *Ionization chamber, proportional counter, Geiger-Muller counter, and semiconductor detector* fall under this category. Gaseous and solid media are used in their detector design.

Photographic Effect

Ionizing radiation affects photographic film and alters its density, in turn forms latent image. The film is processed, and its optical density is measured by a densitometer. The degree of blackness is related to an intensity of radiation exposure. It can be quantified in terms of an *optical density (OD)*, which is proportional to radiation intensity. This type of dose evaluation is called *film dosimetry*, and it can be performed either with *radiographic film or radiochromic film.*

Luminescence

This is a process in which radiation excites atoms of a material and its energy is converted into an ultraviolet or visible light flash. The light flashes can be detected by a *photomultiplier tube (PMT) or photodiode,* which gives an electrical signal. The electrical signal is proportional to an incident radiation intensity. Detectors making use of the above principle are called *scintillators*, e.g., *NaI.*

Thermoluminescence

Radiation imparts energy to certain crystalline materials, which can store this energy for a long time, e.g., *Lithium fluoride, Calcium sulphate, etc.* The energy thus stored can be later released in the form of light or luminescence by heating these materials. Quantity of light released is proportional to radiation intensity. It can be measured and correlated to radiation dose. The devices based on the above effect are called *thermoluminescent dosimeter (TLD)*. Instead heat, laser can be used to stimulate luminance, referred as an *optically stimulated luminescence (OSL)*, e.g., AlO_2.

Chemical Effects

Ionizing radiation can cause chemical changes, e.g., oxidation of ferrous sulphate to ferric sulphate, which is principle of *Fricke dosimeter*. The concentration of ferric ions can be measured to correlate the energy absorbed or radiation dose delivered. Radiation can also cause color changes in certain plastics. Such color changes can also be measured and correlated to radiation dose. Such a systems are called *chemical dosimeters.*

Biological Effects

Radiation exposure alters lymphocytes magnitude and cause aberrations in chromosomes. Exposed individual's blood can be analyzed for chromosomal aberrations, e.g., *dicentric and ring formation.* The aberration score is a measure of radiation and is called *biological dosimetry*. This dosimetry is used during accident exposures, when no other information is available to assess individual's radiation exposure.

TYPES OF DETECTORS

Radiation detectors are classified by type of information they produce. Detectors that indicate number of interactions that occur are called *counters*, e.g., *GM counter.* Detectors giving information about energy distribution of incident radiation is called scintillation detector or *spectrometer*, *e.g., NaI.* Detectors indicating net amount of energy dissipated in the detector by multiple interactions are called *dosimeter.*

Radiation detectors produce an electrical signal following each interaction. The electrical signal passes through a series of an electronic circuit, for signal amplification, signal processing or data storage. The detector and its electronic circuit are called the detection system. There are two ways by which the circuitry may process signal, namely, (1) *pulse mode* and (2) *current mode.*

In pulse mode, signal from an each interaction is processed individually. In current mode, electrical signals from individual interactions are averaged together, forming a net current signal. GM detectors are operated in pulse mode, whereas ion chambers and scintillation detectors are operated in current mode.

Detectors operating under current mode never retain the interaction rate and energy deposited by an individual interaction. Charge collected from an interaction is proportional to energy deposited by the interaction. Total average electrical current measured is proportional to dose rate of the radiation. Current mode measurements are preferred in high interaction rates, for which there is no *dead time* losses. CT detector, flat panel detector used in fluoroscopy and an ion chamber in radiotherapy are operated in current mode.

Detector efficiency is a measure of its ability to detect radiation. It is the product of two terms, namely (1) *geometric efficiency,* and (2) *intrinsic efficiency*. Geometric efficiency is defined as ratio of photons reaching detector to number of photons emitted by source. Intrinsic efficiency is defined as ratio of number of photons detected to number of photons reaching the detector. It is often called as *quantum detection efficiency (QDE)* and it depends on *atomic number, density, thickness of the detector, and energy of radiation*. The detector efficiency varies from 0-1. All radiation detectors are broadly classified as:

- ❑ Gas-filled chamber detectors
- ❑ Solid-state detectors
- ❑ Biological dosimeter
- ❑ Chemical dosimeters

However, first three detectors have more application in diagnostic radiology.

GAS-FILLED DETECTORS

Gas-filled detector has volume of gas in between two electrodes, in which a voltage is applied. When exposed to radiation, the gas gets ionized and ion pairs are formed. Positive ion moves towards negative electrode and negative ion moves towards positive electrode. The electron travels through the circuit and reaches the cathode and recombines with positive ions. This forms an electrical current which can be measured by a meter.

There are three types of gas-filled detectors, namely, (1) ionization chamber, (2) proportional counter, and (3) Geiger-Muller (GM) counter. These detectors are classified based on the applied voltage. **Figure 5.1** shows detector current for various applied voltages between the electrodes. When the voltage is zero, the ion pairs produced by radiation recombine and no current flows through the circuit. If a small voltage is applied, current starts flowing through the circuit. As the voltage increases further, the current also increases, reducing the recombination of charges. This region is called *recombination region* of the curve.

As voltage is increased further no increase in current is observed and a saturation is reached. This is represented by a plateau in the graph stating that all the liberated charges are collected. This region is called an *ionization chamber region,* and ionization chambers operate in this region.

If the applied voltage is increased further, the current also increases further and the region is called *proportional region*. In this region, an electron travels

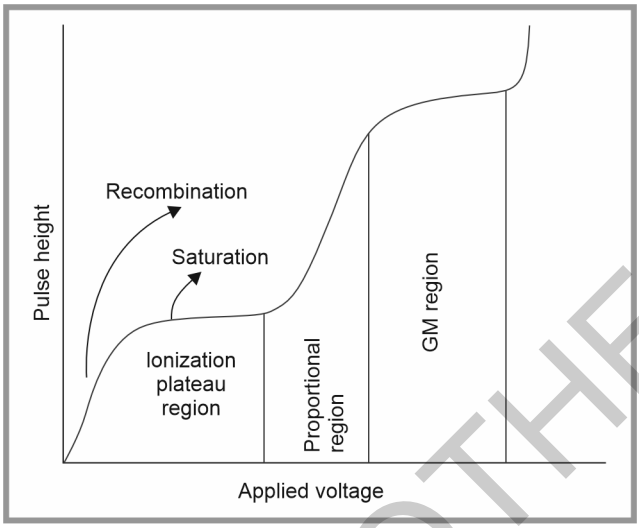


Fig. 5.1: Gas-filled detector: Relation between applied voltage and pulse height.

with high kinetic energy and cause additional ionization, releasing more electrons. This is called *gas multiplication*, which amplifies the detector current. The amplification increases as voltage increases. In this region, the charge collected is proportional to amount of energy deposited in the gas medium.

After the proportional region, the amount of charge collected is the same, regardless of energy deposited. This region is called *GM region*, in which the gas multiplication spread the entire length of the detector. GM counters cannot differentiate energy of radiation. If the voltage is increased further, discharge takes place in the detector, and it should not be operated further.

Ionization Chamber

An ionization chamber usually consists of an outer cylinder coated inside with *graphite* to make it conducting and a central electrode insulated from the chamber wall **(Fig. 5.2).** The cylinder is filled with either an air or with suitable gas for radiation interaction and detection. Air requires 34 eV to produce one ion pair, and a 100 keV photon can create about 3000 ion pairs.

When the chamber is exposed to radiation, ion pairs are formed and are collected by the electrodes. The flow of ions through the circuit, create an current signal. The amplitude of the signal depends upon number of ion pairs formed and independent of applied voltage. The amount of signal obtained from single interaction is very small and require amplification. Therefore, ion chambers are used in current mode, not in pulses mode. They are free from dead time loses and operated with wide range of voltages.

If the chamber is filled with air and an effective atomic number of the wall material is equal to air, then the amount of current produced is proportional

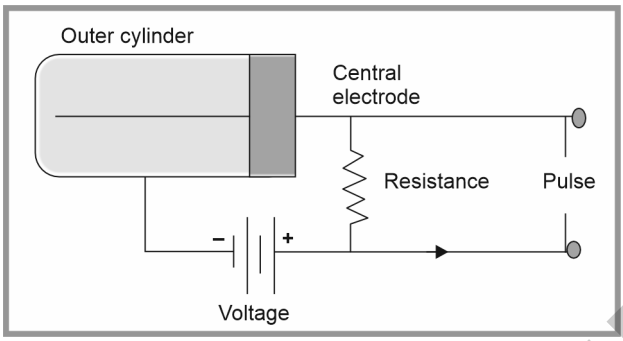


Fig. 5.2: Ionization chamber.

to an exposure rate. Thus, an average rate of energy dissipation in the chamber is measured. Such a measurement is often called a dose-rate or exposure rate measurement. The minimum current that can be conveniently measured is about 10^{-14}A. The ionization current is a measure of intensity of radiation. Such chambers are used as survey meters and dosimeters in radiology. However, their intrinsic efficiency is low because of lower air density.

Instead of air, high atomic number gases, *Argon (Z = 18) or Xenon (Z = 54)* and pressurizing gases can be used, to increase the sensitivity towards x and gamma rays. Such chambers are used in an isotope calibrator and CT scans as detectors. The advantages of an ion chamber are, walls can be made tissue equivalent, all type of radiation can be measured and can be calibrated to any energy. The disadvantage includes small signal current which requires high amplification and restricted sensitivity.

Proportional Counter

In ionization chamber, the applied voltage collects only electrons emitted by direct action of radiation. In the case of proportional counter, not only the electrons produced by direct action, but also secondary electrons are collected to generate electric signal. It is proportional to the energy of an incident radiation as name suggests. They can be operated either in pulse mode as counters or spectrometers.

Proportional counter is a specially designed co-axial cylinder filled with specific gas medium, operated with higher voltages (1000 V). In general, noble gases such as *Argon* and *Xenon* are used. The gas medium should allow easy migration of free electrons. Gas pressure increases density and gives higher *quantum detection efficiency*. Operating voltage varies with nature of gas medium. The design should optimize gas amplification factor. It should address the amount of amplification and an uniformity of amplification within the chamber.

When radiation interacts a gas medium an initial ionization takes place and ion-pairs are produced. About 34 eV energy is required to produce one ion-pair. The higher electric field applied across the electrodes accelerate

the electrons towards anode with high kinetic energy. Electrons collide with neutral gas atoms and causes additional ionization, resulting ion-pairs and so on. This cascade process is called *Towsend avalanche or gas amplification factor*. It increases with increase of an applied voltage as shown in **Figure 5.1**. Thus, gas amplification factor of 10^6 can be obtained.

The electrons accelerated between two collisions must acquire sufficient energy to ionize another neutral gas atom. This means that the electron must acquire energy greater than an ionization potential of the gas atom in one mean free path. The electric field required to initiate secondary ionization is the order of several kV/cm. The electrons reach a critical distance from the anode where the avalanche takes place. This distance is equal to a few mean free path and is closer to the anode.

Detectors operating in this mode are called *proportional counters.* This means that the ionization caused by the incident radiation is multiplied by the gas amplification factor. In other words, the total charge produced is equal to number of ionizations multiplied by an amplification factor. Since, the mobility of electrons and positive ions vary, when the electrons reach a finite distance, the positive ions hardly moved to a negligible distance. The positive ion sheath near the anode reduces the electric field and unable to register another avalanche event. Once the positive ion sheath moves to a critical distance from the anode, next avalanche event is recorded. The voltage pulse at the anode reaches a maximum rapidly and falls slowly. It depends on the mobility of positive charges and time constant of the input circuit of preamplifier. The time during which the counter is unable to respond to another ionizing event is called the *resolving time.*

The electrical signal/pulse produced by the proportional counter per an ionization event is much larger than an ionization chamber. Hence, they are suitable for counting or detecting an individual radiation interaction. The number of electrons collected at the anode, or the pulse height is proportional to an initial ionization. The pulse height depends on linear energy transfer (LET) of an ionizing radiation. Since, an electric pulse is proportional to the amount of deposited energy, it can be used for energy sensitive counting. It can differentiate different energies based on an electrical pulse. However, they are inefficient detectors for high energy X and gamma rays.

Proportional counters are rarely used in medicine but have wider application in health physics research and industry, for measuring α and β particles. It is useful to study alpha and beta particles and analyze their energy spectrum. Alpha particles can be detected at lower voltage than beta particle of low LET. Proportional counters provide a large surface area and serve as detector in CT scan (*Xenon* gas). Its atomic number is high and kept under high pressure, to have greater photoelectric absorption. Proportional counters are superior then an ionization chamber since its output is quite high. It is superior to GM counters since it analyzes spectra, and has smaller resolving time.

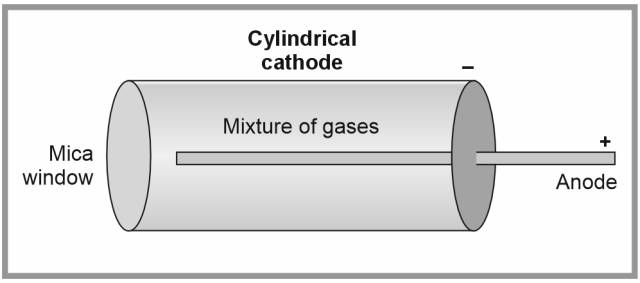


Fig. 5.3: Geiger–Muller tube.

Geiger Counter

The Geiger–Muller (GM) counter consists of a cylindrical cathode with a fine wire anode along its axis **(Fig. 5.3)**. Cathode serves as outer electrode, made by *metal or metallic film* sprayed on inside of a *glass or plastic* tube. A high voltage of 500–1500 V is applied across the chamber. It is filled with a special mixture of gases *(Argon + quenching gas)* at a pressure of about 10 cm of Hg. It is available in two types:

- ❑ End window or thin window (0.1 Al or SS)
- ❑ Windowless (0.01 mm mica).

Former is used for penetrating radiation whereas the later is used for nonpenetrating radiation. Thin window counters are often provided with *pancake type detectors*. Their entrance is provided with removable covers.

Function

When X or gamma ray passes through a gas medium it produces an initial ionization, resulting an ion-pairs. The ion-pairs are accelerated towards respective electrodes. Since the electrons are accelerated towards the anode by a strong electric field, they gain energy and does further ionization in the gas medium, releasing more electrons. This is known as *primary avalanche* of gas or amplification. Accelerating electron can also cause an excitation in the gas medium. The excited molecule returns to ground state within 10^{-9} sec and release visible light and ultraviolet. They interact with cathode and emits electrons by *photoelectric absorption* process. These electrons give *secondary avalanche* in the gas medium while moving towards anode. Both primary and secondary avalanche is called *secondary ion cascade or avalanche ionization*. It becomes more dominant and the initial ionization slowly fads away. It determines pulse size unchanged by energy of the particles. Thus, a huge amplification of the order of 10^{10} is obtained as signal. The ionization current passing through the circuit generates a voltage spike (pulse or signal). It is amplified electronically (5–50 V) and passed to the counter. GM counter can be connected to a loudspeaker for audible sound.

The Geiger counter is operated at a higher applied voltage and the characteristic curve gas four regions, namely *threshold voltage*, *knee, plateau,*

and spontaneous discharge region. Plateau region is about 150–200 voltage long and independent of the applied voltage. It is usual to operate the counter at a voltage midway along the plateau. Operating voltage of the plateau region is about 1/3 of the distance from the knee to the spontaneous discharge region.

GM counter has higher efficiency for charged particles and records every particle separately. However, beta particle cannot penetrate the window. Hence, it is provided with a window, which is opened for beta particle and low energy photon detection. They are inefficient towards X and gamma rays, <1%. It cannot detect neutron and uncharged particles. GM counter voltage pulse size is independent of radiation energy, e.g., 1 keV and 5 keV ionizing radiation gives same size pulse. Hence, they cannot be used as spectrometer to detect energy and as dose rate meter.

Dead Time

GM counters suffer from dead time and recovery time losses. The electron and positive ions differ in mass and velocity. By the time an electron reaches the anode, the positive ion hardly moved at all from the anode. Hence, the potential near the central electrode is lowered and a hose of slow-moving positive ion sheath is formed. This terminates the avalanche process, and no further pulse is possible unless the ion sheath reaches a critical distance. Time during which subsequent an ionizing event cannot produce pulse is called *dead time or pulse resolving time of the detector.* Time during which the pulse height build-up to the threshold value is called *recovery time:*

Resolving time = Dead Time + Recovery time

GM dead time ranges from 50 μs–200 μs, whereas dead time of other detectors is < few μs.

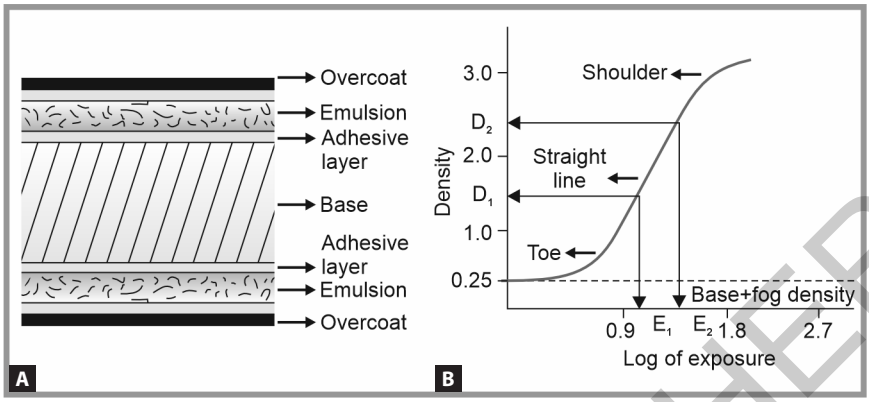
Application

GM counter is rugged, simple, and inexpensive. It detects alpha, beta and gamma radiations. It response to an individual photons, beta particle or single disintegration of atoms. They are used to detect low level radioactive contamination. The particle is counted as counts per minute (CPM), whereas radioactivity is measured in μSv/hr or mR/hr. It can be used as *survey meter as well as contamination monitor.* It is ten times sensitive than an ion chamber and more sensitive in diagnostic radiology energy range. Portable GM counter may be paralyzed in a very high radiation field, and it is seldom used for an accurate reading. Quenching chemicals easily disintegrates, hence life span of GM counter is limited.

SOLID-STATE DETECTORS

Radiographic Film Dosimeter

Radiographic film consists of four layers, namely *base, adhesive layer, emulsion, and overcoat* **(Fig. 5.4A)**. The emulsion is the main component of



Figs. 5.4A and B: (A) Radiographic film cross-section; (B) Characteristics curve of the radiographic film.

film that contains *Silver bromide (Ag Br) crystals*. Usually, Ag Br and Ag I are mixed in the ratio 98% and 2% and used in the crystal. Ag Br crystals are either in tabular or cubic grain size of 0.1 μm thickness. Silver bromide is made by dissolving Silver in *nitric acid* and mixed with *Potassium bromide.* Lattice structure of atoms in the crystal has imperfections, which provide sensitivity centers for latent image formation. Ag Br crystals are spread over *gelatin* in an uniform manner, forms emulsion of 3–5 μm thickness. It is arranged as a single unit consisting *of base, adhesive layer, emulsion, and overcoat*.

The base gives structural support to film, and it is flexible, fracture resistant, and easy to handle without kinking. Adhesive layer is a thin coat that binds emulsion with base and provides integrity to film during processing. The overcoat protects emulsion from scratches, pressure, contamination, and handling damages. In radiographic film, emulsion is coated on both sides and such a film is called *double side coated film*.

When film is exposed to an ionizing radiation Silver bromide gets ionized as Ag^+ and Br, and Bromine is split into Br plus e^-. Thus, Bromine provide secondary electrons, which migrates to sensitivity centers. Silver atoms, Ag^+ also move to sensitivity center and get attached with e^- and become neutral Ag. Neutral Silver atoms are black and form latent image, which is proportional to radiation intensity. In a dark room, film is processed; developed, rinsed, fixed, washed, and dried. Metallic Silver is made visible and unexposed Ag Br are removed from the film.

Blackness of film is evaluated by using an optical densitometer. The densitometer consists of a standard *light source, aperture, and a light detector*. While the film is exposed, transmitted light from film is measured and an optical density is obtained. The optical density (OD) of film is given by the relation:

$$OD = \log_{10}\left(\frac{I_0}{I_t}\right)$$

where, I_0 is light intensity measured without film and I_t is light transmitted through film, $\left(\frac{I_0}{I_t}\right)$ is inverse of transmittance (T), which is measured by a densitometer. If the densitometer is calibrated with known optical density, it gives direct reading of an optical density. Using the **Hurter** and **Driffield** (H and D) characteristic curve of the film, radiation exposure can be obtained **(Fig. 5.4B)**. The H and D curve is drawn between log of radiation exposure and an optical density that gives characteristic response of the film. The curve has *base plus fag, linear and shoulder* regions. Generally, an optical density is measured at the linear part of characteristic curve.

Commercial films are available from *Kodak, Dupont, Agfa and kodak,* which are individually packed in a light proof and airtight covers and directly used with slab phantoms in day light. Care should be taken to avoid air bubbles within airtight cover. To overcome this, film is pierced with pin at one side and slap phantom is pressed over it from other side to remove air. Thus, pin prick can be used as an identification mark for film orientation.

Limitation of film includes change in processing conditions, inter film emulsion differences, and formation of artifacts. Hence, film is not recommended for absolute dosimetry. However, it can be used for checking an optical and radiation field congruence, field flatness and symmetry, and radiation distribution. Since film contains high Z active material, it overresponse to low energy X-ray photons.

Thermoluminescent Dosimeter

Thermoluminescence is a property of certain phosphors, in which irradiated crystal absorbs energy and later release the energy as luminescence while it is heated. The amount of luminescence is proportional to absorbed radiation dose. This phenomenon is known as *thermo luminescence* and the system is called *thermoluminescent dosimeter (TLD).*

Solid crystals possess allowed energy bands such as *valency, conduction, and forbidden* energy bands. The valency energy band is ground state and conduction band is high energy state. At room temperature, conduction band is empty, the electrons are in the valency band or in an equilibrium. The gap between valency and conduction band is having number of traps that are caused by defects in the crystal (caused by impurities). When TLD dosimeter is exposed to radiation, electrons in the valency band receive sufficient energy and move from valence band to conduction band **(Fig. 5.5).** The excited electrons form a trap in meta stable state just below the conduction band. The traps may be shallow, active, deep electron, and deep hole traps, respectively. Correspondingly holes are formed in valency band due to an electron vacancy. Number of electrons in the meta stable trap is proportional to radiation exposure. Thus, it stores absorbed radiation energy in the crystal lattice.

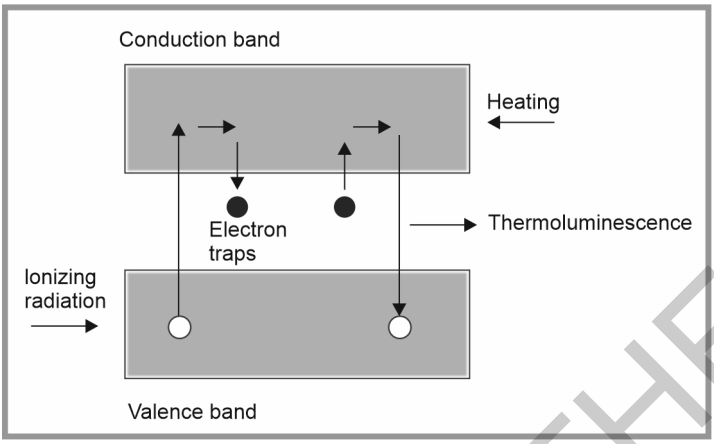


Fig. 5.5: Principle and function of TLD phosphor during irradiation and heating.

TLD Reader

After radiation exposure, dose measurements are made by using a TLD reader **(Fig. 5.6).** The reader has *heater, photomultiplier tube (PMT), amplifier, and a recorder*. TLD dosimeter is placed in the heater *cup or planchet,* where it is heated (300˚C) for a reproducible heating cycle. Temperature is measured by welding a *thermocouple* to the *planchet.* While heating, electrons in the meta stable state absorbs energy from heat and returns to their valency state (ground state) with emission of light and recombine with holes. The amount of light emission depends on temperature and number of trapped electrons. This phenomenon is called *thermoluminescence* (TL). Emitted light is detected by a photomultiplier tube (PMT), which converts light into an electrical signal. PMT signal is then amplified and measured by a recorder.

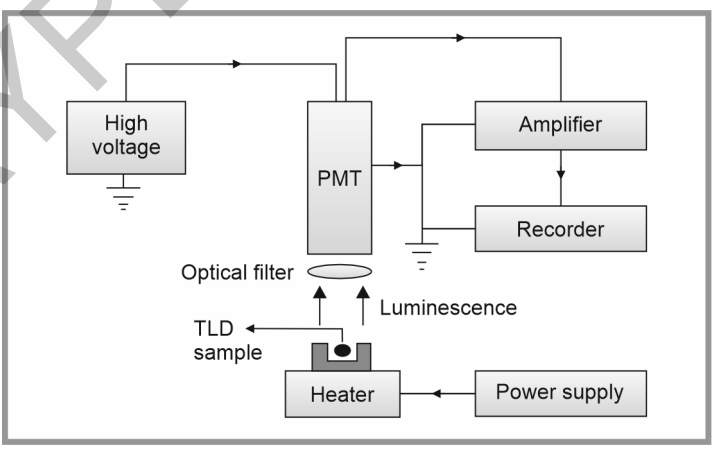


Fig. 5.6: Thermoluminescent dosimeter reader.

The reader is calibrated in terms of milli roentgen (mR) or milli sievert (mSv), so that the reader displays direct dose estimation.

Glow Curve

TLD response is defined as TL output per unit Gy absorbed dose by the phosphor. TL response varies with temperature or duration of heating. If temperature is kept constant, then TL response varies with time. If a linear temperature ramp is applied, TL signal shows number of peaks at specific temperatures, corresponding to traps of different energy levels. A plot drawn between TL response and heating time, is referred as *glow curve*. As temperature increases, electrons leaving the trap increases, in turn TL response also increases, it reaches a maximum and falls to zero. TL *thermogram* can be obtained by plotting an emitted light vs phosphor temperature.

The reading cycle of TLD is divided into *preheating, signal integration and annealing*, In the preheating, dosimeter is heated for few seconds at constant temperature to remove all low temperature signals. During signal integration, temperature is raised to a maximum. Finally, the dosimeter is *annealed* in a dedicated heating *oven* to remove all remaining signals. Now the dosimeter has been reset to zero and can be reused again.

Dedicated *annealing oven* is one in which various levels of temperature can be set. A typical annealing cycle consists of 400°C for 1 h, followed by 80°C for 24 h. However, it varies with phosphor material. Annealing process releases all residual energy stored from earlier exposure or confirms that all electrons in the metastable state is released. After annealing, the peaks in the glow curve disappear and curve becomes stable and predictable.

TLD Phosphors

Phosphors suitable for thermoluminescence are *Lithium fluoride (LiF: Mg, Ti, LiF: Mg, Cu, P)* and *Lithium borate ($Li_2B_4O_7$: Mn)* which are tissue equivalent. Materials having high sensitivity, but not tissue equivalent are *Calcium sulfate ($CaSO_4$: Dy), Aluminum oxide (Al_2O_3:C),* and *Calcium fluoride (CaF_2:MN).* LiF: Mg, Ti (TLD 100) phosphor is most widely used which has wide dose response over 10 μSv–1000 Sv and has less than 10% fading per year. Its effective atomic number (Z = 8.2) is close to that of tissue (Z = 7.4) with an accuracy of ±2%. If dimensions of the dosimeter are equal to an electron range, an *electronic equilibrium exists*, then ratio of absorbed doses of TLD and muscle is equal to their *mass stopping power ratio.* This ratio is constant over an electron energies of 10 keV–20 MeV. LiF: Mg, Ti (TLD 100) is useful for clinical dosimetry in radiology and research applications, which has a detection threshold of 0.1 μGy. However, it shows *supra linearity* at high doses, which requires corrections. $CaSO_4$:Dy is used as TLD material in India for personnel monitoring. It is not tissue equivalent (Z = 15.3), has wide range of dose response from 0.1 mSv–100 Sv with an accuracy of ±10%.

THE PHYSICS OF RADIOLOGY & IMAGING

Salient Features

- Second edition with 15 chapters
- Includes 275 figures and 49 tables with citations and worked examples
- Fulfils the requirement of postgraduate physics teaching in radiology
- Targets MD/DNB/FRCR (Radiology) students from medical universities
- Suitable for MSc Medical Physics and PG Diploma in Radiation Physics courses
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The book addresses the role of ionizing and nonionizing radiation in medical image formation. It describes the physics and principle behind various equipments like Radiography, CT scan, Ultrasound, and MRI including Nuclear Imaging, Gamma Camera, PET-CT, PET-MRI. Recent developments such as Breast Tomosynthesis, Contrast-enhanced Mammography, Harmonic Imaging, Elastography, and MR Imaging sequence topics have been incorporated. Essentials of image quality, quality assurance, bioeffects, and radiological safety have also been included.

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