

CHAPTER 3.

RADIATION DOSIMETERS

JOANNA IZEWSKA

*Dosimetry and Medical Radiation Physics Section
Department of Nuclear Sciences and Applications
International Atomic Energy Agency
Vienna, Austria*

GOVINDA RAJAN

*Medical Physics and Safety Section,
Bhabha Atomic Research Centre,
Mumbai, Maharashtra, India*

3.1. INTRODUCTION

Radiation dosimeter is a device, instrument or system that measures or evaluates, either directly or indirectly, the quantities exposure, kerma, absorbed dose or equivalent dose, or their time derivatives (rates) or related quantities of ionizing radiation. A dosimeter along with its reader is referred to as a dosimetry system.

Measurement of a dosimetric quantity is the process of finding the value of the quantity experimentally using dosimetry systems. The result of measurement is the value of a dosimetric quantity expressed as the product of a numerical value and an appropriate unit.

To function as a radiation dosimeter, the dosimeter must possess at least one physical effect that is a function of the measured dosimetric quantity and can be used for radiation dosimetry with proper calibration. In order to be useful, radiation dosimeters must exhibit several desirable characteristics. For example, in radiotherapy, the exact knowledge of both the absorbed dose to water at a specified point and its spatial distribution are of importance, as well as the possibility to derive the dose to an organ of interest in the patient. In this context, the desirable dosimeter properties will be characterized by accuracy and precision, linearity, dose or dose-rate dependence, energy response, directional dependence and spatial resolution.

Obviously, not all dosimeters can satisfy all characteristics, therefore, the choice of a radiation dosimeter and its reader must be made judiciously, taking into account the requirements of the measurement situation, *e.g.*, in radiotherapy ionisation chambers are recommended for beam calibrations (reference dosimetry – see Chapter 9) and other dosimeters, such as those discussed below, are suitable for the evaluation of the dose distribution (relative dosimetry) or dose verification.

3.2. PROPERTIES OF DOSIMETERS

3.2.1. Accuracy and precision

In radiotherapy dosimetry the uncertainty associated with the measurement is often expressed in terms of *accuracy* and *precision*.

The *precision* of dosimetry measurements specifies the reproducibility of the measurements under similar conditions and can be estimated from the data obtained in repeated measurements. High precision is associated with a small standard deviation of the distribution of measurement results.

The *accuracy* of dosimetry measurements is the proximity of their expectation value to the ‘true value’ of the measured quantity. Results of measurement cannot be absolutely accurate and the inaccuracy of a measurement result is characterized as *uncertainty*.

The *uncertainty* is a parameter that describes the dispersion of the measured values of a quantity; it is evaluated by statistical methods (*type A*) or by other methods (*type B*), it has no known sign and is usually assumed to be symmetrical.

The *error* of measurement is the difference between the measured value of a quantity and the ‘true value’ of that quantity.

- An error has both a numerical value and a sign.
- Typically, the measurement errors are not known exactly, but they are estimated in the best possible way and corrections are made for them.
- After application of all known corrections, the expectation value for errors should be zero and the only quantities of concern are the uncertainties.

Type A standard uncertainties

- If a measurement of a dosimetric quantity x is repeated N times, then the best estimate for x is \bar{x} , the arithmetic mean value of all measurements x_i :

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i . \quad (3.1)$$

- The standard deviation σ_x characterizes the average uncertainty for an individual result x_i and is given by:

$$\sigma_x = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2} . \quad (3.2)$$

- The standard deviation of the mean value is given by:

$$\sigma_{\bar{x}} = \frac{1}{\sqrt{N}} \sigma_x = \sqrt{\frac{1}{N(N-1)} \sum_{i=1}^N (x_i - \bar{x})^2} . \quad (3.3)$$

- The standard uncertainty of type A, denoted u_A , is defined as the standard deviation of the mean value, $u_A = \sigma_{\bar{x}}$.
- The standard uncertainty of type A is obtained by a statistical analysis of repeated measurements and, in principle, it can be reduced by increasing the number of measurements.

Type B standard uncertainties

- Type B standard uncertainties u_B cannot be estimated by repeated measurements, rather, they are intelligent guesses or scientific judgment of non-statistical uncertainties associated with the measurement. They include influences on the measuring process, application of correction factors or physical data taken from the literature.
- It is often assumed that type B standard uncertainties have a probability distribution, such as a normal (Gaussian) or a rectangular distribution (equal probability anywhere within the given limits).
- Type B standard uncertainty can be derived by estimating the limit, beyond which the value of the factor is not going to lie, and a fraction of this limit is taken as u_B . The fraction is chosen according to the distribution assumed.

Combined and expanded uncertainties

- The equation that determines a dosimetric quantity Q at a point P is of the type:

$$Q_P = M \prod_{i=1}^N F_i \quad , \quad (3.4)$$

where M is the reading provided by the dosimetry system and F_i are the correction or conversion factors contained in the Eq. (3.4).

- The combined standard uncertainty, u_C , associated with the quantity Q is a quadratic summation of type A (u_A) and type B (u_B) uncertainties:

$$u_C = \sqrt{u_A^2 + u_B^2} \quad . \quad (3.5)$$

- The combined uncertainty is assumed to exhibit a normal distribution and is multiplied by a coverage factor, denoted by k , to obtain *the expanded uncertainty*, $U = k u_C$. The result of the measurement of the quantity Q is then expressed by $Q_P \pm U$.
- The expanded uncertainty U with the coverage factor $k = 2$, corresponding to the 95% confidence level, is often used to represent the “overall uncertainty” which relates to the accuracy of the measurement of the quantity Q .

3.2.2. Linearity

- Ideally, the dosimeter reading M should be linearly proportional to the dosimetric quantity Q . However, beyond a certain dose range a non-linearity sets in. The linearity range and the non-linearity behavior depend on the type of dosimeter and its physical characteristics.
- Two typical examples of response characteristics of dosimetry systems are sketched in Fig. 3.1. Curve A first exhibits linearity with dose, then a supralinear behavior, and finally saturation. Curve B first exhibits linearity and then saturation at high doses.
- In general, a non-linear behavior should be corrected for. A dosimeter and its reader may both exhibit non-linear characteristics but their combined effect could produce linearity over a wider range.

3.2.3. Dose rate dependence

- Integrating systems measure the integrated response of a dosimetry system. For such systems the measured dosimetric quantity should be independent of the rate of that quantity.
- Ideally, the response of a dosimetry system, M/Q , at two different dose rates: $(dQ/dt)_1$ and $(dQ/dt)_2$ should remain constant. In reality, dose rate may influence the dosimeter readings and the appropriate corrections are necessary, e.g., recombination corrections for ionisation chambers in pulsed beams.

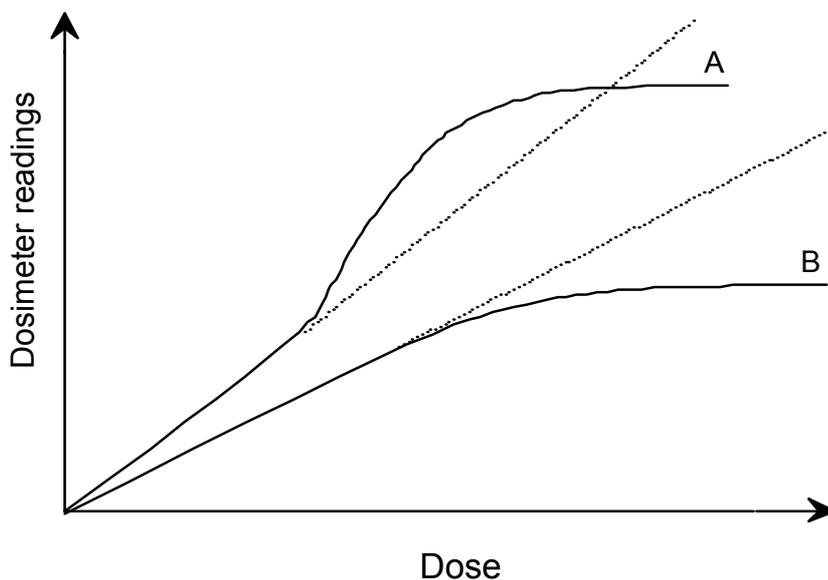


FIG. 3.1. Response characteristics of two dosimetry systems. Curve A first exhibits linearity with dose, then supralinear behavior, and finally saturation. Curve B first exhibits linearity and then saturation at high doses.

3.2.4. Energy dependence

- The response of a dosimetry system, M/Q , is generally a function of radiation beam quality (energy).
- Since the dosimetry systems are calibrated at a specified radiation beam quality (or qualities) and used over a much wider energy range, the variation of the response of a dosimetry system with radiation quality (called *energy dependence*) should be corrected for.
- Ideally, the energy response should be flat, *i.e.*, the system calibration should be independent of energy over a certain range of radiation qualities. In reality, the energy correction has to be included in the determination of the quantity Q for most measurement situations.
- In radiotherapy, the quantity of interest is the dose to water (or to tissue). As no dosimeter is water or tissue equivalent for all radiation beam qualities, the energy dependence is an important characteristic of a dosimetry system.

3.2.5. Directional dependence

- The variation in response of a dosimeter with the angle of incidence of radiation is known as the directional, or angular, dependence of the dosimeter.
- Dosimeters usually exhibit directional dependence due to their constructional details, physical size, and the energy of the incident radiation.
- Directional dependence is important in certain applications, *e.g.*, in *in-vivo* dosimetry while using semiconductor dosimeters. Therapy dosimeters are generally used in the same geometry as that in which they are calibrated.

3.2.6. Spatial resolution and physical size

- Because the dose is a point quantity, the dosimeter should allow the determination of the dose from a very small volume, *i.e.*, one needs a 'point dosimeter' to characterize the dose at a point.
- TLD dosimeters come in very small dimensions and their use, to a great extent, approximates a point measurement. Film dosimeters have excellent 2D and gels 3D resolution, where the 'point' measurement is limited only by the resolution of the evaluation system. Ionisation chamber-type dosimeters, on the other hand, are of finite size to give the required sensitivity, although the new type of pin-point micro-chambers partially overcomes the problem.
- The position of the point where the dose is determined, *i.e.*, its spatial location should be well defined in a reference co-ordinate system.

3.2.7. Readout convenience

- Direct-reading dosimeters (*e.g.*, ionisation chambers) are generally more convenient than passive dosimeters; *i.e.*, the ones that are read after due processing following the exposure (*e.g.*, TLDs, films, etc.).
- While some dosimeters are inherently of the “integrating” type (*e.g.*, TLDs, gel), others can measure in both integral and differential modes (ionisation chambers).

3.2.8. Convenience of use

- Ionisation chambers are reusable with no or little change in sensitivity.
- Semiconductor dosimeters are reusable but with a gradual loss of sensitivity.
- Some dosimeters are not reusable at all (*e.g.*, film, gel, alanine).
- Some dosimeters measure dose distribution in a single exposure (*e.g.*, films, gels).
- Some dosimeters are quite rugged (*i.e.*, handling will not influence sensitivity, *e.g.*, ionisation chambers), while others are sensitive to handling (*e.g.*, TLDs).

3.3. IONISATION CHAMBER DOSIMETRY SYSTEMS

3.3.1. Chambers and electrometers

- Ionisation chambers are used in radiation therapy and in diagnostic radiology for the determination of radiation dose. The dose determination in reference irradiation conditions is also called *beam calibration* (see Chapter 9 for details).
- Ionisation chambers have various shapes and sizes depending upon the specific requirements.
- An ionisation chamber is basically a cavity surrounded by a conductive outer wall and having a central collecting electrode (see Fig. 3.2). The wall and the collecting electrode are separated with a high quality insulator to reduce the leakage current when a polarizing voltage is applied to the chamber.
- A guard electrode is usually provided in the chamber to further reduce the chamber leakage. The guard electrode intercepts the leakage current and allows it to flow to ground bypassing the collecting electrode.

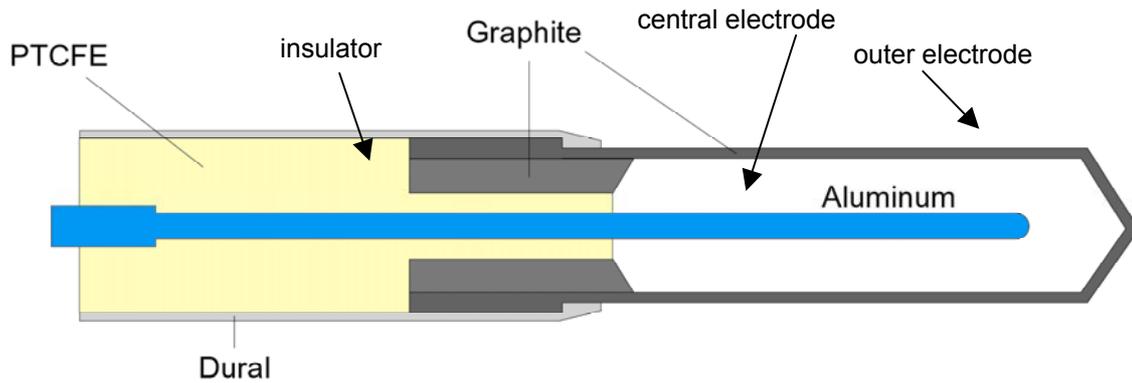
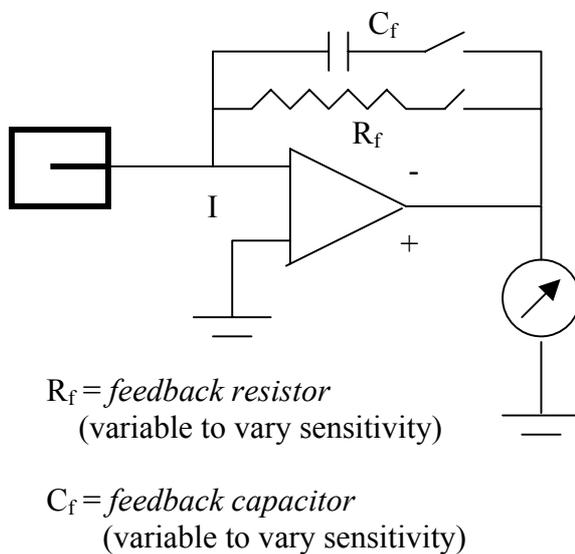


FIG. 3.2. The basic design of a cylindrical Farmer-type ionisation chamber.

- Electrometers are devices for measuring small currents of the order of 10^{-9} A or less.
- An electrometer used in conjunction with an ionisation chamber is a high gain, negative feedback, operational amplifier with a standard resistor or a standard capacitor in the feedback path to measure the chamber current or charge collected over a fixed time interval, as shown schematically in Fig. 3.3.



$$V = I_I R_f \text{ (rate mode)}$$

$$V = (I_I \times t) / C_f \text{ (integrated mode)}$$

FIG. 3.3. Electrometer in feedback mode of operation.

3.3.2. Cylindrical (thimble type) ionisation chambers

- The most popular cylindrical ionisation chamber is the 0.6 cm³ chamber designed by Farmer and manufactured by Baldwin for beam calibration in radiotherapy dosimetry. Its chamber sensitive volume resembles a thimble and hence the Farmer-type chamber is also known as a thimble chamber. A schematic diagram of a Farmer-type thimble ionisation chamber is given in Fig. 3.2; ionisation chamber-based dosimetry systems are discussed in Section 9.2.
- Cylindrical chambers are produced by various manufacturers with active volumes between 0.1 cm³ and 1 cm³. They typically have an internal length of not greater than 25 mm and an internal diameter of not greater than 7 mm. The wall material is of low atomic number Z , *i.e.*, tissue or air equivalent of the thickness less than 0.1 g/cm². A chamber is equipped with a build-up cap of about 0.5 g/cm² for the calibration of such a chamber free in air using cobalt-60 gamma radiation.
- The chamber construction should be as homogenous as possible, although an aluminum central electrode of about 1 mm in diameter is typically used to ensure flat energy dependence.
- The construction details of various commercially available cylindrical chambers are given in the IAEA TRS-277 and TRS-398 codes of practice. The use of the cylindrical chamber in electron and photon beam dosimetry is explained herein.

3.3.3. Parallel-plate (plane-parallel) ionisation chambers

- A parallel-plate ionisation chamber consists of two plane walls, one serving as an entry window and polarizing electrode and the other as the back wall and collecting electrode as well as guard-ring system. The back wall is usually a block of conducting plastic or a non-conducting material (usually perspex or polystyrene) with a thin conducting layer of graphite forming the collecting electrode and the guard-ring system on top. A schematic diagram of a parallel-plate ionisation chamber is provided in Fig. 3.4.
- The parallel-plate chamber is recommended for dosimetry of electron beams with energies below 10 MeV. It is also used for surface dose and depth dose measurements in the build-up region of megavoltage photon beams. Dose measurements in the build-up region of photon beams are discussed in Section 6.13;
- Some parallel-plate chambers require significant fluence perturbation correction because they are provided with an inadequate guard width.
- The characteristics of parallel-plate chambers commercially available and the use of these chambers in electron beam dosimetry are explained in detail in the IAEA TRS-381 and TRS-398 codes of practice.

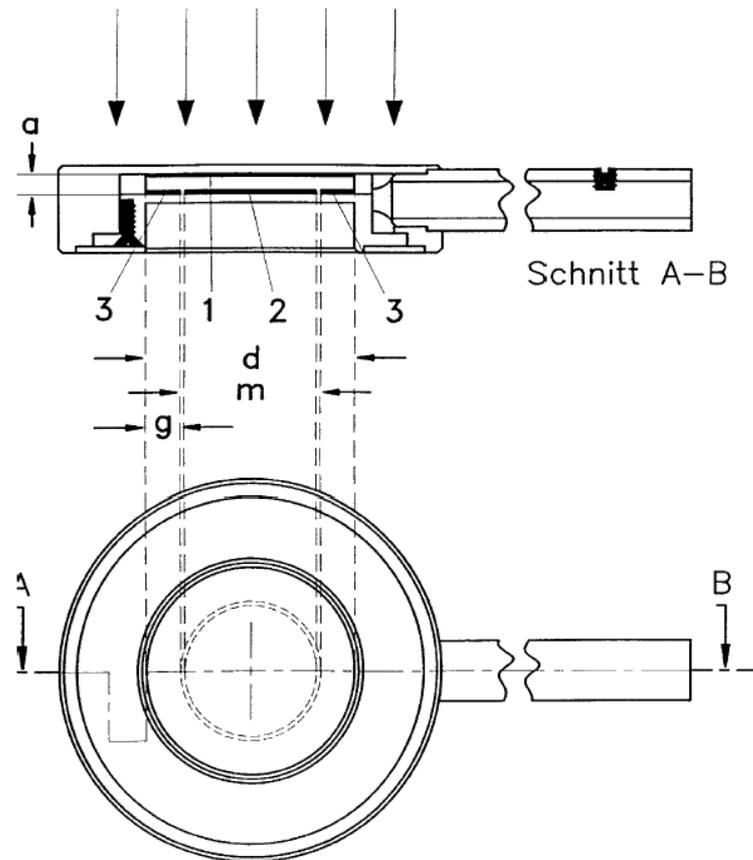


FIG. 3.4. Diagram of a parallel-plate ionisation chamber. (1) is the polarizing electrode; (2) is the measuring electrode; and (3) is the guard ring. (a) is the height (electrode separation) of the air cavity; (d) is the diameter of the polarizing electrode; (m) is the diameter of the collecting electrode; and (g) is the width of the guard ring (adapted from the IAEA TRS-381 dosimetry protocol).

3.3.4. Brachytherapy chambers

- Sources used in brachytherapy are low air-kerma rate sources that require chambers of sufficient volume (about 250 cm³ or more) for adequate sensitivity.
- Well-type chambers or re-entrant chambers are ideally suited for calibration and standardization of brachytherapy sources. Figure 3.5 shows a schematic diagram of a well-type chamber.
- The well-type chambers should be designed to accommodate sources of typical sizes and shapes that are in clinical use in brachytherapy.
- Well-type chambers are calibrated in terms of the reference *air-kerma* rate.

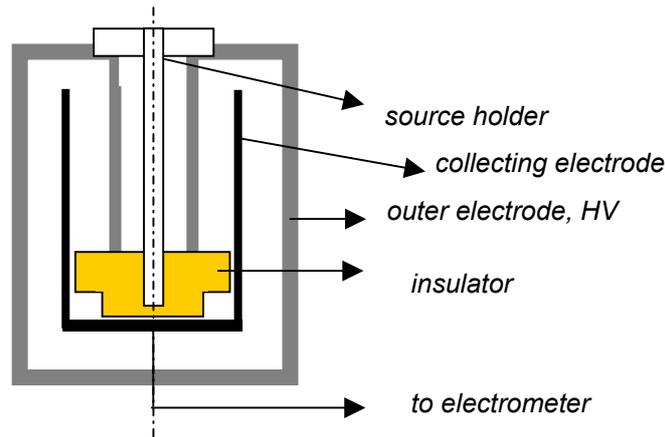


FIG. 3.5. The basic design of a brachytherapy well-type chamber.

3.3.5. Extrapolation chambers

- Extrapolation chambers are parallel-plate chambers with a variable sensitive volume. They are used in measurement of surface doses in orthovoltage and megavoltage x-ray beams and in dosimetry of beta rays, and low energy x rays. They can also be used in absolute radiation dosimetry when directly embedded into a tissue equivalent phantom.
- The cavity perturbation for electrons can be eliminated by making measurements as a function of the cavity thickness and then extrapolating to zero thickness.
- Using this chamber, the cavity perturbation for parallel-plate chambers of finite thickness can be estimated.

3.4. FILM DOSIMETRY

3.4.1. Radiographic film

- Radiographic x-ray film performs several important functions in diagnostic radiology, radiation therapy, and radiation protection. It can serve as radiation detector, relative dosimeter, a display device, and archival medium.
- Unexposed x-ray film consists of a base of thin plastic with a radiation sensitive emulsion (silver bromide AgBr grains suspended in gelatin) coated uniformly on one or both sides of the base.
- Ionisation of AgBr in the grains, as a result of radiation interaction, forms the latent image in the film. Image becomes visible (film blackening) only after development.
- Light transmission is a function of the film opacity and can be measured in terms of optical density (*OD*) with special devices called densitometers.

- Optical density is defined as $OD = \log_{10} (I_0/I)$ and is a function of dose. I_0 is the initial light intensity and I is the intensity transmitted through the film.
- Film gives excellent 2D spatial resolution and, in a single exposure, it provides information about the spatial distribution of radiation in the area of interest or the attenuation of radiation by objects.
- Useful dose range of film is limited; energy dependence is pronounced for lower energy photons, and the response depends on several, difficult to control, parameters.
- Typically, films are used for qualitative dosimetry but with proper calibration, careful use and analysis, film can also be used for dose evaluation.
- Various types of films are available for radiotherapy work (*e.g.*, direct exposure non-screen films for field size verification, phosphor screen films used with simulators, metallic screen films used in portal imaging, etc.).
- Unexposed film would exhibit a background optical density called the fog density (OD_f). The density due to radiation exposure called the net optical density can be obtained from the measured density by subtracting the fog density.
- The OD readers are film densitometers, laser densitometers, automatic film scanners, etc. The principle of operation of a simple film densitometer is shown in Fig. 3.6.
- Ideally, the relationship between the dose and OD should be linear, but unfortunately this is not always the case. Some emulsions are linear, some are linear over a limited dose range and others are non-linear. So the dose vs. OD curve, known as the sensitometric curve (also known as the characteristic or *H&D curve*, in honour of Hurter and Driffield who first investigated the relationship) must be established for each film before using it for dosimetry work.

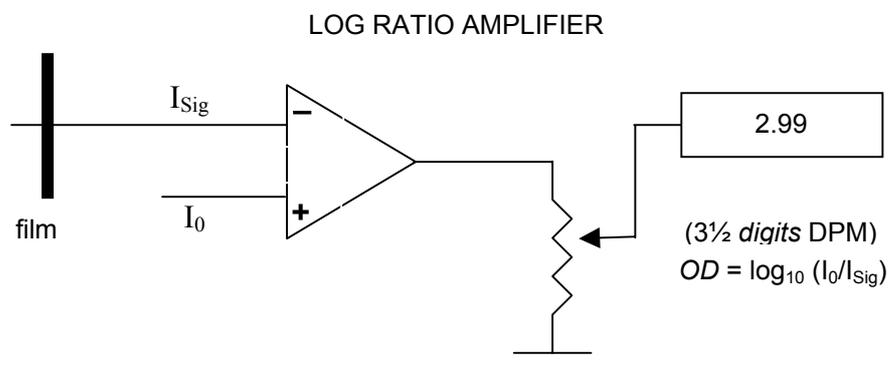


FIG. 3.6. Schematic diagram of a basic film densitometer.

Chapter 3. Radiation Dosimeters

- A typical H&D curve for a radiographic film is shown in Fig. 3.7. It has four regions: (1) fog, at low or zero exposures; (2) toe; (3) linear portion at intermediate exposures; and (4) shoulder and saturation at high exposures. The linear portion is referred to as optimum measurement conditions; the toe is the region of underexposure, and the shoulder as the region of overexposure.
- Important parameters of film response to radiation are: *gamma*, *latitude* and *speed*.
 - The slope of the straight line portion of the H&D curve is called the *gamma* of the film.
 - The exposure should be chosen to make all parts of the radiograph lie on the linear portion of the H&D curve to ensure the same contrast for all optical densities.
 - The *latitude* is defined as the range of exposures over which the densities will lie in the linear region.
 - *Speed* of a film is determined by giving the exposure required to produce an optical density of 1.0 greater than the *OD* of fog.
- Typical applications of a radiographic film in radiotherapy are qualitative and quantitative measurements, including electron beam dosimetry, quality control of radiotherapy machines (e.g., congruence of light and radiation fields, determination of the position of a collimator axis, so called star test), verification of treatment techniques in various phantoms and portal imaging.

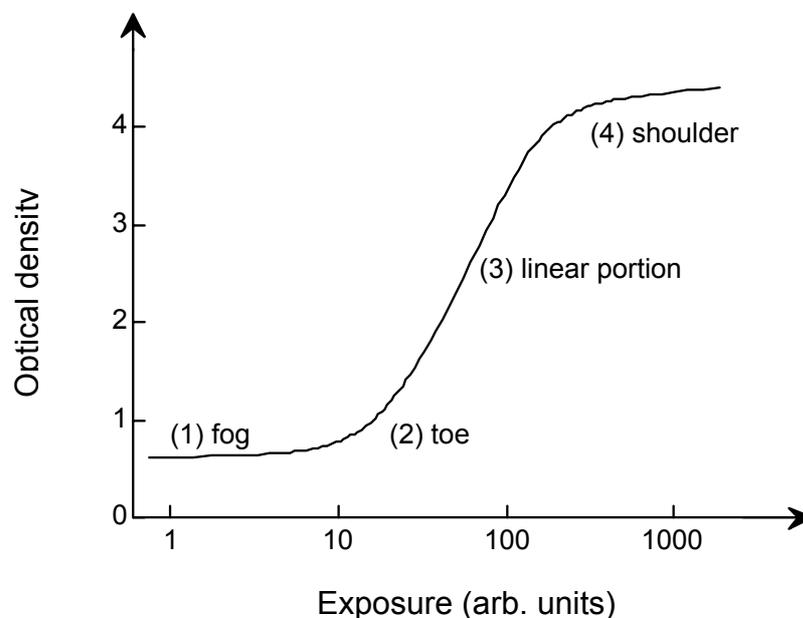


FIG. 3.7. Typical sensitometric (characteristic H&D) curve for a radiographic film.

3.4.2. Radiochromic film

- Radiochromic film is a new type of film in radiotherapy dosimetry. The most commonly used is a GafChromic™ film. It is a colorless film with a nearly tissue equivalent composition (H 9.0%, C 60.6%, N 11.2%, and O 19.2%) that develops a blue color upon radiation exposure.
- Radiochromic film contains a special dye that gets polymerized upon exposure to radiation. The polymer absorbs light and the transmission of light through the film can be measured with a suitable densitometer. Radiochromic film is self-developing, needs neither developer nor fixer.
- Since the radiochromic film is grainless, it has a very high resolution and can be used in high dose gradient regions for dosimetry, *e.g.*, near brachytherapy sources, in measurement of dose distributions in stereotactic fields, etc.
- The dosimetry with GafChromic films has a few advantages over the radiographic films, such as the ease of use, not requiring dark rooms, film cassettes or film processing; dose rate independence; better energy characteristics except for low energy x rays (25 kV); insensitivity to ambient conditions (although excessive humidity should be avoided). GafChromic films are generally less sensitive than radiographic films and are useful at higher doses, although the dose-response non-linearity should be corrected for in the upper dose region.
- Radiochromic film is a relative dosimeter; it is possible to achieve the precision better than 3%, if proper care is taken of its calibration and with the environmental conditions.
- Data on the various characteristics of GafChromic films (*e.g.*, sensitivity, linearity, uniformity, reproducibility, post-irradiation stability, etc.) are available in the literature.

3.5. LUMINESCENCE DOSIMETRY

Some materials, upon absorption of radiation, retain part of the absorbed energy in metastable states. When this energy is subsequently released in the form of ultraviolet, visible or infrared light, the phenomenon is called as luminescence. Two types of luminescence: *fluorescence* and *phosphorescence*, are known depending on the time delay between the stimulation and the emission of light. Fluorescence occurs with a time delay between 10^{-10} to 10^{-8} seconds; phosphorescence with a time delay exceeding 10^{-8} seconds. The process of phosphorescence can be accelerated with a suitable excitation in the form of heat or light.

- If the exciting agent is heat, the phenomenon is known as *thermoluminescence* and the material is called a thermoluminescent (TL) material or a thermoluminescent dosimeter (TLD) when used for purposes of dosimetry.
- If the exciting agent is light, the phenomenon is referred to as *optically stimulated luminescence* (OSL).

Chapter 3. Radiation Dosimeters

As discussed in Section 1.4., the highly energetic secondary charged particles, usually electrons that are produced in the primary interactions of photons with matter are mainly responsible for the photon energy deposition in matter. In a crystalline solid these secondary charged particles release numerous low energy free electrons and holes through ionizations of atoms and ions. The free electrons and holes thus produced will either recombine or become trapped in an electron or hole trap, respectively, somewhere in the crystal.

The traps can be intrinsic or can be introduced in the crystal in the form of lattice imperfections consisting of vacancies or impurities. Two types of traps are known in general: *storage traps* and *recombination centers*.

- A *storage trap* merely traps free charge carriers and releases them during the subsequent (i) heating resulting in the TL process or (ii) irradiation with light resulting in the OSL process.
- A charge carrier released from a storage trap may recombine with a trapped charge carrier of opposite sign in a *recombination center* (luminescence center). The recombination energy is at least partially emitted in the form of ultraviolet, visible or infrared light that can be measured with photodiodes or photomultiplier tubes.

3.5.1. Thermoluminescence

Thermoluminescence (TL) is thermally activated phosphorescence; the most spectacular and the most widely known of a number of different ionizing radiation induced thermally activated phenomena. Its practical applications range from archeological pottery dating to radiation dosimetry. In 1968 Cameron, Suntharalingam and Kenney published a book on the TL process that is still considered an excellent treatise on the practical aspects of the TL phenomenon.

A useful phenomenological model of the TL mechanism is provided in terms of the band model for solids. The storage traps and recombination centers, each type characterized with an activation energy (trap depth) that depends on the crystalline solid and the nature of the trap, are located in the energy gap between the valence band and the conduction band. The states just below the conduction band represent electron traps, the states just above the valence band are hole traps. The trapping levels are empty before irradiation, *i.e.*, the hole traps contain electrons and the electron traps do not.

During the irradiation the secondary charged particles lift electrons into the conduction band either from the valence band (leaving a free hole in the valence band) or from an empty hole trap (filling the hole trap).

The system may approach thermal equilibrium through several means:

- (1) Free charge carriers recombine with the recombination energy converted into heat.
- (2) A free charge carrier recombines with a charge carrier of opposite sign trapped at a luminescence center, the recombination energy being emitted as optical fluorescence.
- (3) The free charge carrier becomes trapped at a storage trap, and this event is then responsible for phosphorescence or the TL and OSL processes.

3.5.2. TLD systems

- TL dosimeters most commonly used in medical applications are LiF:Mg,Ti, LiF:Mg,Cu,P and Li₂B₄O₇:Mn, because of their tissue equivalence. Other TLDs, used because of their high sensitivity, are CaSO₄:Dy, Al₂O₃:C and CaF₂:Mn.
- TLDs are available in various forms (*e.g.*, powder, chips, rods, ribbon, etc.).
- Before they are used, TLDs have to be annealed to erase the residual signal. Well-established reproducible annealing cycles should be used including the heating and cooling rates
- A basic TLD reader system consists of a planchet for placing and heating the TLD dosimeter; a photomultiplier tube (PMT) to detect the TL light emission, convert it into an electrical signal, and amplify it; and an electrometer for recording the PMT signal as charge or current. A basic schematic diagram of a TLD reader is shown in Fig. 3.8.
- The TL intensity emission is a function of the TLD temperature T . Keeping the heating rate constant makes the temperature T proportional to time t and so the TL intensity can be plotted as a function of t if a recorder output is available with the TLD measuring system. The resulting curve is called the TLD glow curve (Fig. 3.9). In general, if the emitted light is plotted against the crystal temperature one obtains a TL thermogram.
- The peaks in the glow curve may be correlated with trap depths responsible for TL emission.
- The main dosimetric peak of the LiF:Mg,Ti glow curve between 180° and 260°C is used for dosimetry. The peak temperature is high enough for not being affected by room temperature and still low enough so as not to interfere with black-body emission from the heating planchet.

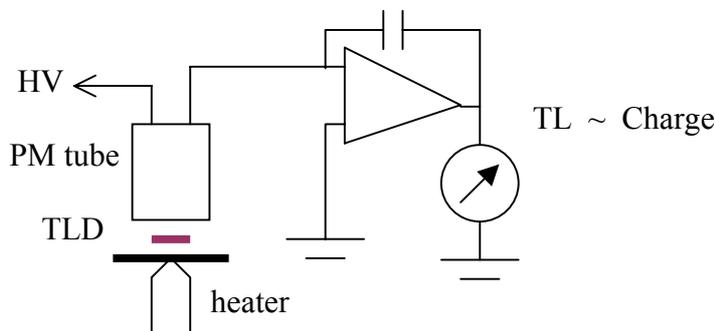


FIG. 3.8. Schematic diagram of a TLD reader.

- The total TL signal emitted, *i.e.*, the area under the appropriate portion of the glow curve, can be correlated to dose through proper calibration.
- Good reproducibility of heating cycles during the readout is important for accurate dosimetry.
- TL signal decreases in time after the irradiation due to spontaneous emission of light at room temperature. This process is called fading. Typically, for LiF:Mg,Ti, the fading of the dosimetric peak does not exceed a few percent per year.
- TL dose response is linear over a wide range of doses used in radiotherapy, although it increases in higher dose region exhibiting supralinear behaviour before it saturates at even higher doses.
- TL dosimeters have to be calibrated before they are used (thus they serve as relative dosimeters). To derive the absorbed dose from the TL-reading a few correction factors have to be applied, such as energy correction, fading and dose-response non-linearity corrections.
- Typical applications of TLD in radiotherapy are: *in vivo* dosimetry on patients (either as a routine QA procedure or for dose monitoring in special cases, *e.g.*, complicated geometries, dose to critical organs, total body irradiation, in brachytherapy, etc.), verification of treatment techniques in various phantoms (*e.g.*, Rando phantom), dosimetry audits (such as the IAEA/WHO TLD postal dose audit programme) and comparisons among hospitals.

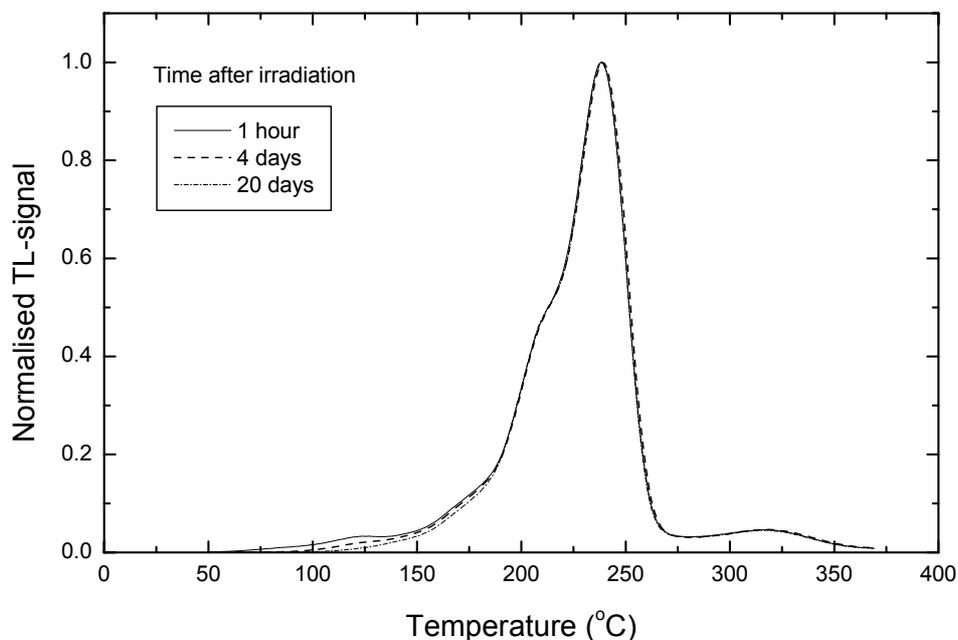


Fig. 3.9. A typical glow-curve (thermogra) of LiF:Mg,Ti measured with a TLD reader at a low heating rate.

3.5.3. OSL systems

- Optically-stimulated luminescence (OSL) is based on a principle similar to that of the TLD. Instead of heat, light (from a laser) is used to release the trapped energy in the form of luminescence. OSL is a novel technique offering a potential for *in vivo* dosimetry in radiotherapy. The integrated dose measured during irradiation can be evaluated using OSL directly afterwards.
- The optical fibre OSL dosimeter consist of a small ($\sim 1 \text{ mm}^3$) chip of carbon-doped aluminium oxide ($\text{Al}_2\text{O}_3:\text{C}$) coupled with a long optical fibre, a laser, a beam-splitter and a collimator, a PM tube, electronics and software. To produce OSL, the chip is excited with a laser light through an optical fibre and the resulting luminescence (blue light) is carried back in the same fibre, reflected through a 90° by the beam-splitter and measured in a PMT.
- The optical fibre dosimeter exhibits high sensitivity over the wide range of dose rates and doses used in radiotherapy. The OSL response is generally linear and independent of energy as well as the dose rate, although the angular response requires correction.
- Various experimental set-ups exist, such as pulsed OSL or OSL used in conjunction with RL (radio-luminescence). RL is emitted promptly at the time of dosimeter irradiation and provides information on the dose rate during irradiation while the OSL provides the integrated dose thereafter. This technique, although not yet used routinely in radiotherapy, may prove to be a valuable tool for *in vivo* dosimetry in the future.

3.6. SEMICONDUCTOR DOSIMETRY

3.6.1. Silicon diode dosimetry systems

- Silicon diode dosimeter is a p-n junction diode. The diodes are produced by taking n-type or p-type silicon and counter-doping the surface to produce the opposite type material. These diodes are referred to as n-Si or p-Si dosimeters, depending upon the base material.
- Both types of diodes are commercially available, but only the p-Si type is suitable for radiotherapy dosimetry, since it is less affected by radiation damage and has a much smaller dark current.
- Radiation produces electron-hole (e-h) pairs in the body of the dosimeter including the depletion layer. The charges (minority carriers) produced in the body of the dosimeter, within the diffusion length, diffuse into the depleted region. They are swept across the depletion region under the action of the electric field due to the intrinsic potential. In this way a current is generated in the reverse direction in the diode.

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- Diodes are used in the short circuit mode, since this mode exhibits a linear relationship between the measured charge and dose. They are usually operated without an external bias to reduce leakage current.
- Diodes are more sensitive and smaller in size compared to typical ionisation chambers. They are relative dosimeters and should not be used for beam calibration, since their sensitivity changes with repeated use due to radiation damage.
- Diodes are particularly useful for measurement in phantoms, *e.g.*, small fields used in stereotactic radiosurgery or high dose gradient areas such as the penumbra region. They are also often used for measurements of depth doses in electron beams. For the use with beam scanning devices in water phantoms, they are packaged in a waterproof encapsulation. When used in electron beam depth dose measurements, diodes measure directly the dose distribution (in contrast to the ionisation measured by ionisation chambers).
- Diodes are widely used in routine *in-vivo* dosimetry on patients or for bladder or rectum dose measurements. Diodes for *in vivo* dosimetry are provided with build-up encapsulation and hence must be appropriately chosen, depending on the type and quality of the clinical beams. The encapsulation also protects the fragile diode from physical damage.
- When diodes are used for *in vivo* dosimetry, they have to be calibrated and several correction factors have to be applied for dose calculation. The sensitivity of diodes depends on their radiation history, so the calibration has to be repeated periodically.
- Diodes show a variation in dose response with temperature (particularly important for long treatments), dependence of signal on the dose rate (care should be taken for different source-skin distances), angular (directional) dependence and energy dependence even for small variation in the spectral composition of radiation beams (important for the measurement of entrance and exit doses).

3.6.2. MOSFET dosimeter

- The Metal-Oxide Semiconductor Field Effect Transistor (MOSFET), a miniature silicon transistor, seems to be a promising candidate for medical dosimetry.
- MOSFETs are small in size even compared to diodes, offering very little attenuation of the beam when used for *in-vivo* dosimetry. They require a special read-out facility.
- A single dosimeter can cover the full energy range of photons and electrons, although the energy response should be examined, since it varies with radiation quality.
- Similarly to diodes, MOSFETs exhibit a temperature dependence. As they show non-linearity of response with total absorbed dose, regular sensitivity checks are

required. MOSFETs are also sensitive to changes in the bias voltage during irradiation (it must be stable) and their response drifts slightly after the irradiation (the reading must be taken in a specified time after exposure). They have a limited life-span.

- MOSFETs have been in use for the past few years in radiotherapy applications, such as surface dose measurements, radiosurgery, *in vivo* dosimetry, and brachytherapy measurements.

3.7. OTHER DOSIMETRY SYSTEMS

3.7.1. Alanine/EPR dosimetry system

- Alanine, one of the amino acids, pressed in the form of rods or pellets with an inert binding material, is typically used for high dose dosimetry. The dosimeter can be used at the level of about 10 Gy or more with sufficient precision for radiotherapy dosimetry.
- The radiation interaction results in the formation of alanine radicals, the concentration of which can be measured using an electron paramagnetic resonance (EPR), known also as electron spin resonance (ESR), spectrometer. The intensity is measured as the peak-to-peak height of the central line in the spectrum. The readout is non-destructive.
- Alanine is tissue-equivalent and it requires no energy correction within the quality range of typical therapeutic beams. It exhibits very little fading for many months after irradiation. The response depends on environmental conditions during irradiation (temperature) and storage (humidity).
- At present, alanine's potential application for radiotherapy is in dosimetry comparisons among hospitals.

3.7.2. Plastic scintillator dosimetry system

- Plastic scintillators are a relatively new development in radiotherapy dosimetry. The light generated in the scintillator during its irradiation is carried away by an optical fibre to a PMT located outside the irradiation room.
- A typical setup requires two sets of optical fibres which are coupled to two different PMTs, allowing subtraction of the background Cerenkov radiation from the measured signal.
- Response of the scintillation dosimeter is linear in the dose range of therapeutic interest.

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- Plastic scintillators are almost water-equivalent in terms of electron density and atomic composition. Typically, they match the water mass stopping power and mass energy absorption coefficient to within $\pm 2\%$ for the range of beam energies in clinical use including the kV region. Scintillators are nearly energy independent and can thus be used directly for relative dose measurements.
- Dosimeter can be made very small (about 1 mm^3 or less) and yet give adequate sensitivity for clinical dosimetry. Hence, it can be used in cases where high spatial resolution is required (*e.g.*, high dose gradient regions, buildup regions, interface regions, small field dosimetry, doses very near to brachytherapy sources, etc.). Due to flat energy dependence and small size, plastic scintillators are ideal dosimeters for brachytherapy applications.
- Dosimetry based on plastic scintillators is characterized with good reproducibility and long term stability. Scintillators suffer no significant radiation damage (up to about 10 kGy) although the light yield should be monitored when used clinically.
- Plastic scintillators are independent of dose rate and can be used from $10 \text{ }\mu\text{Gy}/\text{min}$ (ophthalmic plaque dosimetry) to about $10 \text{ Gy}/\text{min}$ (external beam dosimetry). They have no significant directional dependence and need no ambient temperature or pressure corrections.

3.7.3. Diamond dosimeters

- Diamonds change their resistance upon radiation exposure. When applying a bias voltage, the resulting current is proportional to the dose rate of radiation.
- Commercially-available diamond dosimeters are designed to measure relative dose distributions in high energy photon and electron beams. The dosimeter is based on a natural diamond crystal sealed in polystyrene housing with a bias applied through thin golden contacts.
- Diamonds have a small sensitive volume, on the order of a few mm^3 , which allows the measurement of dose distributions with an excellent spatial resolution.
- Diamond dosimeters are tissue-equivalent and require nearly no energy correction. Thanks to a flat energy response, small physical size and negligible directional dependence diamonds are well suited for the use in high dose gradient regions, *e.g.*, for stereotactic radiosurgery.
- In order to stabilize their dose response, diamonds should be irradiated prior to each use to reduce the polarization effect. They exhibit some dependence of the signal on the dose rate that has to be corrected for when measuring *e.g.* depth doses. Also, they have an insignificant temperature dependence on the order $0.1\% \text{ }^\circ\text{C}^{-1}$ or less.
- High sensitivity and resistance to radiation damage are other important features of the diamond dosimeter. It is waterproof and can be used for measurements in a water phantom.

3.7.4. Gel dosimetry systems

- Gel dosimetry systems are the unique true 3D dosimeters suitable for relative dose measurements. The dosimeter is at the same time a phantom that can measure absorbed dose distribution in a full 3D geometry. Gels are nearly tissue-equivalent and can be shaped to any desirable shape or form.
- Gel dosimetry can be divided in two types:
 - Fricke gels based on the well established Fricke dosimetry and
 - Polymer gels.
- In Fricke gels, Fe^{2+} ions in ferrous sulfate solutions are dispersed throughout gelatine, agarose or PVA matrix. Radiation induced changes are either due to direct absorption of radiation or via intermediate water free radicals. Upon radiation exposure ferrous ions Fe^{2+} are converted into ferric ions Fe^{3+} with a corresponding change in paramagnetic properties that may be measured using Nuclear Magnetic Resonance (NMR) relaxation rates or optical techniques. A 3D image of the dose distribution is created.
- A major limitation of the Fricke gel systems is the continual post-irradiation diffusion of ions resulting in a blurred dose distribution.
- In polymer gel monomers such as acrylamid are dispersed in a gelatine or agarose matrix. Upon radiation exposure, monomers undergo a polymerization reaction resulting in a 3D polymer gel matrix which is a function of absorbed dose that can be evaluated using NMR, x-ray computer tomography, optical tomography, vibrational spectroscopy or ultrasound.
- A number of various polymer gel formulations are available including polyacrylamide gels generally referred as PAG gels (*e.g.*, BANGTM gel) and the new normoxic gels (*e.g.*, MAGIC gel); the latter are not sensitive to the presence of atmospheric oxygen.
- There is a semi-linear relationship between the NMR relaxation rate and the absorbed dose at a point in the gel dosimeter. Hence, by mapping the relaxation rates using an NMR scanner, the dose map can be derived by computation and by proper calibration.
- Due to a large proportion of water, polymer gels are nearly water-equivalent and no energy corrections are required for photon and electron beams used in radiotherapy.
- No significant dose rate effects in polymer gels have been observed using NMR evaluation, although dose response depends on temperature at which the dosimeter is evaluated. The strength of the magnetic field during evaluation may also influence the dose response. Care should be taken of post-irradiation effects such as continual polymerization, gelation and strengthening of the gel matrix that may lead to the image distortion.

- Gel dosimetry is a highly promising relative dosimetry technique that may prove particularly useful for dose verification in complex clinical situations (*e.g.*, intensity modulated radiotherapy), in anatomically shaped phantoms, and for evaluation of doses in brachytherapy, including cardiovascular brachytherapy.

3.8. PRIMARY STANDARDS

Primary standards are instruments of the highest metrological quality that permit determination of the unit of a quantity from its definition, the accuracy of which has been verified by comparison with standards of other institutions of the same level. Primary standards are realized by the Primary Standards Dosimetry Laboratories (PSDLs) in about twenty countries world-wide. Regular international comparisons between the PSDLs, and with the Bureau International des Poids et Mesures (BIPM), ensure international consistency of the dosimetry standards.

Ionisation chambers used in hospitals for calibration of radiation therapy beams must have a calibration traceable (directly or indirectly) to a primary standard. Primary standards are not used for routine calibrations, since they represent the unit for the quantity at all times. Instead, the PSDLs calibrate secondary standard dosimeters for Secondary Standard Dosimetry Laboratories (SSDLs) that in turn are used for calibrating the reference instruments of users, such as therapy level ionisation chambers used at hospitals.

3.8.1. Primary standard for air-kerma in air

- Free-air ionisation chambers are the primary standard for air-kerma in air for superficial and orthovoltage x-rays (up to 300 kV).
- They cannot function as a primary standard for cobalt-60 beams, since the air column surrounding the sensitive volume (for establishing the electronic equilibrium condition in air) would become very long. This would make the chamber very bulky and the various required corrections and their uncertainties would also become problematic.
- At cobalt-60 energy graphite cavity ionisation chambers with accurately known chamber volume are used as the primary standard.
- The use of the graphite cavity chamber is based on the Bragg-Gray cavity theory.

3.8.2. Primary standards for absorbed dose-to-water

The standards for absorbed dose to water enable therapy level ionisation chambers to be calibrated directly in terms of absorbed dose to water instead of air-kerma in air. This simplifies the dose determination procedure at a hospital level and improves the accuracy compared to the air-kerma-based formalism. Standards for absorbed dose to water calibration are now available for cobalt-60 beams in several PSDLs and some have extended their calibration services to high energy photon and electron beams from accelerators.

Ideally, the primary standard for absorbed dose to water should be a water calorimeter that would be an integral part of a water phantom and would measure the dose under reference conditions. However, difficulties in the establishment of this standard have led to the development of primary standard of absorbed dose in various different ways.

At present there are three basic methods used for the determination of absorbed dose to water at the primary standard level. These are: *ionometric method*, *total absorption method* based on chemical dosimetry and *calorimetry*.

3.8.3. Ionometric standard for absorbed dose-to-water

- Graphite cavity ionisation chamber with accurately known active volume, constructed as a close approximation to a Bragg-Gray cavity, is used in a water phantom at a reference depth.
- Absorbed dose to water at the reference point is derived from the cavity theory using the mean specific energy imparted to the air in the cavity and the restricted stopping power ratio of the wall material to the cavity gas.
- BIPM maintains an ionometric standard of absorbed dose to water.

3.8.4. Chemical dosimetry standard for absorbed dose-to-water

- In chemical dosimetry systems the dose is determined by measuring the chemical change produced in the medium (the sensitive volume of the dosimeter) using a suitable measuring system.
- The most widely used chemical dosimetry standard is the Fricke dosimeter.
- The Fricke solution has the following composition: 1 mM FeSO₄ or Fe(NH₄)₂(SO₄)₂ + 0.8 N H₂SO₄ air saturated + 1 mM NaCl.
- Irradiation of Fricke solution oxidizes ferrous ions Fe²⁺ into ferric ions Fe³⁺; the latter exhibit a strong absorption peak at $\lambda = 304$ nm, whereas ferrous ions do not show any absorption at this wavelength.
- Radiation induced ferric ion concentration can be determined using spectrophotometry, which measures the absorbance (in optical density units) of the solution.
- Fricke dosimeter response is expressed in terms of its sensitivity, known as the radiation chemical yield, G-value, and defined as the number of moles of ferric ions produced per joule of the energy absorbed in the solution.
- Chemical dosimetry standard is realized by the calibration of a transfer dosimeter, in a total absorption experiment and the subsequent application of the transfer dosimeter in a water phantom, in reference conditions.

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- The response of the Fricke solution is determined first using the total absorption of an electron beam. An accurate determination of the energy response of the transfer instrument is necessary, *i.e.*, knowing the electron energy, the beam current and the absorbing mass accurately, the total absorbed energy can be determined and related to the change in absorbance of the Fricke solution. Next, the absorbed dose to water at the reference point in a water phantom is obtained using the Fricke dosimeter as the transfer dosimeter.

3.8.5. Calorimetric standard for absorbed dose-to-water

- Calorimetry is the most fundamental method of realizing the primary standard for absorbed dose, since temperature rise is the most direct consequence of energy absorption in a medium.
- Graphite is in general an ideal material for calorimetry, since it is of low atomic number Z and all the absorbed energy reappears as heat, without any loss of heat in other mechanisms (such as the heat defect). The graphite calorimeter is used by several PSDLs to determine the absorbed dose to graphite in a graphite phantom. The conversion to absorbed dose to water at the reference point in a water phantom may be performed by an application of the photon fluence scaling theorem or by measurements based on cavity ionisation theory.
- Graphite calorimeters are electrically calibrated by depositing a known amount of electrical energy into the core.
- Water calorimeters offer a more direct determination of the absorbed dose to water at the reference point in a water phantom. The absorbed dose to water is derived from the measured temperature rise at a point in water relying on an accurate knowledge of the specific heat capacity. No scaling laws are required as is the case in graphite calorimetry. However, there are technical complications related to a heat defect due to water radiolysis and heat transport, which need to be corrected for.
- Water calorimeters are calibrated through the calibration of their thermistors in terms of the absolute temperature difference rather than through the energy depositing as it is the case of graphite calorimeters.

3.9. SUMMARY OF SOME COMMONLY USED DOSIMETRIC SYSTEMS

Radiation dosimeters and dosimetry systems come in many shapes and forms, and they rely on numerous physical effects for storage and readout of the dosimetric signal. The four most commonly used radiation dosimeters are:

- (1) *Ionisation chamber*
- (2) *Radiographic film*
- (3) *Thermoluminescent dosimeter*
- (4) *Diode*

The strengths and weaknesses of the four dosimeters are summarized in Table 3.I.

TABLE 3.I. MAIN ADVANTAGES AND DISADVANTAGES OF FOUR COMMONLY USED DOSIMETRIC SYSTEMS

Dosimeter	Advantages	Disadvantages
<i>Ionisation chamber</i>	Accurate and precise Recommended for beam calibration Necessary corrections well understood Instant readout	Connecting cables required High voltage supply required Many corrections required for high energy dosimetry
Film	2D spatial resolution Very thin - does not perturb the beam	Dark room, processing facilities required Processing difficult to control Variation between films and batches Needs proper calibration against ion chamber measurements Energy dependence problems Cannot be used for beam calibration
<i>TLD</i>	Small in size - point dose measurements possible Many TLDs can be exposed in single exposure Available in various forms Some are reasonably tissue equivalent Not expensive	Signal erased during readout Easy to lose reading No instant readout Accurate results require care Readout and calibration time consuming Not recommended for beam calibration
Diode	Small size High sensitivity Instant readout No external bias voltage Simple instrumentation	Requires connecting cables Variability of calibration with temperature Change in sensitivity with accumulated dose Special care needed to ensure constancy of response Cannot be used for beam calibration

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