Physikalisch
Technische
Bundesanstalt

PTB-Bericht

Wolfgang G. Alberts, Peter Ambrosi, Jürgen Böhm
Günther Dietze, Klaus Hohlfeld, Wolfram Will

New dose quantities in radiation protection

PTB-Dos-23e
Braunschweig, August 1995

ISSN 0172-7095
ISBN 3-89429-932-0

PTB

Die Serien der PTB-Berichte:

Atomphysik	PTB-APh
Dosimetrie	PTB-Dos
Elektrizität	PTB-E
Elektronische Entwicklung	PTB-EW
Fertigungsmeßtechnik	PTB-F
Informationstechnik	PTB-IT
Literaturzusammenstellungen und Veröffentlichungshinweise	PTB-L
Mechanik und Akustik	PTB-MA
Medizinische Meßtechnik	PTB-MM
Neutronenphysik	PTB-N
Internationale Organisation für Gesetzliches Meßwesen	PTB-OIML
Optik	PTB-Opt
Physikalische Grundlagen	PTB-PG
Radioaktivität	PTB-Ra
Technisch-Wissenschaftliche Dienste	PTB-TWD
Thermodynamik	PTB-W

Ausgelaufene Serien:

Akustik	(bis 1985)	PTB-Ak
Forschungs- und Meßreaktor Braunschweig	(bis 1988)	PTB-FMRB
Institut Berlin	(bis 1985)	PTB-IB
Mechanik	(bis 1985)	PTB-Me
Neutronendosimetrie	(bis 1988)	PTB-ND
Sicherstellung und Endlagerung radioaktiver Abfälle	(bis 1989)	PTB-SE

Herausgeber: Physikalisch-Technische Bundesanstalt Braunschweig und Berlin
Referat Öffentlichkeitsarbeit, Schrifttum
Telefon: (05 31) 592-93 12

Bundesallee 100
D-38116 Braunschweig
Telefon: (05 31) 592-0
Telefax: (05 31) 592-92 92
Telex: 95 28 22 ptd d

Vertrieb:
Wirtschaftsverlag NW
Verlag für neue Wissenschaft GmbH
Am Alten Hafen 113-115
D-27568 Bremerhaven
Telefon: (04 71) 4 60 93-95
Telefax: (04 71) 4 27 65

Physikalisch-Technische Bundesanstalt

Dosimetry

PTB Report Dos-23e

in cooperation with the
Normenausschuß Radiologie
(NAR, German Standards Committee on Radiology)

New dose quantities in radiation protection

by

Wolfgang G. Alberts, Peter Ambrosi, Jürgen Böhm
Günther Dietze, Klaus Hohlfeld, Wolfram Will

2nd edition

PTB-Dos-23e
Braunschweig, August 1995

ISSN 0172-7095
ISBN 3-89429-932-0

Authors

Dr. Wolfgang G. Alberts	PTB,	Neutron Dosimetry Group
Dr. Peter Ambrosi	PTB,	Laboratory for Radiation Protection Dosimetry
Dr. Jürgen Böhm	PTB,	Radiation Protection Metrology Group
Dr. Günther Dietze	PTB,	Atomic Physics Division
Dr. Klaus Hohlfeld	PTB,	Photon and Electron Dosimetry Group
Dr. Wolfram Will	BfS,	Dosimetry and Radiation Instrumentation Section (BfS = Federal Office for Radiation Protection)

Preamble

In Germany, the Working Committees 'Dosimetry' (AA1) and 'Radiation Protection' (AA2) of the Standards Committee on Radiology (NAR), together with the Physikalisch-Technische Bundesanstalt (PTB) and the General Assembly for Verification Matters, have recommended the introduction of new measurands (operational quantities) for radiation protection against exposure to external radiation. The properties of the new operational quantities internationally recommended by the ICRU and ICRP are well known and the consequences of their introduction into measurement practice can clearly be seen, although not every regulation is fixed to the last detail.

The present text is a translation of the German Report PTB-Dos-23 issued by the PTB in July 1994. That report has been prepared in order to provide to the radiation protection community in Germany in condensed form the information necessary for the transition to the new operational quantities and to describe the consequences for area and individual monitoring. Many colleagues from foreign countries have already asked for information on this report and have, therefore, encouraged us to translate the text into English. In addition, we think that the distribution of this information will support the trend of harmonization in Europe in the field of radiation protection monitoring.

The authors are aware of the fact that in some cases specific quantities and nomenclature are used which are common in Germany but not in common use in most other countries; for example, for monitoring of photons the measurand photon dose equivalent, H_X*, is used in Germany while in other countries the air kerma free in air,* K_a *is most frequently used. Therefore, an Appendix is added to this translated report repeating all figures and tables that contain data depending on the quantity* H_X *in a modified form with the quantity* K_a*. To indicate that a figure or a table exists in two forms, the quantity* H_X *or* K_a *is given in brackets behind the number of the respective figure or table.*

Data of conversion coefficients for photon radiation have been updated in order to remain consistent with the most recent evaluations; those changes, however, are minor in magnitude.

The Tables 5.3 and 6.2 and the corresponding ones in the Appendix are modified to show the radiation quality symbols of both DIN 6818-1 (1992a) and ISO 4037-3 (1995a).

In accordance with ISO 31 in this translation the decimal point is a comma.

Abstract

The ‘Normenausschuß Radiologie’ (German Standards Committee on Radiology, NAR) and the Physikalisch-Technische Bundesanstalt (PTB) have recommended the introduction of new quantities in the field of radiation protection measurements for external exposure in Germany as of January 1995. The present report serves as a support for this recommendation. It describes the present, radiation type related system of quantities and the new quantities as proposed by the ‘International Commission on Radiation Units and Measurements’ (ICRU) which are the same for all types of radiation. The implications of the introduction of new quantities in individual and area monitoring are described. In particular, changes of calibration procedures are considered, and numerical values needed for these procedures are given. Two chapters deal with special problems connected with instrument testing and verification and with provisional arrangements.

Zusammenfassung

Der „Normenausschuß Radiologie“ (NAR) im DIN und die Physikalisch-Technische Bundesanstalt (PTB) haben die Einführung neuer Meßgrößen für den Bereich des Strahlenschutzes bei externer Strahlung in Deutschland zum 1.1.1995 empfohlen. Der vorliegende Bericht soll zur Unterstützung dieses Vorhabens dienen. Er beschreibt die bisherigen auf jeweils eine Strahlungsart bezogenen Dosis-Meßgrößen und die neuen, von der „International Commission on Radiation Units and Measurements“ (ICRU) vorgeschlagenen Größen, die für alle Strahlungsarten in gleicher Weise gelten. Die Auswirkungen der Einführung der neuen Meßgrößen auf Messungen der Orts- und Personendosis werden dargelegt. Insbesondere wird auf Änderungen in Kalibrierverfahren eingegangen, und es werden die bei diesen Verfahren benötigten numerischen Werte angegeben. Zwei Kapitel befassen sich mit speziellen Fragen der Prüfung und Eichung von Meßinstrumenten sowie mit Übergangsregelungen.

Contents

page

1 Introduction

Ionizing radiation is, in general, not visible to man, its detection is possible only with measuring instruments. Radiation measurements are therefore an essential basis for radiation protection. The physical quantities needed both in radiation protection to characterize the radiation fields and their impact on man and in the measurement practice form a complex system. Quantities related to the risks of exposure to ionizing radiation are needed, with which limits of exposure can be defined (limiting quantities, body doses), as well as quantities suitable for measurements in area and individual monitoring (operational quantities).

In 1977, the ICRP (International Commission on Radiological Protection) proposed a concept of limiting quantities (mean dose equivalents in organs and effective dose equivalent, dose equivalent of the skin and the lens of the eye) (ICRP, 1977) which was introduced rather quickly into German standards and into radiation protection practice. The limits given in the Radiation Protection Ordinance (BMU, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, 1989) and the X-Ray Ordinance (BMA, Federal Ministry of Labour and Social Affairs, 1987) for occupationally exposed persons are related to these quantities.

In 1991 the ICRP published new recommendations for radiation protection (ICRP, 1991), recently also made available in German translation (ICRP, 1993). These recommendations include among other things a new definition of body dose quantities to which the limits are related.

In the European Union (EU) a draft of a ‘Directive laying down the basic safety standards for the health protection of the general public and workers against the dangers of ionizing radiation’ (EU, 1993) is presently under discussion. The new ICRP recommendations are an essential basis of this Directive. Since it is to be expected that the new definition of body doses will be introduced in Germany during the next years, this report also contains a chapter describing body dose quantities.

Body dose quantities are not measurable as they are defined as average doses in organs and tissues of the human body. Moreover, their values depend on the individual person and on the orientation of the person in the radiation field. For radiation protection practice, special ‘operational’ quantities are therefore important whose values can be determined from measurements and in the units of which measuring instruments can be calibrated. For measurements in area and individual monitoring of external radiation, i.e. ionizing radiation from sources outside the human body, as early as in 1985 the ICRU (International Commission on Radiation Units and Measurements) presented a concept of radiation protection quantities (ICRU, 1985). In this concept the quantities are equally defined for all types of ionizing radiation. This concept has been further developed by ICRU in the following years (ICRU, 1988, 1992, 1993). Essential parts are also contained in the new ICRP recommendations.

The new ICRU quantities are increasingly accepted worldwide. For instance, in revising the technical recommendations for monitoring individuals occupationally exposed to external radiation (EU, 1994), the EU recommends to use the new personal dose quantities. Recent draft standards of the International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO) in the field of dosimetry mostly contain the new quantities. In Great Britain, the National Radiological Protection Board (NRPB) and the British Committee on Radiation Units and Measurements (BCRU) already recommended the introduction of the new quantities (NRPB, 1993). Other countries in Europe are preparing for the introduction.

With the introduction of the new quantities, in Germany it is intended to create regulations applicable to all types of ionizing radiation. They will, for instance, replace the quantity ‘photon dose equivalent’ which had been introduced into legal metrology for photons as a transitional solution (REICH, 1980). The photon dose equivalent is based on the old ‘Standard-Ionendosis’ (exposure) and has not been incorporated into international standards. The prerequisites for the introduction of the new quantities were provided in recent years by incorporating the quantities and new terms and definitions into the German standards.

The present report provides important information on the introduction of the new quantities. It is intended for the radiation protection community and anticipates that the reader is acquainted with the basic terms and definitions in the field of ionizing radiation and radiation protection.

At the beginning (Chapter 2), the concept of radiation protection quantities is explained. Following a presentation of the quantities at present in use in Germany (Chapter 3), the new operational quantities for area and individual monitoring are presented and explained, and differences are shown between the new quantities and those hitherto used (Chapter 4). In Chapters 5 and 6, the impact on practical area and individual monitoring is dealt with, and it is explained which changes are to be expected with respect to the construction of measuring instruments. Important changes in the testing and verification of measuring instruments as well as in intercomparison measurements are summarized in Chapter 7. Chapter 8 finally deals with some necessary transition regulations.

2 Concept of dose quantities in radiation protection

2.1 Categories of quantities in radiation protection

A field of ionizing radiation can be fully described at each point by stating the fluence and its distribution in energy and direction of incidence for each radiation type (e.g. photons, neutrons, electrons etc.) at this point. For the purposes of radiation protection, such a description of the field is, however, unsatisfactory for practical application since many field parameters are necessary and the individual person and the interaction of the radiation with the person are not included. ICRP and ICRU have therefore defined various dose quantities for radiation protection. Quantities are required which can be used as a measure of the risk of a damage due to ionizing radiation and which are therefore suited to define exposure limits; in addition, quantities are required which can be used in practice for measurements in individual and area monitoring. The dose quantities for radiation protection can therefore be subdivided into two categories: body dose quantities and operational quantities.

2.2 Body dose quantities

The absorbed dose D (unit: gray (Gy); 1 Gy = 1 J/kg) generated in the body of an exposed individual, is the basis for estimating possible damage due to the impact of ionizing radiation on human tissue. At low dose values, essentially stochastic effects (tumour incidence and genetic alterations) are important. In addition, it should be noted that the probability of the occurrence of such effects depends both on the type of tissue irradiated (organ or tissue in the human body) and the type of radiation (e.g. photons, neutrons, beta or alpha particles). Genetic damage, for instance, occurs only as a consequence of dose absorbed in the gonads.

In its 1990 recommendation (ICRP, 1991) the ICRP has introduced the absorbed dose, $D_{\mathrm{T,R}}$, averaged in a specified organ or tissue, T, and generated by a radiation of type, R, incident on the body from outside. The **equivalent dose, $\boldsymbol{H_{\mathrm{T}}}$, of an organ or tissue**, T, is then defined as the weighted sum of absorbed doses, $D_{\mathrm{T,R}}$, summed over the various radiations, R.

$$H_{\mathrm{T}} = \sum_{\mathrm{R}} w_{\mathrm{R}} \cdot D_{\mathrm{T,R}} \qquad \text{Unit: sievert (Sv); 1 Sv = 1 J/kg.}$$

Here, the factors w_{R} are radiation weighting factors which take the different radiobiological effectiveness of the various types and energies of radiation into account. The radiation weighting factor for calculating organ equivalent doses according to ICRP 60 replaces, in this concept, for the body doses the average (or 'effective') quality factor Q used previously for this purpose (ICRU, 1962). The value of Q was obtained by calculation from the radiation field at the site of the organ, on the basis of the definitions of the quality factor $Q(L)$ (see also Section 4.1.2). In the case of external radiation, the radiation weighting factor is related to the type and energy of the radiation incident on the body; in the case of internal irradiation from incorporated radioactive material it is related to the radiation emitted by the radionuclides. The radiation weighting factors as given by ICRP are listed in Table 2.1.

Table 2.1 Radiation weighting factors w_R for different types of radiation according to ICRP 60

Radiation	Radiation weighting factor w_R
Photons	1
Electrons[1)] , muons	1
Neutrons: E_n < 10 keV E_n 10 keV to 100 keV E_n > 100 keV to 2 MeV E_n > 2 MeV to 20 MeV E_n > 20 MeV	 5 10 20 10 5
Protons E_p > 2 MeV (unless recoil protons)	5
α- particles and heavy particles	20

1) With the exception of Auger electrons from atoms bound to DNA

For photons, electrons and muons, the weighting factor is unity, independent of the energy (comparable to the specification Q = 1 hitherto used). For neutrons, the radiation weighting factor varies with the neutron energy, E_n. As a supplement to the step function given in Table 2.1, ICRP has specified a smooth w_R function, i.e.

$$w_R = 5 + 17 \cdot e^{-[\ln(2 \cdot E_n)]^2/6}$$

(E_n neutron energy in MeV) to support the consistency of calculations. In practice, only this smooth function is used to calculate neutron-induced body doses.

The values of the new radiation weighting factors for neutrons recommended by the ICRP have led to international discussions, because they do not sufficiently take into account, in the lower energy range in particular (below 100 keV), that the external neutron radiation incident on the body is strongly slowed down in the body and generates secondary photon radiation so that the radiation field in the body is strongly modified (photon fraction: about 90%). A modification of the w_R function is therefore at present under discussion (SIEBERT *et al.*, 1994), which maintains the form proposed by the ICRP but uses different parameters:

$$w_R = 2{,}5 + 13 \cdot e^{-[\ln(2 \cdot E_n)]^2/3} \qquad E_n \leqslant 0{,}5 \text{ MeV}$$

$$w_R = 2{,}5 + 13 \cdot e^{-[\ln(2 \cdot E_n)]^2/15} \qquad E_n > 0{,}5 \text{ MeV}$$

(E_n: neutron energy in MeV). By and large, these w_R values are consistent with the average quality factors for the effective dose equivalent (see below).

In 1976, the ICRP had introduced the **effective dose equivalent**, $\boldsymbol{H_E}$, as a quantity for body doses. It is defined as the weighted sum over organ doses, the relative tissue weighting factors taking into account the varying sensitivity of organs with respect to stochastic effects of radiation. For both homogeneous whole-body exposure and partial exposure, such a quantity, related to the whole body, can be equally related to the radiation risk and is therefore a quantity suitable for defining exposure limits.

In 1990, the ICRP recommended a new quantity, the **effective dose *E***. It replaces the quantity H_E, the basic concept remaining, however, the same:

$$E = \sum_{T} w_T \cdot H_T = \sum_{T} w_T \cdot \sum_{R} w_R \cdot D_{T,R} \qquad \text{Unit: sievert (Sv); 1 Sv = 1 J/kg.}$$

Here, H_T is the organ equivalent dose and w_T the respective weighting factor. Summation is to be made over 12 organs or tissues and a remainder (‘other organs and tissues’), for which the ICRP has specified w_T values. According to ICRP 60, the remainder comprises 10 organs and tissues, and the dose equivalent pertaining to this remainder is equal to the arithmetic mean of the respective organ equivalent doses. The weighting factors are given in Table 2.2 together with previous values according to ICRP 26. The w_T values represent a distribution averaged over males and females and over a large age range.

Table 2.2 Tissue weighting factors w_T for various organs or tissues

Organ or tissue	Tissue weighting factor w_T	
	acc. to ICRP 26	acc. to ICRP 60
Gonads	0,25	0,20
Bone marrow (red)	0,12	0,12
Colon		0,12
Lung	0,12	0,12
Stomach		0,12
Bladder		0,05
Breast	0,15	0,05
Liver		0,05
Oesophagus		0,05
Thyroid	0,03	0,05
Skin		0,01
Bone surface	0,03	0,01
other tissues and organs	0,30	0,05

Body doses are in general not measurable since they are defined as mean values of organs or tissues in persons. In a given radiation field, a body dose can approximately be determined by calculation in an anthropoid phantom. Such calculations are, however, very complex and tedious. They have been made for certain radiation fields with the aid of which body doses can be determined in special cases (SSK, 1991). In general, a different approach is made. For externally incident radiation, additional quantities (for area and individual monitoring) have been defined which are measurable and which can provide an estimate for body doses under possibly all realistic exposure conditions. Below so-called investigation levels (e.g. 5 mSv for the personal dose to determine H_E in a monitoring period of one month), these estimates are set equal to the body doses (BMU, 1994a). At higher doses they are under certain circumstances used together with other information on the radiation field and the exposure conditions to calculate body doses (SSK, 1991, 1994).

2.3 Dosimetric terms and quantities

In the Radiation Protection and X-Ray Ordinances (BMU, 1989, BMA, 1987), two terms are distinguished for external irradiation, the 'area dose' and the 'personal dose'. They characterize the different goals of measurement in radiation protection.

Area dose. The area dose provides an estimate of the effective dose which a person would receive if he stayed at this location (area). Measurements with area dosimeters are in general above all intended for preventive radiation protection purposes. On the basis of such measurements, possible exposures of persons at workplaces and in the environment are estimated and radiation protection measures specified. Measurements of the area dose furnish data for establishing restricted and controlled areas and for environmental monitoring around nuclear installations. Area dosimeters can give warning signals when exposures exceed certain levels. In the Radiation Protection Ordinance (BMU, 1989) and in the X-Ray Ordinance (BMA, 1987), the area dose is defined in a generalized form:

> The **area dose** is the dose equivalent in soft tissue, measured at a specified point.
>
> The unit of the area dose is the 'sievert' (Sv). 1 Sv = 1 J/kg.

The area dose is defined at any point in space; it is a *point quantity*. Furthermore, it is an additive quantity, i.e. if several radiation fields are superimposed in one point in space (possibly also one after the other), the total area dose is the sum of the area doses of the component radiation fields.

In most cases it is not known a priori how a person may be oriented in a radiation field. The reading of an area dosimeter should, therefore, give a *conservative estimate of the body dose* which a person exposed to this radiation field would receive regardless of his orientation.

Fig. 2.1 shows for photon radiation that the new operational quantity for area monitoring, $H^*(10)$, gives a conservative estimate of both the effective dose equivalent H_E (ICRP, 1977) and the effective dose E (ICRP, 1991). The figure gives the data for whole-body exposure from the front (AP, anterior-posterior). Since the values of the effective dose are smaller for other irradiation geometries, the new quantity for area monitoring remains conservative also for these geometries.

Fig. 2.2 shows a similar comparison for neutron irradiation. In addition to $H^*(10)$, the quantity used to date is shown which is based on the definition of the 'maximum dose equivalent' $\hat{H}$ (cf. Section 3.4). The underestimation of the effective dose E (ICRP 60) by the new quantity, visible in Fig. 2.2, as regards neutrons with energies between 1 eV and 40 keV, in the region of several MeV and above 40 MeV, is of minor importance in radiation protection practice. The underestimation exists only for monoenergetic neutrons which are not found in practice. In real neutron fields at nuclear installations, $H^*(10)$ will always be a conservative estimate of the effective dose (MARSHALL *et al.*, 1994). Application of the afore-mentioned changed w_R values (SIEBERT *et al.*, 1994) would conservatively estimate the effective dose at almost all neutron energies below 50 MeV.

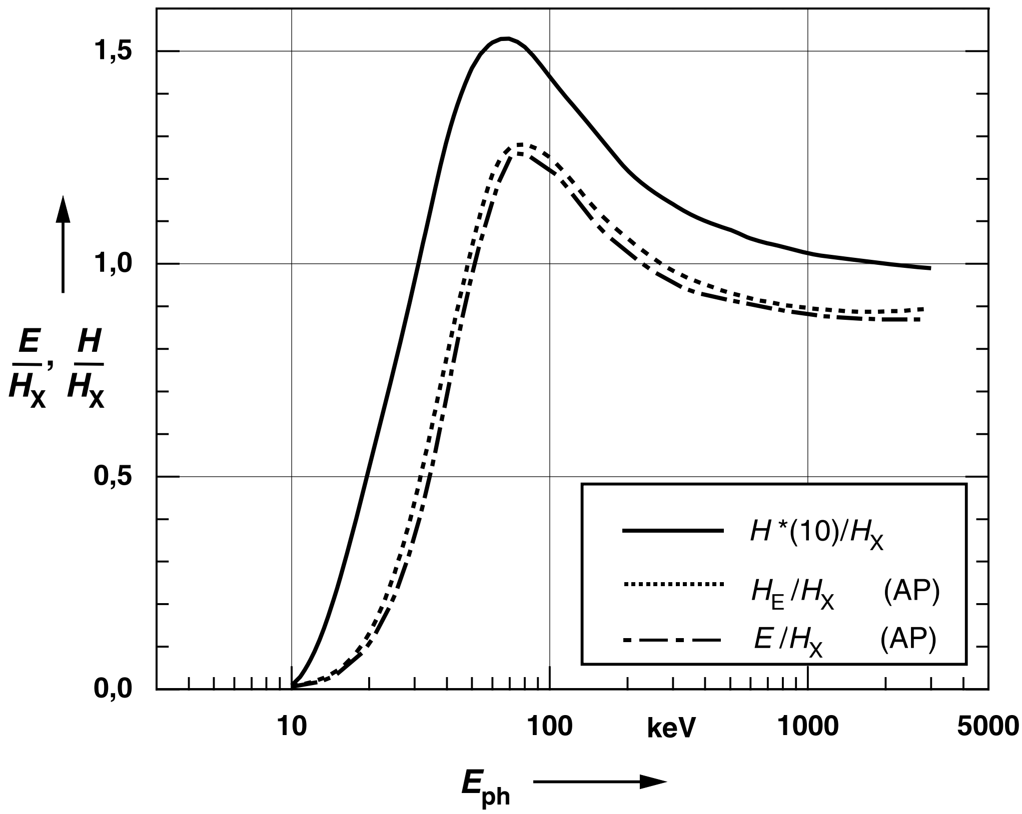


Fig. 2.1 (H_X) Comparison of the new quantity for area monitoring, $H^*(10)$, with the effective dose equivalent, H_E, and the effective dose E for monoenergetic photon radiation (H_X: photon dose equivalent, cf. Section 3.2). The values of H_E and E are valid for whole-body exposure from the front (AP, anterior-posterior); the values of the effective dose are smaller for other irradiation geometries of the whole body. E_{ph} photon energy.

Personal dose. The personal dose is an individual measure of the exposure of a single person to external radiation. In general, it is determined using a dosimeter (personal dosimeter) which is worn on the person's body. In the Radiation Protection Ordinance (BMU, 1989) and in the X-Ray Ordinance (BMA, 1987), the personal dose is defined as follows:

> The **personal dose** is the dose equivalent in soft tissue, measured at a point on the body surface representative of the irradiation conditions prevailing.
>
> The unit of the personal dose is the ‘sievert’ (Sv). 1 Sv = 1 J/kg.

In the radiation protection monitoring of persons at workplaces by the authorized dosimetry services, at low doses below defined investigation levels (BMU, 1994a), the personal dose measured on the trunk is set equal to the effective dose of the person. Since the human body influences the radiation field - radiation is absorbed and scattered in the body - values of area and personal dosimeters measured in the same radiation field differ in general. Both values can be regarded only as estimates of the effective dose of a person. For a more accurate determination of body doses, additional information on radiation type and directional distribution is in principle necessary.

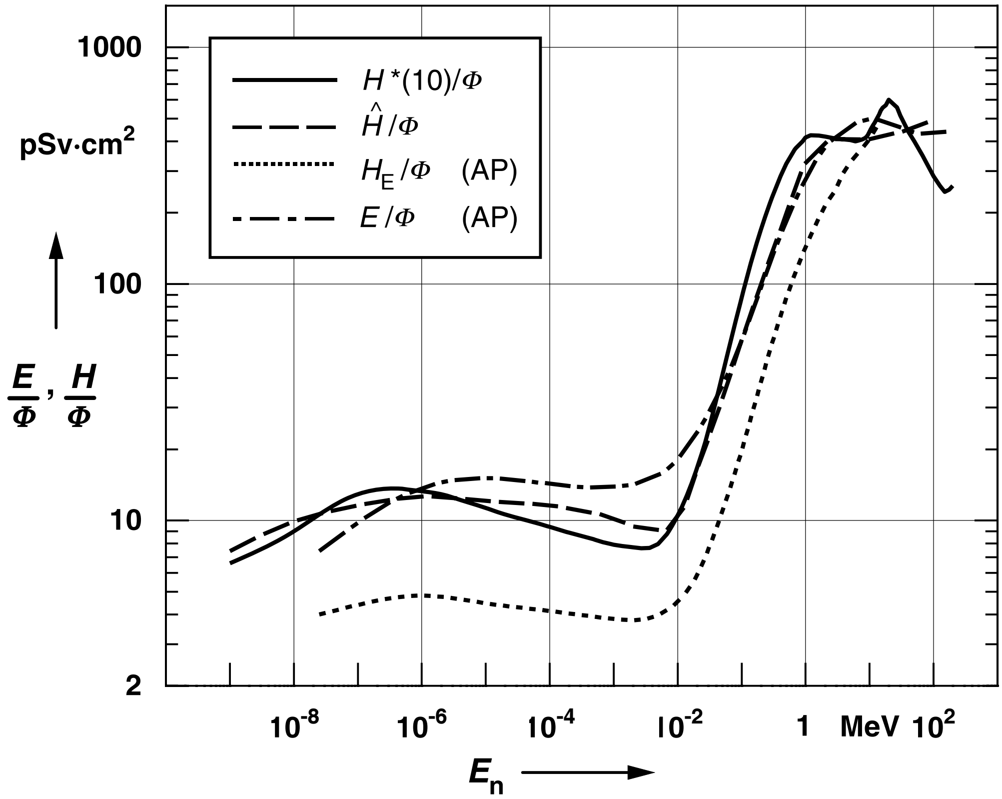


Fig. 2.2 Comparison of the former quantity for area monitoring, $\hat{H}$, and the new quantity for area monitoring $H^*(10)$ with the effective dose equivalent, H_E, and the effective dose, E, for monoenergetic neutron radiation (Φ neutron fluence). The values of H_E and E are valid for whole-body exposure from the front (AP, anterior-posterior). E_n neutron energy.

Operational quantities. The area dose and the personal dose require physically unambiguous definitions in order to be usable as measurands in terms of which dosimeters can be precisely calibrated. In the following chapters, the quantities hitherto used (Chapter 3) and the new quantities (Chapter 4) are described in detail.

The quantities should be defined in a unique manner for all types of ionizing radiation and be applicable to measurements in mixed radiation fields. This is not the case with the quantities hitherto in use in Germany. The new quantities will fulfil these requirements in future.

3 The dosimetric quantities hitherto used for radiation protection purposes

3.1 Review

The dosimetric quantities hitherto in use for photon radiation and defined free in air are closely connected to the **'Röntgenstrahlendosis'** (X-ray dose) and its unit 'röntgen' (symbol R) from 1928: at 1 R, an electric charge of one electrostatic unit is generated in an air volume of 1 cm^3 at 18 °C and at a pressure of 760 mm of mercury. This finally led to the definition of the **'Standard-Ionendosis'** (exposure), J_s, which is the ion charge (ion dose) generated by secondary electrons of the photon radiation per unit mass in air under the special condition of secondary electron equilibrium (DIN, 1985). The unit of J_s is the 'coulomb per kilogram' ($C \cdot kg^{-1}$); up to the end of 1985, use of the unit 'Röntgen' was permissible according to the Units Act considering the definition $1\,R = 2{,}58 \cdot 10^{-4}\,C\,kg^{-1}$.

In the fifties the term **'absorbed dose'** D was introduced. It is the mean energy imparted by radiation to a mass element, divided by the mass of this element. The unit of D used to be the 'rad' (rd), later the 'gray' (Gy) (1 rd = 0,01 Gy = 0,01 J kg^{-1}).

In the sixties the new type of quantity *'dose equivalent'*, H, was introduced for radiation protection. It is defined as the product of the absorbed dose, D, and a quality factor Q: $H = Q \cdot D$. The quality factor is intended to take into account differences in the biological effectiveness of the various radiation types. In ICRP publications (ICRP, 1977, 1991), Q is defined as a function of the linear energy transfer L of charged particles in water (see Section 4.1.2).

These recommendations have been adopted in legal regulations in Germany (BMA, 1987; BMU 1989). The unit of H was first the rem (rem), later on the sievert (Sv) (1 rem = 0,01 Sv = 0,01 J kg^{-1}). In analogy, area and personal doses were defined in the X-Ray Ordinance of 1987 and the Radiation Protection Ordinance of 1989 as dose equivalents in soft tissue.

The exposure itself is not a dose equivalent quantity and could therefore not be used any longer when the Units Act required the change to the unit 'sievert'. Up to that time there had been no agreement on the international level as regards corresponding dose equivalent quantities for radiation protection. A practicable interim solution was the quantity **'photon dose equivalent'**, H_X, introduced in Germany in 1980 (Reich, 1980). It had the advantage of making the further use of existing radiation protection dosimeters easy by just applying a conversion coefficient of 0,01 Sv/R, when the dosimeters had been designed for the measurement of the exposure and calibrated in terms of the unit R.

As a result of this development, different area and personal dose quantities are at present valid in Germany for photon, neutron and beta radiation (see Table 3.1). These are explained in more detail in Sections 3.2 to 3.4 (cf. DIN, 1985). No quantities have so far been defined for other radiation types, e.g. high-energy photons or mesons as found in cosmic radiation or at high-energy accelerators. There is no unique quantity for mixed radiation fields. This is a unsatisfactory situation.

Table 3.1. Survey of the measurands hitherto used, arranged according to the kind of external radiation in compliance with the standard DIN 6814-3 (DIN, 1985)

External radiation	Limiting dose quantity	Measurands hitherto used for area monitoring	Measurands hitherto used for individual monitoring
Photon radiation	Effective dose equivalent, organ dose equivalents (acc. to Appendix 10 to Rad. Prot. Ord.)	Photon dose equivalent, H_X	
Neutron radiation		Reading of a calibrated dosimeter (max. dose equivalent)	
Beta radiation	Dose equivalent of skin and lens of the eye	Reading of a calibrated dosimeter (absorbed dose times 1 Sv/Gy)	

3.2 The former operational quantities for monitoring of photon radiation

The measurand hitherto used for area and individual monitoring is the photon dose equivalent, H_X:

Photon dose equivalent, H_X

For photon radiation with maximum energies up to 3 MeV the photon dose equivalent, H_X, is derived from the 'Standard-Ionendosis' (exposure), J_s:

$$H_X = C_1 \cdot J_s \qquad \text{where } C_1 = 38{,}76 \ \text{Sv C}^{-1}\,\text{kg} \ (= 0{,}01 \ \text{Sv/R})$$

For photon radiation with maximum energies above 3 MeV the photon dose equivalent, H_X, is equal to the reading of an area dosimeter which has been calibrated free in air with ^{60}Co gamma radiation for the measurement of the 'Standard-Ionendosis', multiplied by the factor C_1.

At photon energies above 3 MeV the measurement of J_s and thus the simple determination of H_X is no longer practicable because of the long ranges of the secondary electrons. A different definition of this quantity had therefore to be used in this energy range.

An ideal area or personal dosimeter must have a response independent of the direction of radiation incidence in order to precisely measure the photon dose equivalent H_X. Both types of dosimeters have so far been calibrated free in air. An area dosimeter measures H_X free in air. In contrast to this, measurements with a personal dosimeter are done in a radiation field in which part of the primary radiation incident on the body is scattered or absorbed in the body. Because of these different conditions, measurements in the same primary radiation field in general furnish different values, although both the area dose and the personal dose are measured as photon dose equivalent.

3.3 The former operational quantities for monitoring of electron radiation

In radiation protection practice, electron radiation almost exclusively exists in the form of beta radiation which is why only the term beta radiation will be used in the following. The quantities hitherto used for area and individual monitoring for beta radiation take into account that there is a substitute for the human body (phantom) at the point of measurement, which scatters and absorbs the beta radiation. In general, with beta radiation exposure, the limit of the dose of the skin is the important body dose limit, the dose at a depth of 0,07 mm being taken as the representative value.

Former operational quantity for area and individual monitoring of beta radiation:

Value measured by an area or personal dosimeter calibrated for the measurement of the absorbed dose in soft tissue in a semi-infinitely expanded soft tissue equivalent phantom of density 1 g/cm^3 at a depth of 0,07 mm, multiplied by the factor 1 Sv/Gy.

3.4 The former operational quantities for monitoring of neutron radiation

The quantities hitherto in use for area and individual monitoring of neutron radiation are based on the definition of the 'maximum dose equivalent' for monoenergetic incident neutron radiation in a cylindrical or slab phantom made of soft tissue, for which neutron fluence-to-dose equivalent conversion coefficients have been recommended for monoenergetic neutrons by the ICRP (ICRP, 1971):

Former operational quantity for area monitoring of neutron radiation:

Value measured by an area dosimeter with a dose-equivalent response independent of energy and direction of incidence, calibrated using neutron fluence-to-dose equivalent conversion coefficients.

Former operational quantity for individual monitoring of neutron radiation:

Value measured by a personal dosimeter, calibrated using neutron fluence-to-dose equivalent conversion coefficients on the surface of a cylindrical phantom 30 cm in diameter and 60 cm in length, made of soft-tissue equivalent material of density 1 g/cm^3.

The calibration of a dosimeter is usually performed in a neutron radiation field of known fluence. The conversion coefficients provide the means for converting the fluence of a broad parallel beam of monoenergetic neutrons into the maximum dose equivalent in the respective phantom, which is generated by neutrons incident perpendicularly to the cylinder axis or slab surface. Area dosimeters are calibrated free in air, personal dosimeters in general on a phantom. By this calibration procedure the reading of a dosimeter becomes proportional to the sum of the dose maxima ('dose equivalent ceiling', HARVEY, 1975), generated by the energy components of the neutron spectrum. This sum is termed $\hat{H}$ in the following and is given by

$$\hat{H} = \int \hat{h}_{\Phi}(E) \Phi_E(E) dE$$

($\hat{h}_{\Phi}(E)$:conversion coefficient for monoenergetic neutrons, $\Phi_E(E)$: spectral neutron fluence).

4 The new operational quantities for radiation protection

4.1 The new concept of the operational quantities

4.1.1 Strongly penetrating radiation and weakly penetrating radiation

The radiation incident on man from the outside can be characterized as **strongly penetrating radiation** or **weakly penetrating radiation**, depending on which body dose limits are relevant for the radiation: those of the effective dose or those of the local skin dose (dose equivalent at a depth of 0,07 mm of the skin, averaged over 1 cm^2 in the range of the maximum dose equivalent). The limit of the local skin dose is ten times the limit of the effective dose. Radiation is therefore considered to be strongly penetrating when the dose equivalent received by the germinative layer of the skin (agreed depth: 0,07 mm) upon normal incidence of a broad radiation beam is lower than ten times the effective dose. Radiation is considered to be weakly penetrating when, upon normal radiation incidence, this skin dose is higher than ten times the effective dose. Weakly penetrating radiations are, for example, beta radiation with energies below 2 MeV and photon radiation with energies below 15 keV (DIN, 1992b). Neutron radiation is always strongly penetrating.

Suitable estimates of the local skin dose, the dose for the lens of the eye and the effective dose are obtained by determination of the dose equivalent in ICRU soft tissue at 0,07 mm, 3 mm and 10 mm of depth, respectively, in the human body or in phantoms (ICRU, 1988). The new area dose quantities are defined in the ICRU sphere (see Section 4.1.3), the new personal dose quantities in the exposed person. Phantoms are, however, also used for the calibration of personal dosimeters (see Section 4.3).

In contrast to the definitions of the operational quantities hitherto used, the definitions of the above new quantities are independent of the type of radiation, i.e. of whether photon, electron, neutron or even muon radiation is concerned. Table 4.1 gives a survey of the new quantities, distinguished by the penetrating power of the radiation. Detailed descriptions of the quantities can be found in Sections 4.2 and 4.3.

Table 4.1 Survey of the new quantities (cf. Sections 4.2 and 4.3 for exact definitions)

External radiation	**Limiting body dose**	**New quantity for**	
		area dose	**personal dose**
Strongly penetrating radiation	Effective dose	$H^*(10)$	$H_p(10)$
Weakly penetrating radiation	Skin dose	$H'(0{,}07,\vec{\Omega})$	$H_p(0{,}07)$
	lens of the eye	$H'(3,\vec{\Omega})$	$H_p(3)$

4.1.2 Dose equivalent, quality factor

In contrast to the new body doses (see Section 2.1), the new quantities are still defined as the ‘dose equivalent at a point’ by the product of the absorbed dose D and the quality factor Q at this point, $H = Q \cdot D$; the unit of the dose equivalent is the sievert. The quality factor Q has been introduced to weight the absorbed dose produced by the charged particles with respect to its different biological effectiveness. ICRP has stated a functional dependence of Q on the linear energy transfer, L, of charged particles in water. The new quantities are based on the following numerical equation for $Q(L)$ (ICRP, 1991):

$$Q(L) = \begin{cases} 1 & \text{for} \quad L \leq 10 \\ 0{,}32L - 2{,}2 & \text{for} \quad 10 < L < 100 \\ 300/\sqrt{L} & \text{for} \quad L \geq 100 \end{cases} \qquad (L \text{ in keV/µm}) .$$

The quality factor Q at a point in tissue is then given by (ICRU, 1993):

$$Q = 1/D \int_L Q(L) \cdot D_L \, dL ,$$

where D_L is the distribution of D in L.

4.1.3 The ICRU sphere phantom

For all types of radiation the new quantities for area monitoring have been defined on the basis of a phantom. This phantom is the **ICRU sphere**, a sphere of tissue-equivalent material 30 cm in diameter (density: 1 g cm^{-3}, mass composition: 76,2 % oxygen, 11,1 % carbon, 10,1 % hydrogen and 2,6 % nitrogen). It adequately approximates the human body as regards the scattering and attenuation of the radiation fields under consideration.

4.1.4 Aligned and expanded radiation field

The definition of the new quantities for area monitoring in the ICRU sphere was not to result in the area dose loosing its character of a point quantity and the property of additivity. This has been achieved by introducing into the definitions of the area dose quantities the term of the **expanded radiation field**:

*An **expanded radiation field** is a radiation field in which the spectral fluence and the angular fluence have the same values in all points of a sufficiently large volume as in the actual field at the point of interest*. There is spatial constancy (homogeneity) in such a large volume that, in the case of a further expansion of the range, the spectral and angular fluence of the particles entering an imaginary 30 cm diameter sphere will no longer change. The expansion of the radiation field ensures that the whole ICRU sphere is thought to be exposed to a homogeneous radiation field whose fluence, energy distribution and directional distribution are the same as in the point of reference P of the real radiation field (see Figs. 4.1 (a) and (b)).

*If all beams are (thought to be) aligned in the expanded radiation field so that they are opposed to the radius vector $\vec{\Omega}$ specified for the ICRU sphere (see Figs. 4.1 (c) and 4.2 (b)), the **aligned and expanded radiation field** is obtained*. In this radiation field, the ICRU sphere is homogeneously irradiated from one direction, and the fluence of this radiation field is the integral of the angular fluence in the point of reference P in the real radiation field over all angles. In the expanded and aligned radiation field, the value of the dose equivalent at one point of the ICRU sphere is independent of the directional distribution of the radiation of the real radiation field.

(a) Real radiation field with a fluence at point P, which is composed of three components of different direction, symbolized by three different arrows.

(b) Expanded radiation field of point P, with the ICRU sphere entered (dotted circle) to illustrate the size of the radiation field.

(c) Aligned and expanded radiation field of point P, with the ICRU sphere entered (dotted circle) to illustrate the size of the radiation field. The arrows drawn one behind the other for the sake of clarity are in reality three components superimposed at each point.

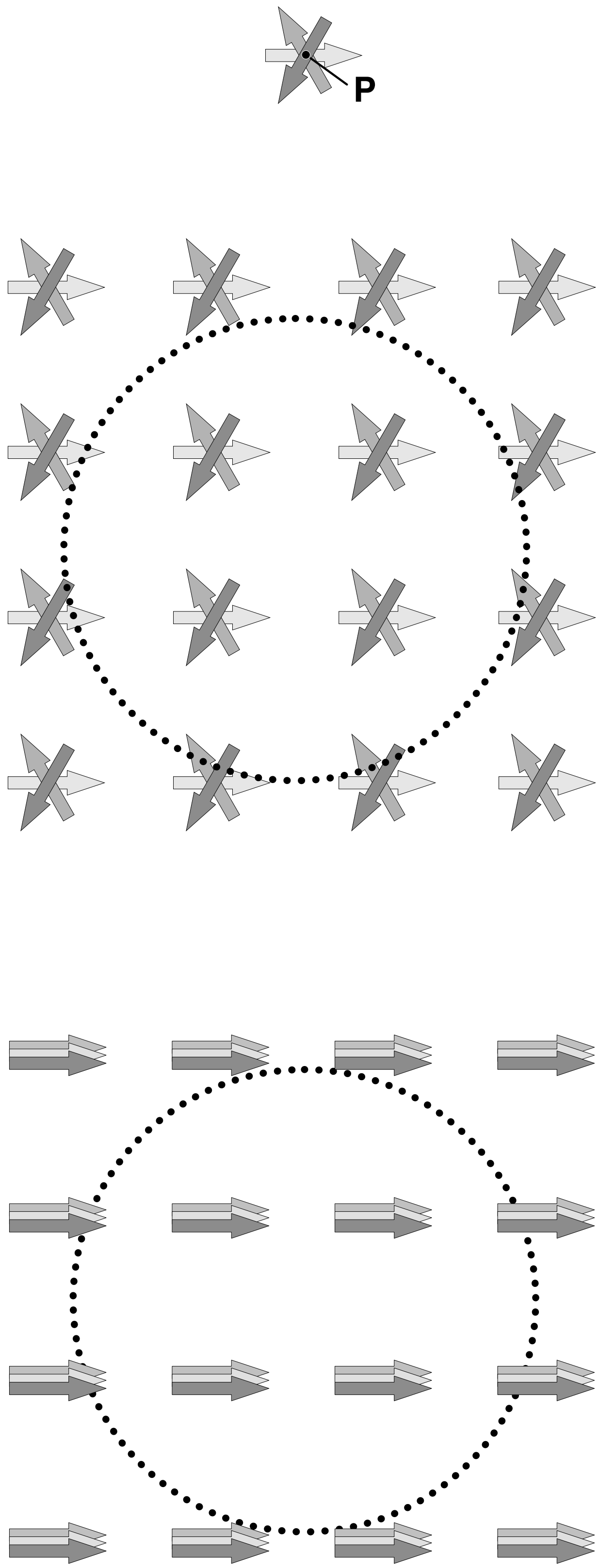
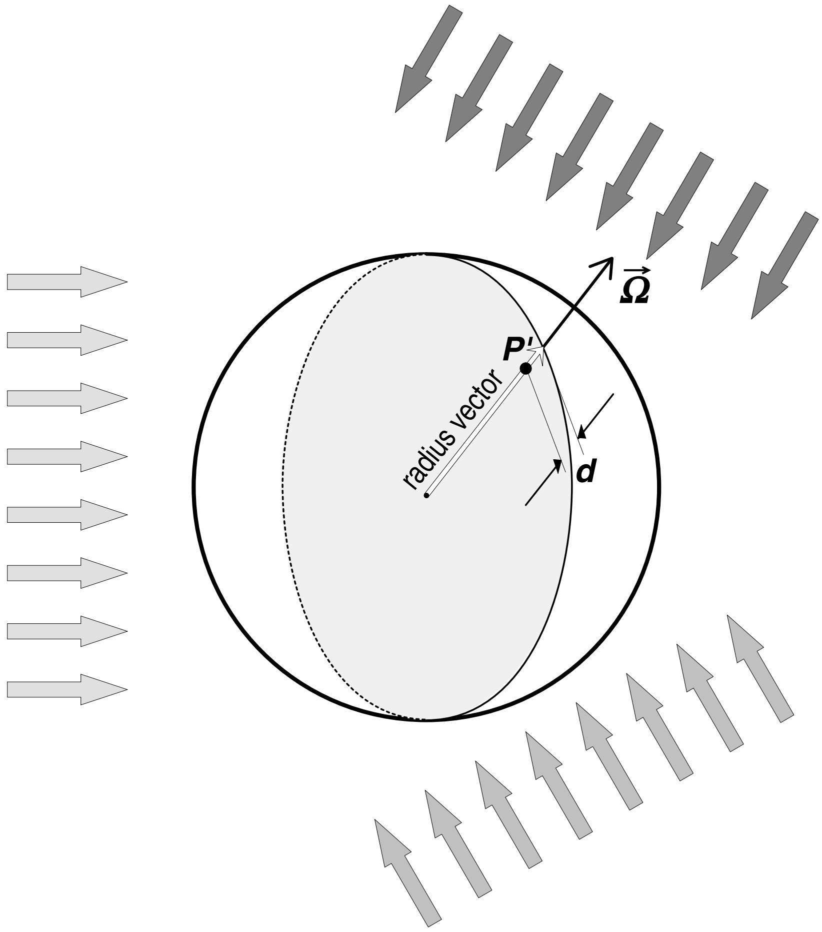


Fig. 4.1 Schematic representation of a (a) real, (b) expanded and (c) expanded and aligned radiation field.

(a)



(b)

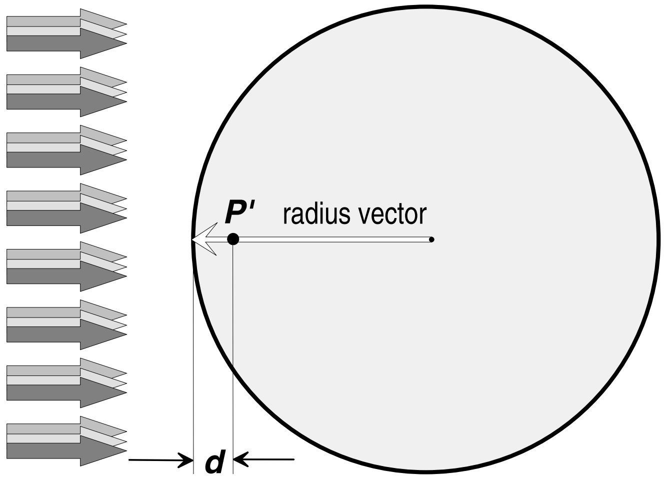


Fig. 4.2 Irradiation geometries of the ICRU sphere and point P' in the sphere, at which the dose equivalent is determined in the expanded radiation field (a) and in the expanded and aligned radiation field (b). In the expanded radiation field, the radiation can hit the ICRU sphere from various directions. $H'(d, \vec{\Omega})$ is defined for the direction $\vec{\Omega}$ of the radius vector. At $H^*(d)$ in the expanded and aligned radiation field, the radius vector to determine $H^*(d)$ is always opposing the (uniform) direction of the radiation field.

4.2 The new operational quantities for area monitoring

The new quantities for area monitoring take into account that estimates are required for two types of body doses (see Section 4.1.1):

- for strongly penetrating radiation: an estimate of the effective dose,
- for weakly penetrating radiation: an estimate of the local skin dose or of the dose for the lens of the eye.

In the definition of the new quantity for strongly penetrating radiation, the term of the expanded and aligned radiation field is used (see Section 4.1.4 and Fig. 4.2. (b)):

New operational quantity for area monitoring of strongly penetrating radiation:

The **ambient dose equivalent, H^*(10)**, at a point of interest in a real radiation field, is the dose equivalent that would be produced by the corresponding aligned and expanded radiation field, in the ICRU sphere at a depth of 10 mm, on the radius vector opposing the direction of the aligned field.

H^*(10) is a conservative estimate of the effective dose.

As a result of the imaginary alignment and expansion of the radiation field, the contributions from all radiation directions add up. The value of H^*(10) is therefore independent of the directional distribution of the radiation in the actual radiation field. This means that in area dosimeters for the measurement of H^*(10), the dependence of the reading on the directional distribution of the radiation should be as low as possible.

For weakly penetrating radiation the term of the expanded radiation field (see Section 4.1.4 and Fig. 4.2 (a)) is integrated into the definition of the quantity for area monitoring:

New operational quantity for area monitoring of weakly penetrating radiation:

The **directional dose equivalent $H'(0{,}07, \vec{\Omega})$**, at a point of interest in a real radiation field, is the dose equivalent that would be produced by the corresponding expanded radiation field, in the ICRU sphere at a depth of 0,07 mm, on a radius in a specified direction $\vec{\Omega}$.

In this report, the maximum value of $H'(0{,}07, \vec{\Omega})$ at a point of interest is referred to as $H'(0{,}07)$.

In area monitoring for weakly penetrating radiation, $H'(0{,}07, \vec{\Omega})$ is used almost exclusively, even for the estimate of the dose for the lens of the eye. Only in a few special cases is it necessary to use the quantity $H'(3, \vec{\Omega})$ defined in analogy.

The value of the directional dose equivalent can strongly depend on the direction $\vec{\Omega}$, i.e. on how the ICRU sphere is oriented in the expanded radiation field (see Fig. 4.2.(A)). The same is true of instruments for measuring weakly penetrating radiation - e.g. beta radiation - whose reading can strongly depend on the orientation in the space. In practical radiation protection, almost exclusively the maximum value of $H'(0{,}07, \vec{\Omega})$ at the point of interest is of importance, which is obtained by rotating the area dosimeter. Unlike ICRU Report 51, the present report refers to the maximum value in simplified terms as $H'(0{,}07)$.

4.3 The new operational quantities for individual monitoring

As in area monitoring, individual monitoring requires measurement values which furnish suitable estimates of the limiting body doses.

To obtain an estimate of the effective dose, for strongly penetrating radiation, the operational quantity for the personal dose $H_p(10)$ defined at 10 mm depth in the body is used:

> **The new operational quantity for individual monitoring of strongly penetrating radiation**
>
> is the personal dose equivalent, $\boldsymbol{H_p(10)}$, defined as the dose equivalent in ICRU soft tissue at a depth of 10 mm in the body at the location where the personal dosimeter is worn.

For weakly penetrating radiation, the depth of 0,07 mm is used to obtain the estimate for the local skin dose:

> **The new operational quantity for individual monitoring of weakly penetrating radiation**
>
> is the personal dose equivalent, $\boldsymbol{H_p(0,07)}$, defined as the dose equivalent in ICRU soft tissue at a depth of 0,07 mm in the body at the location where the personal dosimeter is worn.

Only in special cases is the personal dose equivalent $H_p(3)$ of interest, defined in analogy at a depth of 3 mm.

The new operational quantities for individual monitoring, $H_p(10)$ and $H_p(0,07)$, are defined in the person, in the actually existing radiation field, and are measured directly on the person. During this process, the person influences the radiation field by scattering and attenuating the radiation. Since $H_p(10)$ and $H_p(0,07)$ are defined in the body of the respective person, their values vary from one person to the other and also depend on the body location at which they are measured.

Personal dosimeters cannot be calibrated on the human body. Phantoms are required for this purpose. To have unequivocal reference values for the calibration of personal dosimeters, the person-related definition of $H_p(d)$ is extended to three phantoms made of ICRU soft tissue (see Fig. 4.3) (ALBERTS *et al.*, 1994):

> **The personal dose equivalent $\boldsymbol{H_p(d)}$ for the calibration of personal dosimeters**
>
> is the dose equivalent at the depth d below a specified point on the surface of one of the following phantoms made of ICRU soft tissue:
>
> - **slab phantom**, 300 mm x 300 mm x 150 mm in dimension, to approximate the human torso (for the calibration of whole-body dosimeters),
> - **pillar phantom**, a cylinder 73 mm in diameter and 300 mm in length, to approximate a lower arm or leg (for the calibration of wrist or leg dosimeters),
> - **rod phantom**, a cylinder 19 mm in diameter and 300 mm in length, to approximate a finger (for the calibration of finger dosimeters).

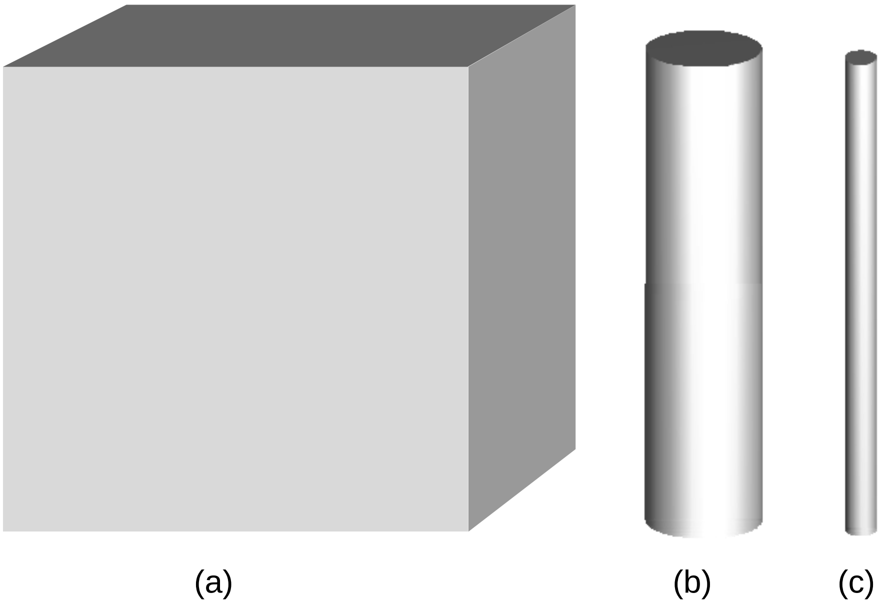


Fig. 4.3 Phantoms made of ICRU tissue, in which the personal dose equivalent, $H_p(d)$, is defined for calibration purposes: slab phantom (a) (300 mm x 300 mm x 150 mm), pillar phantom (b) (73 mm in diameter, 300 mm in height), and rod phantom (c) 19 mm in diameter, 300 mm in height).

4.4 Comparison of the measurands hitherto used with the new quantities

The dosimetric quantities hitherto used and the new quantities are defined as point quantities and traceable to quantities such as fluence and air kerma free in air which are realized at the PTB by primary standard measuring devices. The quantities hitherto in use differ for the different types of particles (photons, electrons and neutrons) and are not additive in this respect. The new quantities are uniform for all types of particles; there are, however, different quantities for area and individual monitoring. Table 4.2 compares the properties of the quantities hitherto used with those of the new quantities.

In a given radiation field, depending on the type of particles and their directional and energy distribution, the dosimetric quantities based on the new concept (see Section 4.1) will lead to changes in the measured dose values. This will be explained in the following:

Photon radiation: The change will be most striking with this type of radiation: The area dose hitherto used is defined as the photon dose equivalent free in air; the personal dose so far in use is also defined as the photon dose equivalent, however on the surface of the exposed person's body. Due to backscattering by the body, in the case of irradiation from the front, differences in the numerical values of the area dose and the personal dose occur, which may exceed the factor 1,5. The new quantities are defined in a phantom or in the body of the exposed person.

To compare the new personal dose and the personal dose hitherto used which are measured on the trunk, one must look at the values of the personal dose, $H_p(10)$, and those of the photon dose equivalent, H_X, multiplied by the backscatter factor of the trunk. At parallel incidence of the radiation from the front, the quotient of these two quantities approximates as a function of energy the shape of the solid curve in Fig. 4.4. Above a photon energy of about 40 keV, the quotient deviates from unity by less than 20 %. The steeply descending slope of the curve towards lower energies is caused by the attenuation of the photon radiation in the ICRU tissue layer 10 mm thick. This has been intended, since H_X strongly overestimates the effective dose at low photon energies.

Table 4.2 Comparison of the properties of the new measurands for area and individual monitoring with those of the quantities hitherto used.

Property of the measurand for area and individual monitoring	Property met by	
	former measurands	new measurands
Point quantity	yes	yes
Additivity	yes, but only for one radiation type (photon, electron or neutron radiation)	yes
Same quantity for all radiation types	no	yes
Direct relation of quantity to human body or suitable phantom	not for photon radiation	yes
Different quantities for strongly penetrating and weakly penetrating radiation	no	yes
Traceable to quantities realised at the PTB	yes	yes

Differences between the new personal dose on the finger and the personal dose on the finger hitherto used can be recognized by comparing $H_p(0,07)$ on the finger with the photon dose equivalent H_X multiplied by the backscatter factor of the finger. At parallel incidence of the radiation from the front, the quotient of these two quantities has approximately the shape of the dashed curve in Fig. 4.4. Above a photon energy of about 8 keV, this quotient deviates from unity by less than 20 %.

At oblique incidence of the photon radiation, it must be taken into consideration in addition that personal dosimeters for the measurement of $H_p(10)$ and $H_p(0,07)$ - in contrast to those for the measurement of H_X - should furnish a reading which is a function of the direction of radiation incidence (see Section 6.1.5). When the radiation is mainly incident from the front and does not include low-energy photons, the values of the new personal dose and those of the personal dose hitherto used differ only slightly.

The differences are greater for the measurement values of the area dose, as the new definitions of the area dose have been related to a phantom (the ICRU sphere) and to specific depths (10 mm or 0,07 mm) in the sphere. Fig. 4.5 shows the quotients $H^*(10)/H_X$ and $H'(0{,}07{,}0°)/H_X$ as a function of the photon energy; Table 5.1 indicates the corresponding numerical values. The quotients' maxima at about 65 keV are caused by the maximum of the photon backscatter by the ICRU sphere. The descending slope towards lower photon energies results from the absorption in the layer, 0,07 mm or 10 mm thick, in front of the point of reference. In the case of an anisotropic radiation field, area dosimeters for the measurement of $H'(0{,}07)$ should furnish a reading which is a function of the dosimeter's orientation (see Section 5.1.6).

Photon radiation fields always include concomitant secondary electron radiation. The quantity H_X hitherto used presupposes secondary electron equilibrium from the very outset. This is not the case with the new quantities. When conversion coefficients related to H_X are stated for the new quantities, these are valid only for secondary electron equilibrium.

This applies also to the data stated in ICRU Report 47 (ICRU, 1991), which were calculated by Monte Carlo methods, because they are based on the so-called ‘kerma approximation’ for dose calculation. In radiation fields with energies above approximately 3 MeV relevant in practical radiation protection, a sufficiently great number of secondary electrons can normally be expected because of the many shieldings provided, so that the low conversion coefficients of Ferrari and Pellicioni (1994) calculated for pure photon radiation are not relevant.

Strong deviations from secondary electron equilibrium can, however, occur in the case of finger dosimeters for the measurement of $H_p(0{,}07)$ when they are used in close proximity to gamma radiators.

Beta radiation: For this type of radiation, the differences between the measured values will be relatively small when the new dosimetric quantities are introduced.

Neutron radiation: The new quantities have been defined in phantoms (or in the body) as have those hitherto in use. The phantoms are, however, the same as for photon and electron radiation, and the reference point in the phantom is always at a depth of 10 mm. Now as before, the values of the new quantities will be determined from the neutron fluence using conversion coefficients for the respective quantity. Figs. 4.6 and 4.7 show the quotients $H_p(10)/\hat{H}$ and $H^*(10)/\hat{H}$ for monoenergetic neutrons; in addition, the respective conversion coefficients with respect to the fluence Φ have been entered (SIEBERT *and* SCHUHMACHER, 1995). The deviations of the quotients $H_p(10)/\hat{H}$ and $H^*(10)/\hat{H}$ from unity are due both to the definition of the new quantities in the ICRU slab and in the ICRU sphere and to the new definition of the quality factor $Q(L)$ (see Section 4.1.2). For monoenergetic neutrons in the energy range up to 20 MeV, they amount to between -20 % and +80 %; the deviations are in general smaller than 50 % for broad neutron spectra (see Section 5.1.4).

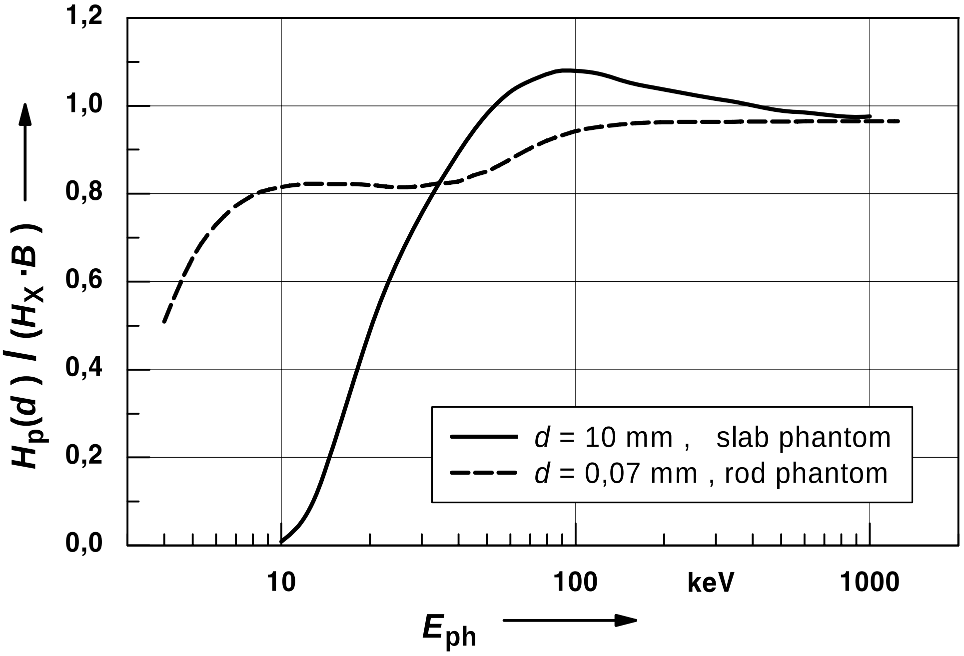


Fig. 4.4 (H_X) Quotients $H_p(d)/(H_X \cdot B)$ for d = 10 mm and a slab phantom (———) (GROSSWENDT, 1990, 1991) and d = 0,07 mm and a rod phantom (— — —) (GROSSWENDT, 1995a) for monoenergetic photon radiation as a function of the photon energy E_{ph}. B is the backscatter factor for the respective phantom.

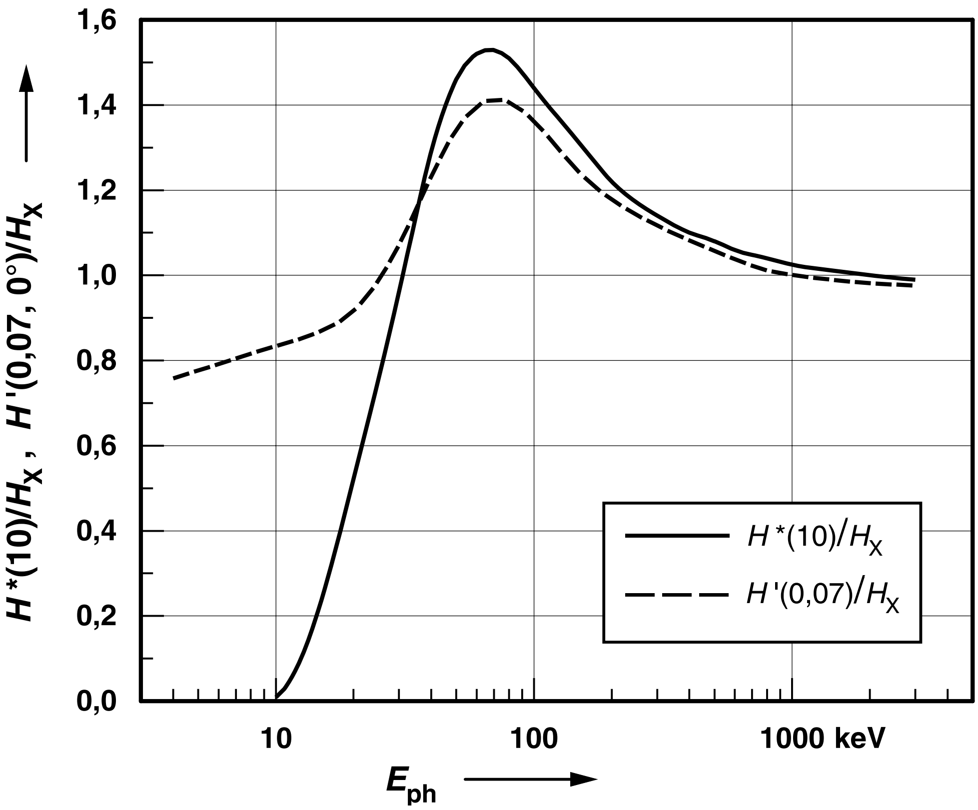


Fig. 4.5 (H_X) Quotients $H^*(10)/H_X$ (———) and $H'(0{,}07, 0°)/H_X$ (— — —) (ICRU, 1992) for monoenergetic photon radiation as a function of the photon energy E_{ph}.

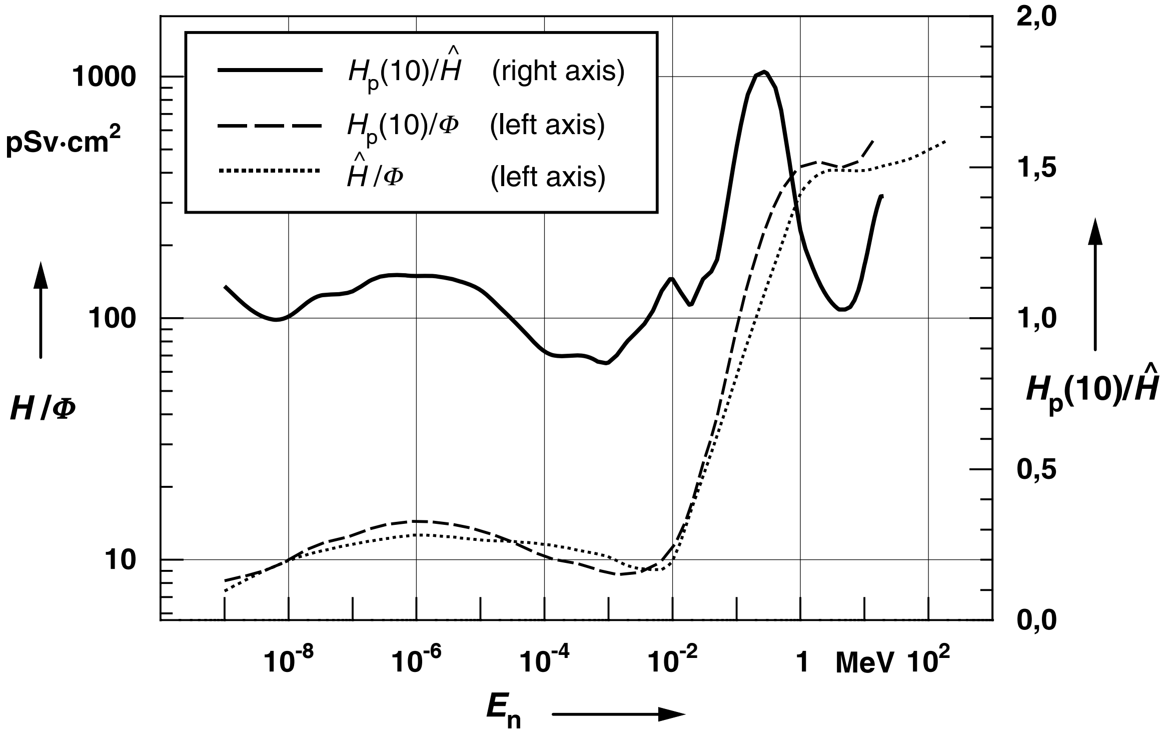


Fig. 4.6 Quotients $H_p(10)/\hat{H}$ (———), $H_p(10)/\Phi$ (— — —) and $\hat{H}/\Phi$ (· · · · · ·) for monoenergetic neutron radiation as a function of the neutron energy E_n.

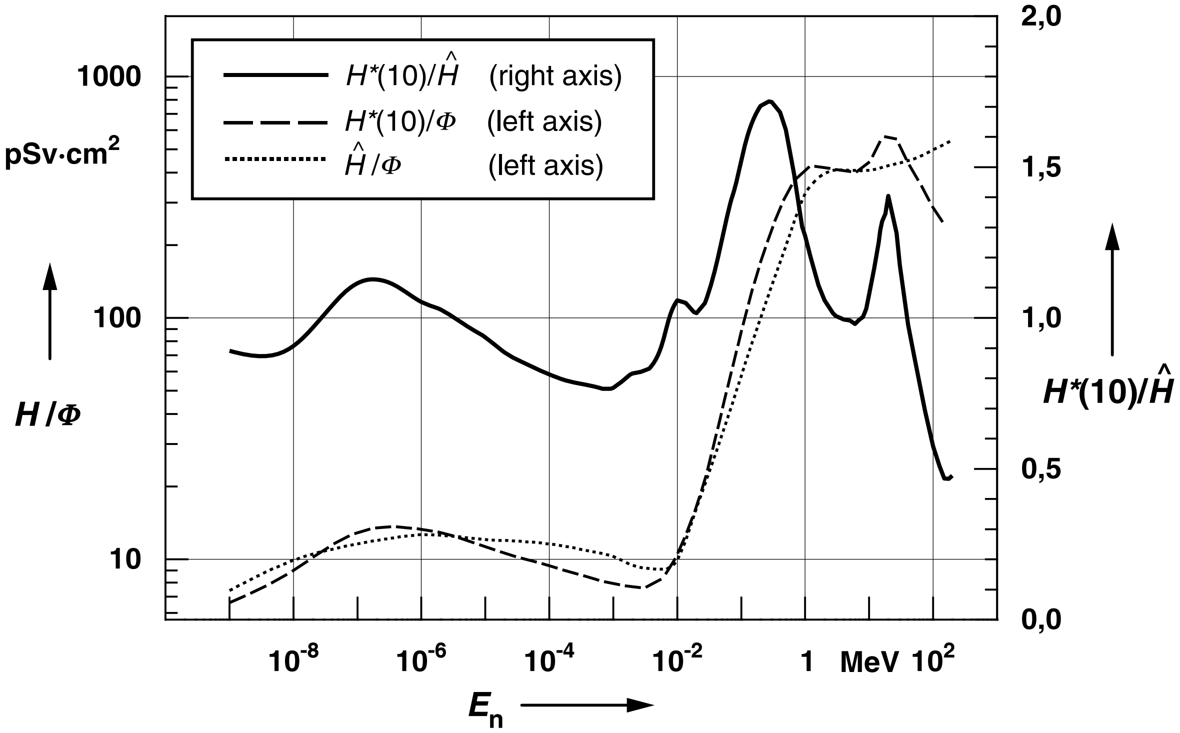


Fig. 4.7 Quotients $H^*(10)/\hat{H}$ (———), $H^*(10)/\Phi$ (— — —) and $\hat{H}/\Phi$ (· · · · ·) for monoenergetic neutron radiation as a function of the neutron energy E_n.

5 Impact on area monitoring

5.1 Measurements in area monitoring - what will change?

5.1.1 Preliminary remark

The impact of the transition to the new quantities for area monitoring applicable to all types of radiation will be different for the different types of radiation. Only in the case of photon radiation will substantial changes occur which will make themselves felt also with respect to mandatory verification. The transition will have practically no effects on beta radiation, and the effects will be only slight for neutron radiation.

As the area dosimeters designed to measure the photon dose equivalent and those designed to measure the ambient or directional dose equivalent will possibly furnish different measurement values in one and the same radiation field, it is necessary to indicate the quantity on the measuring instrument. Either the name (e.g. ‘ambient dose equivalent’) or the symbol (e.g. $H^*(10)$) can be indicated. This information must also be given in the documents accompanying the dosimeter. This requirement will be specified in the draft amending DIN 6818-1/A1 (DIN, 1994c). This applies in analogy to the statement of the measurement results.

When the new quantities are used, the value $H^*(10)$ will be stated for area monitoring for strongly penetrating radiation; for weakly penetrating radiation, the value $H'(0,07)$ will be stated and in rare cases the value $H'(3)$. If both strongly penetrating radiation and weakly penetrating radiation may occur at the same time, statement of the area dose will usually be by the pair of values $H^*(10)$ and $H'(0,07)$.

The inclusion of the term ‘aligned radiation field’ in the definition of the ambient dose equivalent $H^*(10)$ implies that the contribution to the dose equivalent at 10 mm depth in the ICRU sphere is assumed to be the same for all directions of radiation incidence. The same has been assumed for the quantity of photon dose equivalent hitherto used, however, the reason for this is different, namely the definition of the quantity without a phantom, i.e. free in air. Now as before, the reading of an ideal area dosimeter for strongly penetrating radiation must therefore be direction-independent, i.e. in an arbitrary radiation field the reading must not vary when the area dosimeter is rotated. As, in most cases, the measurement of the area dose for radiation protection purposes is to provide information on a potential future exposure to radiation whose directional distribution is unknown, this ‘conservative’ behaviour is desired. It means that the area dose overestimates both the personal dose and the effective dose.

For weakly penetrating radiation, the reading of area dosimeters for the new quantities $H'(0,07, \vec{\Omega})$ and $H'(3, \vec{\Omega})$ should be direction-dependent. In practice, the exposure of the skin is highest where there is predominantly normal radiation incidence. The area dosimeter must therefore be rotated until the maximum value is indicated. The associated orientation $\vec{\Omega}$ of the area dosimeter is part of the measured value which is to be stated in the form $H'(0,07, \vec{\Omega})$ or $H'(3, \vec{\Omega})$. In this report, we will do without the statement of $\vec{\Omega}$; $H'(0,07)$ and $H'(3)$ always denote the maximum value at the point of measurement, which is obtained when the area dosimeter is rotated. When area dosimeters are tested with monodirectional radiation, the angle α between the direction of incidence of the (test) radiation and the area dosimeter's reference direction is of importance. In this case, the quantity is denoted by $H'(0,07, \alpha)$ or $H'(3, \alpha)$.

Testing with monodirectional radiation is sometimes impossible, for example with beta radiation, because of the strong air scatter of the radiation. The angle α then is the angle between the main direction of incidence of the radiation (axis of the radiation field) and the reference direction of the area dosimeter.

In the following, reference will first be made to changes of the area dose of strongly penetrating radiation. Then the measurement of weakly penetrating radiation will be dealt with, and Section 5.1.6 will provide details of the influence of the directional distribution of the radiation. Neutron radiation is always considered to be of the strongly penetrating type, electron radiation (beta radiation) to be of the weakly penetrating type.

5.1.2 Changes in area monitoring of strongly penetrating photon radiation

For monoenergetic photon radiation, the ratio $H^*(10)/H_X$ is given in Table 5.1 (see also Fig. 4.5). The tabular values can be used, for example, for the gamma radiation of the radionuclides ^{137}Cs or ^{241}Am and for the almost monoenergetic X-ray fluorescence radiation in calibration radiation fields. Values of special radionuclides are given in Table 5.2. The values of $H^*(10)/H_X$ for gamma radiation of ^{137}Cs and ^{60}Co are 1,06 and 1,02, respectively, and are thus close to unity. In the case of ^{241}Am, there is a significant increase in the values measured for $H^*(10)$ compared with those obtained for H_X (by 48%).

In most applications the spectral distribution of the radiation field has to be considered. Corresponding quotients were calculated for some photon fluence spectra (KRAMER *et al.*, 1994), taking the quotients $H^*(10)/H_X$ for monoenergetic photon radiation as a basis (Table 5.1). As can be gathered from Table 5.2 (gamma radiators), Table 5.3 (X-ray fields used for calibration) and Table 5.4 (radiation fields found in practice), the quotient $H^*(10)/H_X$ usually deviates from unity by not more than 10%. In the most important field of application of X-ray radiation, the deviations can, however, be as high as 50% (KRAMER *et al.*, 1994).

Whereas the values measured by two ideal dosimeters differ to the same extent as do the values of the dosimetric quantities themselves, the situation is quite different in practice when radiation protection dosimeters with energy-dependent response are used.

When one sticks to the response's greatest variation with photon energy permissible within the framework of the Verification Ordinance - which is ±30 % for the respective quantity - , dosimeters are imaginable which meet the requirements for the energy dependence for both quantities, with the reading remaining unchanged. Such a dosimeter indicates, of course, the same dose value in every radiation field, independent of which dose equivalent quantity is considered to be the quantity to be measured.

The differences between two readings will be greatest when - in the other extreme case - a dosimeter for H_X whose response to H_X is too low by 30% in the energy range around the maximum of the quotient $H^*(10)/H_X$ (at approximately 65 keV), is compared with a dosimeter for $H^*(10)$ whose response with regard to $H^*(10)$ is too high by 30% in the same energy range. Under these especially unfavourable conditions and in a radiation field with an unfavourable spectral energy distribution, differences between the readings of the two dosimeters of up to a factor 2,8 are to be expected. A factor of 1,52 is to be attributed to the variation of the quantities; the second factor, 1,86, follows from the ratio 1,3/0,7, the greatest upward or downward deviation in the case of energy dependence.

Table 5.1 (H_X) Quotients $H^*(10)/H_X$ and $H'(0{,}07,\ 0°)/H_X$ for monoenergetic photon radiation. The values were calculated using the approximate formula stated in Section 5.2.2 and used in ICRU Report 47 (ICRU, 1992) (with the exception of the values for $H^*(10)/H_X$ below 20 keV and the values of $H'(0{,}07,\ 0°)/H_X$ above 50 keV).

Photon energy in keV	$H^*(10)/H_X$	$H'(0{,}07,\ 0°)/H_X$
10	0,01	0,83
15	0,23	0,87
20	0,54	0,92
30	0,96	1,07
40	1,29	1,24
50	1,46	1,34
60	1,53	1,40
80	1,51	1,41
100	1,45	1,36
150	1,31	1,24
200	1,23	1,18
300	1,15	1,11
400	1,11	1,07
500	1,08	1,05
600	1,06	1,04
800	1,04	1,01
1000	1,03	1,00
1500	1,01	0,99

Table 5.2 ($\boldsymbol{H_X}$) Quotient of the ambient dose equivalent $H^*(10)$ and the photon dose equivalent H_X for the photon radiation of some radionuclides. Only photon energies above 20 keV have been taken into consideration.

Nuclide	Half-life	Important photon energies in MeV	$H^*(10)/H_X$
^{24}Na	15,0 h	1,37 2,75	1,04
^{60}Co	5,27 a	1,17 1,33	1,02
^{124}Sb	60 d	0,60 to 2,09	1,04
^{131}I	8,02 d	0,08 to 0,72	1,11
^{137}Cs	30 a	0,66	1,06
^{182}Ta	114 d	0,06 to 1,23	1,03
^{192}Ir	74 d	0,30 to 0,61	1,12
^{226}Ra and progenies	1600 a	0,19 to 2,4	1,05
^{241}Am	458 a	0,06	1,48

Table 5.3 (H_X) Quotients $H^*(10)/H_X$ and $H'(0{,}07, 0°)/H_X$ for photon radiation fields used for calibration and for the determination of the energy dependence of the response. Values are taken from ISO (1996) with the exception of those fields only described by DIN radiation qualities (DIN, 1992a).

	Radiation quality, symbol according to DIN (1992a)	ISO (1996)	Mean energy in keV	$H^*(10)/H_X$	$H'(0{,}07, 0°)/H_X$
Narrow spectra	A 10	N-10	8	0,0006 [1)]	0,80
	A 15	N-15	12	0,05 [1)]	0,84
	A 20	N-20	16	0,25 [1)]	0,88
	-	N-25	20	0,46 [1)]	0,90
	A 30	N-30	24	0,70	0,96
	A 40	N-40	33	1,04	1,10
	A 60	N-60	48	1,39	1,30
	A 80	N-80	65	1,52	1,40
	A 100	N-100	83	1,50	1,39
	A 120	N-120	100	1,44	1,36
	A 150	N-150	118	1,39	1,31
	A 200	N-200	164	1,28	1,22
	A 250	N-250	208	1,22	1,17
	A 300	N-300	250	1,18	1,14
Wide spectra	B 10	-	8	0,0006 [1)]	0,80
	B 15	-	12	0,05 [1)]	0,84
	B 20	-	16	0,27 [1)]	0,88
	B 30	-	23	0,68	0,94
	B 40	-	31	0,86	1,04
	B 60	W-60	45	1,31	1,25
	B 80	W-80	57	1,46	1,35
	B 110	W-110	79	1,50	1,40
	B 150	W-150	104	1,42	1,34
	B 200	W-200	137	1,33	1,26
	B 250	W-250	173	1,26	1,20
	B 300	W-300	208	1,22	1,17
High air kerma rate spectra	C 10	H-10	7,5	0,0001 [1)]	0,78
	C 20	H-20	12,9	0,08 [1)]	0,84
	C 30	H-30	19,7	0,33 [1)]	0,89
	C 40	-	25	0,61	1,02
	C 60	H-60	37,3	1,01	1,11
	C 80	-	49	1,23	1,31
	C 100	H-100	57,4	1,38	1,31
	C 150	-	78	1,46	1,38
	C 200	H-200	102	1,41	1,32
	C 250	H-250	122	1,35	1,28
	-	H-280	146	1,31	1,24
	C 300	H-300	147	1,30	1,24

[1)] The quotient must be determined separately for the respective irradiation device; see Section 5.2.2.

Table 5.4 (H_X) Quotient $H^*(10)/H_X$ for some typical photon radiation fields

Radiation field	$H^*(10)/H_X$
Environmental radiation	1,07
Radiation field after contamination due to a reactor accident	1,06 bis 1,10
Radiation field in nuclear reactor	1,03
^{16}N gamma radiation(6 MeV)	0,97
Leakage radiation through the housing of an X-ray tube	up to 1,5
Radiation of ^{192}Ir behind 5 cm lead shield	1,06
20 MeV bremsstrahlung behind 1,7 m concrete	0,98

5.1.3 Changes in area monitoring of weakly penetrating photon radiation

For monoenergetic photon radiation, the quotient $H'(0{,}07{,}0°)/H_X$ has been stated in Fig. 4.5 and in Table 5.1. In the range from 10 keV to 30 keV, the quotient deviates from unity by less than 20 %; in the range from 30 keV to 200 keV, the deviation is up to + 40 %. The angular dependence of the area dosimeter reading must be taken into account in addition, see Section 5.1.6.

5.1.4 Changes in area monitoring of neutron radiation

For monoenergetic neutron radiation, the quotient $H^*(10)/\hat{H}$ has been indicated in Fig. 4.7. For the radiation fields with broad energy distribution usually found in practice, the quotient's deviations from unity are not as pronounced as for monoenergetic neutrons at certain energies. Table 5.5 lists the quotient $H^*(10)/\hat{H}$ for some calibration radiation fields and for radiation fields occurring in practice.

Table 5.5 Quotient $H^*(10)/\hat{H}$ (see Section 3.4 for $\hat{H}$) for some typical neutron radiation fields

Radiation field	$H^*(10)/\hat{H}$
^{252}Cf- fission neutrons	1,14
^{252}Cf (D_2O- moderated neutrons)	1,15
Am-Be(α,n) neutron source	1,05
Neutron radiation fields in the nuclear reactor	1,2 to 1,3
Neutron radiation fields at fuel element shipping casks	1,4 to 1,5
Neutron component of cosmic radiation (sea level)	1,3

5.1.5 Changes in area monitoring of beta radiation

With the quantities $H'(0{,}07)$ and $H'(3)$, clearly defined area dose quantities for beta radiation are now available. It should be noted that, in contrast to photon radiation, the quotients $H'(0{,}07,\alpha)/H'(0{,}07, 0°)$ and $H'(3,\alpha)/H'(3, 0°)$ have a maximum in a wide energy range when there is oblique radiation incidence (see Fig. 5.2, Fig. 5.3 and Table 5.6).

Calibration certificates for secondary beta standards have so far stated - in addition to other quantities - the absorbed dose in ICRU tissue on the surface of a semi-infinitely expanded phantom made of ICRU tissue, and the depth dose curve. The value of the absorbed dose in tissue at 0,07 mm depth calculated from this is equal to $H'(0{,}07{,}0°)$. In addition, the angular dependence of the reading of the area dosimeter must be taken into account, see Section 5.1.6.

5.1.6 Influence of the directional distribution for weakly penetrating radiation

As the radiation is absorbed in the layer in front of the point of reference, the value of the dose equivalent at a depth of 0,07 mm in the ICRU sphere depends on the direction of radiation incidence on the sphere in relation to the specified radius vector (see Section 4.2). Information on the ratio $H'(0{,}07,\alpha)/H'(0{,}07, 0°)$ for photon radiation is given in Fig. 5.1, α denoting the angle between the direction of incidence of the (test) radiation and the reference direction (see Section 5.1.1). The reading of area dosimeters for the measurement of $H'(0{,}07)$ should exhibit a corresponding directional dependence.

Fig. 5.2 shows values of $H'(0{,}07,\alpha)/H'(0{,}07, 0°)$, and Fig. 5.3 values of $H'(3,\alpha)/H'(3, 0°)$ for electron radiation. Due to air scattering, test radiation fields always show a more or less broad angular distribution of the beta particles, and the angle α indicates the main direction of incidence of the beta radiation. Table 5.6 states the values of $H'(0{,}07,\alpha)/H'(0{,}07, 0°)$ for three beta radiators with compensation filter according to the standard ISO 6980, which are part of the PTB's secondary beta standard (HELMSTÄDTER and BÖHM, 1992).

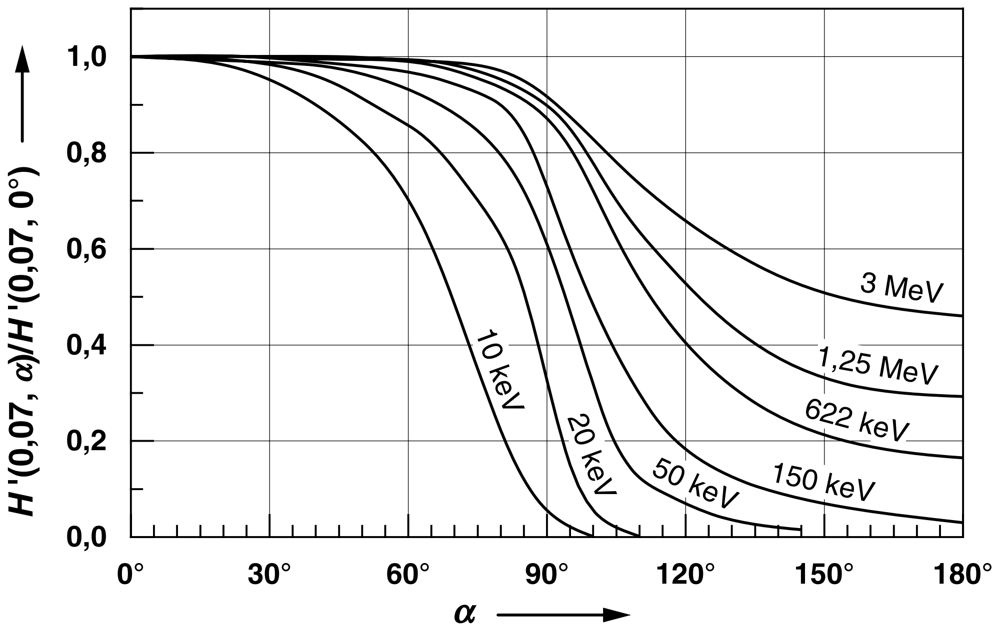


Fig. 5.1 Change of the ratio $H'(0{,}07,\alpha)/H'(0{,}07, 0°)$ with the direction of incidence, α, of monodirectional and monoenergetic photon radiation on the ICRU sphere (GROSSWENDT und HOHLFELD, 1982). The photon energy is the parameter of the different curves.

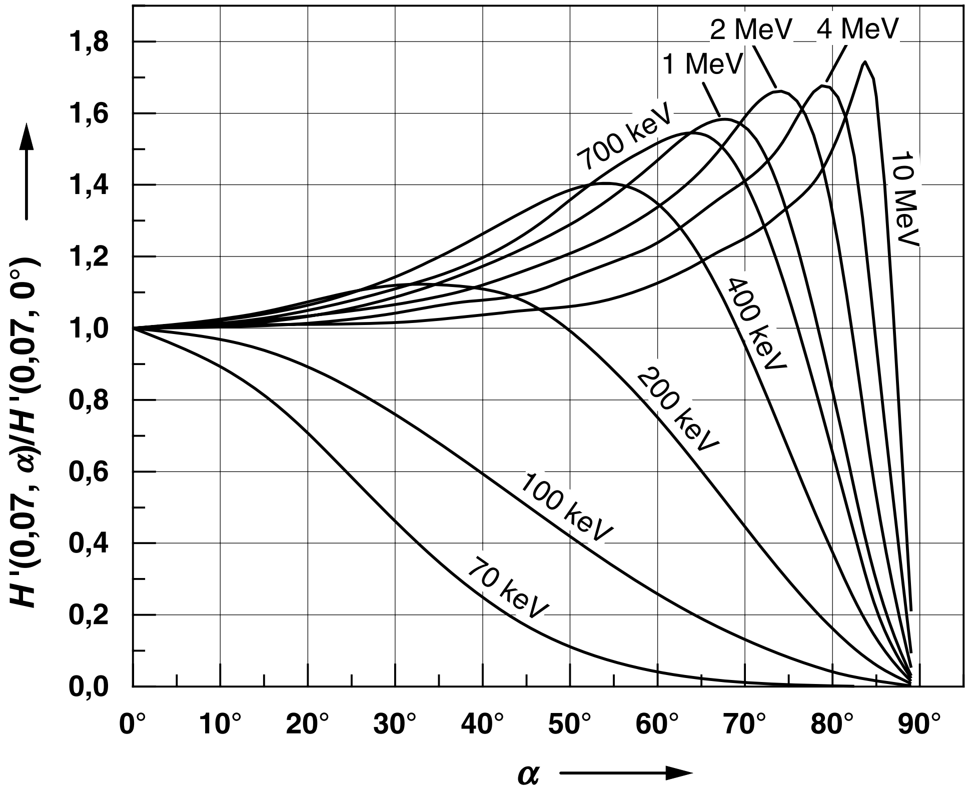


Fig. 5.2 Change of the ratio $H'(0{,}07, \alpha)/H'(0{,}07, 0°)$ with the direction of incidence, α, of monodirectional and monoenergetic electron radiation on the ICRU sphere (GROSSWENDT und CHARTIER, 1994). The electron energy is the parameter of the different curves.

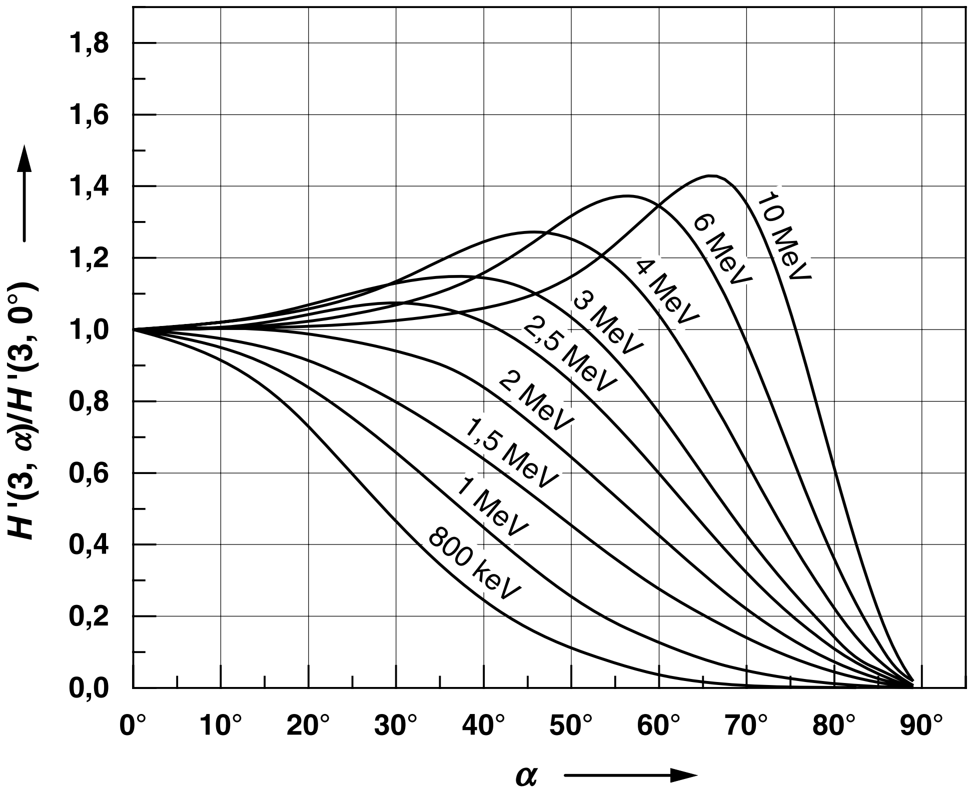


Fig. 5.3 Change of the ratio $H'(3, \alpha)/H'(3, 0°)$ with the direction of incidence, α, of monodirectional and monoenergetic electron radiation on the ICRU sphere (GROSSWENDT und CHARTIER, 1994). The electron energy is the parameter of the different curves.

Table 5.6 Quotient $H'(0{,}07,\ \alpha)/H'(0{,}07,\ 0°)$ for three sources of the PTB's secondary beta standard with beam-flattening filter.

Angle of incidence α in degrees	**$H'(0{,}07,\ \alpha)/H'(0{,}07,\ 0°)$ for the beta-ray source** $^{90}Sr + ^{90}Y$	^{204}Tl	^{147}Pm
0	1,00	1,00	1,00
15	1,01	0,99	0,98
30	1,05	0,96	0.84
45	1,12	0,90	0,69
60	1,15	0,73	-
75	0,89	0,50	-

5.2 Calibration of area dosimeters and measurement of the energy dependence of the response

5.2.1 Conventional true value of the ambient dose equivalent and the directional dose equivalent

The *calibration* of a dosimeter is the establishment of the relationship between the reading of the dosimeter and the *conventional true value* (the value regarded as true) *of the measurand*. Within the scope of the calibration, the calibration factor is determined or checked. The *calibration factor* is the ratio of the conventional true value of the measurand and the reading under *reference conditions*. The reference conditions specify the values of the influence quantities for which the calibration factor is valid without corrections. In general, a calibration factor with the value unity under reference conditions is aimed at. Manufacturers of area dosimeters for photon radiation usually achieve this by an adjustment which eliminates a systematic measurement error. When photon dosimeters are examined and tested for the purpose of verification, it is checked above all whether the maximum permissible errors on verification are complied with. Knowledge of the conventional true value is necessary for these procedures.

The calibration factor must be clearly distinguished from the *response* of a dosimeter, which is the ratio of the reading and the conventional true value of the measurand. The calibration factor is the reciprocal value of the response under reference conditions.

For the new dosimetric quantities for photon and neutron radiation, the conventional true value, i.e. the best approximation to the true value, is not determined with a primary standard as is common practice with most physical quantities, but derived from other dose quantities or radiation field quantities using conversion coefficients. Only for beta radiation is the directional dose equivalent determined using an extrapolation chamber as the primary standard device.

For photon radiation, it would basically be possible to adapt existing primary standard measuring devices for the absorbed dose in water to the reference conditions for the area dose quantities.

However, the overall uncertainty of measurement achievable is not superior to that of the method employed today. The primary standard measuring devices for the air kerma and the photon dose equivalent (identical with those for the exposure), and those for the neutron fluence in the case of neutron radiation, have been well established for a long time. The conversion coefficients for monoenergetic radiation mainly obtained from Monte Carlo calculations are laid down by international agreement as values to which no uncertainty is assigned.

5.2.2 Calibration and determination of the energy dependence of the response for photon radiation

The values for the quotients $H^*(10)/H_X$ and $H'(0{,}07)/H_X$ stated in the following are based on the photon dose equivalent or the air kerma measured in the calibration radiation field. These quantities are measured correctly only at secondary electron equilibrium. For photon radiation with energies of up to 400 keV, this is ensured when free-air chambers are used as primary standard measuring devices; the calibration factor of calibrated standard dosimeters takes the condition of secondary electron equilibrium into account.

At higher photon energies, secondary electron equilibrium free in air is no longer achieved due to the electrons' wide range. For example, the range of an electron in air released with the highest impartable energy during a Compton process of ^{60}Co gamma radiation is approximately 4 m. The photon dose equivalent (and the air kerma) are therefore measured with graphite cavity chambers whose wall thickness is sufficient to allow the dose to build up and thus secondary electron equilibrium to be established. This is also possible in high-energy photon radiation fields of up to 6 MeV.

In dosimeters for routine use, secondary electron equilibrium is not reached in the sensitive detector volume. In some cases, the detector wall or detector sheath is not thick enough to allow the dose to build up - a prerequisite for secondary electron equilibrium. In photon radiation fields with different proportions of secondary electrons, dosimeters of this type will furnish different readings. Reproducible results can be obtained by providing the detector with a pre-layer which, together with the wall material and the sheath, has a mass per unit area which is larger than the range of the secondary electrons with the highest energy. Experience has shown that no pre-layers are required for photon energies below 250 keV. Up to 0,66 MeV, a layer made of polymethyl methacrylate (PMMA, e.g. Plexiglas©), 1,5 mm thick, has proved to be sufficient, and up to 1,33 MeV a PMMA layer 4 mm thick. Only if these pre-layers are used can calibrations in different radiation fields be compared.

The quotients $H^*(10)/H_X$ for the conversion of the photon dose equivalent H_X into the ambient dose equivalent $H^*(10)$ are listed in Table 5.3 for the photon radiation qualities used for calibrations. For calibrations in terms of the directional dose equivalent, the quotients $H'(0{,}07)/H_X$ for monoenergetic photon radiation for perpendicular radiation incidence can be gathered from Table 5.1; the quotients for the radiation qualities mostly used for the determination of the energy dependence are given in Table 5.3.

Calibrations are carried out without a phantom. The reference point of the area dosimeter to be calibrated is placed in the location for which the conventional true value of the photon dose equivalent is known. This value is multiplied by the quotient $H^*(10)/H_X$ or $H'(0{,}07)/H_X$ and compared with the reading. The quotients are to be selected for the spectra existing in the individual case.

Special care in the calculation of the quotient $H^*(10)/H_X$ is necessary in photon radiation fields in the photon energy range below approximately 20 keV, since the quotient's energy dependence is very strong in this range. As a result, even with nominally equal radiation quality at different irradiation facilities, the quotients may be different (due, for example, to different tube windows and an air-pressure-dependent hardening of the beam in the air layer between radiation source and dosimeter) and must therefore be determined separately.

The quotients $H^*(10)/H_X$ and $H'(0{,}07)/H_X$ allow the photon dose equivalent to be directly converted into the new quantities. If the air kerma or the ‘Standard-Ionendosis’ (exposure) is the reference quantity, the relationship between the photon dose equivalent and the air kerma or ‘Standard-Ionendosis’ furnishes the following quotients:

$$H^*(10)/K_a = c_1 \cdot H^*(10)/H_X \qquad \text{with } c_1 = 1{,}14 \text{ Sv/Gy}$$

$$H^*(10)/J_s = c_2 \cdot H^*(10)/H_X \qquad \text{with } c_2 = 0{,}01 \text{ Sv/R}$$

The conversions are analogous for $H'(0{,}07)/H_X$.

ICRU Report 47 (ICRU, 1992) states for the quotients $H^*(10)/K_a$ and $H'(0{,}07)/K_a$ the approximate formulas established by WAGNER *et al.* (1985) to simplify numerical calculations (the unit of $H^*(10)/K_a$ or $H'(0{,}07)/K_a$ is Sv/Gy, E is to be inserted in keV and the arctan in radians):

$$H^*(10)/K_a = x/(ax^2+bx+c) + d \arctan(gx)$$

with $x = \ln(E/E_0)$, $20 \text{ keV} < E < 10 \text{ MeV}$, $E_0 = 9{,}85$ keV,
a = 1,465 , b = -4,414, c = 4,789,
d = 0,7006 and g = 0,6519.

$$H'(0{,}07)/K_a = a + bx + c\, x^d \exp(gx^2)$$

with $x = \ln(E/E_0)$, $10 \text{ keV} < E < 250 \text{ keV}$, $E_0 = 9{,}85$ keV,
a = 0,9505, b = 0,09432, c = 0,2302
d = 5,082 and g = -0,6997.

5.2.3 Calibration and determination of the energy dependence of the response for neutron radiation

The practice usually followed with neutrons, i.e. to calibrate area dosimeters in terms of neutron fluence and to ensure calibration in terms of the dose equivalent quantity using conversion coefficients $h_\Phi = H/\Phi$ for monoenergetic neutrons, is not affected by the introduction of the new quantities. This applies also to the determination of the energy dependence of the response. The area dosimeter is placed in the location for which the conventional true value of the neutron fluence is known. This value is multiplied by the quotient calculated for the respective neutron spectrum,

$$h_\Phi = \frac{\int h_\Phi(E) \cdot \Phi_E(E) dE}{\int \Phi_E(E) dE}$$

(E: neutron energy, $\Phi_E(E)$: spectral neutron fluence) and compared with the reading of the measuring instrument. When the calibration factor in terms of the quantity $\hat{H}$ hitherto used is converted into the calibration factor in terms of the new quantity $H^*(10)$, attention must be paid to the fact that the fluence-to-dose-equivalent conversion coefficient $\hat{h}_\Phi$ or. h^*_Φ valid for the respective neutron spectrum must be calculated separately for both quantities.

The response R_H is calculated from the measured value M to be $R_H = M/H^*(10)$. R_H is frequently also calculated on the basis of the fluence response $R_\Phi = M/\Phi$, according to the equation $R_H = R_\Phi / h^*_\Phi$. When values of R_Φ are available for an instrument, R_H in terms of the new quantity can be directly calculated from the conversion coefficients of Fig. 4.7.

5.2.4 Calibration and determination of the energy dependence of the response for beta radiation

For the calibration and the determination of the energy dependence of the area dosimeters' response, beta radiators of the radionuclides ^{147}Pm, ^{204}Tl and ^{90}Sr/^{90}Y (maximum energies: 224 keV, 764 keV and 2281 keV) are mainly used. If possible, point sources are employed. Special compensation filters consisting of thin foils (see Draft ISO Standard 6980 (ISO, 1993)) are placed between the point source and the area dosimeter to be calibrated to achieve as homogeneous a beta radiation field as possible. The value of the directional dose equivalent is usually determined with an extrapolation chamber.

5.3 Will new area dosimeters be required?

5.3.1 Preliminary remark

There are two replies to the question of whether new area dosimeters will be required.

As it is permissible to apply the quantities hitherto used, e.g. the photon dose equivalent, during a prolonged transition period, the use of area dosimeters at present in use can be continued.

It will be discussed in detail in the following Sections to what extent the new quantities are ‘correctly’ measured by the area dosimeters at present in use. As regards photon radiation, new dosimeters will have to be developed for the most part to meet future pattern approval requirements.

5.3.2 Changes for the area dosimeters for photon radiation

Requirements to be met by radiation protection dosimeters have been laid down in the standards of the DIN 6818 series. The tests for pattern approval for verification are carried out according to the criteria specified in Appendix 23 (BMWI, 1992) to the Verification Ordinance. For the time being, the above requirements still relate to the quantity ‘photon dose equivalent’, but they will be converted to the new quantities in the near future. As regards the radiological requirements to be met, above all those concerning the energy dependence of the response are of importance; for the directional dose equivalent, those of the directional dependence are also important.

With the introduction of the new quantities, requirements concerning the quantity ‘directional dose equivalent’ will be formulated for the first time. It is difficult to say whether, in practice, this will strongly affect the radiation protection dosimeters submitted for pattern approval. The energy range in which this quantity is significant is at present hardly covered by the rated range of use of approved area dosimeters for photon radiation. International standardization pursued by IEC (IEC, 1994) and ISO (ISO, 1995a) already incorporates the directional dose equivalent $H'(0{,}07)$ into the standards at present under discussion. Corresponding conclusions will have to be drawn for DIN standards and the PTB pattern requirements. This means that new measuring instruments will be required if the range of application is to be covered.

As regards the ambient dose equivalent $H^*(10)$, it follows from what has been said above concerning the difference between H_X and $H^*(10)$ that one and the same dosimeter will be able to fulfil the requirements for the energy and directional dependence of the response only in exceptional cases.

If it is assumed that the maximum permissible relative change of the response with the energy continues to be ± 30% for the new quantities, the measured response with regard to the ambient dose equivalent or the directional dose equivalent must remain within the band between 0,7 and 1,3 if it is plotted against the photon energy. Fig. 5.4 shows corresponding examples.

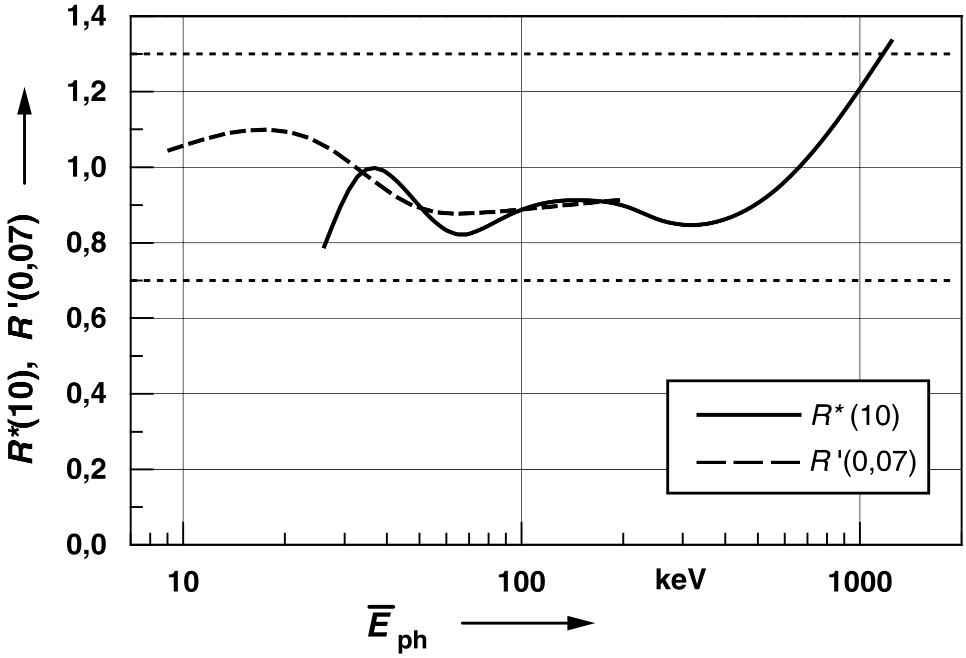


Fig. 5.4 Examples of the energy dependence of the response $R^*(10)$ to the ambient dose equivalent, and of $R'(0{,}07)$ to the directional dose equivalent. $\overline{E}_{ph}$ is the mean photon energy of the test radiation. Plotted are the curves for a proportional counter tube dosimeter (for $R^*(10)$) and an ionization chamber dosimeter with thin chamber wall (for $R'(0{,}07)$). The permissible limits of the energy dependence of ± 30 % have also been indicated.

Considering physical aspects and the experience gained so far, it should not be difficult to construct dosimeters which have been optimized for the new quantities as regards energy dependence. As regards the ambient dose equivalent, the detectors will have to approximately simulate the attenuation of a layer of ICRU tissue-equivalent material 10 mm thick. As the majority of the detectors is provided with a wall or with an insensitive outer layer (shielding), optimization is simpler than has hitherto been the case and will make it possible to fulfil the requirement for energy dependence down to lower photon energies. In addition, attention must be given to the effect of the scatter (here: above all the backscatter) by the ICRU sphere, which leads to excessive values at ‘mean’ photon energies (see curve in Fig. 4.5). For most detectors, materials with an effective atomic number higher than that of the ICRU material are used. Due to the higher proportion of the photoelectric effect as compared with the ICRU material, these materials furnish the desired excessive values of the response in the range of the ‘mean’ photon energies. Dosimeters equipped with detectors of this type are better suited to measure the ambient dose equivalent than the photon dose equivalent H_X. The modification of the energy dependence by means of filters, as is customary above all with counter tubes, must be slightly changed compared with what has been common practice to date (SELBACH *et al.*, 1984).

The above considerations apply in analogy to area dosimeters for photon radiation intended for the measurement of the directional dose equivalent. The layer thickness is 0,07 mm in this case, compared with 10 mm for the ambient dose equivalent.

A survey of the properties of radiation protection dosimeters equipped with different types of detectors is given in ICRU Report 47 (ICRU, 1992).

In summary, it can be stated that new patterns of measuring instruments will be required for area monitoring. It should not, however, be difficult to modify former designs in such a way that the new requirements will be met.

5.3.3 Changes for area dosimeters for neutron radiation

Area dosimeters for neutron radiation are usually neutron fluence measuring instruments in which the energy dependence of the fluence response has been approximated as far as possible to that of the fluence-to-dose-equivalent conversion coefficient, either by constructional measures or, occasionally, by the method adopted for the evaluation of the measurement results. The new quantity for the area dose does not alter this concept. The change in the numerical values of the fluence-to-dose-equivalent conversion coefficients only leads to a change in the calibration factors in the different calibration radiation fields. The transition alone to the new quantities will not make new measuring instruments necessary. Direction-independent response has been a requirement right up to the present. This applies, for example, to most of the portable rem counters.

No requirements have so far been specified for patterns of area dosimeters for neutron radiation; they are not subject to mandatory verification. International standards (e.g. IEC, 1990) prescribe that the energy dependence of the dose equivalent response must be known over the whole rated range of use of the energy. After the introduction of the new quantity, this requirement can be easily met with the aid of the fluence-to-dose-equivalent conversion coefficients which will then be valid (see Fig. 4.7). With most dosimeters commonly used, this energy dependence is so strong that it will not be substantially changed by the new quantity. A change of the reading (if at all necessary) by recalibration does not present any problems.

5.3.4 Changes for area dosimeters for beta radiation

Up to now, area dosimeters for beta radiation have been calibrated so that they measure the absorbed dose in tissue at 0,07 mm depth in a semi-infinite phantom. With the new quantities $H'(0{,}07)$ and $H'(3)$, the shape of the phantom will in fact be modified; because of the small range of the beta particles, the influence on the value measured at a depth of 0,07 mm will be negligible. The depth of 3 mm makes, however, modifications of the measuring instruments necessary, in the simplest case by the provision of a suitable pre-layer. The directional dependence of the area dosimeter reading required for $H'(0{,}07)$ and $H'(3)$ is likely to facilitate the design of these dosimeters.

6 Impact on individual monitoring

6.1 Measurement in individual monitoring - what will change?

6.1.1 Preliminary remark

In the measurement of the personal dose, much will remain unchanged when the new quantities are introduced. The measurement point will remain a location on the body surface representative of the radiation exposure. This will not even be changed by the fact that, now as before, the dosimeter measures on the surface of a person's body while the measured value will in future be related to a dose at 10 mm or 0,07 mm depth inside the person.

There will be a substantial difference as regards calibration. Personal dosimeters will in future be calibrated on a phantom (see also Section 7.3.2). A water slab phantom will have to be used for whole-body dosimeters and a finger phantom made of PMMA for finger dosimeters (see Section 6.2.1). In contrast to what has been usual up to now, the values of all types of radiation measured with the personal dosimeters will in future be stated in uniformly defined quantities, i.e. the *dose equivalent in ICRU soft tissue at a depth of 10 mm and 0,07 mm in the body at the location where the personal dosimeter is worn; the quantities are denoted by* $H_p(10)$ *and* $H_p(0,07)$ *respectively*.

This definition takes the following aspects into account:

1. Now as before, the personal dose is defined individually, in relation to the body of the exposed person. Due to the different scatter and absorption of radiation in the bodies of different persons, the personal dose in the same external radiation field differs from one person to the other. However, by specifying appropriate phantoms (see Section 6.2.1), uniform conditions have been created for the calibration of personal dosimeters, which correspond to the most important locations on the body (trunk, finger) where the dosimeter is worn.
2. The personal dose is defined at different depths in the exposed person. $H_\mathrm{p}(10)$ and $H_\mathrm{p}(0,07)$ estimate the effective dose and the skin dose relevant for radiation protection. The depth to which a personal dosimeter must have been adapted depends on the penetration of the radiation. For strongly penetrating radiation it is 10 mm (for whole-body dosimeters), for weakly penetrating radiation it is 0,07 mm (for partial-body dosimeters).

The results of individual monitoring have so far been stated separately according to the types of radiation to which the persons were exposed. In future, the personal dose of strongly penetrating radiation will normally be indicated by the value $H_\mathrm{p}(10)$ measured on the trunk, that of weakly penetrating radiation by the value $H_\mathrm{p}(0,07)$ measured on the extremities. If strongly and weakly penetrating radiation occurs simultaneously, the personal dose will be given by the pair of $H_\mathrm{p}(10)$ and $H_\mathrm{p}(0,07)$, normally measured at different locations on the body surface. Dose components of different types of radiation at the same depths are added up. It may, however, be useful also in future to indicate the type of radiation to obtain information about the sources of exposure, for example for the calculation of body doses. If different measuring methods are applied to obtain the measurement value, as is, for example, the case with photon and neutron radiation, this additional information should be given also in future.

$H_\mathrm{p}(3)$ is to be stated in special cases, for example if the body dose limit for the lens of the eye might be exceeded. It can, however, normally be assumed that - as a result of the limits set to $H_\mathrm{p}(10)$ and $H_\mathrm{p}(0,07)$ - the lens of the eye is also sufficiently protected.

In contrast to the area dose $H^*(10)$, the personal doses $H_\mathrm{p}(10)$ and $H_\mathrm{p}(0,07)$ defined in the body (and in the phantoms as well) vary with the direction of radiation incidence (see also Section 6.1.5).

A personal dosimeter for the new quantities must approximate this directional dependence if possible. When personal dosimeters are tested with monodirectional radiation, the angle α between the direction of incidence of the (test) radiation and the reference direction of the personal dosimeter is of importance. In such tests, the quantity measured is denoted by $H_p(10, \alpha)$ or $H_p(0{,}07, \alpha)$. The angular dependence of the response must always be measured on the respective calibration phantom, with the phantom and the personal dosimeter being rotated simultaneously.

In the following, reference will first be made to changes in the measurement of the different types of radiation. Section 6.1.5 contains closer details of the influence of the directional distribution of the radiation. As has already been mentioned, neutron radiation is always considered to be strongly penetrating radiation whereas electron radiation (beta radiation) is regarded as weakly penetrating.

6.1.2 Changes in individual monitoring of photon radiation

As has been explained in Section 4.4 by Fig. 4.4, the photon dose equivalent H_X multiplied by the backscatter factor deviates only slightly from the new quantities in a wide energy range, i.e. the values measured by ideal personal dosimeters in terms of the quantity hitherto in use differ only slightly from those measured in the new quantities. A personal dosimeter which measures H_X independently of the direction and with low energy dependence of the response, and which also determines correctly the backscatter by the body of the person wearing the dosimeter, already takes into account the maximum of $H_p(10, 0°)/H_X$ at approximately 65 keV (see Fig. 6.1). This is demonstrated by the flat shape of the curve of the quotient $H_p(10, 0°)/(H_X{\cdot}B)$ at energies above about 40 keV (see solid curve in Fig. 4.4). Towards low energies this curve shows a steeply descending slope which is caused by the attenuation in the 10 mm thick layer of ICRU tissue in front of the reference point. This decrease must be taken into consideration in the dosimeter design by appropriate measures.

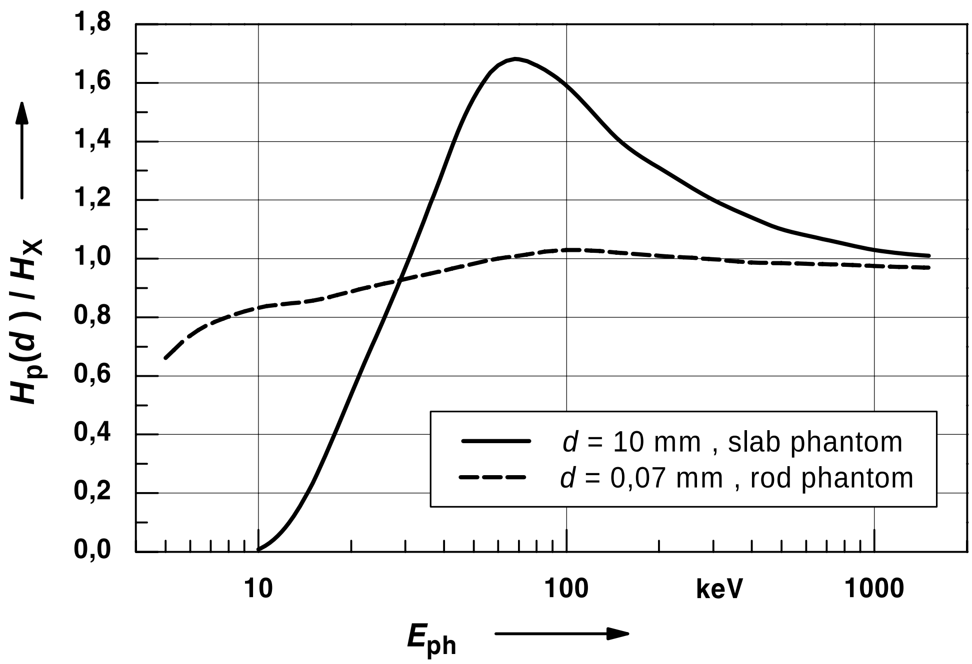


Fig. 6.1 (H_X) Energy dependence of the quotients $H_p(10)/H_X$ for the slab phantom (solid curve) (GROSSWENDT, 1991) and $H_p(0{,}07)/H_X$ for the rod phantom (dashed curve) (GROSSWENDT, 1995a) for monoenergetic and monodirectional photon radiation. E_{ph} photon energy.

For the calibration of dosimeters, the new quantities $H_p(10)$ and $H_p(0{,}07)$ are calculated from the photon dose equivalent determined free in air (i.e. without backscatter by a phantom) using conversion coefficients. Fig. 6.1 shows, for monoenergetic photon radiation, values of the quotient of $H_p(10, 0°)$ in the slab phantom (made of ICRU tissue) and the photon dose equivalent H_X free in air, $H_p(10, 0°)/H_X$; in addition, corresponding values of the quotient of $H_p(0{,}07, 0°)$ in the rod phantom (made of ICRU tissue) and the photon dose equivalent H_X free in air, $H_p(0{,}07, 0°)/H_X$, have been plotted (GROSSWENDT, 1995a). The quotients are listed in Table 6.1. From the values of this table for monoenergetic radiation, values of the quotient for X-ray spectra (DIN, 1992a) were calculated (GROSSWENDT, 1992, 1995b), which can be used for calibration and for determining the energy dependence of the response of personal dosimeters (Table 6.2).

In the case of $H_p(0{,}07)$, due to the thin finger phantom, the contribution of the backscattered photons to the quantity measured is small. This explains the small difference between the dashed lines in Figs. 4.4 and 6.1. The quotient $H_p(0{,}07, 0°)/H_X$ in Tables 6.1 and 6.2 is close to unity in a very wide photon energy range.

Table 6.1 (H_X) Quotients $H_p(10, 0°)/H_X$ for the slab phantom (GROSSWENDT, 1991) and $H_p(0{,}07, 0°)/H_X$ for the rod phantom (GROSSWENDT, 1995a) for a homogeneous broad beam of monoenergetic photons incident perpendicularly on the phantom surface.

Photon energy in keV	$H_p(10, 0°)/H_X$ for the slab phantom	$H_p(0{,}07, 0°)/H_X$ for the rod phantom
5	-	0,66
6	-	0,74
8	-	0,81
10	0,009	0,83
15	0,24	0,86
20	0,54	0,89
30	0,97	0,93
40	1,31	0,96
50	1,55	0,98
60	1,66	1,00
70	1,68	1,01
80	1,66	1,02
100	1,59	1,03
150	1,40	1,02
200	1,31	1,01
300	1,20	1,00
400	1,14	0,99
500	1,10	0,99
600	1,08	0,98
800	1,05	0,98
1000	1,03	0,98
1500	1,01	0,97

Table 6.2 ($\boldsymbol{H}_\mathrm{X}$) Quotients $H_\mathrm{p}(10, 0°)/H_\mathrm{X}$ for the slab phantom (GROSSWENDT, 1992) and $H_\mathrm{p}(0{,}07, 0°)/H_\mathrm{X}$ for the rod phantom (GROSSWENDT, 1995b) for radiation fields used for calibration and for determining the energy dependence of the response. Whenever possible, values for the mean energy are taken from ISO (1995a), otherwise from DIN 6818-1 (DIN, 1992a).

	Radiation quality, symbol according to DIN (1992a)	Radiation quality, symbol according to ISO (1995a)	Mean energy in keV	$H_\mathrm{p}(10, 0°)/H_\mathrm{X}$ for the slab phantom	$H_\mathrm{p}(0{,}07, 0°)/H_\mathrm{X}$ for the rod phantom
Narrow spectra	A 10	N-10	8	0,002 [1)]	0,80
	A 15	N-15	12	0,06 [1)]	0,84
	A 20	N-20	16	0,25 [1)]	0,86
	-	N-25	20	0,48 [1)]	0,88
	A 30	N-30	24	0,69	0,90
	A 40	N-40	33	1,03	0,94
	A 60	N-60	48	1,45	0,97
	A 80	N-80	65	1,65	1,00
	A 100	N-100	83	1,64	1,02
	A 120	N-120	100	1,58	1,03
	A 150	N-150	118	1,50	1,02
	A 200	N-200	164	1,37	1,01
	A 250	N-250	208	1,30	1,01
	A 300	N-300	250	1,25	1,00
Wide spectra	B 10	-	8	0,002 [1)]	0,79
	B 15	-	12	0,06 [1)]	0,83
	B 20	-	17	0,25 [1)]	0,85
	B 30	-	23	0,59	0,89
	B 40	-	31	0,88	0,92
	B 60	W-60	45	1,39	0,96
	B 80	W-80	57	1,56	0,98
	B 110	W-110	79	1,64	1,02
	B 150	W-150	104	1,55	1,02
	B 200	W-200	137	1,44	1,02
	B 250	W-250	173	1,35	1,01
	B 300	W-300	208	1,29	1,01
High air kerma rate spectra	C 10	H-10	7,5	0,001 [1)]	0,77
	C 20	H-20	12,9	0,08 [1)]	0,84
	C 30	H-30	19,7	0,35 [1)]	0,87
	C 40	-	25	0,62	0,90
	C 60	H-60	37,3	1,04	0,94
	C 80	-	49	1,35	0,97
	C 100	H-100	57,4	1,47	0,98
	C 150	-	78	1,58	1,01
	C 200	H-200	102	1,53	1,02
	C 250	H-250	122	1,46	1,02
	-	H-280	146	1,40	1,01
	C 300	H-300	147	1,38	1,01

1) The quotient must be determined separately for the respective irradiation facility; see Section 6.2.3.

6.1.3 Changes in individual monitoring of neutron radiation

As a rule, personal dosimeters for neutron radiation have up to now been calibrated on a phantom to ensure neutron backscatter corresponding to practice. The relevant quantity $\hat{H}$ was identical with that for the area dose and defined in a phantom. In future, $H_p(10)$ will bring about a change of the reference depth and - as regards calibrations - of the phantom. This manifests itself in modified values of the conversion coefficients $H_p(10)/\Phi$ for the calibration quantities (see Fig. 4.6). In view of the relatively strong energy dependence of the dose equivalent response of customary personal dosimeters, the changes will have only minor consequences in practice.

6.1.4 Changes in individual monitoring of beta radiation

The quantity for beta radiation has always been phantom-related, i.e. it has been defined for the reference depth in a tissue-equivalent medium considered to be representative of the skin's basal cells. This concept and the depth of 0,07 mm so far adopted have remained unchanged. Personal dosimeters have always been calibrated on a phantom (for example on a PMMA plate of saturation thickness for backscattered beta radiation). No significant differences are to be expected for the phantoms used in the future (see Section 6.2.1).

6.1.5 Taking into account the directional distribution of the radiation

Figs. 6.2 and 6.4 provide information on the ratio $H_p(10, \alpha)/H_p(10, 0°)$ in the slab phantom for monoenergetic and monodirectional photon and neutron radiation, respectively, of different energies as a function of the angle of incidence; Fig. 6.3 shows corresponding curves of $H_p(0{,}07, \alpha)/H_p(0{,}07, 0°)$ in the rod phantom for photon radiation. Personal dosimeters should exhibit corresponding directional dependences of the response.

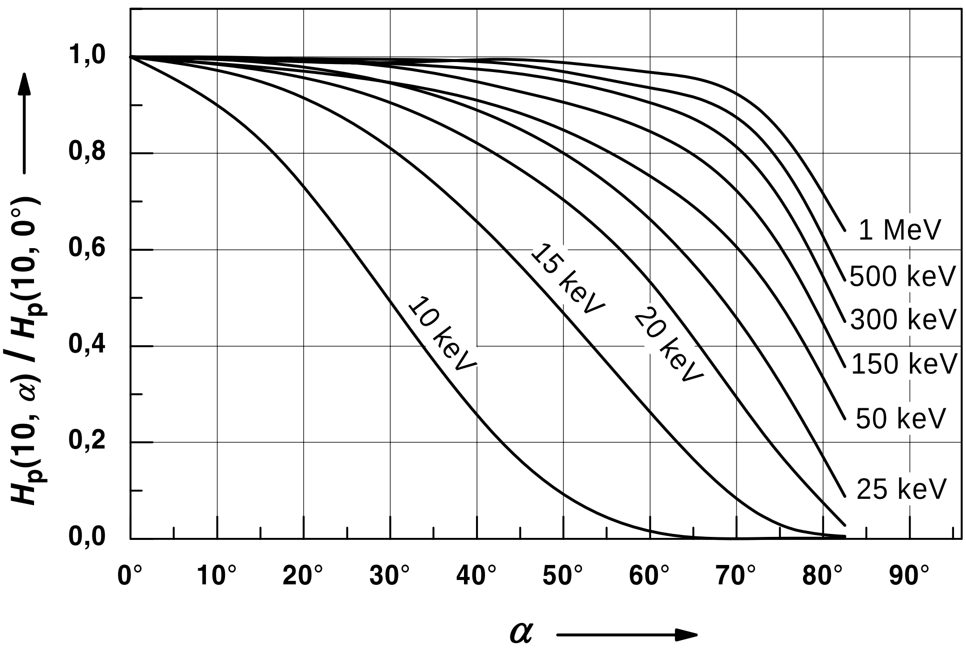


Fig. 6.2 Change of the ratio $H_p(10, \alpha)/H_p(10, 0°)$ with the direction of incidence of monodirectional and monoenergetic photon radiation on the slab phantom (GROSSWENDT, 1991). The photon energy is the parameter of the different curves. The angle α is the angle between the direction of radiation incidence and the normal on the phantom surface.

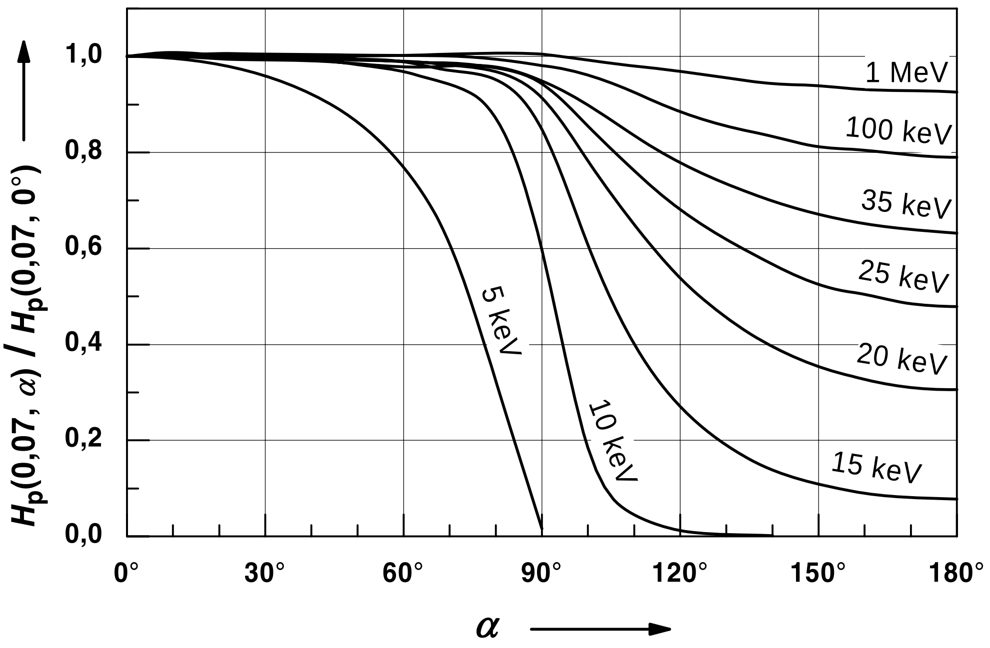


Fig. 6.3 Change of the ratio $H_p(0,07, \alpha)/H_p(0,07, 0°)$ with the direction of incidence of monodirectional and monoenergetic photon radiation on the rod phantom (GROSSWENDT, 1995b). The photon energy is the parameter of the different curves. The angle α is the angle between the direction of radiation incidence and the normal on the phantom surface, the axis of rotation is parallel to the axis of the rod.

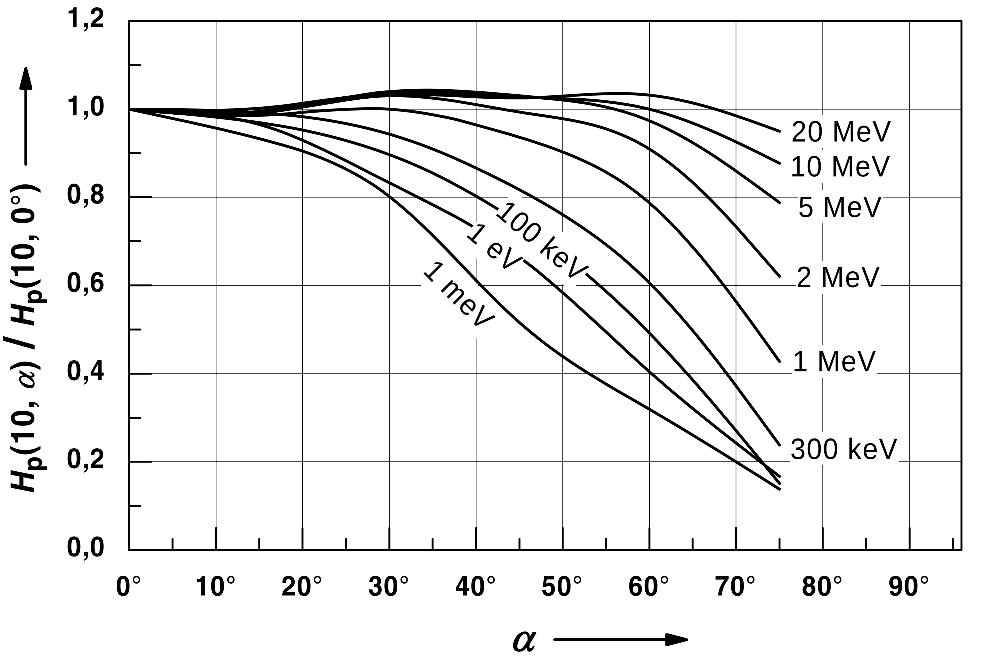


Fig. 6.4 Change of the ratio $H_p(10, \alpha)/H_p(10, 0°)$ with the direction of incidence of monodirectional and monoenergetic neutron radiation on the slab phantom (SIEBERT *and* SCHUHMACHER, 1995). The neutron energy is the parameter of the different curves. The angle α is the angle between the direction of radiation incidence and the normal on the phantom surface.

6.2 Calibration of personal dosimeters and measurement of the energy dependence of the response

6.2.1 Phantoms

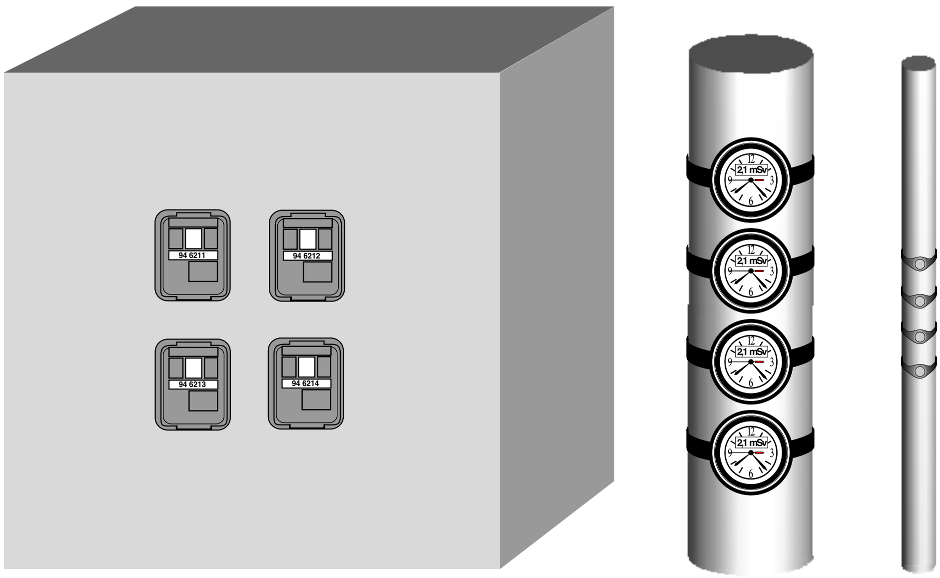
For calibrations of whole-body dosimeters, ICRU has extended the definition of $H_p(10)$ to a slab phantom made of ICRU material, with the dimensions 300 mm × 300 mm × 150 mm (Report 47 (ICRU, 1993)). The ISO sub-committee TC85/SC2 (ALBERTS *et al.*, 1994) has supplemented this recommendation by proposing two phantoms for the definition of the calibration quantities for extremity dosimeters (see also Section 4.3): a pillar phantom 73 mm in diameter and 300 mm in length as an approximation to forearms or legs, and a rod phantom 19 mm in diameter and 300 mm in length as an approximation to a finger. These three phantoms are assumed to consist of ICRU tissue.

As the ICRU tissue cannot be realized in practice, the dosimeters to be calibrated are to be irradiated on the following phantoms recommended by ISO (ALBERTS *et al.*, 1994), which thus have only the function of backscatter bodies.

- ISO water slab phantom with the dimensions 300 mm × 300 mm × 150 mm: walls made of PMMA, front side 2,5 mm thick, other sides 10 mm thick (substitute for the trunk);
- ISO water pillar phantom, a cylinder 73 mm in diameter and 300 mm in length: walls made of PMMA. Cylindrical wall 2,5 mm thick, the others 10 mm (substitute for leg or arm);
- ISO PMMA rod phantom, a cylinder 19 mm in diameter and 300 mm in length made of PMMA (substitute for finger).

The ISO water pillar phantom is intended only for leg and arm dosimeters which are practically not used in Germany.

The following holds for all phantoms and all types of radiation: The conversion coefficients for calibrations are calculated using phantoms made of ICRU tissue; the slight differences in back-scattering between the phantoms made of ICRU tissue and those recommended by ISO are neglected. For photon radiation, Fig. 6.6 shows a comparison of the backscatter factors of the ISO



(a) (b) (c)

Fig. 6.5 Phantoms for the calibration of personal dosimeters: ISO water slab phantom (a) (300 mm × 300 mm × 150 mm), ISO water pillar phantom (b) (73 mm in diameter, 300 mm in height) and ISO PMMA rod phantom (c) (19 mm in diameter, 300 mmm in height). As an example, four personal dosimeters have been fastened on each phantom.

water slab phantom and of the PMMA slab phantom originally favoured by ICRU, with the backscatter factors of the slab phantom made of ICRU tissue.

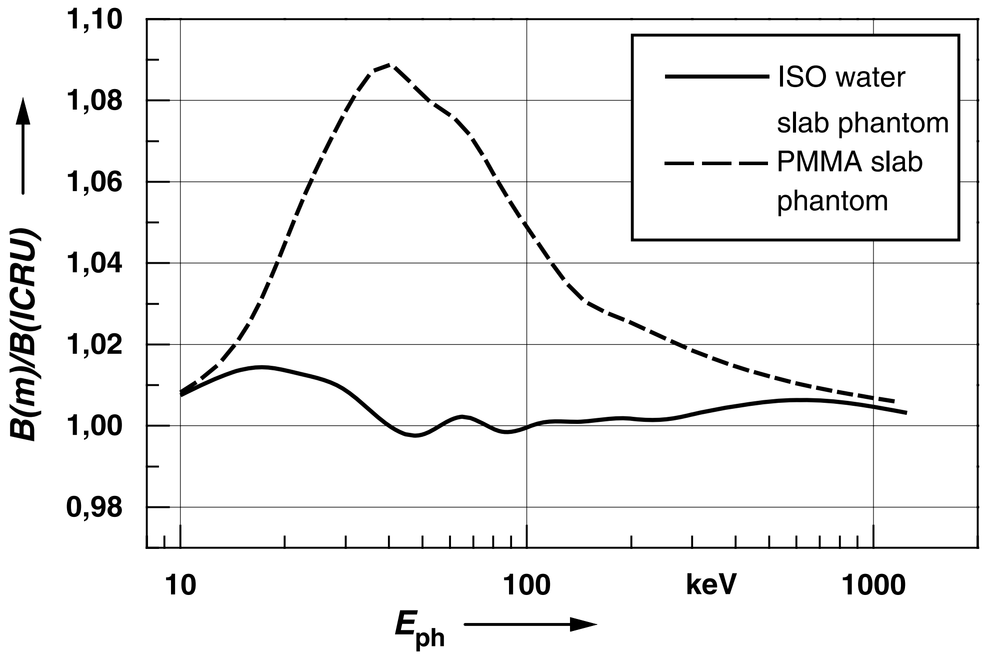


Fig. 6.6 Quotient of the backscatter factor for a slab phantom made of the material *m*, *B*(*m*), and that of a slab phantom made of ICRU tissue, *B*(*ICRU*). The phantom materials *m* are water with PMMA walls (ISO water slab phantom: solid curve) and PMMA (dashed curve) (KRAMER *et al.*, 1994). E_{ph} photon energy.

6.2.2 Conventional true value of $H_p(10, \alpha)$ and $H_p(0{,}07, \alpha)$

As has already been mentioned, the *calibration* of a dosimeter is the establishment of the relationship between the reading of the dosimeter and the *conventional true value* (the value regarded as true) *of the measurand*. Within the scope of the calibration, the calibration factor is determined or checked. The *calibration factor* is the ratio of the conventional true value of the measurand and the reading under *reference conditions*. The reference conditions specify the values of the influence quantities for which the calibration factor is valid without corrections. In general, a calibration factor with the value unity under reference conditions is aimed at. When personal dosimeters are calibrated, all irradiations must (at least in principle) be made on the phantoms specified in Section 6.2.1.

The calibration factor must be clearly distinguished from the *response* of a dosimeter, which is the ratio of the reading to the conventional true value of the measurand. The calibration factor is the reciprocal value of the response under reference conditions.

For photon and neutron radiation, the conventional true value of $H_p(10, \alpha)$ and $H_p(0{,}07, \alpha)$ is determined from other dose quantities or from radiation field quantities using conversion coefficients; it is not determined by means of primary standard measuring devices. Suitable quantities are, for example, the photon dose equivalent (for photon radiation) and the fluence (for neutron radiation). Dose equivalents at 10 mm and 0,07 mm depth in a phantom are determined by Monte Carlo calculations, occasionally also by measurements. One is about to agree on a uniform set of factors which can be considered to be free from errors and will allow the primary quantities to be converted into the dose equivalents in the phantom (ISO, 1995a, b). The data indicated in Figs. 4.6, 6.1, 6.2, 6.3 and 6.4 and in Tables 6.1 and 6.2 correspond to this data set to the extent as it was available when this report was printed.

In the case of photon and neutron radiation, broad homogeneous parallel radiation fields must be used when the dosimeters are irradiated on the phantoms, because the conversion coefficients required for the determination of the conventional true value have been calculated only for such fields. The phantom should be exposed as uniformly as possible. In the case of photon radiation, this uniformity is ensured by placing the phantom at a great distance from the radiation source (at least 2 m). For neutron radiation, smaller distances from the radiation source are regarded as sufficient. Great distances are not expedient for beta radiation. In this case, the conventional true value of $H_\mathrm{p}(0{,}07,\, \alpha)$ is determined for the respective radiation fields by direct measurement at small distances from the source.

In a similar way as in Section 5.2.3, $H_\mathrm{p}(10)$ for neutron radiation is determined according to the equation

$$H_\mathrm{p}(10) = \int h_{\mathrm{p}\Phi}(E) \cdot \Phi_E(E) dE$$

using the response $R_H = M/H_\mathrm{p}(10)$, occasionally also $R_\Phi = M/\Phi$ und $R_H = R_\Phi / h_{\mathrm{p}\Phi}$. Here, too, the values for R_H in terms of the new quantity can be directly calculated from the conversion coefficients of Fig. 4.6 if the values of R_Φ are available.

6.2.3 Calibration and determination of the energy dependence of the response for photon radiation

In future, personal dosimeters are to be calibrated in principle on a phantom. In a first step, the value of the photon dose equivalent is determined as hitherto, i.e. without phantom and without dosimeter at the point of test, and the conventional true value of $H_\mathrm{p}(10,\, \alpha)$ and $H_\mathrm{p}(0{,}07,\, \alpha)$ is calculated using the quotients listed in Table 6.2. Then the reference point of the personal dosimeter fastened on the phantom is brought to the point of test and the angle α between the direction of radiation incidence and the dosimeter's reference direction adjusted. When several personal dosimeters are to be irradiated simultaneously, the inhomogeneity of the backscattered field must be taken into account. In addition, the personal dosimeters may mutually influence one another. It should also be noted that all calculations for the quotients $H_\mathrm{p}(10)/H_\mathrm{X}$ and $H_\mathrm{p}(0{,}07)/H_\mathrm{X}$ are valid only for secondary electron equilibrium. To allow calibrations carried out in different radiation fields to be compared, PMMA-layers in front of the personal dosimeter are recommended at photon energies above 250 keV. At energies of up to 0,66 MeV, a layer 1,5 mm in thickness is sufficient. At energies higher than 0,66 MeV and up to 1,33 MeV, a layer 4 mm in thickness will suffice (see Section 5.2.2).

The quotients stated in Table 6.2 are valid only for a parallel beam by which the phantom is uniformly irradiated. From a distance of 2 m from the source, the photon radiation backscatter factor on the slab phantom differs from that for an infinite distance by less than 1 %; the quotients stated in Table 6.2 and Figs. 6.2 and 6.3 can then be used. In energy ranges in which scatter by the phantom is small (e.g. photon radiation with mean energies below or above the range from 30 keV to 250 keV), full irradiation of the phantom is not, however, an absolute must, and smaller irradiation distances are possible to reduce the irradiation time. Standard values of recommended irradiation parameters are given in ISO Standard 4037-3 (ISO, 1995a).

Special care in the calculation of the quotient $H_\mathrm{p}(10)/H_\mathrm{X}$ is necessary in photon radiation fields in the photon energy range below approximately 20 keV, since the quotient's energy dependence is very strong in this range. As a result, even with nominally equal radiation quality at different irradiation facilities, the quotients are different (due, for example, to different tube windows and an air-pressure-dependent hardening of the beam in the air layer between radiation source and dosimeter) and must therefore be determined separately.

The calibration of personal dosimeters on a phantom, which is basically necessary, does not mean that regular routine calibrations cannot be carried out free in air when the performance characteristics of a personal dosimeter is known from a previous test (e.g. a pattern evaluation) which covered irradiations on a phantom. The calibration free in air must then be corrected for the influence of the phantom.

6.2.4 Calibration and determination of the energy dependence of the response for neutron radiation

No substantial changes due to the new quantities are to be expected for the calibration of personal dosimeters in neutron radiation fields of uniform direction. Changes may, however, result from the introduction of the new quantity (which has been defined without the radiation field characteristics being limited) if the personal dosimeters are irradiated in radiation fields with different directions (e.g. scattered radiation fields). In this case, the conventional true value of the personal dose equivalent is to be calculated using conversion coefficients for the expanded radiation field corresponding to the radiation field at the point of test, and the dose value obtained is to be compared with the reading of the personal dosimeter. This means that the response of the personal dosimeter (always with phantom) is checked over a larger range of solid angles of the incident neutron radiation. The albedo dosimeters officially introduced in Germany have been calibrated in scattered radiation fields of this type for some years now using conversion coefficients similar to those of $H_\mathrm{p}(10)$.

6.2.5 Calibration and determination of the energy dependence of the response to beta radiation

Calibrations of finger dosimeters for $H_\mathrm{p}(0{,}07, \alpha)$ are always carried out on the rod phantom. Beta-ray sources of the radionuclides ^{147}Pm, ^{204}Tl and ^{90}Sr/^{90}Y (maximum energies: 224 keV, 764 keV and 2281 keV) are mainly used as radiation sources. If possible, point sources are employed. Special beam-flattening filters consisting of thin foils (see ISO Standard 6980 (ISO, 1993)) are placed between the point source and the personal dosimeter to be calibrated to achieve as homogeneous a beta radiation field as possible. The value of $H_\mathrm{p}(0{,}07, \alpha)$ is usually determined with an extrapolation chamber.

6.3 Will new personal dosimeters be required?

6.3.1 Preliminary remark

The intention to make individual monitoring more uniform and clear by the introduction of the new quantities may, at first glance, lead to a wide variety of personal dosimeters: Three types are conceivable in view of the monitoring task (wearing position) and three types in view of the reference depth. This number is increased further by the different types of radiation which make different personal dosimeters necessary because of the different measurement principles. Some of the personal dosimeters are, however, of only insignificant importance in routine monitoring, for example finger dosimeters for neutron radiation or wrist and eye dosimeters. They are used almost exclusively in special in-plant monitoring or for methodical investigations. For example, under most exposure conditions, the limits for the lenses of the eye are not exceeded if the limits for the whole body and the skin are complied with. Monitoring of $H_\mathrm{p}(3)$ is therefore necessary only under very special conditions.

From this it follows that only the whole-body dosimeter for the measurement of $H_p(10)$ for strongly penetrating radiation and finger dosimeters for the measurement of $H_p(0{,}07)$ for weakly penetrating radiation are of considerable practical importance. Personal dosimeters for the measurement of the whole-body exposure may possibly allow $H_p(0{,}07)$ to be measured as well, however, the radiation fields of weakly penetrating radiation (for example when beta radiation sources or X-ray microstructure facilities are handled) are usually so inhomogeneous that the values measured on the trunk provide only little information on the actual exposure situation of the person to be monitored. The personal dosimeter serves only as an indicator of such a radiation field, and the measurement values at best point to the necessity of measuring $H_p(0{,}07)$ with a finger dosimeter and analysing the radiation field more thoroughly using an area dosimeter.

6.3.2 Changes for personal dosimeters for photon radiation

It can be concluded from Figs. 4.4, 6.2 and 6.3 that no essential changes will be necessary in personal dosimeters for photon radiation. Only below about 40 keV and at angles of incidence greater than 50° do the quantities $H_p(10)$ in the slab phantom and H_X in front of the slab phantom differ by more than 20 %. In analogy, $H_p(0{,}07)$ in the rod phantom and H_X in front of the rod phantom differ by more than 20 % only below approximately 10 keV and at angles of incidence greater than 80°.

For personal dosimeters subject to mandatory verification, the permissible errors for the rated range of use of the energy and of the direction of radiation incidence, which must be specified, have been laid down in PTB Requirements. If the PTB Requirements to be met up to now are transferred to the new quantities without modifications, it follows from the above considerations concerning an ideal personal dosimeter for the quantity H_X that the minimum requirements for energy and directional dependence of the response are fulfilled. Fig. 6.7 shows by the example of a phosphate glass dosimeter that this is also possible in practice. In general, the changes for personal dosimeters will therefore be smaller than those for area dosimeters.

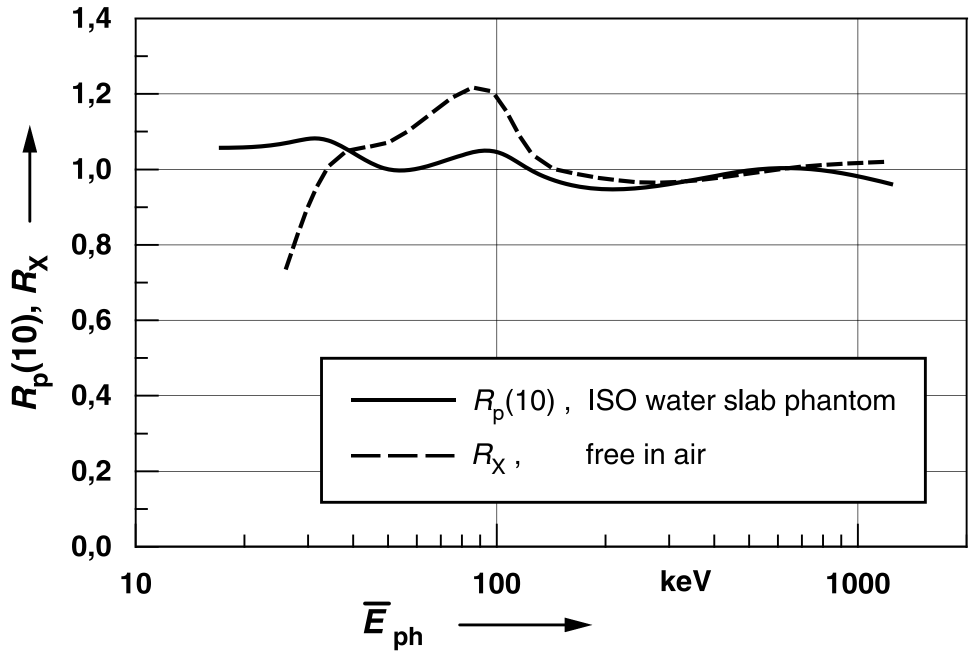


Fig. 6.7 (H_X) Example of the possibility of measuring the quantities H_X and $H_p(10)$ with the same personal dosimeter. The response R_X with regard to the photon dose equivalent H_X and the response $R_p(10)$ with regard to the new quantity $H_p(10, 0°)$ have been indicated for a phosphate glass dosimeter as a function of the mean photon energy $\bar{E}_{ph}$ (662 keV being in each case the reference energy).

For some of the passive personal dosimeters with several detectors, only the evaluation method will have to be optimized; in some other cases the energy compensation filters will have to be modified as well. With electronic personal dosimeters in particular, problems may result from the fact that the radiation backscattered by the person contributes only little to the measured value, for example because of shielding by a battery. For the quantity $H_p(10)$, the requirements for energy and angular dependence can possibly be met more easily than for the quantity H_X. For H_X, each personal dosimeter exhibits a decrease in the response towards low energies due to absorption in the pre-layer or in the detector itself. As a consequence, the energy dependence of the quantity hitherto used was frequently rather strong. An attenuation equivalent to that in a tissue layer 10 mm thick is now desired by definition. It will have to be checked in each individual case whether the dosimeters continue to fulfil the PTB Requirements.

When designing a new personal dosimeter, one might first of all - in compliance with the definition of the quantities - think of measuring this quantity with a thin tissue-equivalent detector covered by a layer of tissue-equivalent material, 10 mm or 0,07 mm in thickness, and worn on the body surface. In reality, the required thicknesses of the detector and of its coating material, and the tissue equivalence of the detector material in particular, can be met only inadequately. And this is in fact not necessary. The only important thing is that the response with regard to the calibration quantity $H_p(10, \alpha)$ or $H_p(0{,}07, \alpha)$ upon irradiation on the calibration phantom of interest, in defined test radiation fields, is energy-independent within specified error limits and that the directional dependence of the response corresponds to the quotient $H_p(10, \alpha)/H_p(10, 0°)$ or $H_p(0{,}07, \alpha)/H_p(0{,}07, 0°)$ respectively. It is, for example, possible to use an aluminium filter, approximately 1 mm thick, as an absorber (AMBROSI *et al.*, 1988) to measure $H_p(10)$ with LiF thermoluminescence detectors in the energy range of conventional X-rays.

From the definition of the personal dose equivalent it follows that the design of the dosimeters should be such that they are sensitive to the radiation backscattered by the body. A whole-body dosimeter worn on the chest will then also detect radiation incident on the body from behind if this radiation penetrates the body.

The reference orientation and the reference point of the dosimeter, to which the readings always relate, must be clearly specified by the manufacturer, either by a mark on the dosimeter or by a note in the accompanying documents.

A summary of the characteristics of radiation protection dosimeters with different detectors is given in ICRU Report 47 (ICRU, 1992).

In summary, it can be said that changes of the patterns of personal dosimeters will be necessary only in exceptional cases. There may be such exceptional cases if the former dosimeter pattern shows imperfections also with regard to the quantity hitherto used, the photon dose equivalent, (e.g. film dosimeter with lead filter) or if the personal dosimeter is completely insensitive to backscattered radiation (e.g. electronic dosimeter with battery behind the detector).

6.3.3 Changes for personal dosimeters for neutron radiation

Changes in the patterns of personal dosimeters for neutron radiation do not seem to be necessary. The modified conversion coefficients only lead to changes in the quality factors in the evaluation algorithms or lie within the range of the permissible measurement errors. As the majority of personal dosimeters for neutron radiation exhibit a more or less pronounced directional dependence, the directional dependence of the conversion coefficient for the quantity $H_p(10)$ is usually even advantageous. On the whole, the difficulty well known for a long time is hardly reduced, namely to develop neutron dosimeters with an energy and directional dependence of the response, which is acceptable and not too significant.

6.3.4 Changes for personal dosimeters for beta radiation

The difficulties in the realization of dosimeters for the measurement of $H_p(0,07)$ for beta radiation continue to exist. No additional difficulties due to the new quantities will result. Now as before, very thin detectors covered by very thin layers will be necessary, which must meet the requirements of routine use.

7 Impacts on dosimeter tests

7.1 Preliminary remark

Tests of the metrological properties of dosimeters are an essential part of quality assurance in radiation protection metrology. In the following, the changes due to the new quantities and relevant to (pattern approval) tests, verifications and comparison measurements are briefly summarized, reference being made, if necessary, to more detailed information given in the previous Sections.

The new quantities will be introduced in a basically different way, depending on the requirements concerned which are of a quite different nature. The rather general requirements for radiation protection dosimeters laid down in the Radiation Protection Ordinance (BMU, 1989), the X-Ray Ordinance (BMA, 1987), the Verification Ordinance (BMWI, 1988) and the Recommendations of the 'German Commission on Radiological Protection' concerning 'Requirements for personal dosimeters' (SSK, 1993) use only the terms 'area dosimeter' and 'personal dosimeter' explained in Section 2.3; these requirements need not be changed. Fundamental DIN standards (DIN, 1985 to 1995) explain in detail what is to be understood by these terms. Special requirements relevant to tests, for example the PTB Requirements (PTB, 1992), special DIN standards of the 6818 series (DIN, 1988 to 1994b) and some of the Appendices to the Verification Ordinance will have to be adapted. More recent national and international standards will then have to be taken into consideration as well.

7.2 Information on (pattern approval) tests

7.2.1 Test of the response of area dosimeters (energy dependence and angular dependence)

Now as before, area dosimeters are irradiated free in air. The radiation qualities to be used in the tests are not changed by the introduction of the new quantities; they have been specified in ISO standards (ISO, 1989, 1992, 1993, 1995a), DIN standards (DIN, 1992) and PTB Requirements.

When tests are carried out with photon radiation, it is to be made sure that the condition of secondary electron equilibrium has been satisfied when the specified conversion coefficients are used. It is therefore recommended to arrange, if necessary, depending on photon energy and quantity, a PMMA layer of a certain thickness in front of the dosimeter (see Section 5.2.2).

If a dosimeter is to be used in photon radiation fields where there is no secondary electron equilibrium free in air, this is to be taken into consideration in the test. For example, the reading of an area dosimeter for the measurement of $H^*(10)$ upon irradiation with ^{60}Co gamma radiation should be independent of how far there is secondary electron equilibrium free in air.

When the angular dependence of the response of area dosimeters is measured, the area dosimeter is rotated about an axis through its point of reference. When the radiation field is unchanged, the readings of area dosimeters intended for the measurement of $H^*(10)$ should not vary during rotation; the readings of area dosimeters for the measurement of $H'(0{,}07)$ must vary during rotation in conformity with the curves in Fig. 5.1 and the values in Table 5.6.

From measurement values previously obtained for the angular dependence and the energy dependence of the response with regard to the quantities hitherto used, the angular and energy dependence of the new quantities can be calculated without additional measurements being carried out, using the quotients stated in Section 5.1.

7.2.2 Test of the response of personal dosimeters (energy dependence and angular dependence)

When the energy dependence and the angular dependence of the response of personal dosimeters intended for the measurement of $H_p(10)$ for photon radiation are measured, all irradiations must be carried out in front of the ISO water slab phantom (see Section 6.2.1) whereas the ISO PMMA rod phantom must be used for finger dosimeters for the measurement of $H_p(0{,}07)$. In a first step, the dosimeter is fastened on the phantom's front surface (and the finger put on the rod phantom) so that the dosimeter's reference direction coincides with the normal on the phantom's front surface. Then the dosimeter's reference point and the point of test in the radiation field are brought into coincidence and, finally, the *combination of dosimeter and phantom* is rotated about an axis passing through the reference point of the dosimeter so that the reference direction of the dosimeter and the direction of radiation incidence of the irradiation facility form the desired angle. Irradiations with beta and neutron radiation were already carried out on phantoms in the past. Only the shape of the phantom is changed here. The radiation qualities to be used for the tests are not affected by the introduction of the new quantities; they have been specified in ISO standards (ISO, 1989, 1992, 1993, 1995a), DIN standards (1992) and PTB Requirements.

For photon radiation, the diameter of the typical radiation field has so far been 10 cm; now the diameter of the radiation field on the ISO water slab phantom should be approx. 40 cm. As a rule, an increase in the distance between dosimeter and radiation source will be necessary, resulting in a prolongation of the irradiation times (by up to a factor 10).

If more than one dosimeter is to be irradiated at the same time, care must be taken that the measurement values are not falsified.

When the tests are carried out with photon radiation it is to be made sure that the condition of secondary electron equilibrium is fulfilled when the specified conversion coefficients are used. It is therefore recommended to arrange, if necessary, depending on photon energy and quantity, a PMMA layer of specified thickness in front of the dosimeter (see Section 6.2.3).

If a dosimeter is to be used in photon radiation fields where there is no secondary electron equilibrium free in air, this is to be taken into consideration in the test. For example, the reading of a finger dosimeter for the measurement of $H_p(0{,}07)$ upon irradiation with ^{60}Co gamma radiation should be dependent on how far there is secondary electron equilibrium free in air. This can be ensured, for example, by defining requirements for the response to beta radiation (^{90}Sr/^{90}Y and ^{204}Tl beta-ray sources).

For photon radiation, the conventional true value (see Section 6.2.2) of the new quantities $H_p(10, \alpha)$ or $H_p(0{,}07, \alpha)$ is determined from the photon dose equivalent H_X, in the case of neutron radiation from the fluence Φ, applying conversion coefficients. Only for beta radiation is $H'(0{,}07, \alpha)$ determined directly. Data can be found in Sections 5.1 and 6.1.

When personal dosimeters for the measurement of $H_p(10)$ and $H_p(0{,}07)$ are rotated in an unchanged radiation field, their readings should vary with the angle in compliance with the curves in Figs. 6.2 to 6.4.

As regards personal dosimeters for photon radiation, test results previously obtained by irraditions free in air cannot be converted to results for the new quantities.

7.2.3 Test of the impact of influence quantities (other than photon energy and direction of radiation incidence)

Some tests are carried out to ascertain to what extent the measured value is changed by so-called influence quantities (e.g. sunlight, mechanical shock, temperature and humidity of the air). These influence quantities are not, however, the object of the measurement. During the measurement, the dosimeter is exposed to the respective influence quantity (e.g. sunlight), whereas all other influence quantities are kept unchanged, close to the reference values (standard test conditions) (see Sections 5.2.1 and 6.2.2). A change in an influence quantity may change the response; the maximum value just permissible for this change in the response has been specified, for example, in the PTB Requirements. With the exception of the influence quantities of photon energy and direction of radiation incidence, the quantity selected for these tests is of no importance; the relative change of the measured value due to the influence quantity is independent of the quantity itself. This means that, as before, such tests can be carried out by irradiations *free in air*, both H_X and $H^*(10)$ or $H'(0{,}07)$ being suitable quantities. The same quantity must, of course, be used to determine the comparison value (response under reference conditions). Test results already available can be taken over unchanged for the new quantities.

7.2.4 Test of the deviation from linearity

In the test for linearity in the measurement range, the maximum value and the minimum value of the response within the measurement range are determined for the quantity concerned. The absolute value of the response is of no importance in this context. These investigations can be carried out with any other quantity, provided that, during the test, the measuring signals or the readings of the detectors concerned cover the same range of measurement as with the quantity to be used. Measurement values already available can be taken over unchanged for the new quantities.

7.3 Information on verifications

7.3.1 Verification of area dosimeters

On the occasion of the pattern approval test, the conditions for verification are laid down by the PTB, in agreement with the verification authorities. For the purpose of verification, area dosimeters will continue to be irradiated *free in air*. The conventional true value of the quantity will be determined as described in Section 5.2.2. Verification values already available can be converted to the new quantities.

7.3.2 Verification of personal dosimeters

In the course of the pattern approval test, the conditions for verification are laid down by the PTB, in agreement with the verification authorities. Irradiations for the verification of personal dosimeters must in principle be made *on a phantom*. However, an irradiation free in air will remain possible in most cases. For the ‘radiation quality for verification’, the difference between the value measured during irradiation on the phantom and that obtained during irradiation free in air must already be determined during the pattern approval test. Upon verification, the measured value is then corrected by this factor. This factor can also be determined for dosimeter patterns already in use. If such a pattern is approved for the new quantities without changes in the design, the verification values previously determined can be converted into the new quantities. The conventional true value of the quantity is determined as described in Section 6.2.2.

7.4 Comparison measurements of personal dosimeters

In Germany, comparison measurements of personal dosimeters for photon and neutron radiation to be used by the dosimetry services responsible under state law are carried out by the PTB. Comparison measurements of photon dosimeters are required by the Verification Ordinance. Comparisons of neutron dosimeters, neutron albedo dosimeters in particular, are performed on the basis of a decision taken by the Technical Committee ‘Radiation Protection’ of the State Committee ‘Nuclear Energy’. According to the ‘Directive on requirements to be met by dosimetry services in compliance with the Radiation Protection Ordinance and the X-Ray Ordinance dated 26.4.1994’ (BMU,1994b), outside verification law, comparison measurements will also be required for beta dosimeters after January 1, 1995. They will also be carried out by the PTB.

Only dosimeters whose patterns have been approved are allowed to participate in comparison measurements of photon dosimeters; their metrological characteristics can be gathered from the approval certificate. It is the fundamental aim of comparison measurements to check the stability and correctness in routine operation. For this purpose, all irradiations are carried out applying the same method as during the pattern approval test: For dosimeters approved for the quantities hitherto used this means that they continue to be irradiated free in air; for the dosimeters approved for the new quantities it follows in analogy that the irradiations during comparison measurements are carried out on phantoms.

In future, all dosimeter patterns used dosimetry services will be included in the comparison measurements for beta and neutron dosimeters (BMU, 1994b). For the albedo dosimeter already investigated within the framework of comparison measurements, the quantity $H'(10)$ defined in the ICRU sphere has been taken as a basis. The conversion coefficients used by ALBERTS *and* KLUGE (1993) for these quantities differ from those for $H_p(10)$ for all directions of incidence. The transition to the new quantity $H_p(10)$ (in the slab phantom) will lead to new calibration factors which must be taken into consideration in future comparison measurements; however, it is not to be expected that they will substantially affect the suitability of personal dosimeters.

In future comparison measurements, beta dosimeters will, without exception, be irradiated on phantoms as has been common practice to date.

8 Transitional provisions

The recommended use of the new quantities from 01.01.1995 would not mean that the radiation protection dosimeters so far used must be replaced within a short time. During a transition period whose duration has not yet been established, old and new quantities can be used concurrently.

The PTB has requested the Federal Minister of Economics to take all steps necessary within the framework of mandatory verification and required for the introduction of the new quantities. The PTB has suggested that, in a transition period lasting until December 31, 1997, measuring instruments indicating the photon dose equivalent can still be approved and that initial verifications in terms of this quantity be permissible until December 31, 2000.

According to the recommendations of ICRP (ICRP, 1991), a conversion of the data so far available from individual routine monitoring is not necessary, i.e. the values measured in the quantities hitherto used are considered to be equal to body doses, as are those measured in the new quantities, as long as the investigation levels are not exceeded. In compliance with the Directive on physical radiation protection control (BMU, 1994a), the measurement values will be treated as before.

9 References

ALBERTS, W.G. and KLUGE, H. (1993). „PTB-Vergleichsmessungen an Personendosimetern für Neutronenstrahlung“, PTB-Bericht PTB-N-15, Braunschweig.

ALBERTS, W.G., BÖHM, J., KRAMER, H-M., ILES, W.J., MCDONALD, J., SCHWARTZ, R.B. and THOMPSON, I.M.G. (1994). „International Standardization of Reference Radiations and Calibration Procedures for Radiation Protection Instruments“, in *Strahlenschutz: Physik und Meßtechnik*, Band 1, Hrsg. W. Kölzer, R. Maushart, S. 181-188, ISSN 1013-4506, Verlag TÜV Rheinland GmbH, Köln.

AMBROSI, P.; BÖHM, J.; HENKEL, U. und RITZENHOFF, K.H. (1988). „Experimental Studies on Solid-state Detectors for Use in Discriminating Individual Dosemeters“, *PTB-Mitt*. **98**, S. 138-142.

BMA (1987). Bundesministerium für Arbeit, *Verordnung über den Schutz vor Schäden durch Röntgenstrahlen (Röntgenverordnung)*, Bundesgesetzblatt I, Nr. **3**, S. 114.

BMU (1989). Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, *Verordnung über den Schutz vor Schäden durch ionisierende Strahlen (Strahlenschutzverordnung)*, Bundesgesetzblatt I, Nr. **34**, S. 1321.

BMU (1994a). Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, *Richtlinie für die physikalische Strahlenschutzkontrolle zur Ermittlung von Körperdosen (§§ 62, 63, 63a StrlSchV; §§ 35, 35a RöV)*. GMBl **45**, Nr. 7, S. 286-307.

BMU (1994b). Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, *Richtlinie über Anforderungen an Personendosismeßstellen nach Strahlenschutz- und Röntgenverordnung vom 26.April.1994.* GMBl **45**, Nr. 33, S. 967-974.

BMWI (1988). Bundesministerium für Wirtschaft, *Eichordnung vom 12. August 1988*, Bundesgesetzblatt I, S. 1657, zuletzt geändert durch die *Verordnung zur Änderung der Eichordnung vom 24. September 1992* Bundesgesetzblatt I, S. 1653.

BMWI (1992). Bundesministerium für Wirtschaft, *Anlage 23 zur Eichordnung*, Eichordnung, Strahlenschutzmeßgeräte, Anlage 23 zur Eichordnung, Ausgabe 1990 mit Ergänzung 1992, Deutscher Eichverlag, Braunschweig.

DIN (1985). Deutsches Institut für Normung e.V., *Begriffe und Benennungen in der radiologischen Technik; Dosisgrößen und Dosiseinheiten,* DIN 6814-3, Ausgabe 12.85, Beuth Verlag, Berlin.

DIN (1988). Deutsches Institut für Normung e.V., *Strahlenschutzdosimeter - Thermolumineszenzdosimetrie-Systeme*, DIN 6818-6, Ausgabe 12.88, Beuth Verlag, Berlin.

DIN (1992a). Deutsches Institut für Normung e.V., *Strahlenschutzdosimeter - Allgemeine Regeln*, DIN 6818-1, Ausgabe 04.92, Beuth Verlag, Berlin.

DIN (1992b). Deutsches Institut für Normung e.V., *Begriffe und Benennungen in der radiologischen Technik; Dosisgrößen und Dosiseinheiten,* Entwurf DIN 6814-3/A1, Stand 12.92, Beuth Verlag, Berlin.

DIN (1992c). Deutsches Institut für Normung e.V., *Strahlenschutzdosimeter - Direkt ablesbare Ionisationskammer- Stabdosimeter für Gamma und Röntgenstrahlen*, DIN 6818-2, Ausgabe 10.92, Beuth Verlag, Berlin.

DIN (1994a). Deutsches Institut für Normung e.V., *Strahlenschutzdosimeter - Tragbare Zählrohrdosimeter für Gamma und Röntgenstrahlen*, DIN 6818, Teil 5, Ausgabe 01.94, Beuth Verlag, Berlin.

DIN (1994b). Deutsches Institut für Normung e.V., *Strahlenschutzdosimeter - Filmdosimetrie-Systeme*, DIN 6818-10, Manuskript Entwurf, Normenausschuß Radiologie, Erlangen.

DIN (1994c). Deutsches Institut für Normung e.V., *Strahlenschutzdosimeter - Allgemeine Regeln*, Manuskript Entwurf DIN 6818-1/A1, Normenausschuß Radiologie, Erlangen.

DIN (1995). Deutsches Institut für Normung e.V., *Begriffe und Benennungen in der radiologischen Technik; Dosisgrößen und Dosiseinheiten,* Entwurf DIN 6814-3/A2, Stand Januar 1995, Normenausschuß Radiologie, Erlangen.

EU (1994). Kommission der Europäischen Gemeinschaften, *Technical recommendations for monitoring individuals occupationally exposed to external radiation*, Report EUR 14852 EN, Luxembourg.

EU (1993). Rat der Europäischen Gemeinschaften, *Richtlinie zur Festlegung der grundlegenden Sicherheitsnormen für den Schutz der Gesundheit der Arbeitskräfte und der Bevölkerung gegen die Gefahren durch ionisierende Strahlen*, Kommissionsvorschlag KOM(93), Ratsdok. 8305/93, Brüssel.

FERRARI, A. and PELLICCIONI, M. (1994). „On the Conversion Coefficients from Fluence to Ambient Dose Equivalent“, *Radiat. Prot. Dosim.* **51**, 251-255.

GROSSWENDT, B. (1990). „Conversion Coefficients for Calibrating Individual Photon Dosemeters in Terms of Dose Equivalents Defined in an ICRU Tissue Cube and PMMA Slabs“, *Radiat. Prot. Dosim.* **32**, 219-231.

GROSSWENDT, B. (1991). „The Angular Dependence and Irradiation Geometry Factor for the Dose Equivalent for Photons in Slab Phantoms of Tissue-Equivalent Material and PMMA“, *Radiat. Prot. Dosim.* **35**, 221-235.

GROSSWENDT, B. (1992). „Coefficients for the Conversion of Air Collision Kerma to Dose Equivalent for the Calibration of Individual Dosemeters in X Ray Fields“, *Radiat. Prot. Dosim.* **40**, 169-184.

GROSSWENDT, B. (1995a). „Angular Dependence Factors and Air Kerma to Dose Equivalent Conversion Coefficients for Cylindrical Phantoms Irradiated by Plane-Parallel Extended Monoenergetic Photon Beams“, *Radiat. Prot. Dosim.* **59**, 165-179.

GROSSWENDT, B. (1995b). „Angular Dependence Factors and Air Kerma to Dose Equivalent Conversion Coefficients for 1,9 cm Rod and 7,3 cm Pillar Phantoms Irradiated by Extended Monodirectional X Ray Beams“, *Radiat. Prot. Dosim.* **59**, 181-193.

GROSSWENDT, B. and CHARTIER, J.-L. (1994). „Fluence-to Absorbed-Dose Conversion Coefficients and Angular-Dependence Factors for 4-Element ICRU Tissue, Water and PMMA Slab Phantoms Irradiated by Broad Electron Beams“, PTB-Bericht PTB-Dos-22, ISSN 0172-7095, Braunschweig.

GROSSWENDT, B. and HOHLFELD, K. (1982). „Angular Dependence of Specified Depth Dose Equivalent Quantities in the ICRU Sphere For Photon Radiation“, *Radiat. Prot. Dosim.* **3**, 169-174.

HARVEY, J.R. (1975). „An Approach to the Surveying of Radiation Environments for Radiation Protection Purposes,“ *Phys. Med. Biol.* **20,** 1003-1006

HELMSTÄDTER, K., and BÖHM, J., (1992). „The PTB Beta Secondary Standard for the Absorbed Dose to Tissue“ in *Radiation Protection Pysics*, Proceedings of the 24th International Symposium on Radiation Protection Physics, Gaussig (bei Dresden), Hrsg. Dresden University of Technology, Institute of Radiation Protection Physics, S. 259-269

ICRP (1969). International Commission on Radiological Protection, *Protection against Ionizing Radiation from External Sources*, ICRP Publication 15, ICRP.

ICRP (1971). International Commission on Radiological Protection, *Data for Protection against Ionizing Radiation from External Sources*. ICRP Publication 21, ICRP.

ICRP (1977). International Commission on Radiological Protection, *Recommendations of the International Commission on Radiological Protection*, ICRP Publication 26, Annals of ICRP 1, Nr.**3**.

ICRP (1991). International Commission on Radiological Protection, *Recommendations of the International Commission on Radiological Protection*. ICRP Publication 60, Annals of ICRP 21, Nr.**1-3.**

ICRP (1993). International Commission on Radiological Protection, *Empfehlungen der Internationalen Strahlenschutzkommission 1990*. Bundesamt für Strahlenschutz (Hrsg.), Gustav Fischer Verlag, Stuttgart, Jena, New York**.**

ICRU (1962). International Commission on Radiation Units and Measurements, *Radiation Quantities and Units. ICRU Report 10a*, NBS Handbook **84**, Washington, D.C.

ICRU (1973). International Commission on Radiation Units and Measurements, *Dose Equivalent,* ICRU Report 19S, (*Supplement to ICRU Report 19)*. ICRU Publications, Bethesda, MD.

ICRU (1980). International Commission on Radiation Units and Measurements, *Radiation Quantities and Units*, ICRU Report 33,“ ICRU Publications, Bethesda, MD.

ICRU (1985). International Commission on Radiation Units and Measurements, *Determination of Dose Equivalents Resulting from External Radiation Sources*, ICRU Report 39, ICRU Publications, Bethesda, MD.

ICRU (1988). International Commission on Radiation Units and Measurements, *Determination of Dose Equivalents from External Radiation Sources - Part 2,* ICRU Report 43, ICRU Publications, Bethesda, MD.

ICRU (1992). International Commission on Radiation Units and Measurements, *Measurement of Dose Equivalents from External Photon and Electron Radiations*. ICRU Report 47, ICRU Publications, Bethesda, MD.

ICRU (1993). International Commission on Radiation Units and Measurements, *Quantities and Units in Radiation Protection Dosimetry*. ICRU Report 51, ICRU Publications, Bethesda, MD.

IEC (1990). International Electrotechnical Commission, *Portable Neutron Dose Equivalent Rate Meters for Use in Radiation Protection*, IEC-Standard 1005

IEC (1994). International Electrotechnical Commission, *Direct Reading Personal Dose Equivalent and/or Dose Equivalent Rate Meters for the Measurements of Personal Dose Equivalents* $H_p(10)$ *and* $H_p(0,07)$ *for X, Gamma and Beta Radiation*, IEC SC 45 B WG 8 - WD 1

ISO (1989). International Standards Organisation, *Neutron Reference Radiations for Calibrating Neutron Measuring Devices used for Radiation Protection Purposes and for Determination their Response as a Function of Neutron Energy*, ISO-Standard 8529.

ISO (1992). International Standards Organisation, *X and Gamma Reference Radiations for Calibrating Dosemeters and Dose Ratemeters and for Determination their Response as a Function of Photon Energy - Part 1: Characteristics of the radiation and their Methods of production*, ISO/CD 4037-1.

ISO (1993). International Standards Organisation, *Reference Beta Radiations for Calibrating Dosemeters and doserate Meters and for Determining their Response as a Function of Beta Radiation Energy* - ISO/DIS 6980.

ISO (1995a). International Standards Organisation, *Reference Photon Radiations: Calibration of Area and Personal Dosemeters and the Determination of their Response as a Function of Photon Energy and Angle of Incidence*, ISO/CDV 4037-3.

ISO (1995b). International Standards Organisation, *Reference Neutron Radiations: Calibration of Area and Personal Dosimeters and the Determination of their Response as a Function of Neutron Energy and Angle of Incidence*, ISO/CDV 8529-3.

ISO (1996). International Standards Organisation, *Reference Photon Radiations: Calibration of Area and Personal Dosemeters and the Determination of their Response as a Function of Photon Energy and Angle of Incidence*, ISO/DIS 4037-3 (in preparation).

KRAMER, H. M. BÖHM, J., ILES, W.J., and THOMPSON, I.M.G. (1994). „On the Current Status of an ISO Working Document on the Calibrating and Type-Testing of Radiation Protection Dosemeters for Photons“, *Radiat. Prot. Dosim.* **54**, 267-272.

KRAMER, H. M., BÜERMANN, L., HOHLFELD, K., and SELBACH, H.J. (1994). „Wie verändern sich die Meßwerte der Ortsdosisleistung beim Übergang von ‘alten’ zu ‘neuen’ Meßgrößen?“ in *Strahlenschutz: Physik und Meßtechnik*, Band 1, Hrsg. W. Kölzer, R. Maushart, S. 189-194, ISSN 1013-4506, Verlag TÜV Rheinland GmbH, Köln.

MARSHALL, M., THOMAS, D.J., PERKS, C.A., and NAISMITH, O.F. (1994). „Radiation Quantities: Significance of the Angular and Energy Distribution of the Radiation Field“, *Radiat. Prot. Dosim.* **54**, 139-248.

NRPB (1993). „Dose Quantities for Protection Against External Radiations“, *Documents of the NRPB*, Vol. **4** No 3, Chilton, Didcot, Oxon Ox ORQ1

PTB (1992). Physikalisch-Technische Bundesanstalt, „PTB-Anforderungen PTB-A 23.1 bis 23.4“, Eichordnung, Strahlenschutzmeßgeräte, Anlage 23 zur Eichordnung, Ausgabe 1990 mit Ergänzung 1992, Deutscher Eichverlag, Braunschweig.

REICH, H. (1980). „Neue Meßgröße für Strahlenschutzdosimeter für Photonenstrahlung“, PTB-Mitt. **90**, 290-292.

SELBACH, H.J., HOHLFELD, K., and KRAMER, H. M. (1984). „Radiation Characteristics of Dose Equivalent Meters“ Compacts 6th Int. Congr. International Radiation Protection Association, Berlin, S. 1178-1180, Verlag TÜV Rheinland GmbH, Köln.

SIEBERT, B.R.L., SCHUHMACHER, H. (1995). Quality Factors, Ambient and Personal Dose Equivalent for Neutrons, Based on the New ICRU Stopping Power Data for Protons and Alpha Particles. *Rad. Prot. Dosim.*, **58**, 177-183.

SIEBERT, B.R.L., ALBERTS, W.G., HOLLNAGEL, R.A., LEUTHOLD, G., and SCHRAUBE, H. (1994). „A proposal to revise the radiation weighting factors for neutrons on the basis of new calculations“, Letter to the editor, *Radiat. Prot. Dosim.,* **58**, 69-71.

SSK (1991). Strahlenschutzkommission, „Berechnungsgrundlage für die Ermittlung von Körperdosen bei äußerer Bestrahlung durch Photonenstrahlung und Berechnungsgrundlage für die Ermittlung von Körperdosen bei äußerer Bestrahlung durch Elektronen, insbesondere durch β-Strahlung“, Zweite, durchgesehene Auflage, *Veröffentlichungen der Strahlenschutzkommission*, Band **3**, Gustav Fischer Verlag, Stuttgart, Jena, New York.

SSK (1993). Strahlenschutzkommission, „Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. Anforderungen an Personendosimeter; Empfehlung der Strahlenschutzkommission“, *BGBl.* Teil II Nr. **207** 9817-9819

SSK (1994). Strahlenschutzkommission, „Berechnungsgrundlage für die Ermittlung von Körperdosen bei äußerer Strahlenexposition“, Entwurf einer Neufassung, *Veröffentlichungen der Strahlenschutzkommission*, Band **3**, in preparation.

WAGNER, S.R., GROSSWENDT, B., HARVEY, J.R., MILL, A.J., SELBACH, H.-J. and SIEBERT, B.R.L.(1985). „Unified Conversion Functions for the new ICRU Operational Radiation Protection Quantities“, *Radiat. Prot. Dosim.* **12**, 231-235.

10 Appendix

10.1 Figures where the quantity H_X is replaced by the quantity K_a

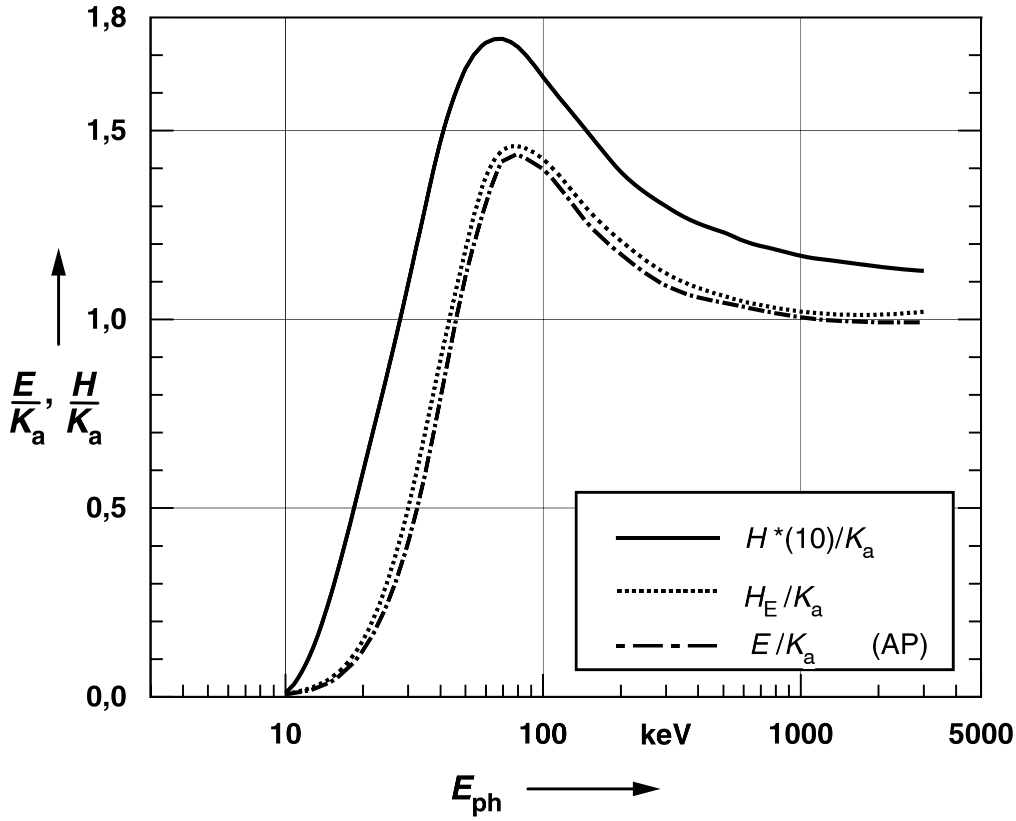


Fig. 2.1 (K_a) Comparison of the new quantity for area monitoring, $H^*(10)$, with the effective dose equivalent, H_E, and the effective dose E for monoenergetic photon radiation (K_a: air kerma). The values of H_E and E are valid for whole-body exposure from the front (AP, anterior-posterior); the values of the effective dose are smaller for other irradiation geometries of the whole body. E_{ph} photon energy.

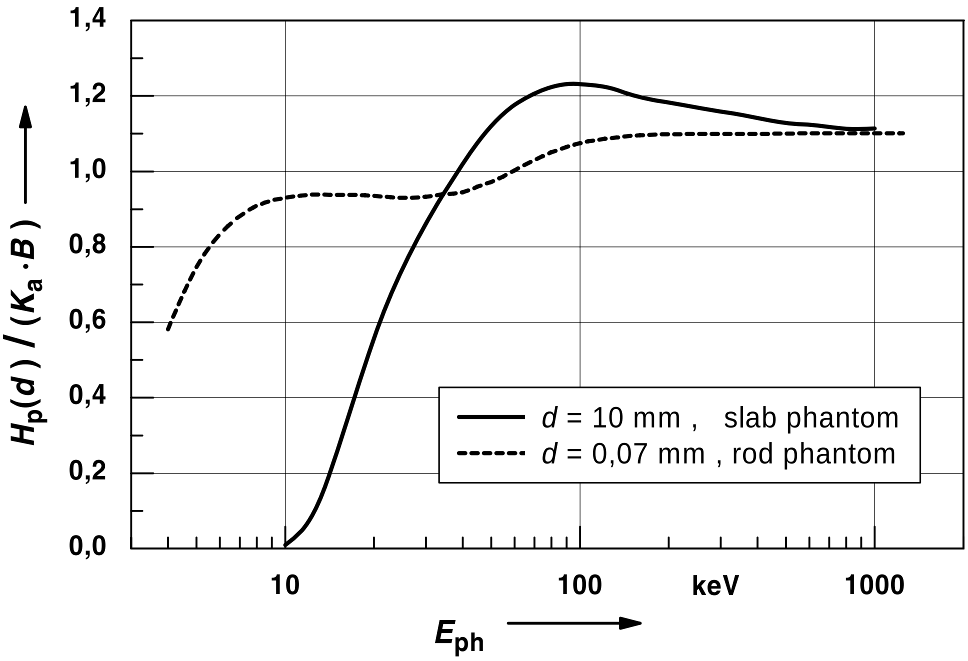


Fig. 4.4 (K_a) Quotients $H_p(d)/(K_a \cdot B)$ for d = 10 mm and a slab phantom (———) (GROSSWENDT, 1990, 1991) and d = 0,07 mm and a rod phantom (— — —) (GROSSWENDT, 1995a) for monoenergetic photon radiation as a function of the photon energy E. B is the backscatter factor for the respective phantom. E_{ph} photon energy.

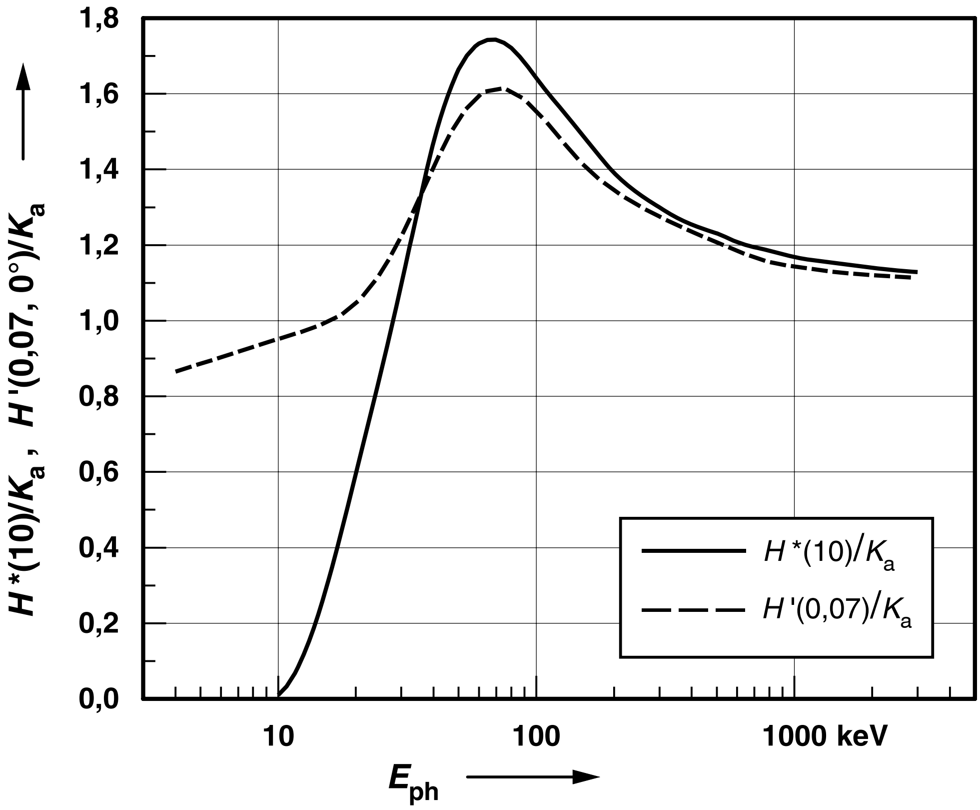


Fig. 4.5 (K_a) Quotients $H^*(10)/K_a$ (———) and $H'(0,07, 0°)/K_a$ (— — —) (ICRU, 1992) for monoenergetic photon radiation as a function of the photon energy E_{ph}.

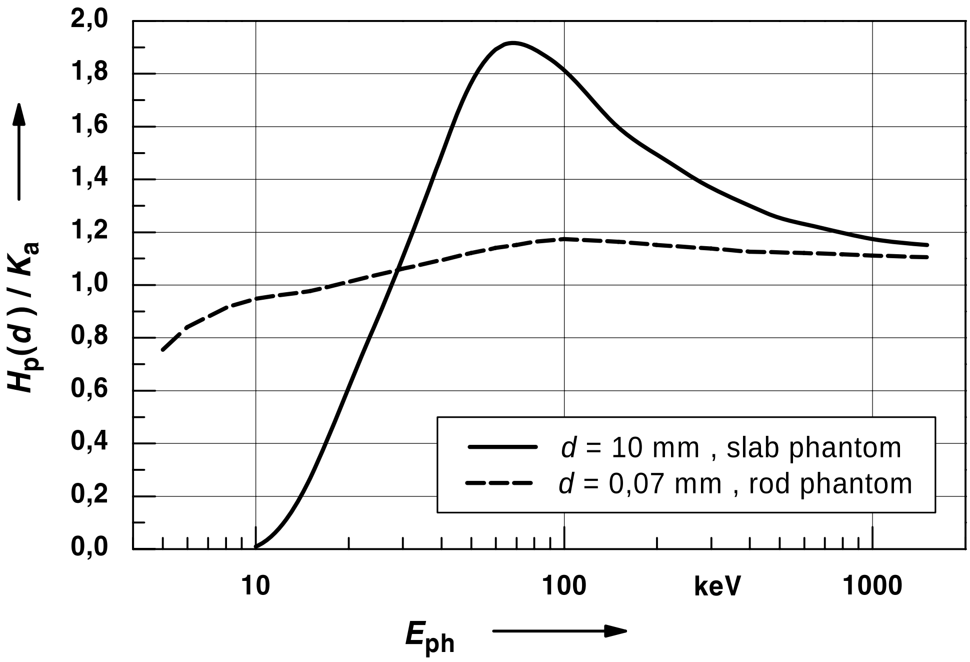


Fig. 6.1 (K_a) Energy dependence of the quotients $H_p(10)/K_a$ for the slab phantom (solid curve) (GROSSWENDT, 1991) and $H_p(0{,}07)/K_a$ for the rod phantom (dashed curve) (GROSSWENDT, 1995a) for monoenergetic and monodirectional photon radiation. E_{ph} photon energy.

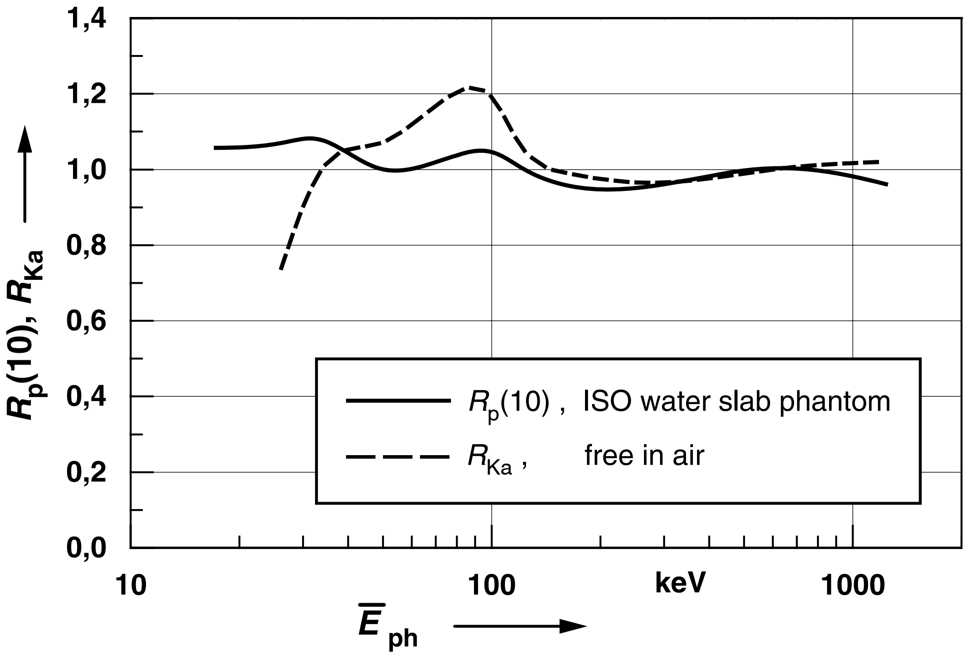


Fig. 6.7 (K_a) Example of the possibility of measuring the quantities K_a and $H_p(10)$ with the same personal dosimeter. The response R_{Ka} with regard to the air kerma K_a and the response $R_p(10)$ with regard to the new quantity $H_p(10, 0°)$ have been indicated for a phosphate glass dosimeter as a function of the mean photon energy $\overline{E}_{ph}$ (662 keV being in each case the reference energy).

10.2 Tables where the quantity H_X is replaced by the quantity K_a

Table 5.1 (K_a) Quotients $H^*(10)/K_a$ and $H'(0{,}07,\ 0°)/K_a$ for monoenergetic photon radiation. The values were calculated using the approximate formula stated in Section 5.2.2 and used in ICRU Report 47 (ICRU, 1992) (with the exception of the values for $H^*(10)/K_a$ below 20 keV and the values of $H'(0{,}07,\ 0°)/K_a$ above 50 keV).

Photon energy in keV	$H^*(10)/K_a$	$H'(0{,}07,\ 0°)/K_a$
10	0,01	0,95
15	0,26	0,99
20	0,61	1,05
30	1,10	1,22
40	1,47	1,41
50	1,67	1,53
60	1,74	1,60
80	1,72	1,61
100	1,65	1,55
150	1,49	1,42
200	1,40	1,34
300	1,31	1,27
400	1,26	1,22
500	1,23	1,20
600	1,21	1,19
800	1,19	1,15
1000	1,17	1,14
1500	1,15	1,13

Table 5.2 (K_a) Quotient of the ambient dose equivalent $H^*(10)$ and the air kerma K_a for the photon radiation of some radionuclides. Only photon energies above 20 keV have been taken into consideration.

Nuclide	Half-life	Important photon energies in MeV	$H^*(10)/K_a$
^{24}Na	15,0 h	1,37 2,75	1,19
^{60}Co	5,27 a	1,17 1,33	1,16
^{124}Sb	60 d	0,60 to 2,09	1,19
^{131}I	8,02 d	0,08 to 0,72	1,27
^{137}Cs	30 a	0,66	1,21
^{182}Ta	114 d	0,06 to 1,23	1,17
^{192}Ir	74 d	0,30 to 0,61	1,28
^{226}Ra and progenies	1600 a	0,19 to 2,4	1,20
^{241}Am	458 a	0,06	1,69

Table 5.3 (K_a) Quotients $H^*(10)/K_a$ and H'(0,07, 0°)/K_a for photon radiation fields used for calibration and for the determination of the energy dependence of the response. Values are taken from ISO (1996) with the exception of those fields only described by DIN radiation qualities (DIN, 1992a).

	Radiation quality, symbol according to DIN (1992a)	ISO (1996)	Mean energy in keV	$H^*(10)/K_a$	$H'(0,07, 0°)/K_a$
Narrow spectra	A 10	N-10	8	0,0007 [1)]	0,91
	A 15	N-15	12	0,06 [1)]	0,96
	A 20	N-20	16	0,28 [1)]	1,00
	-	N-25	20	0,52 [1)]	1,03
	A 30	N-30	24	0,80	1,10
	A 40	N-40	33	1,18	1,25
	A 60	N-60	48	1,58	1,48
	A 80	N-80	65	1,73	1,60
	A 100	N-100	83	1,71	1,59
	A 120	N-120	100	1,64	1,55
	A 150	N-150	118	1,58	1,49
	A 200	N-200	164	1,46	1,39
	A 250	N-250	208	1,39	1,33
	A 300	N-300	250	1,35	1,30
Wide spectra	B 10	-	8	0,0007 [1)]	0,91
	B 15	-	12	0,06 [1)]	0,96
	B 20	-	16	0,28 [1)]	1,00
	B 30	-	23	0,78	1,07
	B 40	-	31	0,98	1,19
	B 60	W-60	45	1,49	1,43
	B 80	W-80	57	1,66	1,54
	B 110	W-110	79	1,71	1,60
	B 150	W-150	104	1,62	1,53
	B 200	W-200	137	1,52	1,44
	B 250	W-250	173	1,44	1,37
	B 300	W-300	208	1,39	1,33
High air kerma rate spectra	C 10	H-10	7,5	0,0001 [1)]	0,89
	C 20	H-20	12,9	0,09 [1)]	0,96
	C 30	H-30	19,7	0,38 [1)]	1,02
	C 40	-	25	0,70	1,16
	C 60	H-60	37,3	1,15	1,26
	C 80	-	49	1,40	1,49
	C 100	H-100	57,4	1,57	1,49
	C 150	-	78	1,66	1,57
	C 200	H-200	102	1,61	1,51
	C 250	H-250	122	1,54	1,46
	-	H-280	146	1,49	1,41
	C 300	H-300	147	1,48	1,41

[1)] The quotient must be determined separately for the respective irradiation device; see Section 5.2.2.

Table 5.4 (K_a) Quotient $H^*(10)/K_a$ for some typical photon radiation fields

Radiation field	$H^*(10)/K_a$
Environmental radiation	1,22
Radiation field after contamination due to a reactor accident	1,21 bis 1,25
Radiation field in nuclear reactor	1,17
^{16}N gamma radiation (6 MeV)	1,11
Leakage radiation through the housing of an X-ray tube	up to 1,7
Radiation of ^{192}Ir behind 5 cm lead shield	1,21
20 MeV bremsstrahlung behind 1,7 m concrete	1,12

Table 6.1 (K_a) Quotients $H_p(10, 0°)/K_a$ for the slab phantom (GROSSWENDT, 1991) and $H_p(0{,}07, 0°)/K_a$ for the rod phantom (GROSSWENDT, 1995a) for a homogeneous broad beam of monoenergetic photons incident perpendicularly on the phantom surface.

Photon energy in keV	$H_p(10, 0°)/K_a$ **for the slab phantom**	$H_p(0{,}07, 0°)/K_a$ **for the rod phantom**
5	-	0,76
6	-	0,84
8	-	0,92
10	0,01	0,95
15	0,27	0,98
20	0,61	1,01
30	1,11	1,06
40	1,50	1,09
50	1,77	1,12
60	1,89	1,14
70	1,91	1,16
80	1,89	1,16
100	1,81	1,17
150	1,60	1,16
200	1,49	1,15
300	1,37	1,14
400	1,30	1,12
500	1,26	1,12
600	1,23	1,12
800	1,19	1,11
1000	1,18	1,11
1500	1,15	1,11

Table 6.2 (K_a) Quotients $H_p(10, 0°)/K_a$ for the slab phantom (GROSSWENDT, 1992) and $H_p(0{,}07, 0°)/K_a$ for the rod phantom (GROSSWENDT, 1995b) for radiation fields used for calibration and for determining the energy dependence of the response. Whenever possible, values for the mean energy are taken from ISO (1995a), otherwise from DIN 6818-1 (DIN, 1992a).

	Radiation quality, symbol according to DIN (1992a)	ISO (1995a)	Mean energy in keV	$H_p(10, 0°)/K_a$ for the slab phantom	$H_p(0{,}07, 0°)/K_a$ for the rod phantom
Narrow spectra	A 10	N-10	8	0,002 [1)]	0,91
	A 15	N-15	12	0,07 [1)]	0,95
	A 20	N-20	16	0,28 [1)]	0,98
	-	N-25	20	0,55 [1)]	1,00
	A 30	N-30	24	0,79	1,03
	A 40	N-40	33	1,17	1,07
	A 60	N-60	48	1,65	1,11
	A 80	N-80	65	1,88	1,15
	A 100	N-100	83	1,87	1,17
	A 120	N-120	100	1,80	1,17
	A 150	N-150	118	1,71	1,17
	A 200	N-200	164	1,56	1,16
	A 250	N-250	208	1,48	1,15
	A 300	N-300	250	1,42	1,14
Wide spectra	B 10	-	8	0,002 [1)]	0,91
	B 15	-	12	0,07 [1)]	0,95
	B 20	-	17	0,28 [1)]	0,98
	B 30	-	23	0,67	1,02
	B 40	-	31	1,00	1,05
	B 60	W-60	45	1,55	1,10
	B 80	W-80	57	1,77	1,13
	B 110	W-110	79	1,87	1,16
	B 150	W-150	104	1,76	1,17
	B 200	W-200	137	1,64	1,16
	B 250	W-250	173	1,54	1,15
	B 300	W-300	208	1,48	1,15
High air kerma rate spectra	C 10	H-10	7,5	0,001 [1)]	0,88
	C 20	H-20	12,9	0,10 [1)]	0,95
	C 30	H-30	19,7	0,40 [1)]	0,99
	C 40	-	25	0,71	1,02
	C 60	H-60	37,3	1,19	1,07
	C 80	-	49	1,54	1,10
	C 100	H-100	57,4	1,68	1,12
	C 150	-	78	1,80	1,15
	C 200	H-200	102	1,74	1,16
	C 250	H-250	122	1,66	1,16
	-	H-280	146	1,60	1,16
	C 300	H-300	147	1,59	1,16

[1)] The quotient must be determined separately for the respective irradiation facility; see Section 6.2.3.