Chapter 4

RADIATION MONITORING INSTRUMENTS

G. RAJAN
Medical Physics and Safety Section,
Bhabha Atomic Research Centre,
Mumbai, Maharashtra, India

J. IZEWSKA
Division of Human Health,
International Atomic Energy Agency,
Vienna

4.1. INTRODUCTION

Radiation exposure to humans can be broadly classified as internal and external exposure. Sealed sources, which are unlikely to cause internal exposure, are used almost exclusively in radiotherapy. This chapter deals with the monitoring of external exposures.

- External exposure monitoring refers to measuring:
  - Radiation levels in and around work areas;
  - Radiation levels around radiotherapy equipment or source containers;
  - Equivalent doses received by individuals working with radiation.
- Radiation monitoring is carried out:
  - To assess workplace conditions and individual exposures;
  - To ensure acceptably safe and satisfactory radiological conditions in the workplace;
  - To keep records of monitoring, over a long period of time, for the purposes of regulation or good practice.
- Radiation monitoring instruments are used both for area monitoring and for individual monitoring. The instruments used for measuring radiation levels are referred to as area survey meters (or area monitors) and the instruments used for recording the equivalent doses received by individuals working with radiation are referred to as personal dosimeters (or individual dosimeters). All instruments must be calibrated in terms of the appropriate quantities used in radiation protection.

4.2. OPERATIONAL QUANTITIES FOR RADIATION MONITORING

Recommendations regarding dosimetric quantities and units in radiation protection dosimetry are set forth by the International Commission on Radiation Units and Measurements (ICRU). The recommendations on the practical application of these quantities in radiation protection are established by the International Commission on Radiological Protection (ICRP).

The operational quantities are defined for practical measurements both for area and individual monitoring. In radiation protection radiation is characterized as either weakly or strongly penetrating, depending on which dose equivalent is closer to its limiting value. In practice, the term 'weakly penetrating' radiation usually applies to photons below 15 keV and to β radiation.

For the purpose of area monitoring, the ambient dose equivalent $H^*(d)$ and directional dose equivalent $H'(d,\Omega)$ are defined. They link the external radiation field to the effective dose equivalent in the ICRU sphere phantom (see Chapter 16), at depth d, on a radius in a specified direction Ω.

- For strongly penetrating radiation the depth d = 10 mm is used; the ambient dose equivalent is denoted as $H^*(10)$ and the directional dose equivalent as $H'(10,\Omega)$.
- For weakly penetrating radiation the ambient and directional dose equivalents in the skin at d = 0.07 mm, $H^*(0.07)$ and $H'(0.07,\Omega)$, are relevant, and in the lens of the eye at d = 3 mm, $H^*(3)$ and $H'(3,\Omega)$, are relevant.

For individual monitoring the personal dose equivalent $H_p(d)$ is defined, which is the dose equivalent in soft tissue below a specified point on the body at depth d (see also Chapter 16).

- For strongly penetrating radiation the depth d = 10 mm is used and the personal dose equivalent is denoted as $H_p(10)$.
- For weakly penetrating radiation the personal dose equivalent in the skin at d = 0.07 mm, $H_p(0.07)$, and in the lens of the eye at d = 3 mm, $H_p(3)$, are used.
- $H_p(d)$ can be measured with a dosimeter that is worn at the surface of the body and covered with an appropriate layer of tissue equivalent material.

4.3. AREA SURVEY METERS

Radiation instruments used as survey monitors are either gas filled detectors or solid state detectors (e.g. scintillator or semiconductor detectors). A gas filled detector is usually cylindrical in shape, with an outer wall and a central electrode well insulated from each other. The wall is usually made of tissue equivalent material for ionization chamber detectors and of brass or copper for other types of detector.

Depending upon the design of the gas filled detector and the voltage applied between the two electrodes, the detector can operate in one of three regions, shown in Fig. 4.1 (i.e. the ionization region B, proportional region C or Geiger–Müller (GM) region E). Regions of recombination and of limited proportionality in the 'signal versus applied voltage' plot (regions A and D, respectively, in Fig. 4.1) are not used for survey meters.

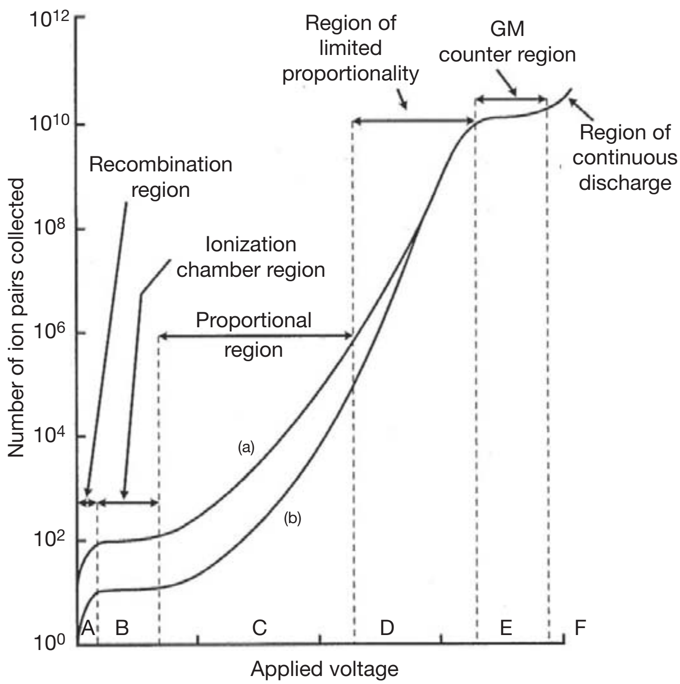

FIG. 4.1. Various regions of operation of a gas filled detector. Region A represents the recombination region, region B the ionization region, region C the proportionality region, region D the region of limited proportionality and region E the GM region. Curve (a) is for 1 MeV β particles, curve (b) for 100 keV β particles.

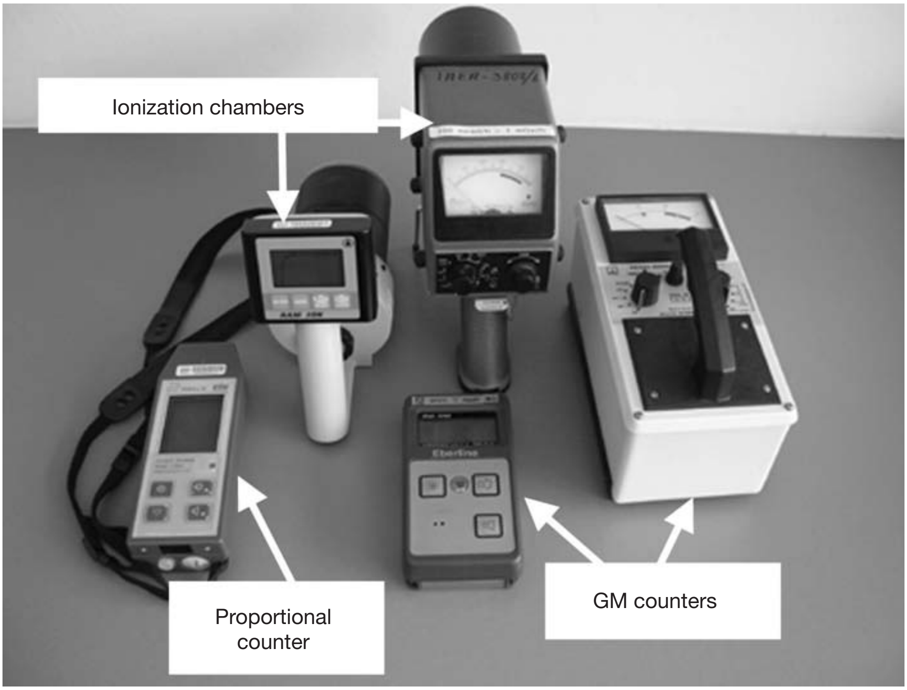

FIG. 4.2. Area survey meters commonly used for radiation protection level measurements: ionization chambers, a proportional counter and GM counters.

- Survey meters come in different shapes and sizes, depending upon the specific application (see Fig. 4.2).
- The gas is usually a non-electronegative gas in order to avoid negative ion formation by electron attachment, which would increase the collection time in the detector, thus limiting the dose rate that can be monitored. The increase in charge collection time results from the relatively slow mobility of ions, which is about three orders of magnitude smaller than that of electrons. Noble gases are generally used in these detectors.
- β–γ survey meters have a thin end window to register weakly penetrating radiation. The γ efficiency of these detectors is only a few per cent (as determined by the wall absorption), while the β response is near 100% for β particles entering the detector.
- Owing to their high sensitivity, the tubes of GM based γ monitors are smaller in size than ionization chamber type detectors.

- Depending upon the electronics used, detectors can operate in a 'pulse' mode or in the 'mean level' or current mode. Proportional and GM counters are normally operated in the pulse mode.
- Owing to the finite resolving time (the time required by the detector to regain its normal state after registering a pulse), these detectors will saturate at high intensity radiation fields. Ionization chambers operating in the current mode are more suitable for higher dose rate measurements.

4.3.1. Ionization chambers

In the ionization region the number of primary ions of either sign collected is proportional to the energy deposited by the charged particle tracks in the detector volume. Owing to the linear energy transfer (LET) differences, the particle discrimination function can be used (see Fig. 4.1). Buildup caps are required to improve detection efficiency when measuring high energy photon radiation, but they should be removed when measuring lower energy photons (10–100 keV) and β particles.

4.3.2. Proportional counters

In the proportional region there is an amplification of the primary ion signal due to ionization by collision between ions and gas molecules (charge multiplication). This occurs when, between successive collisions, the primary ions gain sufficient energy in the neighbourhood of the thin central electrode to cause further ionization in the detector. The amplification is about 10^3–10^4-fold.

Proportional counters are more sensitive than ionization chambers and are suitable for measurements in low intensity radiation fields. The amount of charge collected from each interaction is proportional to the amount of energy deposited in the gas of the counter by the interaction.

4.3.3. Neutron area survey meters

Neutron area survey meters operate in the proportional region so that the photon background can be easily discriminated against.

- Thermal neutron detectors usually have a coating of a boron compound on the inside of the wall, or the counter is filled with BF_3 gas.
- A thermal neutron interacts with a ^{10}B nucleus causing an (n, α) reaction, and the α particles can easily be detected by their ionizing interactions.
- To detect fast neutrons the same counter is surrounded by a moderator made of hydrogenous material (Fig. 4.3); the whole assembly is then a fast

FIG. 4.3. Neutron dose equivalent rate meter with a thermalizing polyethylene sphere with a diameter of 20 cm.

neutron counter. The fast neutrons interacting with the moderator are thermalized and are subsequently detected by a BF_3 counter placed inside the moderator.

- Filter compensation is applied to reduce thermal range over-response so that the response follows the ICRP radiation weighting factors w_R (see Chapter 16). The output is approximately proportional to the dose equivalent in soft tissue over a wide range (10 decades) of neutron energy spectra.
- Other neutron detectors (e.g. those based on ^{3}He) also function on the same principles.

4.3.4. Geiger–Müller counters

The discharge spreads in the GM region throughout the volume of the detector and the pulse height becomes independent of the primary ionization or the energy of the interacting particles. In a GM counter detector the gas multiplication spreads along the entire length of the anode. Gas filled detectors cannot be operated at voltages beyond the GM region because they continuously discharge.

Owing to the large charge amplification (nine to ten orders of magnitude), GM survey meters are widely used at very low radiation levels (e.g. in areas of public occupancy around radiotherapy treatment rooms). They are particularly applicable for leak testing and detection of radioactive contamination.

GM counters exhibit strong energy dependence at low photon energies and are not suitable for use in pulsed radiation fields. They are considered indicators of radiation, whereas ionization chambers are used for more precise measurements.

GM detectors suffer from very long dead times, ranging from tens to hundreds of milliseconds. For this reason, GM counters are not used when accurate measurements are required of count rates of more than a few hundred counts per second. A portable GM survey meter may become paralysed in a very high radiation field and yield a zero reading. Ionization chambers should therefore be used in areas where radiation rates are high.

4.3.5. Scintillator detectors

Detectors based on scintillation (light emission) are known as scintillation detectors and belong to the class of solid state detectors. Certain organic and inorganic crystals contain activator atoms, emit scintillations upon absorption of radiation and are referred to as phosphors. High atomic number phosphors are mostly used for the measurement of γ rays, while plastic scintillators are mostly used with β particles.

- Scintillating phosphors include solid organic materials such as anthracene, stilbene and plastic scintillators as well as thallium activated inorganic phosphors such as NaI(Tl) or CsI(Tl).
- A photomultiplier tube (PMT) is optically coupled to the scintillator to convert the light pulse into an electric pulse. Some survey meters use photodiodes in place of PMTs.

4.3.6. Semiconductor detectors

Bulk conductivity detectors are formed from intrinsic semiconductors of very high bulk resistivity (e.g. CdS or CdSe). They act like solid state ionization chambers on exposure to radiation and, like scintillation detectors, belong to the class of solid state detectors.

Extrinsic (i.e. doped with trace quantities of impurities such as phosphorus or lithium) semiconductors such as silicon or germanium are used to form junction detectors. They too act as solid state ionization chambers on application of a reverse bias to the detectors and on exposure to radiation.

The sensitivity of solid state detectors is about 10^4 times higher than that of gas filled detectors, owing to the lower average energy required to produce an ion pair in solid detector materials compared with air (typically one order of magnitude lower) and the higher density of the solid detector materials compared with air (typically three orders of magnitude higher). These properties facilitate the miniaturization of solid state radiation monitoring instruments.

4.3.7. Commonly available features of area survey meters

The commonly available features of area survey meters are:

- A 'low battery' visual indication;
- Automatic zeroing, automatic ranging and automatic back-illumination facilities;
- A variable response time and memory to store the data;
- The option of both 'rate' and 'integrate' modes of operation;
- An analog or digital display, marked in conventional (exposure/air kerma) or 'ambient dose equivalent' or 'personal dose equivalent' units;
- An audio indication of radiation levels (through the 'chirp' rate);
- A resettable/non-resettable alarm facility with adjustable alarm levels;
- A visual indication of radiation with flashing LEDs;
- Remote operation and display of readings.

4.3.8. Calibration of survey meters

Protection level area survey meters must be calibrated against a reference instrument that is traceable (directly or indirectly) to a national standards laboratory.

A reference instrument for γ radiation is generally an ionization chamber (Fig. 4.4) with a measuring assembly. Reference instruments do not indicate directly the dose equivalent H required for calibration of radiation protection monitoring instruments. Rather, they measure basic radiation quantities such as the air kerma in air for photon radiation, and the dose equivalent H is then determined by using appropriate conversion coefficients h:

$$H = hN_R M_R \tag{4.1}$$

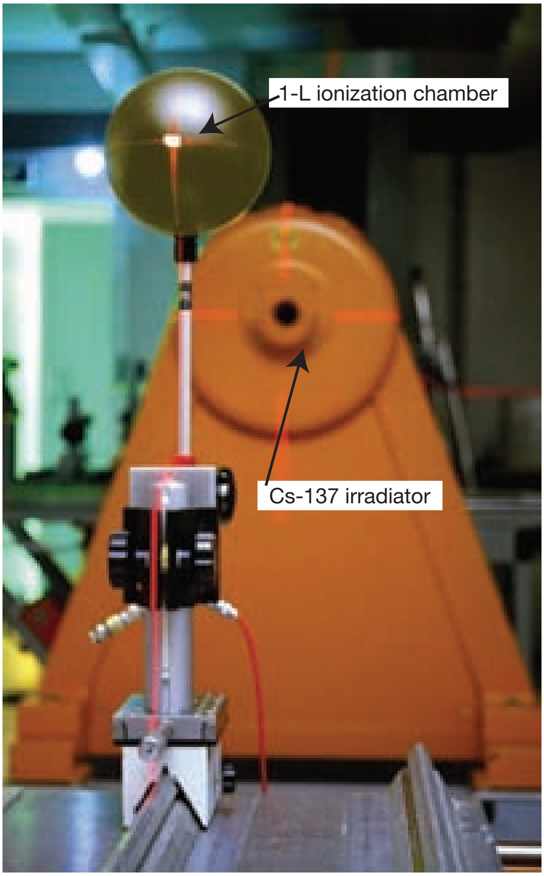

FIG. 4.4. Reference ionization chamber used for the calibration of area survey meters in a ^{137}Cs γ beam.

where

N_R is the calibration factor (e.g. in terms of air kerma in air or air kerma rate in air) of the reference chamber under reference conditions;

M_R is the reading of the reference instrument corrected for influence quantities.

A reference instrument is calibrated free in air for the range of reference radiation qualities (defined by the International Organization for Standardization (ISO)). The same reference qualities should be used for the calibration of radiation protection monitoring instruments.

Typically, calibration of survey meters in terms of the ambient dose equivalent $H^*(10)$ involves three steps:

- The air kerma in air is measured in a reference field, using a reference standard.
- The values of the conversion coefficient:

  $$h_{H^*} = [H^*(10)/(K_{\text{air}})_{\text{air}}]$$

  are theoretically available. Using these data for the calibration beam quality, a reference instrument reading can be converted to $H^*(10)$.
- The survey monitor being calibrated is then placed at the calibration point and its reading M is determined. The calibration factor in terms of the ambient dose equivalent N_{H^*} for the survey monitor is determined from the equation $N_{H^*} = H^*(10)/M$.

4.3.9. Properties of survey meters

4.3.9.1. Sensitivity

The sensitivity S is defined as the inverse of the calibration coefficient N. Using decade resistances, larger detector volumes or detector gases under higher pressures, a wide range of equivalent dose rates can be covered with ionization chamber based survey meters (e.g. 1 μSv/h–1 Sv/h).

Owing to finite resolving time, GM based systems would saturate beyond a few thousand counts per second. Low dead time counters or dead time correction circuits enable these detectors to operate at higher intensity radiation fields.

Scintillation based systems are more sensitive than GM counters because of higher γ conversion efficiency and dynode amplification. Scintillation based systems are generally used for surveys at very low radiation levels (e.g. contamination monitoring and lost source detection surveys). However, they can also be used at higher radiation levels, since their resolving time is quite low (a few microseconds or lower) compared with GM counters.

4.3.9.2. Energy dependence

Survey meters are calibrated at one or more beam qualities, but are often used in situations in which the radiation field is complex or unknown. These survey meters should hence have a low energy dependence over a wide energy range.

In the past, survey meters were designed to exhibit a flat energy response that follows exposure or air kerma in air.

For measuring the equivalent dose:

$$N_{H*} = [H*(10)/M] = [H*(10)/(K_{\text{air}})_{\text{air}}]/[(K_{\text{air}})_{\text{air}}/\text{M}]$$

a meter's response with energy should vary as the quantity:

$$[H*(10)/(K_{\text{air}})_{\text{air}}]$$

GM counters exhibit strong energy dependence for low energy photons (<80 keV).

4.3.9.3. Directional dependence

By rotating the survey monitor about its vertical axis, the directional response of the instrument can be studied. A survey monitor usually exhibits isotropic response, as required for measuring ambient dose equivalent, within ±60° to ±80° with respect to the reference direction of calibration, and typically has a much better response for higher photon energies (>80 keV).

4.3.9.4. Dose equivalent range

Survey meters may cover a range from nSv/h to Sv/h, but the typical range in use is μSv/h to mSv/h.

4.3.9.5. Response time

The response time of the survey monitor is defined as the RC time constant of the measuring circuit, where R is the decade resistor used and C the capacitance of the circuit.

Low dose equivalent ranges would have high R and hence high RC values, and so the indicator movement would be sluggish. It takes at least three to five time constants for the monitor reading to stabilize.

4.3.9.6. Overload characteristics

Survey meters must be subjected to dose rates of about ten times the maximum scale range to ensure that they read full scale rather than near zero on saturation.

Some survey meters, especially the older models, may read zero on overload (i.e. when the equivalent dose rate exceeds the scale range). Such survey meters should not be used for monitoring, since the worker may wrongly assume that there is no radiation in an area where the radiation field is actually very high.

GM survey meters are not suitable for use in pulsed fields, due to the possible overload effect, and ionization chamber based survey meters should be used instead.

4.3.9.7. Long term stability

Survey meters must be calibrated in a standards dosimetry laboratory with the frequency prescribed by the regulatory requirements of the country, typically once every three years; they also need calibration immediately after repair or immediately upon detection of any sudden change in response.

The long term stability of survey meters must be checked at regular intervals using a long half-life source in a reproducible geometry.

4.3.9.8. Discrimination between different types of radiation

End window GM counters have a removable buildup cap to discriminate β from γ rays. For β measurements the end cap must be removed to allow β particles to enter the sensitive volume.

4.3.9.9. Uncertainties in area survey measurements

The standards laboratory provides, along with the survey monitor calibration, the uncertainty associated with the calibration factor. Subsequent measurements at the user department provide a type A uncertainty. The uncertainties due to energy dependence and angular dependence of the detector, and the variation in the user field conditions compared with calibration conditions, contribute to type B uncertainties. These two types of uncertainty are added in quadrature to obtain the combined uncertainty associated with the survey meter measurements.

The combined uncertainty is multiplied by the coverage factor $k = 2$ or $k = 3$ to correspond to the confidence limits of 95% or 99%, respectively. The uncertainty of measurements with area monitors is typically within ±30% under standard laboratory conditions.

4.4. INDIVIDUAL MONITORING

Individual monitoring is the measurement of the radiation doses received by individuals working with radiation. Individuals who regularly work in controlled areas or those who work full time in supervised areas (see Chapter 16 for the definitions) should wear personal dosimeters to have their doses monitored on a regular basis. Individual monitoring is also used to verify the effectiveness of radiation control practices in the workplace. It is useful for detecting changes in radiation levels in the workplace and to provide information in the event of accidental exposures.

- The most widely used individual monitoring systems are based on thermoluminescence or film dosimetry, although other techniques, such as radiophotoluminescence (RPL) and optically stimulated luminescence (OSL), are in use in some countries. Albedo dosimeters and nuclear track emulsions are used for monitoring fast neutron doses.
- Self-reading pocket dosimeters and electronic personal dosimeters (EPDs) are direct reading dosimeters and show both the instantaneous dose rate and the accumulated dose at any point in time.

As explained in Section 4.2, the operational quantity for the individual monitoring of external exposure is the personal dose equivalent $H_p(d)$ with the recommended depth d = 10 mm for strongly penetrating radiation and d = 0.07 mm for weakly penetrating radiation. Personal dosimeters are calibrated in these quantities.

4.4.1. Film badge

A special emulsion photographic film in a light-tight wrapper enclosed in a case or holder with windows, with appropriate filters, is known as a film badge (Fig. 4.5). The badge holder creates a distinctive pattern on the film indicating the type and energy of the radiation received. While one filter is adequate for photons of energy above 100 keV, the use of a multiple filter system is necessary for lower energy photons.

Since the film is non-tissue equivalent, a filter system must be used to flatten the energy response, especially at lower photon beam qualities, to approximate the response of a tissue equivalent material.

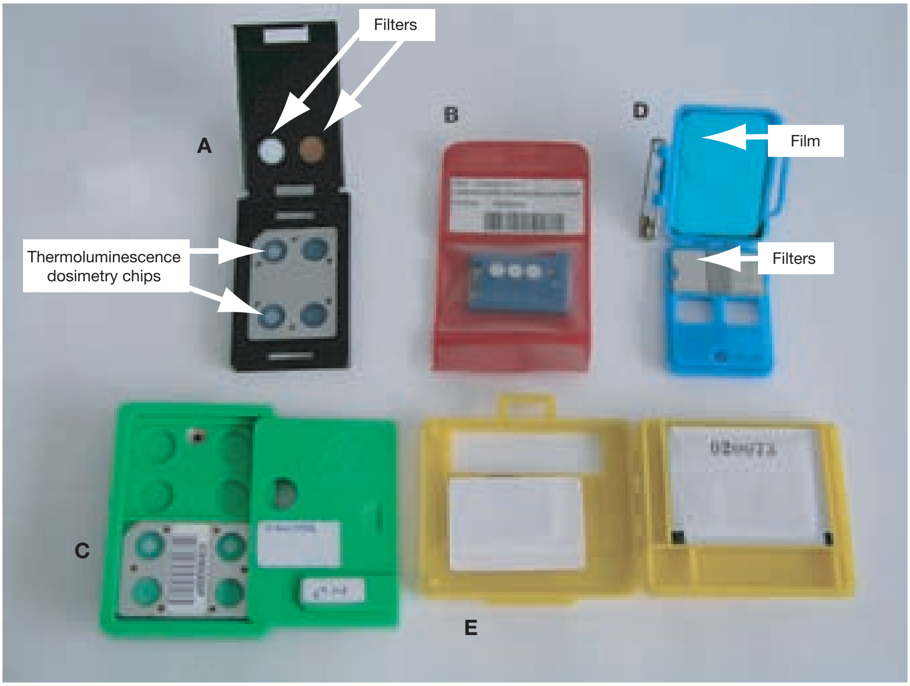

FIG. 4.5. Personal dosimeters: examples of thermoluminescence dosimetry badges (A, B, C) and film badges (D, E).

- Cumulative doses from β, X, γ and thermal neutron radiation are evaluated by measuring the film optical densities (ODs) under different filters and then comparing the results with calibration films that have been exposed to known doses of well defined radiation of different types.
- Film can also serve as a monitor for thermal neutrons. The cadmium window absorbs thermal neutrons and the resulting γ radiation blackens the film below this window as an indication of the neutron dose.
- Nuclear track emulsions are used for monitoring of fast neutrons. The neutrons interact with hydrogen nuclei in the emulsion and surrounding material, producing recoil protons by elastic collisions. These particles create a latent image, which leads to darkening of the film along their tracks after processing.
- Films are adversely affected by many external agents, such as heat, liquids and excessive humidity. The latent image on undeveloped film fades with time, limiting possible wearing periods to three months in ideal conditions.

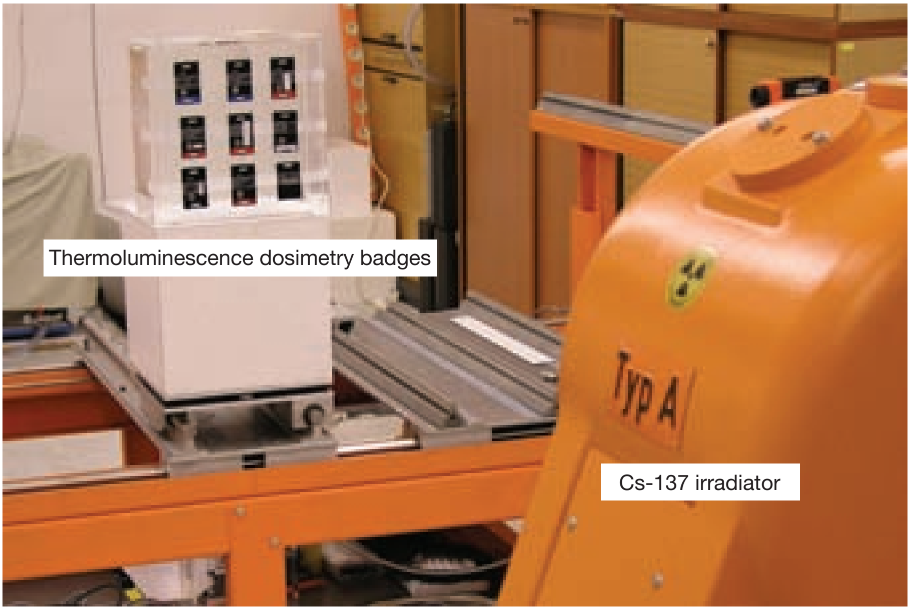

FIG. 4.6. Calibration of personal dosimeters on a PMMA slab phantom using a standard ^{137}Cs γ beam.

4.4.2. Thermoluminescence dosimetry badge

A thermoluminescence dosimetry badge (see Fig. 4.5) consists of a set of thermoluminescent dosimeter (TLD) chips enclosed in a plastic holder with filters. The most frequently used thermoluminescence dosimetry materials (also referred to as phosphors) are LiF:Ti,Mg, $CaSO_4$:Dy and CaF_2:Mn. Different badge designs (thermoluminescence dosimetry materials and filters) are in use in different countries.

The doses of β, X and γ radiation registered by the dosimeter are evaluated by measuring the output under different filters and then comparing the results with calibration curves established for the calibration badge, which has been exposed to known doses under well defined conditions.

- Badges that use high atomic number Z thermoluminescence dosimetry materials are not tissue equivalent and, like film, also require filters to match their energy response to that of tissue. Badges using low Z phosphors do not require such complex filter systems.

- The thermoluminescence signal exhibits fading, but the problem is less significant than for films.
- The badges currently used for β monitoring have a relatively high threshold for β particles (about 50 keV) because of the thickness of the detector and its cover.
- TLDs are convenient for monitoring doses to parts of the body (e.g. eyes, arm or wrist, or fingers) using special types of dosimeter, including extremity dosimeters.
- Various techniques have been used for neutron monitoring, such as using the body as a moderator to thermalize neutrons (similarly to albedo dosimeters) or using LiF enriched with ^{6}Li for enhanced thermal neutron sensitivity due to the (n, α) reaction of thermal neutrons in ^{6}Li.

4.4.3. Radiophotoluminescent glass dosimetry systems

Radiophotoluminescent glass dosimeters are accumulation type solid state dosimeters that use the phenomenon of RPL to measure the radiation dose. The material used is silver activated phosphate glass. The dosimeters come in the shape of small glass rods.

- When silver activated phosphate glass is exposed to radiation, stable luminescence centres are created in silver ions Ag^{+} and Ag^{++}. The readout technique uses pulsed ultraviolet laser excitation. A PMT registers the orange fluorescence emitted by the glass.
- The RPL signal is not erased during the readout, thus the dosimeter can be reanalysed several times and the measured data reproduced. Accumulation of the dose is also possible, and may be used for registration of the lifetime dose.
- Commercially available radiophotoluminescent dosimeters typically cover the dose range of 30 μSv to 10 Sv. They have a flat energy response within 12 keV to 8 MeV for $H_p(10)$.
- The RPL signal exhibits very low fading and is not sensitive to the environmental temperature, making it convenient for individual monitoring.

4.4.4. Optically stimulated luminescence systems

OSL is now commercially available for measuring personal doses. Optically stimulated luminescent dosimeters contain a thin layer of aluminium oxide (Al_2O_3:C). During analysis the aluminium oxide is stimulated with selected frequencies of laser light producing luminescence proportional to the radiation exposure.

- Commercially available badges are integrated, self-contained packets that come preloaded, incorporating an aluminium oxyde (Al_2O_3) strip sandwiched within a filter pack that is heat sealed. Special filter patterns provide qualitative information about conditions during exposure.
- Optically stimulated luminescent dosimeters are highly sensitive; for example, the Luxel system can be used down to 10 μSv with a precision of ±10 μSv. This high sensitivity is particularly suitable for individual monitoring in low radiation environments. The dosimeters can be used in a wide dose range of up to 10 Sv in photon beams from 5 keV to 40 MeV.
- The dosimeters can be reanalysed several times without losing sensitivity and may be used for up to one year.

4.4.5. Direct reading personal monitors

In addition to passive dosimetry badges, direct reading personal dosimeters are widely used:

- To provide a direct readout of the dose at any time;
- For tracking the doses received in day to day activities;
- In special operations (e.g. source loading surveys and handling of radiation incidents or emergencies).

Direct reading personal dosimeters fall into two categories: (1) self-reading pocket dosimeters and (2) electronic personal dosimeters (EPDs).

Self-reading pocket dosimeters resemble a pen and consist of an ionization chamber that acts as a capacitor. The capacitor is fully charged and reads zero before use. On exposure to radiation for a period of time, the ionization produced in the chamber discharges the capacitor; the exposure (or air kerma) is proportional to the discharge, which can be directly read against light through a built-in eyepiece. However, the use of pocket dosimeters has declined in recent years because of their poor useful range, charge leakage problems and poor sensitivity compared with EPDs.

EPDs based on miniature GM counters or silicon detectors are available with a measurement range of down to 30 keV photon energy.

— Modern EPDs are calibrated in the personal equivalent dose (i.e. in terms of $H_p(10)$ or $H_p(0.07)$ for both photons and β radiation). EPDs provide an instantaneous display of accumulated equivalent dose at any time.

— EPDs have automatic ranging facilities and give a visual and an audio indication (flashing or a chirping frequency proportional to the dose equivalent rate), so that changes in the radiation field can be recognized immediately.
— EPDs are very useful in emergency situations for immediate readout of the equivalent doses received.

4.4.6. Calibration of personal dosimeters

Personal dosimeters should be calibrated in terms of operational quantities for individual monitoring of external exposure (i.e. the personal dose equivalent $H_p(d)$ with the recommended depth d = 10 mm for strongly penetrating radiation and d = 0.07 mm for weakly penetrating radiation (see Section 4.2)).

For calibration, dosimeters should be irradiated on standardized phantoms that provide an approximation of the backscatter conditions of the human body. Three types of phantom are recommended that cover the needs of calibration of whole body dosimeters, wrist or ankle dosimeters and finger dosimeters: a slab phantom to represent a human torso, a pillar phantom for wrist or ankle dosimeters and a rod phantom for finger dosimeters. The standard phantoms are composed of ICRU tissue. The ISO recommends special water phantoms (referred to as ISO slab phantoms), although in practice PMMA phantoms are used with the appropriate corrections.

Calibration of personal dosimeters in terms of $H_p(d)$ involves three steps:

- Air kerma in air $(K_{air})_{air}$ is measured in a reference field, using a reference ionization chamber calibrated by a standards laboratory.
- $[H_p(d)/(K_{air})_{air}]_{slab} = h_{kHp}$ values are theoretically available. Using these data for the calibration beam quality, a reference instrument reading can be converted to $[H_p(d)]_{slab}$.
- The dosimeter badge being calibrated is then placed at the calibration point on a phantom and its reading M is determined. $N_{Hp} = H_p(d)/M$ gives the calibration factor in terms of the personal dose equivalent for the dosimeter badge.

4.4.7. Properties of personal monitors

4.4.7.1. Sensitivity

Film and thermoluminescence dosimetry badges can measure equivalent doses as low as 0.1 mSv and up to 10 Sv; optically stimulated luminescent and radiophotoluminescent dosimeters are more sensitive, with a lower detection limit of 10–30 μSv. Personal dosimeters are generally linear in the dose range of interest in radiation protection.

4.4.7.2. Energy dependence

Film exhibits a strong energy dependence and film badges are empirically designed to reduce their energy response to within ±20%. A LiF TLD is nearly tissue equivalent and exhibits acceptable energy dependence characteristics. $CaSO_4$:Dy shows significant energy dependence and its energy response is reduced by empirical adjustments in the badge design.

Commercially available radiophotoluminescent dosimeters (e.g. Asahi, PTW and Toshiba) have a flat energy response from 12 keV to 8 MeV, while commercially available optically stimulated luminescent dosimeters (e.g. Landauer) have a flat energy response from 5 keV to 40 MeV.

For direct reading pocket dosimeters the energy dependence is within ±20% over the range from 40 keV to 2 MeV. For EPDs containing energy compensated detectors the energy dependence is within ±20% over the energy range from 30 keV to 1.3 MeV.

The energy response values quoted above can vary in energy range and in the degree of flatness, depending on the individual monitor material and construction details.

4.4.7.3. Uncertainties in personal monitoring measurements

The ICRP has stated that, in practice, it is usually possible to achieve an uncertainty of about 10% at the 95% confidence level (k = 2) for measurements of radiation fields in laboratory conditions. However, in the workplace, where the energy spectrum and orientation of the radiation field are generally not well known, the uncertainties in a measurement made with an individual dosimeter will be significantly greater, and may be a factor of one for photons and still greater for neutrons and electrons.

The uncertainty in measurements with EPDs is about 10% for low dose rates (2 mSv/h) and increases to 20% for higher dose rates (<100 mSv/h) in laboratory conditions.

4.4.7.4. Equivalent dose range

Personal monitors must have as wide a dose range as possible so that they can cover both radiation protection and accidental situations (typically from 10 μSv to about 10 Sv). The dose range normally covered by film and TLDs is from about 100 μSv to 10 Sv and that by optically stimulated luminescent and radiophotoluminescent dosimeters is 10 μSv to 10 Sv.

Self-reading pocket dosimeters can measure down to about 50 μSv; the upper dose limit of the available pocket dosimeters is around 200 mSv. EPDs measure in the range from 0.1 μSv to 10 Sv.

4.4.7.5. Directional dependence

According to the ICRU, an individual dosimeter must be iso-directional, (i.e. its angular response relative to normal incidence must vary as the ICRU directional dose equivalent quantity $H'(10, \Omega)$) (see Section 4.2). The directional dependence must be evaluated and the appropriate corrections derived.

4.4.7.6. Discrimination between different types of radiation

Film dosimeters can identify and estimate doses of X rays, γ rays, β particles and thermal neutrons. TLDs and optically stimulated luminescent and radiophotoluminescent dosimeters generally identify and estimate doses of X rays and γ and β radiation.

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