10.2 Radiological protection measurements: external exposure

Radiological protection aims at the restriction of the doses to the human body, the effective dose and the equivalent dose in an organ or tissue by applying constraints and limits. The assessment of these doses is therefore fundamental to the practice of radiological protection. However, neither the equivalent dose in an organ or tissue nor the effective dose can be measured directly. Values of these quantities must be inferred from measurable quantities with the aid of models. Radiological protection measurements therefore include measurements related to the system of radiological protection and the interpretation of these measurements in the assessment of external and internal exposures. For monitoring external exposure specific operational dose quantities have been defined which normally provide an estimate of effective dose sufficiently accurate for the purpose of radiological protection (see Sect. 10.2.1). Details about the types of detectors, which can be used to measure these operational quantities are described in Sect. 10.1.

The primary justification of any monitoring program is to achieve and demonstrate an appropriate level of protection. Further objectives of monitoring programs are to

- estimate the actual radiation exposure level,
- demonstrate compliance with legal requirements,
- demonstrate good working practices,
- provide data for use in reviewing optimization programs,
- provide data for medical purposes as required,
- provide data for use in epidemiological studies.

Monitoring programs can be distinguished with regard to the objectives and the location of monitoring. While area monitoring provides a dose or dose rate which enable to estimate the dose a person would receive when staying for a specified time period at the location of interest, individual monitoring provides an estimate of the dose a person has already received. Monitoring can be organized as routine, task-related and special monitoring. Local monitoring can be performed at the workplace, e.g. by means of area monitoring. Individual monitoring can be performed by measuring the external exposure, the internal exposure, and the skin contamination.

Routine monitoring is associated with continuous operation and is largely of confirmatory nature. Operational individual monitoring is associated with a particular operation. It may make use of supplementary dosimeters in addition to those used for routine monitoring. Special individual monitoring will be applied in actual or suspected abnormal conditions including incidents and accidents.

The result of monitoring may be used to initiate certain actions when a pre-defined dose level is exceeded.

10.2.1 Operational quantities

The International Commission on Radiation Units and Measurements (ICRU) has defined a set of operational dose quantities for area and individual monitoring of external exposure [85ICR, 92ICR, 93ICR] which were designed to provide an estimate of the protection quantities defined by ICRP [77ICR] and to serve as calibration quantities for dosimeters used in monitoring. More information about the definition of the operational quantities is given in Sect. 4.5.

For area monitoring, the appropriate operational quantities are the ambient dose equivalent $H^*(10)$ for *strongly penetrating radiation*, and the directional dose equivalent $H'(0.07,\Omega)$, for *weakly penetrating radiation* (see Sect. 4.5.3.3).

For individual monitoring, the quantity personal dose equivalent $H_p(d)$ was defined, which is the dose equivalent in ICRU soft tissue, at an appropriate depth d below a specified point on the body where the individual dosimeter is worn [92ICR, 93ICR]. For strongly penetrating radiation a depth of 10 mm, denoted by $H_p(10)$, and for weakly penetrating radiation a depth of 0.07 mm, denoted by $H_p(0.07)$, is used. A depth of 3 mm, denoted by $H_p(3)$, was also proposed for monitoring the exposure of the lens of the eyes but has never been used in practice.

Personal dose equivalent is defined in the human body and may, therefore, in a given exposure situation vary between individuals. The value may also depend on the position of the dosimeter worn on the body. Consequently, the personal dose equivalent can be expected to vary between locations of any given individual and is anticipated to be a multi-valued quantity [96ICR, 98ICR, 99Zan]. For routine monitoring in cases where the readings are far beyond the corresponding legal limits those values are seen to provide a sufficient approximation to the corresponding protection quantity, e. g. effective dose, if the dosimeter is worn at a position representative for the exposure. To make this quantity single-valued in a given exposure situation, both a particular location of the dosimeter on the human body and a particular phantom of the body need to be specified for evaluation. More information is given in Chap. 6.

Table 10.5 summarizes the objective of dose control and the corresponding operational dose quantities used and specifies their application.

Table 10.5. Operational dose quantities and their objectives in external monitoring

Objective	Dose quantities for area monitoring	individual monitoring
control of effective dose	ambient dose equivalent, $H^*(10)$	personal dose equivalent, $H_p(10)$
control of skin equivalent dose	directional dose equivalent, $H'(0.07)$	personal dose equivalent, $H_p(0.07)$
control of equivalent dose of the eye lens	directional dose equivalent, $H'(3)$	personal dose equivalent, $H_p(3)$

The operational quantities for area and individual monitoring of external exposure are chosen to approximately assess the effective dose under most exposure conditions. Because of the different models used in the definition of the quantities the ratio of the operational quantities and the effective dose depends on the type and the energy of the radiation considered and on the direction of radiation incidence on the body. Figs. 10.23, 10.24, and 10.25 show the ratios $E/H^*(10)$ and $E/H_p(10)$ for photons and neutrons under various exposure conditions.

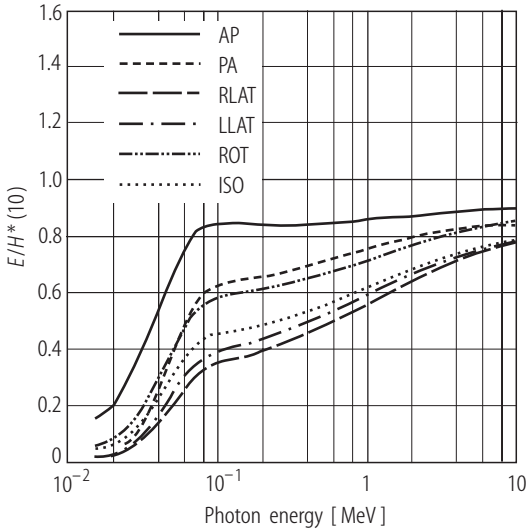

Fig. 10.23. Ratio of effective dose E and ambient dose equivalent $H^*(10)$ versus photon energy for various directions of photon radiation incidence on the human body [96ICR]. AP: frontal incidence, LLAT: left lateral incidence, RLAT: right lateral incidence, PA: incidence from the back, ROT: incidence rotational to the vertical axis, ISO: isotropic incidence.

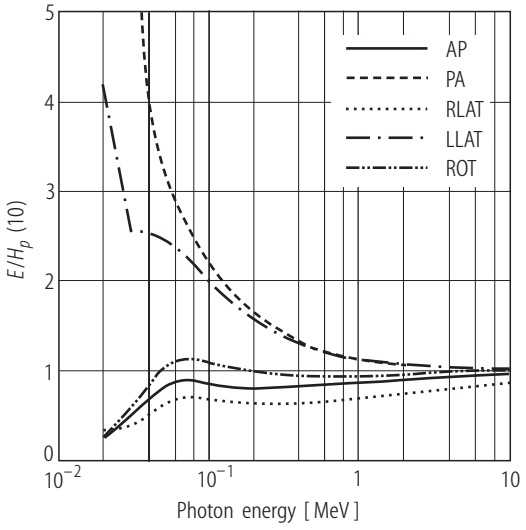

Fig. 10.24. Ratio of effective dose E and personal dose equivalent $H_p(10)$ versus photon energy for various directions of photon radiation incidence on the human body and the dosimeter worn in front of the lung [96ICR, 99Zan]. AP: frontal incidence, LLAT: left lateral incidence, RLAT: right lateral incidence, PA: incidence from the back, ROT: incidence rotational to the vertical axis.

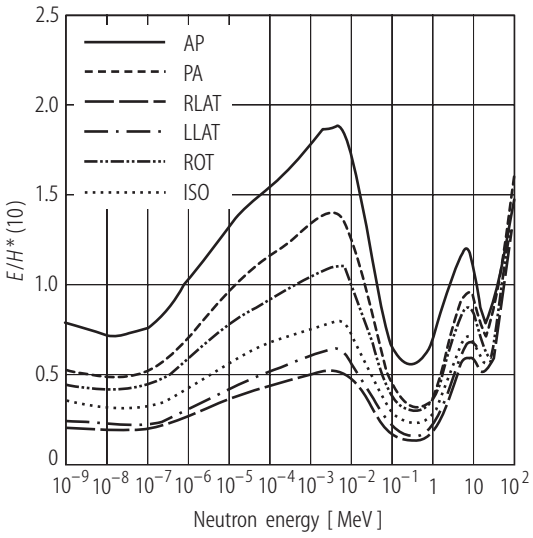

Fig. 10.25. Ratio of effective dose E and ambient dose equivalent $H^*(10)$ versus neutron energy for various directions of neutron radiation incidence on the human body [96ICR]. AP: frontal incidence, LLAT: left lateral incidence, RLAT: right lateral incidence, PA: incidence from the back, ROT: incidence rotational to the vertical axis, ISO: isotropic incidence.

10.2.2 Reference levels

Reference levels are values of measured quantities above which specific actions or decisions should be taken. In the context of this section the most important reference levels are the “Investigation Level” and the “Intervention Level” also called „Action Level“ (see Sect. 4.8). In practical implementation of monitoring programs additional reference levels might be required. They may include levels for recording the monitoring results (“Recording Level”) and for their reporting (“Reporting Level” or “Notification Level”).

Measured values above the “Investigation Level” require an investigation of the reason and the implication of the measured value. “Investigation Levels” are specifically defined by the operating management and they can apply both to the individual and the working environment. It is appropriate to select “Investigation Levels” for individual dose and intake on the basis of expected levels or on the basis of a selected fraction of the relevant dose limit. “Investigation Levels” should be defined at the planning stage of any practice although they may need to be revised on the basis of operational experience.

In the medical field specific “Diagnostic Reference Levels” for patients and for standard applications of ionizing radiation and radioactive substances are defined which characterize a dose level corresponding to the technical and operational state of the art which should be considered for avoiding situations where the level of dose to a patient or the administered activity is unusually high.

Intervention applies to those situations where the source, pathways and exposed individuals are already in place when the decisions about control or remedial measures are being considered. “Intervention Levels” are set by competent authorities and are often mandatory. Typical examples of interventions are actions taken after a radiological emergency to protect the members of the public. There may also be the need to undertake an intervention to protect workers involved in accidents at the workplace. Intervention may also be necessary to decrease the exposure of workers in de-facto situations, e.g. to elevated levels of natural radiation.

10.2.3 Types of exposure

For the purpose of discussing the various aspects of radiological protection measurements it is convenient to distinguish between occupational and public exposure.

10.2.3.1 Occupational exposure

Radiation work is defined [91ICR1, 96EU] as work in which the annual effective dose of an exposed worker of age 18 or over from radiation sources at work may exceed the annual dose limits for members of the public, e.g. an effective dose of 1 mSv or an equivalent dose of the lens of the eye of 15 mSv or an equivalent dose of the skin of 50 mSv averaged over any 1 cm^2 area, regardless of the area exposed. For occupational exposure the ICRP has recommended a limit on the effective dose of 20 mSv per year averaged over 5 years (100 mSv in 5 years) [91ICR1] with the further provision that the effective dose should not exceed 50 mSv in any single year. The limit on equivalent dose for the lens of the eye is 150 mSv in a year, the limit on equivalent dose for the skin is 500 mSv in a year. It is implicit in these recommended dose limits that the dose constraint for optimization should not exceed 20 mSv in a year. The limits on effective dose for apprentices and students aged between 16 and 18 years who, in the course of their studies are obliged to use radioactive sources, is 6 mSv per year. Special protection is required during pregnancy: the equivalent dose to the child to be born is limited to 1 mSv to the reminder of the duration of pregnancy (see also Sect. 4.8).

The decision to provide individual monitoring for an individual or a group of workers depends on three major factors: the expected dose in relation to the constraint or limit, the likely variations in the dose in time and space, and the complexity of the measurement and of the interpretation procedures. Individual monitoring is required for category A workers. It should be established and monitored by an approved dosimetric service. Category A includes any radiation work in which the annual effective dose is or might be higher than 6 mSv, or the annual equivalent dose of the lens of the eye, the skin or hands and feet is or may be higher than 3/10 of the dose limit stipulated for these tissues or organs. Category B includes all other radiation work. For practical reasons, monitoring of category B workers is often treated similar to category A workers by individual monitoring.

In many cases the individual monitoring of external exposure is fairly simple and does not require a heavy commitment of local resources (see 10.2.6). However, in mixed radiation fields, e.g. neutron/photon fields, monitoring is much more complex (see 10.2.6). For special groups of workers, e.g. to the air craft crew, doses caused by cosmic radiation are determined by calculations based on their flying hours and the flight plans rather than by individual measurement.

In situations where individual monitoring is not appropriate or feasible the occupational exposure shall be assessed on the basis of the results of area monitoring at the workplace and on information on the location within the area considered and the duration of exposure.

The control of occupational exposure can be simplified by the designation of work places as “controlled” and “supervised” areas. “Controlled Areas” are subject to special rules for the purpose of radiation protection and to which access is controlled. In “Supervised Areas”, a minimum radiological surveillance of the working environment will be organized. Outside these designated areas, the dose rates from sources and the risk of contamination by unsealed radioactive material will be low enough to ensure that the level of protection for those who work in the premises will be comparable with the level of protection required for the public.

In several areas of medicine the control of occupational exposures is of particular importance, e.g. nursing of brachytherapy patients, palpation of patients during fluoroscopy, and interventional radiology [96ICR]. In these cases individual monitoring with careful scrutiny of the results is always important.

10.2.3.2 Public exposure

The control of public exposure in all normal situations is exercised by the application of control at the source. Almost all public exposure is controlled by the procedures of constrained optimization and the use of dose limits. In particular, appropriate monitoring equipment and surveillance programs are required from the licensee to assess public exposure related to any practice or source and to demonstrate that the dose to members of the public does not exceed authorized dose limits.

This includes environmental monitoring systems measuring doses or dose rates in the vicinity of a source or widely distributed in a country for the purpose of surveillance or early warning. Routine individual monitoring of public exposure is not necessary under normal conditions.

In all areas of medicine there are no restrictions on the public access to non-designated areas. Public access to controlled areas should be limited to visitors of patients only, who should be advised of any restrictions on their behavior.

All reasonable steps shall be undertaken to assess any exposure incurred by members of the public as a consequence of an accident. This assessment will be based on data of area dosimeters installed in and around the facility involved, on model calculations based on plant status or on information about any environmental contamination, and on results of environmental and individual (physical and biological) monitoring. For practical purposes decisions on interventions are often based on derived secondary limits of dose rate and on values of the contamination level in agricultural and other environmental products, which can easily be measured [99IAE].

Emergency response personnel, although not normally occupationally exposed may have to carry out their duties in areas where there is a potential for elevated radiation exposure. Protection of this personnel should be treated as part of the occupational exposure incurred in a practice.

10.2.4 Types of monitoring programs

In the context of this Section, two types of monitoring programs will be discussed, e.g. individual and area monitoring. In many cases where photon radiation is dominant both programs can be considered as independent means to estimate the effective dose a person would receive or has received. In situations with significant contribution of β-radiation or in mixed neutron-photon radiation fields, data and information from both types of monitoring programs might be required to arrive at reliable estimates of the total dose.

10.2.4.1 Individual monitoring for external exposure

External dosimetry deals with radiation that originates outside the body. The external exposure may result from photon irradiation (X- or γ-rays), particle irradiation (electrons, neutrons, protons, heavy particles) or from mixed irradiation (e.g. γ-rays and neutrons). The exposure may involve the whole body or may be confined to a sizeable part of the body. It may be localized, from a narrow beam irradiation or a small radiation source near to the body.

The design of a monitoring program should include the specification of the type(s) of dosimeter to be used and how and where they should be worn (see Sect. 10.2.5). In complex and inhomogeneous fields it will often be necessary to use more than one dosimeter. In particular, operations involving manipulations of radioactive sources may call for dosimeters worn on the fingers. In radiation fields with both penetrating and weakly-penetrating radiations, e.g. γ- and β-rays, a two component dosimeter is required. Sometimes neutrons may contribute to the total dose from occupational exposure. In situations where neutron exposures are likely to significantly contribute to the effective dose special neutron dosimeters are necessary for monitoring. A detailed overview on individual monitoring of external radiation is given in [01Bar].

In the case of radiological accidents with low external exposures only, the assessment of effective and equivalent dose would be covered by routine monitoring programs. In cases where highly elevated dose levels can not be excluded additional dosimeters, preferentially with direct reading of the dose and dose rate and with the option of an audible or acoustical warning should be considered.

10.2.4.2 Area monitoring for external exposure

The purpose of area monitoring at workplaces is to ascertain that a working area is free of significant levels of radiation and contamination. Area monitoring allows the warning of personnel to avoid hazardous areas. The nature and frequency of workplace monitoring shall be sufficient to evaluate the

radiological condition at the workplace and to assess the exposure in controlled areas. The routine workplace monitoring program will usually involve the use of repeated survey measurements. Such a program may include the use of continuously operating monitors installed at fixed and representative locations to monitor the normal radiation level and to identify the onset of abnormal or emergency conditions. The frequency with which routine monitoring will be conducted is determined by the stability of the radiation environment. If the radiation fields are liable to increase rapidly and unpredictably to significant levels, the monitoring program should include instrumentation with technical provisions for fast early warning.

Most of the instruments used at the workplace will measure dose rate rather than dose. Particular care is required in the selection and calibration of instruments used to measure neutrons, β-rays and low energy photons.

Task related monitoring will provide forecast of the doses likely to be accumulated during a task. For this purpose portable instruments will preferably be used. Particular care is needed when working with beta and other weakly penetrating radiations. Special care should be given to the measurement of the dose rate adjacent to surface or point sources.

10.2.4.3 Calibration

Calibration aims at establishing the relationship between values indicated by a measuring instrument or system (see Sect. 10.1) and the corresponding true values of a quantity to be measured. The radiation types used for the calibration of dosimeters are mainly photons, neutrons and beta particles. Calibrations for each of these types are performed differently using different instrumentation and techniques. Calibration should closely follow the recommendations of the International Organisation for Standardisation (ISO) dealing with reference radiations and be based on the methods described in these standards [96ISO1, 96ISO2, 97ISO, 98ISO, 99ISO, 00ISO1, 01ISO]. A detailed description of the calibration procedures can be found in [94Alb, 00Die].

The calibration of personal dosimeters or area survey meters used for radiation protection purposes is mostly a three step process. First, the value of a physical quantity such as air kerma rate or particle fluence rate of which primary standards usually exist, is determined by a reference instrument at a reference point in the radiation field used for calibration. Second, the value of the appropriate operational quantity is determined by application of a conversion coefficient relating the physical quantity to the radiation protection quantity. Conversion coefficients used to determine operational quantities for neutrons and photons were evaluated by international committees and finally accepted for general use by international agreements (see Sect. 6.12, 6.3 and 6.4). Third, the device being calibrated is placed at this reference point to determine the response of the instrument to the operational quantity, e.g. the personal, ambient or directional dose equivalent or their corresponding rates. While area dosimeters are generally calibrated free in air, personal dosimeters are always calibrated in front of a standardized phantom (details see Sect. 4.5.3.4).

The primary physical quantity used to specify a photon radiation field is exposure or air kerma, and the primary standard instruments used for its measurement are air-filled ionization chambers. For photon energies up to about 150 keV, mostly a free-air chamber is used as a standard instrument to measure air kerma. For higher photon energies, air-equivalent walled cavity chambers are generally employed. Properties of radiation fields used for the calibration of photon dosimeters are described in ISO standard 4037 [96ISO1].

Calibrations of dosimeters and survey instruments for the measurement of beta radiation are performed using standard reference beta sources as specified in ISO standard 6980 [96ISO2]. Determination of the conventional true value of the absorbed dose, and hence the directional dose equivalent, is achieved with a thin-window extrapolation ionization chamber [97Amb].

The primary quantity measured for neutrons is the fluence. In monoenergetic neutron fields the fluence is measured either directly by a reference instrument (e.g. proton recoil telescope, proportional counter or Long Counter) or by applying the associated particle method. As regards radioactive neutron sources, e. g. ^{252}Cf without or with a surrounding D_2O-sphere, the neutron fluence is determined from the source emission rate which is usually determined from comparative activation measurements performed

by a national standards laboratory. The emission rate is then used to compute the neutron fluence or fluence rate. In addition, the neutron energy spectrum must be known. With the known spectral fluence mean conversion coefficients can be calculated and applied to determine the ambient dose equivalent at a reference point [98ISO] (see Sect. 6.4).

The calibration of a personal dosimeter or area survey meter is not complete without the calibration being documented. National regulations often specify the details and format of both calibration records and certificates, as well as the frequency of calibration and the period of time for which calibration records are to be kept. The following list gives a general guideline for calibration records or certificates. A certificate should include:

1. Date and place of calibration,
2. Description of dosimeter or instrument (type and serial number),
3 Owner of device,
4. Descriptions of reference radiation sources and standard instruments,
5. Reference conditions, calibration conditions or standard test conditions,
6. Results with statement of uncertainties,
7. Names of the person who performed the calibration and of the reviewer,
8. Any special observations.

10.2.5 Requirements for individual monitoring of external exposure

The basic requirement for personal dosimeters are to provide a reliable measurement of the appropriate quantities, i.e. $H_p(10)$ and $H_p(0.07)$ for almost all practical situations, independent of type, energy and direction of incidence of the radiation and with prescribed overall accuracy. These basic requirements can be expressed in terms of operational and technical parameters influencing the performance of the dosimeter, e.g. its response to radiation type, spectral and directional distribution, environmental influences and practical aspects. The most important ones are described below.

The following minimum requirements apply to all types of personal dosimeters:

- convenient in size and shape, low weight, easy to wear
- inexpensive
- mechanically robust
- easy to handle
- adaptable to various applications (assessment of whole body dose or extremity dose)
- a broad range of doses should be measured
- response should be reasonably independent of the radiation energy and dose rate
- response should not be strongly influenced by normal changes of environmental conditions (minimum temperature range 10 °C to 40 °C, relative humidity: 10 to 90 %)
- the measured dose should not be influenced by other unconsidered types of radiation
- the dosimeter reading should be independent of any delay between irradiation time and time of evaluation.

Electronic personal dosimeters are usually capable to measure dose and dose rate and additionally include an immediate warning capability.

For extremity dosimeters where, due to the close proximity to the source large variations in the dose rate may occur, small-sized detectors such as detectors kept in finger rings are required (cf. Fig. 10.16).

Detailed technical requirements are specified for detectors suitable for measuring whole body exposures and partial exposures in [94EU]. Some are summarized in Tables 10.6 and 10.7.

Table 10.6. Technical requirements for measuring whole body exposures

	Photons		Neutrons	
	Measurement range	Max. range	Measurement range	Max. range
Dose range	0.2 mSv to 1 Sv	up to 10 Sv	0.2 mSv to 1 Sv	up to 10 Sv
Energy range(s)	15 keV to 250 keV or 70 keV to 1.5 MeV	10 keV to 10 MeV	10^{-3} keV to 1.5 MeV or 1.5 MeV to 15 MeV	up to 100 MeV
Dosimeter orientation	0° to ± 60°	0° to ± 180°	0° to ± 60°	0° to ± 180°

Table 10.7. Technical requirements for measuring partial body exposures

	Photons		Beta radiation	
	Measurement range	Max. range	Measurement range	Max. range
Dose range	1 mSv to 10 Sv	0.1 mSv to 10 Sv	1 mSv to 10 Sv	0.1 mSv to 10 Sv
Energy range	15 keV to 1.5 MeV	10 keV to 10 MeV	0.2 MeV to 0.5 MeV[1)]	0.06 MeV to 1.0 MeV[1)]
Dosimeter orientation	0° to ± 60°	0° to ± 180°	0° to ± 60°	0° to ± 180°

[1)] mean beta energy

10.2.5.1 Operational requirements

Two principal questions have to be answered before a measurement of $H_p(10)$ and $H_p(0.07)$ can be interpreted for radiation protection purposes. The personal dosimeter has to be worn at a *"representative" place* on the surface of the body and it will measure the dose at this point for a predefined *period of time*. In many practical cases the radiation field will be inhomogeneous and multidirectional. The value measured will therefore often depend on the orientation of the body in the field. While the use of several dosimeters could in principle improve the situation and lead to a more representative assessment of the effective dose, mostly one dosimeter measuring $H_p(10)$ is sufficient for routine monitoring.

In order to measure $H_p(10)$ for assessment of effective dose, a personal dosimeter is usually worn in front of the body between the shoulders and the waist. Dosimetry of the skin dose or an extremity dose can be performed by using finger batches worn on the hand as rings. An estimate of the eye equivalent dose is obtained by wearing a whole body dosimeter placed at the collar. This is a reasonable location to measure both the eye and the whole body dose. Alternative locations for dosimetry may be necessary in the course of certain types of work. An example is the use of lead aprons in X-ray applications. In this case two dosimeters may be necessary, one under the apron to measure $H_p(10)$ and one at the collar to measure the dose to the head. Other situations may necessitate relocation of dosimeters including fetal monitoring where the monitor should be placed in front of the abdomen to assess the uterus or fetal dose.

In many practical cases of routine monitoring, dosimeters will be worn over a period of one month. In low dose environments this period could be extended up to 6 months. In cases with highly variable radiation fields and in situations where there are indications that dose limits could be reached or exceeded, an evaluation of the dose within a shorter time period could be required. If for operational reasons daily monitoring is required, a direct reading dosimeter with sufficient sensitivity should be used in addition to the routine dosimeter. Direct reading dosimeters are frequently used to monitor the dose received during a particular task, e.g. one working day or one shift. In the case of a pregnant woman an electronic dosimeter would be an appropriate way of individual monitoring (cf. Fig. 10.13).

10.2.5.2 Accuracy requirement

Basic rules in the description of uncertainties in measurements are given in a joint document of BIPM/ /IEC/ISO/OIML [95ISO]. The errors and uncertainties in the use of monitoring to provide estimates of individual doses and intakes result from the measurements and from the models used to link the measured and the required quantities. Different types which contribute to the overall uncertainties can be distinguished: random uncertainties due to counting statistics, systematic errors due to calibration errors and errors in dosimetric and metabolic models and errors in practical application of the models. For most assessments, the systematic errors in modelling result in a bias towards over-estimation of the true dose.

Basic recommendations on the acceptable uncertainty in routine individual monitoring are given by ICRP Publication 60 (par. 271) [91ICR1], Publication 75 [97ICR] and by ISO [00ISO2]: for annual doses of the order of the relevant annual limit, the apparent annual dose to an individual as indicated by routine dosimeters should not differ from the annual dose equivalent indicated by an ideal dosimeter by more than –33 % or +50 % at the 95 % confidence level. The 95 % confidence level means that the given requirement must be fulfilled for 19 of 20 different measurements. For dose values equal to or close to the annual dose limit, e. g. 20 mSv (see 10.2.3.1), the relation between the measured and the true value may thus vary between 1.5 and 1/1.5 times this value in 19 of 20 different measurements.

For individual doses much below the annual limit the accuracy requirements are less than the values given above. For characterising the acceptable uncertainty in performance tests of individual dosimeters trumpet curves as proposed by Böhm et al. [90Boe] have been defined by ISO [00ISO2] describing the requirement by an interval for H_m/H_t (measured dose value/conventionally true dose value) as a function of dose. A detailed overview on requirements for photon dosimeters and dosimetry services as published in the various international recommendations and standards is given by Ambrosi et al. [98Amb, 01Amb]. As example, Fig. 10.26 shows the recommendation of the European Commission [94EU] and the IAEA [97IAE] for photon dosimeters. While many countries, e.g. Germany, Italy, Sweden and Switzerland, use this procedure in performance tests, other countries, e.g. Spain, UK and USA, uses a statistical evaluation of the measured values together with criteria for a bias setting [01Amb].

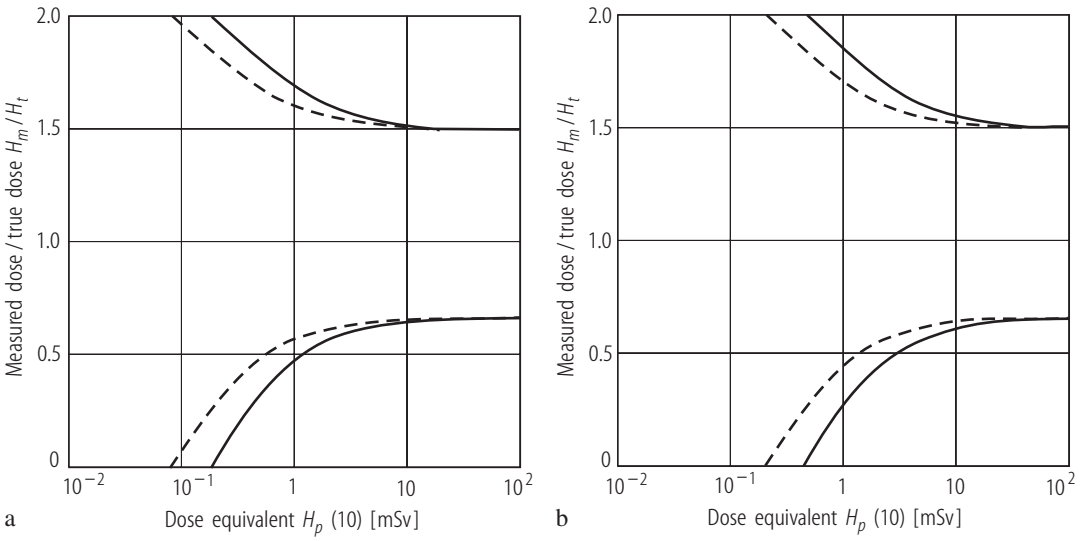

Fig. 10.26. Requirements in performance tests of individual dosimeters for photons showing upper and lower limits for the ratio of the measured dose to the true dose value, H_m/H_t, as a function of dose [90Boe, 98Amb] where 95 % of all measured values must be within these limits. Full lines: monthly monitoring period; broken lines: bi-weekly monitoring periods. (a) limits for $H_p(10)$; (b) limits for $H_p(0.07)$.

The accuracy requirements for individual dosimeters for neutrons are mostly less than those for photon dosimeters because of the difficulties in realising a dosimeter response sufficient independent of neutron energy (cf. Sect. 10.1.7). Often it may be necessary to use some information about the spectral

distribution of the neutrons in order to apply an approximate calibration factor to the dosimeters used. In situations where the contribution of the neutron dose is substantial and where the total dose may approach the dose limit, the radiation field should be characterised by application of more sophisticated equipment, e.g. neutron spectrometry, to get better information about the neutron spectrum and its directional dependence.

10.2.6 Personal dosimeters for individual monitoring in different radiation fields

The most abundant types of detectors used for the purpose of personal dosimetry in routine monitoring are the film dosimeter, the photoluminescence (glass) dosimeter (PLD), thermoluminescence dosimeters (TLD) and ionization chambers. Also electronic dosimeters, based e.g. on GM-counters, proportional counters or semiconductor detectors (see Sect. 10.1), are used. Film dosimeters and ionization chambers are used to monitor X-, γ- and high energy β-ray exposures by measuring $H_p(10)$. Glass and TLD´s are able to measure both $H_p(10)$ and $H_p(0.07)$. They are used to monitor β-, γ-, X-rays, and neutron radiations. Etched-track detectors and bubble detectors measuring $H_p(10)$ are mainly sensitive to neutrons only. Small TLD badges, e.g. finger badges are designed to be worn on the finger to record the dose to the hand. They are sensitive to X- and γ-rays and high energy beta rays. A detailed description of the various detector types is given in Sect. 10.1.

In many practical situations where task monitoring is required in environments with the possibility of elevated radiation levels, “active” dosimeters are needed which include immediate warning capabilities, e.g. electronic dosimeters. Advanced methods of active neutron dosimetry in mixed radiation fields are of particular importance. Potential fields of application of active dosimeters of this kind are at nuclear power plants and particle accelerators.

10.2.6.1 Photon dosimetry

In most work situations with exposures by strongly penetrating electron/photon radiation, an estimate of $H_p(10)$ can be obtained from a single dosimeter sensitive to electrons and photons. The overwhelming share of occupational exposure is caused by photons. Mostly film or TL dosimeters are used in routine monitoring, sometimes also PLD´s are in use [01Bar]. Since 1980, the application of TLD´s has increased considerably. For partial body dosimeters nearly always TLD´s are used. In a few cases where the workers doses are at or near the limits, it may be necessary to obtain additional information about the exposure conditions, e.g. from field measurements at the workplace to better estimate the effective dose equivalent.

Film dosimeters (Sect. 10.1.6) as compared with solid state dosimeters involve a somewhat greater uncertainty of measurement in the lower dose range (<0.4 mSv) in the case of very hard gamma radiation. Test measurements have shown that all three dosimeter types fulfill the performance requirements mentioned in Sect. 10.2.5.2 (see Fig. 10.27). If well designed the dosimeter types are suitable for dose measurements up to photon energies of 15 MeV. Their response to neutrons with energies up to about 1 MeV is usually very low, i.e. they measure the photon dose independent of the neutron dose.

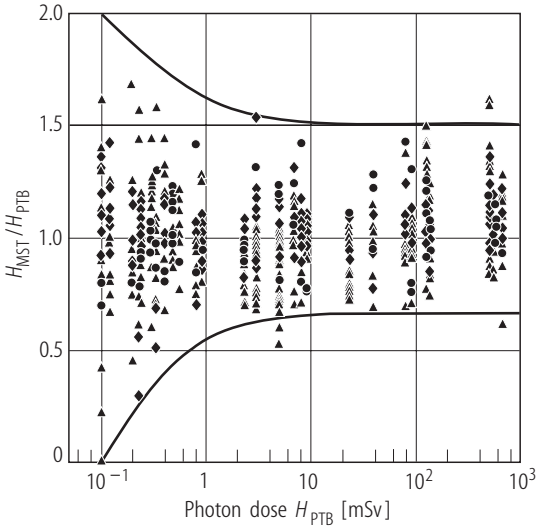

Fig. 10.27. Results of test measurements with different personal dosimeters. The ratio of the measured dose to the true dose as a function of photon dose is shown [01Amb]. The lines mark the accuracy limits for a monthly monitoring period.
▲ Film dosimeter
● Thermoluminescence dosimeter
♦ Photoluminescence dosimeter.

10.2.6.2 Beta dosimetry

In most cases the dose generated by weakly penetrating beta radiation is a partial body dose of the skin of uncovered extremities. Although the depth of the sensitive layer of the skin vary between individuals and over the body of individuals, $H_p(0.07)$ is considered to be a reasonable quantity to apply for the assessment of doses if the dosimeter is worn at a position representative for the exposure. Monitoring of weakly penetrating radiation is predominantly achieved by partial body dosimeters with thermoluminescence probes. In the case of hard beta radiation, e.g. from $^{90}Sr/^{90}Y$ or ^{204}Tl, the dose is detected with a sufficient degree of reliability with film dosimeters. Sensitivity and energy-dependence of the film are sufficient for all practical purposes even in the low dose range. For a detection of beta radiation with intermediate energies above 100 keV the film dosimeter is, in principle, well suited. In practice, most radiation fields are mixed photon/beta fields and when measuring $H_p(0.07)$ correctly it is generally difficult to obtain a separate assessment of the fractions of the dose from photon and beta radiation. In this case an interpretation of the measured data must be based on additional information by the licensee.

The detection of weakly penetrating beta radiation to the skin of the hands with standard finger dosimeters is not always satisfactory. Many of these dosimeters are intended to be used for measuring photon radiation. They may considerably underestimate exposures from beta radiation. Sensitive thin layer thermoluminescence dosimeters need to be used for this purpose. In most practical situations the skin will be exposed to weakly penetrating radiation together with strongly penetrating radiation and an estimate of the skin dose will have to take account of both types of radiation.

10.2.6.3 Neutron dosimetry

Personal dosimeters for neutrons have not yet reached the quality standards of photon dosimetry. This is mainly because their sensitivity and their variation of response with neutron energy and with the angle of radiation incidence are unsatisfactory. The nuclear track film which has frequently been used is only suited for fast neutrons with energies >1 MeV. A special type of thermoluminescence probes, e.g. the albedo dosimeter, is suitable to measure both the photon and the neutron dose. The photon energy range of this dosimeter type is 15 keV to 10 MeV, for neutrons from thermal neutrons up to 20 MeV while the response to neutrons, however, is strongly decreasing with neutron energy (see Sect. 10.1.7).

A reasonable approach for individual neutron dosimetry is to use more than one type of detector to cover the whole energy spectrum, e.g. an Albedo dosimeter for neutrons in the low energy region together with a solid state etched-track dosimeter to cover the energy range above approximately 100 keV

(cf. Sect. 10.1.7). Even with this detector system neutrons with intermediate energies may not be measured to full satisfaction. More recently, electronic personal dosimeters for neutrons based on semiconductor devices became available which partially improve the situation. In cases where the neutron dose contributes significantly to the total dose and the total dose is likely to approach dose limits, a more elaborate approach may be necessary. In such situations the use of area monitors and of neutron spectrometers is recommended to better characterize the radiation field.

10.2.6.4 Dosimetry in mixed field situations (photons and neutrons)

In a mixed field situation with photons and neutrons the *personal dose equivalent*, $H_p(10)$, includes the contributions of both photon and neutron dose. In mixed field situations an improvement of the measuring methods is still required. There are several ways to estimate the total dose and some commercial devices exist to perform appropriate measurements. Either two dosimeters are used each of them sensitive to photons or neutrons only, or one detector which measures the total dose directly. But often the energy response of these devices fails where their physical properties would be attractive, i.e. inside the containment of nuclear power plants, where low energy neutrons dominate. Bubble detectors for neutrons are available on the market but in the attempt to make them robust their unique response properties have been neglected. Tissue equivalent proportional counters (TEPC), which measure the total dose equivalent in a mixed field rather than being just neutron dosimeters have been developed but without real breakthrough on the market.

There have been ongoing developments in recent years [99Alb] and a few most promising monitoring techniques may be ready for routine application in near future. The TEPC personal dosimeter can determine neutron dose equivalents down to 10 μSv with sufficient accuracy. The dosimeter offers the option of a detailed quantification of any radiation exposure in terms of a microdosimetric spectrum. Combined neutron and photon dosimeters of very small dimension, e.g. ionization chambers with direct ion storage (DIS) are recommended for application in radiation fields with high contributions of neutron doses and in places where light-weight and small dimensions are important because of the type of work performed. Dosimeters based on superheated drop detectors reveal a high sensitivity to neutrons with no sensitivity to photons.

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