

Chapter 3

RADIATION DOSIMETERS

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3.1. INTRODUCTION

A 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 a 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 property that is a function of the measured dosimetric quantity and that 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 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 of deriving 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. The choice of a radiation dosimeter and its reader must therefore be made judiciously, taking into account the requirements of the measurement situation; for example, in radiotherapy ionization 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 the measurement results. The accuracy of dosimetry measurements is the proximity of their expectation value to the 'true value' of the measured quantity. Results of measurements 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), 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, where possible, compensating corrections are introduced.
- After application of all known corrections, the expectation value for errors should be zero and the only quantities of concern are the uncertainties.

3.2.1.1. 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 :

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

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, can be reduced by increasing the number of measurements.

3.2.1.2. Type B standard uncertainties

Type B standard uncertainties u_B cannot be estimated by repeated measurements; rather, they are intelligent guesses or scientific judgements 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 uncertainties 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.

3.2.1.3. Combined and expanded uncertainties

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

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

where M is the reading provided by the dosimetry system and F_i is the correction or conversion coefficient.

- 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:

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

- 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 $U = ku_C$. 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 behaviour depend on the type of dosimeter and its physical characteristics.

Two typical examples of response characteristics of dosimetry systems are shown in Fig. 3.1. Curve A first exhibits linearity with dose, then a supralinear behaviour, and finally saturation. Curve B first exhibits linearity and then saturation at high doses.

In general, a non-linear behaviour 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.

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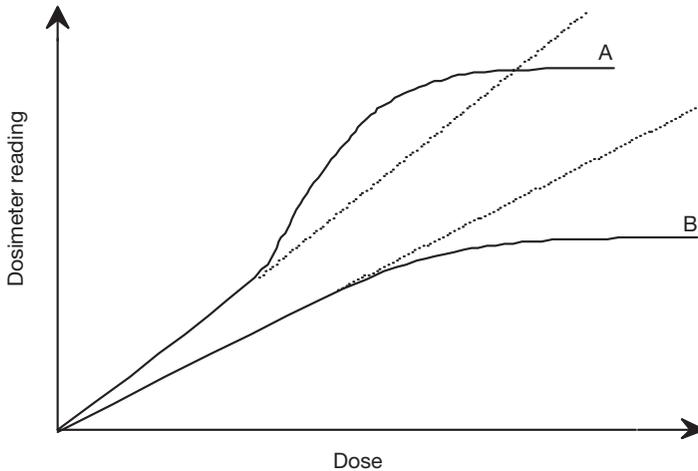


FIG. 3.1. Response characteristics of two dosimetry systems. Curve A first exhibits linearity with dose, then supralinear behaviour and finally saturation. Curve B first exhibits linearity and then saturation at high doses.

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, the dose rate may influence the dosimeter readings and appropriate corrections are necessary, for example recombination corrections for ionization chambers in pulsed beams.

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) requires correction.

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, for example 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

Since 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). The position of the point where the dose is determined (i.e. its spatial location) should be well defined in a reference coordinate system.

Thermoluminescent dosimeters (TLDs) come in very small dimensions and their use, to a great extent, approximates a point measurement. Film dosimeters have excellent 2-D and gels 3-D resolution, where the point measurement is limited only by the resolution of the evaluation system. Ionization chamber type dosimeters, however, are of finite size to give the required sensitivity, although the new type of pinpoint microchambers partially overcomes the problem.

3.2.7. Readout convenience

Direct reading dosimeters (e.g. ionization chambers) are generally more convenient than passive dosimeters (i.e. those that are read after due processing following the exposure, for example TLDs and films). While some dosimeters are inherently of the integrating type (e.g. TLDs and gels), others can measure in both integral and differential modes (ionization chambers).

3.2.8. Convenience of use

Ionization chambers are reusable, with no or little change in sensitivity within their lifespan. Semiconductor dosimeters are reusable, but with a gradual loss of sensitivity within their lifespan; however, some dosimeters are not reusable (e.g. films, gels and alanine). Some dosimeters measure dose distribution in a single exposure (e.g. films and gels) and some dosimeters are

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quite rugged (i.e. handling will not influence sensitivity, for example ionization chambers), while others are sensitive to handling (e.g. TLDs).

3.3. IONIZATION CHAMBER DOSIMETRY SYSTEMS

3.3.1. Chambers and electrometers

Ionization chambers are used in radiotherapy 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). Ionization chambers come in various shapes and sizes, depending upon the specific requirements, but generally they all have the following properties:

- An ionization chamber is basically a gas filled 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 chamber leakage. The guard electrode intercepts the leakage current and allows it to flow to ground, bypassing the collecting electrode. It also ensures improved field uniformity in the active or sensitive volume of the chamber, with resulting advantages in charge collection.
- Measurements with open air ionization chambers require temperature and pressure correction to account for the change in the mass of air in the chamber volume, which changes with the ambient temperature and pressure.

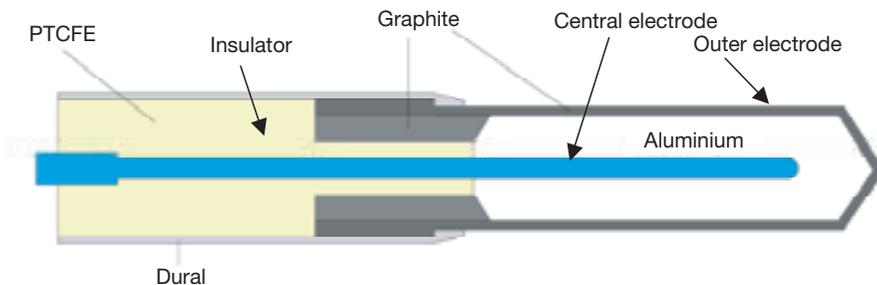


FIG. 3.2. Basic design of a cylindrical Farmer type ionization chamber.

Electrometers are devices for measuring small currents, of the order of 10^{-9} A or less. An electrometer used in conjunction with an ionization 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.

3.3.2. Cylindrical (thimble type) ionization chambers

The most popular cylindrical ionization chamber is the 0.6 cm^3 chamber designed by Farmer and originally manufactured by Baldwin, but now available from several vendors, 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 ionization chamber is shown in Fig. 3.2; ionization chamber based dosimetry systems are discussed in Section 9.2.

Cylindrical chambers are produced by various manufacturers, with active volumes between 0.1 and 1 cm^3 . They typically have an internal length no greater than 25 mm and an internal diameter no greater than 7 mm . The wall material is of low atomic number Z (i.e. tissue or air equivalent), with the thickness less than 0.1 g/cm^2 . A chamber is equipped with a buildup cap with a thickness of about 0.5 g/cm^2 for calibration free in air using ^{60}Co radiation.

The chamber construction should be as homogeneous as possible, although an aluminium central electrode of about 1 mm in diameter is typically

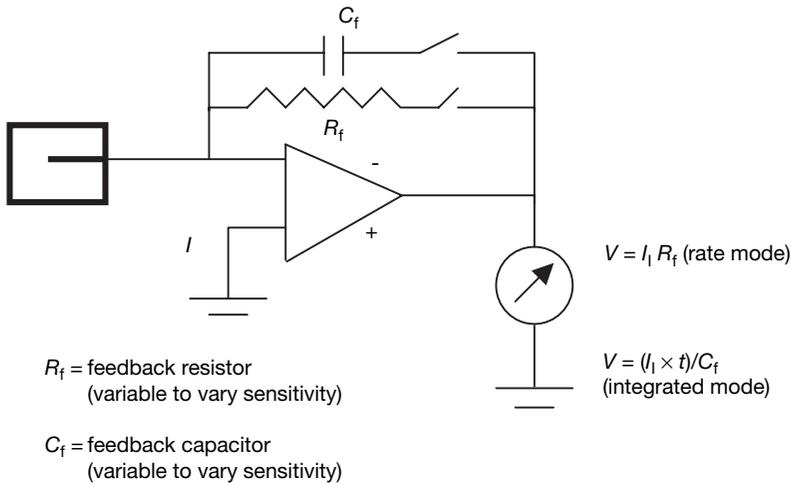


FIG. 3.3. Electrometer in feedback mode of operation.

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used to ensure flat energy dependence. Construction details of various commercially available cylindrical chambers are given in the IAEA Technical Reports Series (TRS) 277 and TRS 398 codes of practice. The use of the cylindrical chamber in electron and photon beam dosimetry is discussed in Chapter 9.

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

A parallel-plate ionization 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 a 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 ionization chamber is shown 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 buildup region of megavoltage photon beams. Dose measurements in the buildup region of photon beams are discussed in Section 6.13. The characteristics of commercially available parallel-plate chambers and the use of these chambers in electron beam dosimetry are explained in detail in the TRS 381 and TRS 398 codes of practice. Some parallel-plate chambers require significant fluence perturbation correction because they are provided with an inadequate guard width.

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.

Well type chambers should be designed to accommodate sources of the typical sizes and shapes that are in clinical use in brachytherapy and are usually calibrated in terms of the reference air kerma rate.

3.3.5. Extrapolation chambers

Extrapolation chambers are parallel-plate chambers with a variable sensitive volume. They are used in the measurement of surface doses in ortho-

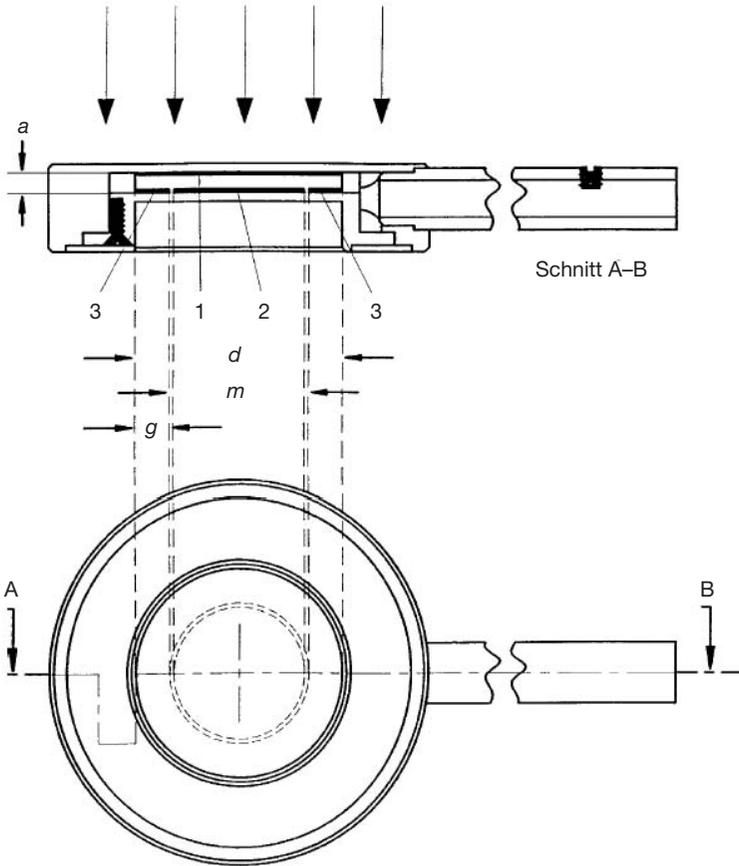


FIG. 3.4. Parallel-plate ionization chamber. 1: the polarizing electrode. 2: the measuring electrode. 3: the guard ring. a : the height (electrode separation) of the air cavity. d : the diameter of the polarizing electrode. m : the diameter of the collecting electrode. g : the width of the guard ring.

voltage and megavoltage X ray beams and in the dosimetry of β 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.

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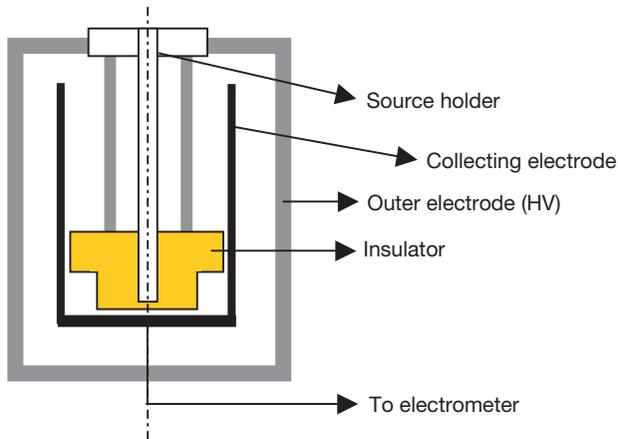


FIG. 3.5. Basic design of a brachytherapy well type chamber.

3.4. FILM DOSIMETRY

3.4.1. Radiographic film

Radiographic X ray film performs several important functions in diagnostic radiology, radiotherapy and radiation protection. It can serve as a radiation detector, a relative dosimeter, a display device and an 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.

- Ionization of AgBr grains, as a result of radiation interaction, forms a latent image in the film. This image only becomes visible (film blackening) and permanent subsequently to processing.
- Light transmission is a function of the film opacity and can be measured in terms of optical density (OD) with devices called densitometers.
- The OD 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 2-D spatial resolution and, in a single exposure, provides information about the spatial distribution of radiation in the area of interest or the attenuation of radiation by intervening objects.

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- The useful dose range of film is limited and the energy dependence is pronounced for lower energy photons. The response of the film depends on several parameters, which are difficult to control. Consistent processing of the film is a particular challenge in this regard.
- Typically, film is used for qualitative dosimetry, but with proper calibration, careful use and analysis film can also be used for dose evaluation.
- Various types of film are available for radiotherapy work (e.g. direct exposure non-screen films for field size verification, phosphor screen films used with simulators and metallic screen films used in portal imaging).
- Unexposed film would exhibit a background OD called the fog density (OD_f). The density due to radiation exposure, called the net OD, can be obtained from the measured density by subtracting the fog density.
- OD readers include film densitometers, laser densitometers and automatic film scanners. 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 this is not always the case. Some emulsions are linear, some are linear over a limited dose range and others are non-linear. The dose versus 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 therefore be established for each film before using it for dosimetry work.

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) a linear portion at

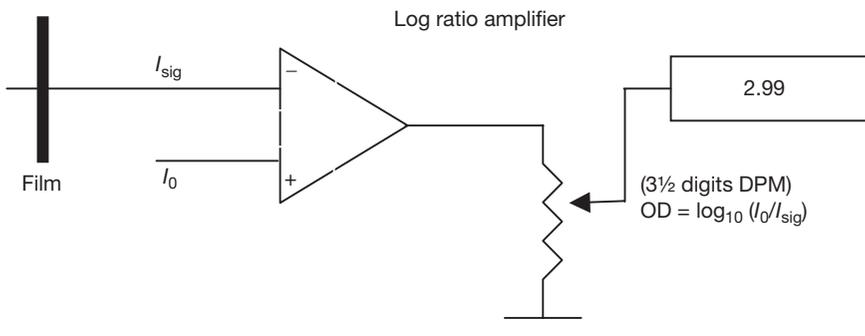


FIG. 3.6. Basic film densitometer.

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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 is 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 ODs.
- The latitude is defined as the range of exposures over which the ODs will lie in the linear region.
- The speed of a film is determined by giving the exposure required to produce an OD 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 and the determination of the position of a collimator axis, the so called star

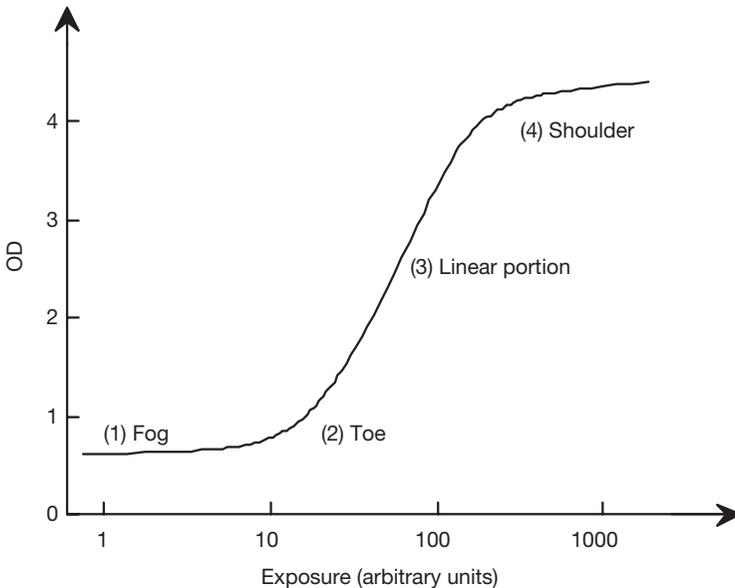


FIG. 3.7. Typical sensitometric (characteristic H&D) curve for a radiographic film.

test), verification of treatment techniques in various phantoms and portal imaging.

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 colourless film with a nearly tissue equivalent composition (9.0% hydrogen, 60.6% carbon, 11.2% nitrogen and 19.2% oxygen) that develops a blue colour upon radiation exposure.

Radiochromic film contains a special dye that is 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, requiring neither developer nor fixer. Since radiochromic film is grainless, it has a very high resolution and can be used in high dose gradient regions for dosimetry (e.g. measurements of dose distributions in stereotactic fields and in the vicinity of brachytherapy sources).

Dosimetry with radiochromic films has a few advantages over radiographic films, such as ease of use; elimination of the need for darkroom facilities, film cassettes or film processing; dose rate independence; better energy characteristics (except for low energy X rays of 25 kV or less); and insensitivity to ambient conditions (although excessive humidity should be avoided). Radiochromic 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. If proper care is taken with calibration and the environmental conditions, a precision better than 3% is achievable.
- Data on the various characteristics of radiochromic films (e.g. sensitivity, linearity, uniformity, reproducibility and post-irradiation stability) 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 luminescence. Two types of luminescence, fluorescence and phosphorescence, are known, which depend on the time delay between stimulation and the emission of light. Fluorescence occurs with a time delay of between 10^{-10} and 10^{-8} s;

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phosphorescence occurs with a time delay exceeding 10^{-8} s. 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 material, or a TLD when used for purposes of dosimetry.
- If the exciting agent is light, the phenomenon is referred to as optically stimulated luminescence (OSL).

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 trap are known in general: storage traps and recombination centres.

- A storage trap merely traps free charge carriers and releases them during the subsequent (a) heating, resulting in the thermoluminescence process, or (b) 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 centre (luminescence centre). 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 (PMTs).

3.5.1. Thermoluminescence

Thermoluminescence is thermally activated phosphorescence; it is the most spectacular and widely known of a number of different ionizing radiation induced thermally activated phenomena. Its practical applications range from archaeological pottery dating to radiation dosimetry. In 1968 Cameron, Suntharalingam and Kenney published a book on the thermoluminescence process that is still considered an excellent treatise on the practical aspects of the thermoluminescence phenomenon. A useful phenomenological model of the thermoluminescence mechanism is provided in terms of the band model for

solids. The storage traps and recombination centres, 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 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:

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

3.5.2. Thermoluminescent dosimeter systems

The TLDs 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 and ribbons).
- Before they are used, TLDs need to be annealed to erase the residual signal. Well established and reproducible annealing cycles, including the heating and cooling rates, should be used.

A basic TLD reader system consists of a planchet for placing and heating the TLD, a PMT to detect the thermoluminescence light emission and convert it into an electrical signal linearly proportional to the detected photon fluence and an electrometer for recording the PMT signal as a charge or current. A basic schematic diagram of a TLD reader is shown in Fig. 3.8.

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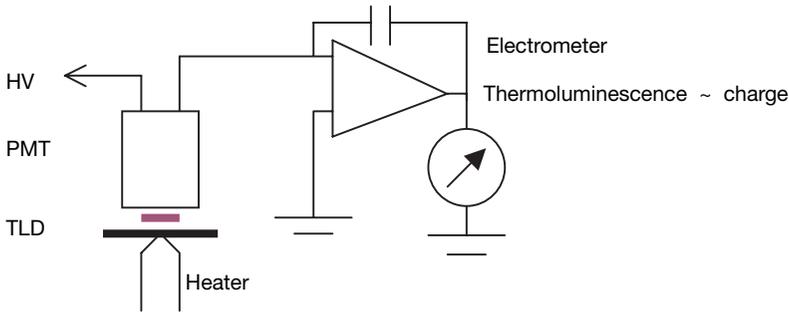


FIG. 3.8. TLD reader.

- The thermoluminescence 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 thermoluminescence 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. In general, if the emitted light is plotted against the crystal temperature one obtains a thermoluminescence thermogram (Fig. 3.9).
- The peaks in the glow curve may be correlated with trap depths responsible for thermoluminescence emission.
- The main dosimetric peak of the LiF:Mg,Ti glow curve between 180°C and 260°C is used for dosimetry. The peak temperature is high enough so as not to be affected by room temperature and still low enough so as not to interfere with black body emission from the heating planchet.
- The total thermoluminescence 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.
- The thermoluminescence 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 per cent in the months after irradiation.
- The thermoluminescence dose response is linear over a wide range of doses used in radiotherapy, although it increases in the higher dose region, exhibiting supralinear behaviour before it saturates at even higher doses.

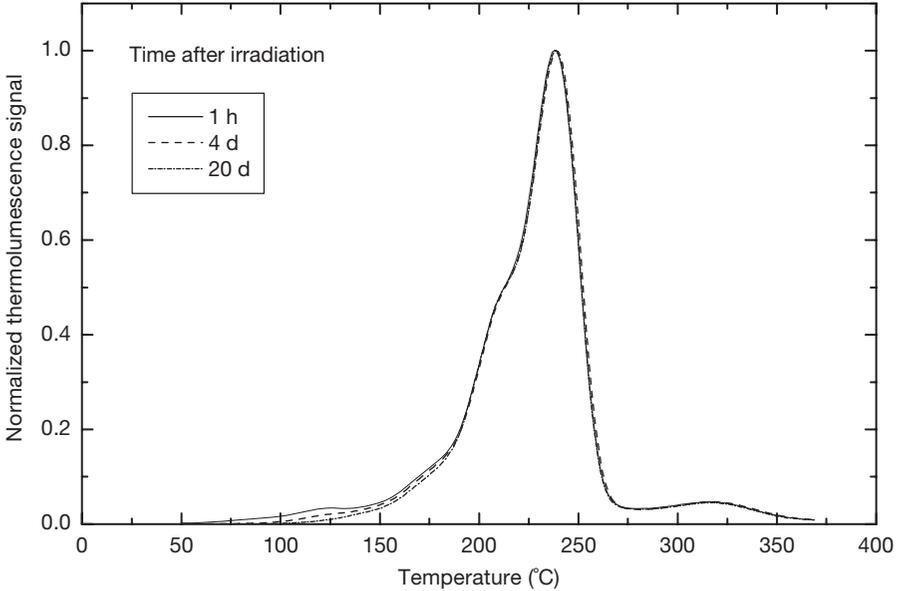


FIG. 3.9. A typical thermogram (glow curve) of LiF:Mg,Ti measured with a TLD reader at a low heating rate.

- TLDs need to be calibrated before they are used (thus they serve as relative dosimeters). To derive the absorbed dose from the thermoluminescence reading a few correction factors have to be applied, such as those for energy, fading and dose response non-linearity.
- Typical applications of TLDs in radiotherapy are: in vivo dosimetry on patients (either as a routine quality assurance procedure or for dose monitoring in special cases, for example complicated geometries, dose to critical organs, total body irradiation (TBI), brachytherapy); verification of treatment techniques in various phantoms (e.g. anthropomorphic phantoms); dosimetry audits (such as the IAEA–World Health Organization (WHO) TLD postal dose audit programme); and comparisons among hospitals.

3.5.3. Optically stimulated luminescence systems

OSL is based on a principle similar to that of thermoluminescence dosimetry. 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

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potential for in vivo dosimetry in radiotherapy. The integrated dose measured during irradiation can be evaluated using OSL directly afterwards.

The optical fibre optically stimulated thermoluminescent dosimeter consists 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 PMT, electronics and software. To produce OSL, the chip is excited with laser light through an optical fibre, and the resulting luminescence (blue light) is carried back in the same fibre, reflected through 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 radioluminescence. Radioluminescence is emitted promptly at the time of dosimeter irradiation and provides information on the dose rate during irradiation, while 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

A 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 diode 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 charge 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 than typical ionization 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, for example of 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 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 ionization measured by ionization 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 buildup 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.
- Diodes need to be calibrated when they are used for in vivo dosimetry, and several correction factors have to be applied for dose calculation. The sensitivity of diodes depends on their radiation history, and hence the calibration has to be repeated periodically.
- Diodes show a variation in dose response with temperature (this is particularly important for long radiotherapy treatments), dependence of signal on the dose rate (care should be taken for different source to skin distances), angular (directional) dependence and energy dependence even for small variations in the spectral composition of radiation beams (important for the measurement of entrance and exit doses).

3.6.2. MOSFET dosimetry systems

A metal-oxide semiconductor field effect transistor (MOSFET), a miniature silicon transistor, possesses excellent spatial resolution and offers very little attenuation of the beam due to its small size, which is particularly useful for in vivo dosimetry. MOSFET dosimeters are based on the measurement of the threshold voltage, which is a linear function of absorbed dose. Ionizing radiation penetrating the oxide generates charge that is permanently trapped, thus causing a change in threshold voltage. The integrated dose may be measured during or after irradiation. MOSFETs

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require a connection to a bias voltage during irradiation. They have a limited lifespan.

- A single MOSFET dosimeter can cover the full energy range of photons and electrons, although the energy response should be examined, since it varies with radiation quality. For megavoltage beams, however, MOSFETs do not require energy correction, and a single calibration factor can be used.
- MOSFETs exhibit small axial anisotropy ($\pm 2\%$ for 360°) and do not require dose rate corrections.
- Similarly to diodes, single MOSFETs exhibit a temperature dependence, but this effect has been overcome by specially designed double detector MOSFET systems. In general, they show non-linearity of response with the total absorbed dose; however, during their specified lifespan, MOSFETs retain adequate linearity. 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).
- MOSFETs have been in use for the past few years in a variety of radiotherapy applications for in vivo and phantom dose measurements, including routine patient dose verification, brachytherapy, TBI, intensity modulated radiotherapy (IMRT), intraoperative radiotherapy and radio-surgery. They are used with or without additional buildup, depending on the application.

3.7. OTHER DOSIMETRY SYSTEMS

3.7.1. Alanine/electron paramagnetic resonance 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 a 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 (known also as electron spin resonance) 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 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 set-up requires two sets of optical fibres, which are coupled to two different PMTs, allowing subtraction of the background Cerenkov radiation from the measured signal. The response of the scintillation dosimeter is linear in the dose range of therapeutic interest.

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 kilovoltage region. Scintillators are nearly energy independent and can thus be used directly for relative dose measurements.

- Plastic scintillation dosimeters can be made very small (about 1 mm^3 or less) and yet give adequate sensitivity for clinical dosimetry. Hence they can be used in cases where high spatial resolution is required (e.g. high dose gradient regions, buildup regions, interface regions, small field dosimetry and doses very close to brachytherapy sources). Due to flat energy dependence and small size, plastic scintillators are ideal dosimeters for brachytherapy applications.
- Dosimetry based on plastic scintillators is characterized by 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 $10 \mu\text{Gy}/\text{min}$ (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

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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 a polystyrene housing with a bias applied through thin golden contacts.

- Diamonds have a small sensitive volume, of the order of a few cubic millimetres, which allows the measurement of dose distributions with an excellent spatial resolution.
- Diamond dosimeters are tissue equivalent and require nearly no energy correction. Owing to their flat energy response, small physical size and negligible directional dependence, diamonds are well suited for use in high dose gradient regions, for example 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, which has to be corrected for when measuring a given physical quantity (e.g. depth dose). Also, they have an insignificant temperature dependence, of the order of 0.1%/°C or less.
- High sensitivity and resistance to radiation damage are other important features of diamond dosimeters. They are waterproof and can be used for measurements in a water phantom.

3.7.4. Gel dosimetry systems

Gel dosimetry systems are the only true 3-D dosimeters suitable for relative dose measurements. The dosimeter is at the same time a phantom that can measure absorbed dose distribution in a full 3-D geometry. Gels are nearly tissue equivalent and can be moulded to any desired shape or form.

Gel dosimetry can be divided into two types:

- Fricke gels based on the well established Fricke dosimetry;
- Polymer gels.

In Fricke gels, Fe^{2+} ions in ferrous sulphate solutions are dispersed throughout gelatin, 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 3-D image of the dose distribution is created. A major limitation of Fricke gel systems is the continual post-irradiation diffusion of ions, resulting in a blurred dose distribution.

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In polymer gel, monomers such as acrylamid are dispersed in a gelatin or agarose matrix. Upon radiation exposure, monomers undergo a polymerization reaction, resulting in a 3-D polymer gel matrix that is a function of absorbed dose that can be evaluated using NMR, X ray computed tomography (CT), optical tomography, vibrational spectroscopy or ultrasound.

- A number of polymer gel formulations are available, including polyacrylamide gels, generally referred to as PAG gels (e.g. BANG gel), and the new normoxic gels (e.g. MAGIC gel); the latter are not sensitive to the presence of atmospheric oxygen.
- There is a semilinear 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 the 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 the 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, which may lead to 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. IMRT), 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 20 countries worldwide. Regular international comparisons between the PSDLs, and with the Bureau international des poids et mesures (BIPM), ensure international consistency of the dosimetry standards.

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Ionization chambers used in hospitals for calibration of radiotherapy 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 standards dosimetry laboratories (SSDLs) that in turn are used for calibrating the reference instruments of users, such as therapy level ionization chambers used in hospitals.

3.8.1. Primary standard for air kerma in air

Free-air ionization 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 ^{60}Co 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 become problematic.

- At ^{60}Co energy, graphite cavity ionization chambers with an 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 ionization 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 the hospital level and improves the accuracy compared with the air kerma based formalism. Standards for absorbed dose to water calibration are now available for ^{60}Co beams in several PSDLs, some of which 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 a 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: (1) the ionometric method; (2) the total absorption method based on chemical dosimetry; and

(3) calorimetry. The three methods are discussed below and in more detail in Chapter 9.

3.8.3. Ionometric standard for absorbed dose to water

A graphite cavity ionization chamber with an 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. The 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: 1mM FeSO_4 or $\text{Fe}(\text{NH}_4)_2(\text{SO}_4)_2 + 0.8\text{N H}_2\text{SO}_4$ air saturated + 1mM NaCl.
- Irradiation of a Fricke solution oxidizes ferrous ions Fe^{2+} into ferric ions Fe^{3+} ; the latter exhibit a strong absorption peak at $\lambda = 304 \text{ nm}$, 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 OD units) of the solution.
- The 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.
- The 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.
- 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

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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 ionization 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 in the case of graphite calorimetry; however, there are corrections that need to be introduced to compensate for technical complications related to a heat defect due to water radiolysis and heat transport.
- Water calorimeters are calibrated through the calibration of their thermistors in terms of the absolute temperature difference rather than through energy deposition, as is the case for 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:

- Ionization chambers;
- Radiographic films;

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- TLDs;
- Diodes.

The strengths and weaknesses of these four dosimeters are summarized in Table 3.1.

TABLE 3.1. MAIN ADVANTAGES AND DISADVANTAGES OF THE FOUR COMMONLY USED DOSIMETRIC SYSTEMS

	Advantage	Disadvantage
Ionization chamber	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 beam dosimetry
Film	2-D spatial resolution Very thin: does not perturb the beam	Darkroom and processing facilities required Processing difficult to control Variation between films and batches Needs proper calibration against ionization chamber measurements Energy dependence problems Cannot be used for beam calibration
TLD	Small in size: point dose measurements possible Many TLDs can be exposed in a 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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