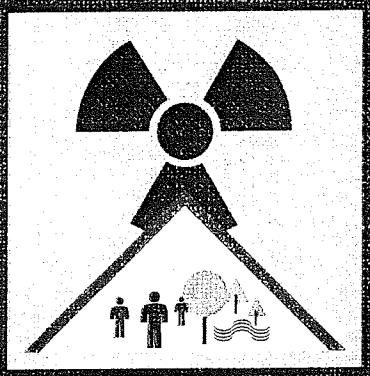
RADIATION PROTECTION 73



Technical recommendations

for monitoring individuals occupationally exposed to external radiation

EUROPEAN COMMISSION

DIRECTORATE-GENERAL DG XI
ENVIRONMENT, NUCLEAR SAFETY
AND CIVIL PROTECTION

Report
EUR 14852 EN

European Commission

radiation protection 73

Technical recommendations

for monitoring individuals occupationally exposed to external radiation

P. Christensen, H. W. Julius and T. O. Marshall

Directorate-General for Environment, Nuclear Safety and Civil Protection
Directorate-General for Science, Research and Development

1994

EUR 14852 EN

Published by the
EUROPEAN COMMISSION
Directorate-General XI
Environment, Nuclear Safety and Civil Protection
L-2920 Luxembourg

Cataloguing data can be found at the end of this publication

Luxembourg: Office for Official Publications of the European Communities, 1994

ISBN 92-826-7364-2

Printed in Germany

PREFACE

The European Community is obliged by the Euratom Treaty to lay down basic safety standards for the protection of workers and the general public against the hazards arising from ionizing radiation. The Community has fulfilled this obligation by adopting a series of directives which form the basis for the administrative and legislative measures taken within the 12 EC Member States. The first such directive dates back to 1959, but the standards have been updated several times since then. The directive currently in force, adopted in 1980 (and modified in 1984), is currently undergoing a thorough revision to take account of the latest scientific knowledge.

The prime requirement for the effective implementation of occupational radiation protection in practice is the ability to make accurate measurements of the radiation exposure received by workers. In order to harmonize the methods for deducing from these measurements the relevant doses received, the ›mmission published, in 1975, a report entitled "Technical Recommendations for Monitoring the Exposure of Individuals to External Radiation" (EUR 5287 e). The present document represents both an enlargement and an updating of the 1975 recommendations, and is based on work carried out by H.W. Julius, T.O. Marshall and P. Christensen. The initial draft was subject to comments from radiation protection institutions in all 12 EC Member States. Thereafter L. Lembo, J.P. Moroni and G. Dietze oversaw the final revision of the document. The Commission would like to thank all those involved for their valuable co-operation and personal commitment and hopes that these new technical recommendations will provide useful guidance to all those concerned with the practical implementation of occupational radiation protection.

Dr. H. Eriskat
Head of Division

L.J. Brinkhorst
Director-General

1. INTRODUCTION

In 1975 the Commission of the European Communities (CEC) published the first edition of "Technical Recommendations for Monitoring the Exposure of Individuals to External Radiation", EUR 5287 [1]. Since the date of publication the concepts and methods of individual monitoring have changed substantially. As a result the CEC has taken the advice of its Technical Experts Committee on Radiation Protection Dosimetry and decided to commission a small expert drafting group to revise the document.

The major changes indicated above stem from the recommendations of the International Commission on Radiological Protection (ICRP) and the International Commission on Radiation Units and Measurements (ICRU). In Publication 26 (1977) [2], ICRP introduced a new dosimetric quantity, named the effective dose equivalent, H_E, to assess the radiation risk to the individual for stochastic effects. In Publication 60 (1991) [3] ICRP modified this quantity and changed its name to effective dose, E. The quantity effective dose equivalent which is the dose limiting quantity in the current Basic Safety Standards requires a knowledge of the dose equivalent in a number of specified and unspecified organs of the body and as such is impossible to measure. To overcome this problem ICRU in Report 39 (1985) [4] recommended operational quantities for individual monitoring (the individual dose equivalent, penetrating, and individual dose equivalent, superficial), designed to give a reasonable estimate of effective dose equivalent. This approach will also apply, in future, to the quantity effective dose. ICRU have since published two further reports in support of these quantities. The first, Report 43 [5] gives the background information behind their formulation and Report 47 [6] gives information on the design of dosemeters and instruments to measure the operational quantities and on the way these devices should be calibrated and type tested. These new quantities may require changes to be made to some current dosemeter designs, to the methods of dose evaluation and dosemeter type testing. Therefore a complete chapter has been devoted to dosimetric concepts and another to type testing of dosemeters.

Both the principle that radiation doses should be kept as low as reasonably achievable (i.e. the ALARA principle) and ICRP's Publication 35 (1982) [7] on "General Principles of Monitoring for Radiation Protection of Workers" – which is a revision of Publication 12 [8] of the same title – also have implications as far as individual monitoring is concerned.

This document addresses a larger part of the radiation protection community than did the previous version. It is intended to provide guidance for those operating individual monitoring services, for those responsible for individual monitoring programmes, for those involved in dosemeter and personal dosimetry sys-

tem design and for those responsible for the formulation of legislation in this field. Therefore the scope of the revised document has been extended, as a result of which special chapters have been added, devoted to some new topics. One such topic is quality assurance which is of increasing importance for individual monitoring since a number of countries operate an approval system for individual monitoring services, which often requires services to demonstrate regularly to the legal authorities that the standard of their services is adequate. To this end each monitoring service must include a comprehensive quality control procedure in its methods of operation, which may include performance tests of the dosimetry system. (In the past the CEC has regularly carried out intercomparison exercises for the benefit of individual monitoring services.)

It is clearly essential to keep an accurate, reliable and secure record of workers' doses in a system which allows continuity if he changes employer. A complete chapter has therefore also been devoted to this subject. In some countries approval must also be granted to operate a dose record keeping system for workers and sometimes a summary of the data stored by the individual approved dosimetry service is held in a central index of dose information.

Finally a chapter has been devoted to certain aspects of management and administration of individual monitoring services.

The authors have sought guidance from a number of authoritive documents, in particular those issued by the ICRP and ICRU, and from others considered to reflect a consensus viewpoint in the field. These documents are given in the list of references. Verbatim quotations from these documents are put between inverted commas.

The terminology used in these recommendations is, as far as possible, identical to that defined in the CEC Directive on Basic Safety Standards for the Health Protection of the Population and Workers Against Ionising Radiations (BSS) [9].

The recommendations given in ICRP Publication 60 [3] will in due course require changes to this document. However, the current legal situation is set out in the CEC Directive [9] dealing with the basic safety standards and this situation will not change until a new Directive is issued and has been incorporated into the national legislation of the Member States. This is likely to take several years. In view of this, the document is based, at present, on the above mentioned CEC Directive with the exception of the reduction in the annual dose limit from 50 mSv to 20 mSv since it is reasonable to assume that this will be adopted by CEC in due course. Similarly, in the interim, in the control of neutron exposures, it may be prudent to assume the values of significant neutron doses to be greater by a factor 1.5 to take into account the new Q - L relationship recommended by ICRP. Nevertheless in order to allow monitoring services the maximum amount of time to prepare their systems to meet the requirements of the

forthcoming Directive this documents, as far as possible, also specifies the changes which will probably be necessary.
These recommendations may have to be revised when the new CEC Directive is published.

References

1. Commission of the European Communities, "Technical Recommendations for Monitoring the Exposure of Individuals to External Radiation", CEC EUR 5287 (1975).
2. International Commission on Radiological Protection, "Recommendations of the International Commission on Radiological Protection", ICRP Publication 26, Ann. ICRP, 1, No. 3, (Pergamon Press, Oxford) (1977).
3. International Commission on Radiological Protection, "Recommendations of the International Commission on Radiological Protection", ICRP Publication 60, Ann. ICRP, 21, No. 1-3, (Pergamon Press, Oxford) (1991).
4. International Commission on Radiation Units and Measurements, "Determina-tion of Dose Equivalents Resulting from External Radiation Sources", ICRU Report 39, Bethesda, MD (1985).
5. International Commission on Radiation Units and Measurements, "Determination of Dose Equivalents Resulting from External Radiation Sources - Part 2", Report 43 (Bethesda, MD: ICRU Publication) (1988).
6. International Commission on Radiation Units and Measurements, "Determina-tion of Dose Equivalents Resulting from External Radiation Sources - Part 3", Report 47 (Bethesda, MD: ICRU Publication) (1992).
7. International Commission on Radiological Protection, "General Principles of Monitoring for Radiation Protection of Workers", ICRP Publication 35, (Pergamon Press, Oxford) (1982).
8. International Commission on Radiological Protection, "General Principles of Monitoring for Radiation Protection of Workers", ICRP Publication 12, (Pergamon Press, Oxford) (1968).
9. Commission of the European Communities, "Council Directive of 15 July 1980 amending the Directive laying down the basic safety standards for the health protection of the general public and workers against the dangers of ionising radiation", Official Journal of the European Communities L246, 1980 and "Council Directive of 3rd September 1984 amending Directive 80/836/Euratom as regards the basic safety standards for the health protection of the general public and workers against the dangers of ionising radiation", Official Journal of the European Communities, L265, 1984.

2. OBJECTIVES AND PRINCIPLES OF INDIVIDUAL MONITORING

2.1 General Aspects

2.1.1 Objectives

Monitoring of workers constitutes an integral part of any radiological protection programme and aids in assuring acceptably safe and satisfactory radiation conditions in the workplace.

ICRP, in Publication 35 [1], state that: "The primary purpose of individual monitoring is to obtain an estimate of the mean dose equivalent and of the effective dose equivalent in significantly exposed tissues. This information is useful in limiting radiation doses to individual workers and in demonstrating compliance with the full system of dose limitation recommended by the Commission and with authorized limits."

A programme of individual monitoring may be used for a number of specific purposes depending on the extent and nature of the radiation practice as well as on national and local requirements.

In the following a range of benefits that may accrue from an individual monitoring programme is mentioned:

- Demonstration of good working practices which indicate the adequacy of supervision, training and engineering standards. The results of individual monitoring can be used to give information about conditions in the workplace and thus provide a means of establishing whether these are under satisfactory control and whether operational changes have improved or worsened the working conditions.
- Estimation of the actual radiation exposure of workers to demonstrate compliance with legal requirements.
- Evaluation and development of radiation procedures by means of collected data both for individuals and groups. Individual monitoring data may be used to identify both good and bad features of operating procedures and design characteristics and thereby contribute to the development of safer radiation practices. Collected dose data may also be useful for risk-benefit analysis.
- Provision of information for the evaluation of dose in the event of accidental exposures, for the assessment of possible high levels of radiation exposures.
- Provision of information which can be used to motivate workers to reduce their exposure as a result of the information given to them.

- Provision of data for medical purposes.
- Provision of data for use in epidemiological studies of the exposed population.

A distinction may be made between three types of monitoring: *Routine monitoring, Operational monitoring* and *Special monitoring.*

Routine individual monitoring is associated with continuing operations and constitutes regularly repeated or continuous measurements made on an individual worker. Routine monitoring is largely of confirmative nature, but may also contribute important information in the event of unexpected abnormal working situations.

Operational individual monitoring is associated with a particular operation or a series of operations and is limited in time. It may make use of supplementary dosemeters in addition to those used for routine monitoring. A special purpose of operational monitoring may be to establish whether routine monitoring is required.

Special individual monitoring refers to monitoring applied to actual or suspected abnormal conditions, including accidents. Special monitoring is beyond the scope of this document.

The results of individual monitoring may be used for initiating a certain action when a pre-defined dose level, a *Reference level*, has been exceeded. The most common forms of reference levels of interest in radiation protection programmes are *Recording levels*, *Reporting levels*, *Investigation levels* and *Intervention levels* (see also Chapter 7).

2.1.2 Compliance with Dose Limits

Both the CEC Basic Safety Standards [6] and ICRP, in Publications 26 [2] and 60 [3], provide means of minimizing the risk of radiation work by setting out a system of dose limitation, the main principles of which are:

- no practice shall be adopted unless its introduction produces net benefit;
- all exposures shall be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account;
- the dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission.

The recommended dose limits refer to the mean dose equivalent in organs or tissues and effective dose equivalent and they relate to the sum of the dose equiva-

lents from external exposures during one year and the committed dose equivalents from that year's intake of radionuclides. The dose limits are intended to prevent non-stochastic effects and to limit the occurrence of stochastic effects to a tolerable level. In practice the pursuit of the ALARA principle will ensure that doses are kept well below the limits. This implies that in most cases it is not necessary to measure the primary dose quantity, i.e. organ dose equivalent and effective dose equivalent. It will be satisfactory to use simpler operational quantities (see Chapter 3), such as personal dose equivalent at a depth of 10 mm, $H_p(10)$, to give a conservative estimate of effective dose equivalent due to strongly penetrating radiation, and personal dose equivalent at a depth of 0.07 mm, $H_p(0.07)$, to provide an upper estimate of organ dose due to weakly penetrating radiation [4]. These quantities may be deemed to represent the primary limiting quantities and hence can be used to demonstrate compliance with the dose limits. The dose limits most commonly needed in the control of external radiation are those for effective dose equivalent and dose equivalent to the skin. In most practical situations the dose limit for the lens of the eye will be automatically controlled if the limits for effective dose and skin equivalent dose are not exceeded. Only for some special radiation situations, e.g. where high energy beta rays are involved, the lens of the eye may become the limiting organ.

If, in isolated cases, it is necessary for doses to approach the dose limits the use of $H_p(10)$ as an estimate of effective dose equivalent may be over restrictive for photons, but this may not be the case for low E neutrons. In such cases it may be worthwhile characterising the radiation field in sufficient detail to get a better estimate of effective dose equivalent. Information contained in ICRU report no. 43 [5], which relates $H_p(10)$ to the organ dose and effective dose equivalent for various radiation conditions is helpful for such dose evaluations.

Sometimes a competent authority or the management of an institution may lay down *authorised dose equivalent limits*. They may be established by a process of optimization of protection or by other considerations. The ICRP recommend that authorized dose limits should never exceed the Commission's primary limits or appropriate derived limits and should rather be lower than these.

2.1.3 Scale of Individual Monitoring

The need for individual monitoring of workers will depend on the radiation conditions in the area concerned and the type of work.

The CEC Directive on Basic Safety Standards [6] states that the following classification of working conditions should be made:

- Working condition A: this describes conditions where the annual dose equiva-

lents might exceed three tenths of the relevant annual limits.

- Working condition B: this describes conditions where it is most unlikely that the annual dose equivalents will exceed three tenths of the relevant annual limits.

It should be noted that the concept of working conditions A and B, as defined in the present BSS, may be changed in the new BSS based on new concepts described by ICRP Publication 60.

These definitions relate to the probability of reaching this dose level and not to the dose level of the actual exposure incurred in a particular year. In practice, the majority of the annual dose equivalents actually incurred by workers in working condition A are lower than three tenths of the dose equivalent limits.

In the CEC Directive on Basic Safety Standards, it is required that systematic individual monitoring shall be performed for Category A workers.

Category B workers need not be issued with individual dosemeters, if sufficient known from monitoring of the working environment to indicate unambiguously that they belong to this category. However, in many work situations it is not possible to estimate with adequate precision the doses which people will receive simply by studying their working habits and their working environment. In such situations persons working in these areas shall be issued with personal dosemeters, at least for an experimental period, in order to establish that they are not in Category A.

Although not strictly required dosemeters are often issued to Category B workers for mainly two reasons:

a. For reassurance of workers on dose levels;
b. For protection of employers against claims for compensation for radiation related diseases.

When personal dosemeters are issued to Category B workers, the principles which determine the choice of dosemeter type are the same as they are for Category A workers.

Visitors should be considered to be individual members of the public. Although monitoring is not required, simple individual monitoring is often advisable.
Temporary personnel such as visiting scientists, research fellows, students and contractors who may be engaged in radiation work must be monitored to at least the same standards as permanent radiation workers.

2.2 Special Aspects

2.2.1 Monitoring for Strongly Penetrating Radiation

2.2.1.1 Electrons and Photons

In most work situations an estimate of $H_p(10)$ obtained from a single *basic* dosemeter (see Section 3.7.1) for electron/photon monitoring worn on the trunk of the body will provide an acceptable value for the body dose from exposures to strongly penetrating electron/photon radiation (see Chapter 3). In a few cases where the worker's doses are at or near the dose limits, it may be worthwhile obtaining additional information about the radiation conditions, e.g. from measurements at the workplace or by using *discriminating* dosemeters (see Sections 2.2.5 and 3.7.2) enabling a better estimate of effective dose equivalent to be made.

Dosemeter placement in case of protective clothing requires special consideration. For monitoring in medical radiology, where the use of lead aprons is common the following advice is given by ICRP in Publication 35, paragraph 84:
"In special situations where installed shielding or protective clothing such as lead aprons provide significant attenuation of the incident radiation on some parts of the body, more than one dosemeter may be required. In particular, the following advice applies in medical radiology, where the use of lead aprons is common. If a single dosemeter is used it should be worn outside the apron, usually high on the trunk. The recorded result will provide information on the dose equivalent to the skin, eye, and unshielded parts of the body (though not necessarily to the hands) but will overestimate the effective dose equivalent. When the recorded values indicate annual totals approaching dose limits for effective dose equivalent or when realistic estimates of effective dose equivalent are needed as in the optimization of protection, this over-estimation may be unacceptable. Two dosemeters should then be used, one over and one under the protective apron. The interpretation of the combined results will have to depend on the local irradiation conditions and any regulatory requirements."

2.2.1.2 Neutrons

The principles of individual monitoring apply equally to neutrons although it is difficult to meet the requirements with current designs of personal neutron dosemeters. This is mainly because the sensitivity and the variation of response with neutron energy and the angle of incidence are unsatisfactory.
In the past a constant ratio between neutron and gamma ray dose equivalent has been assumed to derive the neutron dose from the measurement of the accompanying gamma ray dose. However, this ratio has been found to vary substantially with position within an establishment and this method is now not recommended.

A more reliable system is to use more than one type of dosemeter to cover the whole energy range e.g. an Albedo dosemeter for neutrons in a low energy re-

gion together with a solid state track etch dosemeter to cover the energy range above approximately 100 keV.

Even with this system intermediate energy neutrons may not be measured satisfactorily. Thus when neutron doses contribute significantly to total doses likely to approach the dose limits a more elaborate approach may be necessary. The approach recommended is to use area monitors and, if possible, neutron spectrometers to characterise the radiation field so that site specific correction factors can be applied to the results of personal neutron doses to obtain more accurate values.

2.2.2 Monitoring for Weakly Penetrating Radiation

Although the depth of the sensitive layers of the skin vary between individuals and over the body of individuals, an estimate of $H_p(0.07)$ is considered to be a reasonable quantity to apply for the assessment of doses to the skin for practical radiological protection (see Chapter 3). When protective clothing is worn over the whole body the dosemeter should be worn under the clothing at the position of the body where the skin is likely to be most seriously exposed (i.e. either under the clothing or on the unprotected part of the body). In the case of inhomogeneous exposure of the body, it may be necessary to use more than one dosemeter and the maximum value of the measurements should be used as representative of $H_p(0.07)$. The method used to estimate $H_p(10)$ from exposures from inhomogeneous beams (Section 2.2.1.1) should also apply to $H_p(0.07)$.

In most practical situations the skin will be exposed to weakly penetrating radiation together with strongly penetrating radiation and an estimate of the skin dose will have to be made for both types of radiation together. For weak beta radiation (< 0.5 MeV) the same difficulty in measurement exists as for neutrons.

2.2.3 Monitoring for Extremity Doses

If the dose to any part of the extremities of a worker is likely to exceed three tenths of the annual dose limit on a pro rata basis an additional dosemeter of appropriate design should be worn on the part of the extremity where the dose is expected to have its highest value. Although not strictly required extremity dosemeters are often issued also to workers receiving lower doses in order to reassure the workers on their dose levels. Most often monitoring of the extremities will involve the hand and in particular the finger tips. An extremity dosemeter should provide an estimate of $H_p(0.07)$ for the extremity concerned (see Chapter 3.)

2.2.4 Monitoring Period

The choice of monitoring period should be related to the exposure situation. If for operational reasons daily monitoring is required, a direct reading dosemeter with sufficient sensitivity should be used in addition to the official dosemeter. Except in situations where people are being exposed at a very non-uniform rate, a monitoring period of between a week and a month is likely to be convenient. Unless exposures are particularly low or uniform, an issue period of more than 1 month is undesirable, since the longer the time which has elapsed, the more difficult it becomes to establish the reason for the exposure. For people who rarely receive any dose e.g. persons who occasionally enter radiation areas with a low radiation level, a monitoring period of three months may be suitable, if the dosemeter used permits long monitoring periods.

Direct reading dosemeters are sometimes used to monitor the dose received during a particular task. The issue period is therefore usually short e.g. one working day or one shift. However, dosemeters of this type are under development which are suitable for use as official basic dosemeters for photon and beta-radiations.

2.2.5 Qualitative Information Additional to Dose

Information concerning the conditions of exposure on, for example, the type and energy of the radiation and its angular distribution may be useful in determining the source of the exposure or to provide a better estimate of effective dose equivalent when doses approach the dose limits or when an accidental overexposure has occurred. It also serves, in some cases, to provide information on conditions within the workplace including the presence of radioactive contamination. Qualitative information in addition to dose can be obtained by using discriminating dosemeters (see Section 3.7.2).

EURADOS-CENDOS have discussed the relative merits of discriminating and non- discriminating dosemeters and given guidance on requirements for using discriminating dosemeters [7]. Here the following general consideration is given:

"Thus, although there seems to be a role for discriminating dosemeters it is only a small one. Clearly, they are not required where small doses are involved, so that if Category B workers are given personal dosemeters, they should be of the non-discriminating type. It should be noted that discrimination becomes progressively more unreliable as the dose gets smaller and that it is generally not possible for doses less than 1 - 2 mSv. Moreover, it should also be noted that at low doses the ALARA principle does not call for detailed investigation. Discriminating dosemeters may be of some value to Category A workers but only to those who work with complex radiation fields involving more than one source and even then only if the worker concerned regularly receives doses around the dose limits."

References

1. International Commission on Radiological Protection, "General Principles of Monitoring for Radiation Protection of Workers", ICRP Publication 35, Ann. ICRP 9 (4), (Pergamon Press, Oxford) (1982).
2. International Commission on Radiological Protection, "Recommendations of the ICRP", ICRP Publication 26, Ann. ICRP 1 (3), (Pergamon Press, Oxford) (1977).
3. International Commission on Radiological Protection, "Recommendations of the International Commission on Radiological Protection", ICRP Publication 60, Ann. ICRP, 21, No. 1-3, (Pergamon Press, Oxford) (1991).
4. International Commission on Radiation Units and Measurements, "Determina-tion of Dose Equivalents Resulting from External Radiation Sources", ICRU Report 39, Bethesda, MD (1985).
5. International Commission on Radiation Units and Measurements, "Determina-tion of Dose Equivalents from External Radiation Sources - Part 2", ICRU Report 43, Bethesda, MD (1988).
6. Commission of European Communities, "Council Directive of 15 July 1980 amending the Directives laying down the basic safety standards for the health protection of the general public and workers against the dangers of ionizing radiation", Official Journal of the European Communities L246, 1980 and "Council Directive of 3rd September 1984 amending Directive 80/836/Euratom as regards the basic safety standards for the health protection of the general public and workers against the dangers of ionising radiation", Official Journal of the European Communities, L265, 1984.
7. Marshall, T.O., Christensen, P., Julius, H.W. and Smith, J.W., "The Relative Merits of Discriminating and Non-discriminating Dosemeters", Radiation Protection Dosimetry 14 (1), 5 - 10 (1986).

3. DOSIMETRIC CONCEPTS IN INDIVIDUAL MONITORING

3.1 General

In 1976 the International Commission on Radiological Protection (ICRP) recommended in Publication 26 [1] that dose limitation for stochastic effects should be based on the quantity *effective dose equivalent*. This recommendation was subsequently adopted by the CEC in its Basic Safety Standards [2]. It was recognised at the time, however, that this concept required knowledge of the dose equivalent in various organs or tissues in the body, and the quantity is therefore difficult to assess and impossible to measure. It was to overcome these problems that the International Commission on Radiation Units and Measurements (ICRU) introduced in 1985, in Report 39 [3], operational quantities for practical use in radiological protection where external sources are concerned. In 1988 the ICRU published Report 43 [4], which is the second part of the Commission's guidance on operational quantities. Report 43 presents the justification for the choice of the operational quantities. It was shown that these quantities give both a reasonable approximation of the effective dose equivalent, limiting underestimation and excessive overestimation, and an adequate approximation of the dose equivalent to the skin. In addition they give, in general, an indication of the maximum dose equivalent in any organ. This report also contained information which would allow more accurate values of organ dose equivalents and effective dose equivalent to be obtained when additional information on the irradiation conditions is available. More recently ICRU, in Report 47 [5] give details on the design and calibration of instruments and dosemeters for the measurement of the operational quantities. Some changes to the way in which the definitions of the operational quantities are presented were also introduced, together with some changes to the nomenclature. In the following primary limiting quantities and operational quantities will be discussed in some detail.

In early 1991 ICRP in Publication 60 [6] issued a completely new set of recommendations some of which have implications as far as radiation monitoring is concerned. In radiological protection the quantity that is considered to be of interest is the absorbed dose averaged over a tissue or organ (rather than at a point), and weighted for the radiation quality. The weighting factor is now called the radiation weighting factor, W_R, and is selected for the type and energy of the radiation incident on the body for external radiations. This weighted absorbed dose is called the equivalent dose in a tissue or organ, using the symbol H_T. The equivalent dose in tissue T is given by the expression

$$H_T = \sum_R W_R \cdot D_{T,R}$$

where $D_{T,R}$ is the absorbed dose averaged over the tissue or organ T due to radiation R. The radiation weighting factors which are tissue independent are given in Table 3.1.

Dose limitation for stochastic and deterministic effects is now based on a quantity which in many respects is similar to effective dose equivalent but there are a number of significant differences and the new quantity is called the *effective dose* (E).

The number of specified organs has been increased to twelve as shown in Table 3.2 and remainder organs are treated differently. The tissue weighting factors which are radiation independent are also shown in Table 3.2. They are reduced to 4 values - 0.01, 0.05, 0.12 and 0.20.

values in Table 3.2 have been developed from a reference population of equal numbers of both sexes and a wide range of ages. In the definition of effective dose they apply to workers, to the whole population, and to either sex.

For purposes of calculation, the remainder is composed of the following additional tissues and organs: adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus and uterus. The list includes organs which are likely to be selectively irradiated. Some organs in the list are known to be susceptible to cancer induction. If other tissues and organs subsequently become identified as having a significant risk of induced cancer they will then be included either with a specific W_T or in this additional list constituting the remainder. The latter may also include other tissues or organs selectively irradiated.

In those exceptional cases in which a single one of the remainder tissues or organs receives an equivalent dose in excess of the highest dose in any of the twelve organs for which a weighting factor is specified, a weighting factor of 0.025 should be applied to that tissue or organ and a weighting factor of 0.025 to the average dose in the rest of the remainder as defined above.

The effective dose, E, is the sum of the weighted equivalent doses in all the tissues and organs of the body. It is given by the expression

$$E = \sum_T W_T \cdot H_T$$

where H_T is the equivalent dose in tissue or organ T and W_T is the weighting factor for tissue T.

Radiation quality factors are based on a Q - L relationship both for use in deriving the ICRU operational quantities, and to provide an approximate value for W_R for radiation not included in Table 3.1. The Q - L relationship is given in Table 3.3. The values of Q for high LET radiations are approximately a factor 1.5 higher than in the previous Q - L relationship as described in ICRP Publication 26 [1].

It is important to note that the ICRU operational quantities are recommended for use in obtaining an estimate of *effective dose equivalent* as prescribed by the current Basic Safety Standards and in future for obtaining an estimate of *effective dose* as will be prescribed by the forthcoming Basic Safety Standards based on ICRP Publication 60. The operational quantities reflect the Q - L relationship. The latter will in future still yield a Q of 1 for photons and electrons but will give values for neutrons about a factor 1.5 greater than is the case with the original Q - L relationship.

3.2 Operational Quantities

The procedure of using the ICRU operational quantities to obtain estimates of the limiting quantities has been discussed extensively and has now been widely accepted. The necessary data for the design and type testing of instruments for photon, beta and neutron measurements were made available. These data have been used for the type testing of personal dosemeters on the ICRU sphere. Quantities for area monitoring are, therefore, included in this discussion because they have relevance to interpretation of quantities for individual monitoring. This is particularly true for neutrons because of a current lack of specific guidance or selection of a phantom for practical calibration purposes. For type testing of photon and beta dosimeters, a 30 cm x 30 cm x 15 cm tissue equivalent slab phantom was recommended in ICRU Report 47 [5].

3.2.1 Quantities for Area Monitoring

The quantities for area monitoring, as recommended in ICRU Report 39 [3], are defined using a spherical phantom, the "ICRU sphere". This is a 30 cm diameter, tissue equivalent sphere with a density of 1 $g.cm^{-3}$ and a mass composition

of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen.

Two quantities for area monitoring are specified in ICRU Report 39: *the ambient dose equivalent* H*(d) and *directional dose equivalent* H'(d).

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

The special name for the unit of ambient dose equivalent is Sievert (Sv) and is equal to an energy absorption of 1 Joule per kilogramme.

ICRU note the following on ambient dose equivalent in Report 47 [5].

a) Any statement of ambient dose equivalent should include a specification of the reference depth, d. For strongly penetrating radiation the currently recommended depth is 10 mm.

b) In order to simplify the notation, d should be expressed in mm. Then H*(10) is understood to be ambient dose equivalent for a depth of 10 mm.

c) Measurement of H*(d) requires that the radiation field be uniform over the dimensions of the instrument, and that the instrument has an isotropic response.

d) When d = 10, H*(10) may be written H*.

Expansion and alignment
ICRU explain the concepts of expanded and aligned fields in Report 39 [3] "In the expanded field, the fluence and its angular and energy distributions have the same values throughout the volume of aligned field, the fluence and its energy distribution are the same as in the expanded field, but the fluence is unidirectional".

Weakly and strongly penetrating radiations
ICRU also defines weakly and strongly penetrating radiations as follows: "If the dose equivalent received by any small area of the sensitive layer of the skin is more than 10 times larger than the effective dose equivalent for a given orientation of the body in a uniform and unidirectional radiation field, the radiation is said to be weakly penetrating. "If the dose equivalent received by any small area of the skin is less than 10 times larger than the effective dose equivalent for a given uniform and unidirectional field and orientation of the body, the radiation is said to be strongly penetrating"

The *directional dose equivalent* $\underline{H}'(\underline{d},\Omega)$, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at a depth, d, on a radius in a specified direction Ω. The special name for the unit of directional dose equivalent is Sievert (Sv) and is equal to an energy absorption of 1 Joule per kilogramme.

ICRU note the following on directional dose equivalent in Report 47 [5].

a) Any statement of directional dose equivalent should include a specification of the reference depth, $\underline{d}$, as well as the direction Ω of the radiation. For weakly penetrating and strongly penetrating radiations recommended depths are 0.07 mm and 10 mm respectively.
b) In order to simplify notation, d should be expressed in mm. Then $\underline{H}'(10,\Omega)$ and $\underline{H}'(0.07,\Omega)$ are understood to be the directional dose equivalent for depths of 10 mm and 0.07 mm respectively.
c) If the field is unidirectional the direction can be specified in terms of the angle, $\underline{\omega}$, between the radius opposing the incident field and the specified radius. When ω=0 the quantity $\underline{H}'(\underline{d},\omega)$ may be written $\underline{H}'(\underline{d})$. [The direction of the radius is from the centre to the circumference].
d) In a unidirectional field the quantity $\underline{H}'(\underline{d},o) = \underline{H}^*(d)$.
e) Measurement of $\underline{H}'(\underline{d},\omega)$ requires that the radiation field be uniform over the dimensions of the instrument and that the instrument has the required directional response.
f) For weakly penetrating radiation, an instrument which determines the dose equivalent at the recommended depth in a plane slab of tissue equivalent material will adequately determine $\underline{H}'(0.07,0°)$ if the slab surface is perpendicular to the direction of the radiation field.

When d = 10, $\underline{H}'(10)$ may be written H'.

3.2.2 Quantities for Individual Monitoring

The operational quantity defined for individual monitoring is the personal dose equivalent, $\underline{Hp(d)}$. This is the dose equivalent in soft tissue below a specified point on the body at an appropriate depth $\underline{d}$. The special name of the unit of personal dose equivalent is Sievert (Sv) and is equal to an energy absorption of 1 Joule per kilogramme.

ICRU note the following on the personal dose equivalent in Report No. 47 [5].

a) Hp(d) can be measured with a detector worn at the surface of the body and covered with an appropriate thickness of tissue equivalent (or surrogate) material.
b) Any statement of personal dose equivalent should include a specification of the reference depth d. For weakly penetrating and strongly penetrating radiations the recommended depths are 0.07 mm and 10 mm respectively. Other depths may be appropriate in some cases, such as 3 mm for the lens of the eye.
c) In order to simplify notation d should be expressed in mm. Then Hp(10) and Hp(0.07) are understood to be the personal dose equivalents for depths of 10 mm and 0.07 mm respectively.
d) When d = 10, Hp(10) may be written Hp.
e) The calibration or type testing of dosemeters is done under simplified conventional conditions on an appropriate phantom. The quantity Hp(d) may be used to specify the dose equivalent at a point in a phantom representing the body.

3.3 Relationships Between the Operational Quantities and the Limiting Quantities

The ICRU introduced operational quantities in Report 39 [3]. The measurement of these quantities provides a good estimate of the limiting quantities given by ICRP in Publication 26 [1]. Although new limiting quantities have been introduced in ICRP Report 60 [6], the Commission still recognises the use of the ICRU operational quantities as of value in giving an estimate of the limiting quantity effective dose as can be seen from the following statement. "The use of the ICRU quantities as given in ICRU Report 39 [3] are expected to give reasonable approximations of the effective dose and equivalent dose to skin when these quantities are calculated using the Q - L relationships given in Table 3.3". ICRU and ICRP have set up a joint working group to demonstrate this and to provide the necessary conversion coefficients for instrument and dosemeter type testing. Meanwhile the relationship between the ICRU operational quantities and the current quantity Effective Dose Equivalent has been thoroughly studied and demonstrated.

In order to demonstrate the utility of the personal dose equivalents ICRU [4] have published their relationships to the organ and effective dose equivalents, H_T and H_E. In doing so ICRU state that "Only very limited calculations of $H_p(10)$ on the MIRD phantom are available. However, $H_p(10)$ can be adequately repre-

sented, for this purpose, by the dose equivalent at 10 mm depth on an appropriate radius of the ICRU sphere, i.e., the directional dose equivalent H'(10). Similarly, H'(0.07) can be taken as representative of $H_p(0.07)$.
In the case of photons, the substitution of H'(10) for $H_p(10)$ can be shown to be acceptable by a comparison between H'(10) and the actual personal dose equivalent, penetrating, $H_p(10)$, occurring on the MIRD-5 phantom at the two dosemeter locations frequently used in practice (on the front of the phantom on the abdomen, and on the thorax). The irradiation geometry used for this comparison is AP, which is probably the most frequent orientation in practice. Figure 3.1 shows H'(10) in the ICRU sphere and $H_p(10)$ (for the abdomen and thorax) plotted as a function of photon energy. Between 30 keV and 3 MeV, the difference between H'(10) in the ICRU sphere and $H_p(10)$ for the two locations on the MIRD-5 phantom is never greater than 15 percent".

Because ICRU in a later report [5] have recommended a 30 x 30 x 15 cm tissue equivalent slab phantom the corresponding values for the dose equivalent at 10 mm depth for this phantom are also plotted in Figure 3.1. It can be seen that there is good agreement between the values of the slab and the abdomen of the MIRD-5 phantom.

Figure 3.2 is also taken from ICRU [4] and the Commission suggest that this Figure, together with others published by ICRU [4] but not shown here, gives a reasonable indication of the relationship between the personal dose equivalent, penetrating, on the one hand, and the effective dose equivalent and organ dose equivalents, on the other hand, for irradiation by photons. However, it must be stressed that the size and shape of individuals vary greatly and these data are only presented as being illustrative of the degree of approximation achieved for the "average" person.

The data in Figure 3.2 show, for example, that, in almost all situations, the value of $H_p(10)$ is greater than effective dose equivalent, H_E, provided that $H_p(10)$ is measured at an appropriate location on the body. The data also indicate, as expected, the severe underestimation of H_E and H_T which can occur if H_p is monitored at an inappropriate location on the body. The overestimation which occurs at low-photon energies is not significant since at such energies dose to skin is limiting and $H_p(0.07)$ is the relevant monitoring quantity.

It is clear that $H_p(0.07)$ is equal to the dose equivalent to tissues at a depth of 0.07 mm and will, therefore, give a measure of dose equivalent to basal layer cells at that depth in exposed skin.

It may be helpful to explain the reason behind the above comparisons by reference to Figure 3.3. Figure 3.3(a) shows a dosemeter being worn by a person; the dosemeter is worn on the trunk with the aim of assessing $H_p(10)$ which, it is expected, will give a reasonable estimate of E. To see how well this can be achieved doses can be calculated in, and dosemeters exposed on phantoms. Figure 3.3(b) shows the anthropomorphic phantom in which the values of E and $H_p(10)$ were calculated in formulating the operational quantities. ICRU [3] have stated, in Report 39, that the ICRU tissue equivalent sphere is a suitable phantom on which to calibrate and type test dosemeters which are meant to be worn on the trunk. The data shown in Figure 3.1 supports this view since it shows good agreement between the calculated values of $H_p(10)$ on the anthropomorphic phantom and $H'(10)$ on the ICRU sphere. Hence Figure 3.3(c) shows a dosemeter, intended for the assessment of $H_p(10)$ on the body, fixed to the sphere for type testing against $H'(10)$. In a later report ICRU [5], for simplicity, have recommended a 30x 30x 15cm tissue equivalent slab for type testing. Figure 3.1 also supports this recommendation. Hence, Figure 3.3(d) shows the same dosemeter fixed to a slab for type testing against $H_p(10)$ in the slab. [ICRU [5] have, for type testing purposes, extended the definition of personal dose equivalent into the tissue equivalent slab.]

In making the comparison between E and $H'(10)$ the following assumptions are made:

The calculations of E in the anthropomorphic phantom provides the most probable value of E within a population of human beings irradiated under the same conditions.

2. *A dosemeter designed to assess $H_p(10)$ in the sphere or slab will assess $H_p(10)$ when worn on the body, and*

3. *A dosemeter can be designed to assess $H_p(10)$ in the sphere or slab reasonably accurately. These assumptions represent a substantial amount of scientific licence but they are typical of the type of assumption which has to be made in radiation protection in these circumstances.*

The comparisons made in Figure 3.2 , i.e. for monoenergetic radiations and fixed irradiations geometries, represent an extreme test of the suitability of $H_p(10)$. In practical situations attenuation and scatter will broaden the radiation spectra and the irradiation geometry will change as the person moves within the radiation field. This will give rise to averaging and smoothing processes which will avoid some of the extreme conditions assumed in the figure. Computations [7] for both photon and neutron practical fields have verified this.

Figures 3.2 shows therefore, that for photon radiation $H_p(10)$ gives an estimate of $_E$ which is certainly satisfactory for small doses but for those workers whose doses regularly approach the dose limits, and where this can be justified, it may be worthwhile to do better than this since $H_p(10)$, in these circumstances, may be over restrictive. The information given in ICRU Report 43 [4] relating $H_p(10)$ to the organ dose and effective dose equivalent for various irradiation conditions

will allow this to be achieved provided at least some crude information is known on the radiation type, its energy spectrum and angular distribution. This may be obtained either by a separate study of the radiation environment or by analysing the results of a number of dosemeters (approximately 4) of a suitable design, worn by each worker (see Section 2.2.5).

3.4 Advantages of the Quantities $H_p(10)$ and $H_p(0.07)$

The operational quantities offer a number of important advantages to the health physicist. Of paramount importance is the link between the operational quantities $H_p(10)$ and $H_p(0.07)$ and the primary limiting quantities E and H_T which has been established by an authoritative body, the ICRU, in a manner that is acceptable to the legal authorities. From a practical point of view the operational quantities present a unified system of measurement irrespective of radiation type or energy so that neutron, photon, and beta-ray doses are additive.

The quantities $H_p(10)$ and $H_p(0.07)$ have the further advantage that, at least for photons, it will not be difficult to design dosemeters to measure them. Current designs of thermoluminescent dosemeters will require little modification and film dosemeters although requiring modification to the dose evaluation algorithms will probably need only minor changes to filter systems. In addition the operational quantities provide clear objectives for dosemeter design and a sound basis for dosemeter intercomparison exercises and scientific discussion in general. The unified system, linked to the primary limiting quantities, will be more convincing to the authorities, to the law courts and will be more reassuring to the work force and the general public.

It is therefore recommended that the quantity personal dose equivalent be used for Individual Monitoring with a depth of 0.07 mm for weakly penetrating radiations, $H_p(0.07)$, and a depth of 10 mm for strongly penetrating radiations, $H_p(10)$.

3.5 Required Characteristics of Dosemeters Used to Measure $H_p(10)$ and $H_p(0.07)$

The general requirements of dosemeters are contained in Chapter 4. Those of particular importance to the measurement of $H_p(10)$ and $H_p(0.07)$ are the dependence of the dosemeter response on the energy of the radiation and its direction.

If the sphere is adopted as the phantom to represent the human body, dosemeters required to measure $H_p(10)$ and $H_p(0.07)$ should be designed to measure $H'(10)$ and $H'(0.07)$ as discussed above. The required energy and angle response is determined from the calculation of dose equivalent distributions in the ICRU

sphere. The results are used to relate the response required for directional dose equivalent to that required for one of the field quantities such as absorbed dose to air or air kerma by means of sets of conversion coefficients. This approach enables instruments and dosemeters to be type tested in terms of the ICRU operational quantities without the need for primary or secondary standards for these quantities (see Chapter 5). Sets of conversion coefficients have been published by ICRP in Publication 51 [8]. Those for photons, converting from absorbed dose to air, are given in Table 3.4 and for neutrons, converting from neutron fluence, in Table 3.5. The values apply for radiation incident normally on the dosemeter and as such define the energy response of dosemeters when attached to the sphere for calibration purposes or worn on the body for monitoring purposes. The values in the first column apply to H'(0.07) and those in the second column to H'(10). Note that for neutrons the values for a depth of 0.07 mm are in most cases lower than or approximately equal to the corresponding value for 10 mm. Taken together with the corresponding dose limits this means that neutron radiation is always strongly penetrating so that the skin never becomes the limiting organ and there is no need to design neutron dosemeters to measure $H_p(0.07)$.

The use of computed conversion factors for instrument and dosemeter calibrations and type testing for beta-rays is inappropriate. The dose rate in calibration beams is either known for secondary standard sources, or is measured with an extrapolation chamber, in terms of the dose equivalent rate at a depth of 0.07 mm, and at 10 mm for the more energetic beta-ray emitters, in a tissue equivalent medium which provides the same backscatter and attenuation as soft tissue. The results obtained are practically identical to those which would be obtained in the ICRU sphere because the range of electrons from common beta-ray emitters is relatively limited. Hence, the values can be taken as a measurement of H'(0.07) and H'(10). Extrapolation chambers may be used, therefore, as primary or secondary standard instruments for these quantities in respect of beta radiation.

The definition of directional dose equivalent implies a response which varies with angle, in terms of radiation fluence, because of the increased attenuation, with angle, within the material overlying the point of measurement (see Chapter 4). This extra attenuation is insignificant for H'(0.07), other than for beta-rays, but is substantial for H'(10) for both photons and neutrons especially at the lower energies. The required variations in response with angle can be seen by observing the variation of H'(10) and hence $H_p(10)$ with angle. The ratio $H_p(10, \omega°)/H_p(10, 0°)$ is plotted against angle for a number of representative photon energies in Figure 3.4 [9, 10, 11, 12] and for a number of neutrons energies

in Figure 3.5 [9, 10, 11, 12]. Although the data in Figures 3.4 and 3.5 extend to an angle of 180°, only that below 90° is relevant for individual monitoring. If in a given practical situation, workers are likely to receive the major contribution to their dose from angles larger than 90° then they should be advised to wear their dosemeter on the back of the trunk or preferably wear more than one dosemeter.

The required angular response for the measurement of H'(0.07) from beta-rays has been measured [13] and the results are shown in Table 5.7.

For practical reasons a 30 x 30 x 15 cm tissue equivalent slab is recommended [5] as the phantom to be used for type testing dosemeters (see Chapter 5). Conversion coefficients for photons for this phantom have been published by Grosswendt [14]. These are shown in Table 5.1, Chapter 5.

In practice the radiations used for type testing will be chosen from the reference radiations specified by ISO which have a finite spectral width. Conversion coefficients for the slab phantom for photons at normal incidence and at angles 20°, 40° and 60° are given in Table 5.2, Chapter 5 for $H_p(10)$ and $H_p(0.07)$.

3.6 The Quantity to be Measured for Extremity Monitoring

If it is necessary to issue special dosemeters to monitor exposure of the extremities the design of dosemeter will depend to some extent upon the nature of the radiation, i.e. whether it is strongly or weakly penetrating.

The dose limits for workers are the same for the extremities as for skin, i.e. 500 mSv per annum. For beta and gamma exposures the skin of the extremities is more likely to become the limiting organ than the extremity itself, especially if the field contains a substantial low energy component. Thus the dosemeter essentially becomes a skin dosemeter and should be designed to measure the dose to the sensitive cells of the skin. Over the body as a whole ICRP [1] recommend that the depth of these cells be taken to be in the range 0.05 to 0.1 mm and that the depth of measurement should be 0.07 mm. However, data on the standard man [15] indicate greater depths over some parts of the extremities, for example, ranging from 0.2 mm to 0.5 mm over the palmer surfaces of the hands (the higher value being over the finger tips). For these reasons earlier recommendations suggested that doses for extremity monitoring should be assessed at a depth of 0.3 to 0.5 mm. However, the depth over the wrists, the sides and back of the hands is more nearly 0.07 mm. Therefore, it is now recommended that assessment for extremity monitoring for doses from beta and gamma radiation fields should be made at a depth of 0.07 mm, i.e. the quantity $H_p(0.07)$ should be

measured. For exposure to neutrons where a substantial increase of dose with depth may occur (see Table 3.5) $H_p(10)$ should be taken as the extremity dose.

To measure low energy beta rays thin detectors will be required (approximately 5 $mg.cm^{-2}$) with a cover of a similar thickness. For penetrating radiations the thickness of the detector will be less critical since a much higher energy threshold is acceptable.

3.7 Categories of Dosemeters

3.7.1 Basic Whole-Body Dosemeters

A basic dosemeter is one which is worn to estimate the operational quantities in radiation protection, $H_p(10)$ and $H_p(0.07)$. It is not required to provide any other information.

Examples of basic dosemeters include a simple two-element thermoluminescent dosemeter [using detectors made of nearly tissue equivalent material such as LiF, the one detector being thin and essentially unfiltered, to measure $H_p(0.07)$ and the other covered with a 10 mm thick layer of tissue equivalent plastic, to measure $H_p(10)$] and a direct reading electronic dosemeter designed to measure $H_p(10)$ and $H_p(0.07)$.

For the majority of individual monitoring only information on the dose equivalent is needed and the use of a simple basic dosemeter will be satisfactory.

3.7.2 Discriminating Whole-Body Dosemeters

In addition to the values for $H_p(0.07)$ and $H_p(10)$, a discriminating dosemeter may be required to provide information on the radiation conditions, for example:
– the type, energy and direction of the radiation having caused the exposure and
– contamination of the dosemeter.
This kind of information can help to estimate effective dose following accidental exposure or in situations where workers may regularly receive doses approaching the dose limits in complex radiation fields.

A typical example of a discriminating dosemeter is the photographic film type which is capable of providing a great deal of information on the circumstances of the exposure, such as the type, energy and, in some cases, the direction of the radiation and contamination of the dosemeter. A multi-element thermolumi-

nescent dosemeter with filters of different atomic numbers and thicknesses can give extra information on the type and energy of the radiation.

3.7.3 Extremity Dosemeters

An extremity dosemeter is one which is worn on an extremity, i.e. hand, forearm, foot or ankle, when the extremity may become the limiting organ or tissue. Such dosemeters are usually worn in addition to a whole-body dosemeter.

Thermoluminescent dosemeters are almost invariably used for extremity dosimetry. They often consist of one thin tissue equivalent detector which can be worn reasonably conveniently at the position likely to receive the maximum dose.

References

1. International Commission on Radiological Protection, "Recommendations of the International Commission on Radiological Protection", ICRP Publication 26, Ann. ICRP, 1, No. 3, (Pergamon Press, Oxford) (1977).
2. Commission of the European Communities, "Council Directive of 15 July 1980 amending the Directive laying down the basic safety standards for the health protection of the general public and workers against the dangers of ionising radiation", Official Journal of the European Communities L246, 1980 and "Council Directive of 3rd September 1984 amending Directive 80/836/Euratom as regards the basic safety standards for the health protection of the general public and workers against the dangers of ionising radiation", Official Journal of the European Communities, L265, 1984.
3. International Commission on Radiation Units and Measurements, "Determination of Dose Equivalents Resulting from External Radiation Sources", ICRU Report 39, Bethesda, MD (1985).
4. International Commission on Radiation Units and Measurements, "Determination of Dose Equivalents from External Radiation Sources - Part 2", ICRU Report 43, Bethesda, MD (1988).
5. International Commission on Radiation Units and Measurements, "Determination of Dose Equivalents from External Radiation Sources - Part 3", ICRU Report 47, Bethesda, MD (1992).
6. International Commission on Radiological Protection, "1990 Recommendations of the ICRP", ICRP Publication 60, Ann. ICRP, 21(1).
7. National Radiological Protection Board, "New Radiation Quantities Recommended by ICRU for Practical use in Radiological Protection: Their Implementation in the United Kingdom", NRPB-GS5 (1986).
8. International Commission on Radiological Protection, "Data for Use in

Protection against External Radiation", ICRP Publication 51, Ann. ICRP, 17(2/3) (Pergamon Press, Oxford) (1987).

9. Grosswendt, B. and Hohlfeld, K., "Angular Dependence of Specified Depth Dose Equivalent Quantities in the ICRU Sphere for Photon Radiation", Radiation Protection Dosimetry 3, 169-174 (1982).
10. Chen, S.Y. and Chilton, A.B., "Calculations of Fast Neutron Depth Dose in the ICRU Standard Tissue Phantom and the Derivation of Neutron Fluence to Dose Index Conversion Factors", Radiat. Res. 78, 335-370 (1979).
11. Shiue, Y.L. and Chilton, A.B., "Calculations of Low Energy Neutron Dose Indices and Depth Doses in the ICRU Sphere", Radiat. Res. 93, 421-443 (1983).
12. Lee, J.K., "Assessment of Quantities for Radiation Protection in the ICRU Standard Tissue Sphere for Intermediate Energy Neutrons", PhD. Thesis University of Illinois at Urbana-Chorpaign.
13. Christensen, P., Böhm, J. and Francis, T.M., "Measurement of Absorbed Dose to Tissue in Slab Phantom for Beta Radiation Incident at Various Angles", Proc. of 5th Information Seminar on the European Radiation Protection Beta Dosemeter Intercomparison Programme, 25-27 May 1987, Bologna, 39-75 (1988).
14. Grosswendt, B., "The Angular Dependence and Irradiation Geometry Factor for the Dose Equivalent for Photons in Slab Phantoms of Tissue-Equivalent Material and PMMA", Rad. Prot. Dosim., Vol. 35, No. 4, pp 221-235 (1991).
15. International Commission on Radiological Protection, "Report of the Task Group on Reference Man", ICRP Publication 23, (Pergamon Press, Oxford) (1974).

Table 3.1 Radiation weighting factors[1] [6]

Type and energy range[2]		Radiation weighting factor, W_R
Photons, all energies		1
Electrons and muons, all energies[3]		1
Neutrons, energy	< 10 keV	5
	10 keV to 100 keV	10
	> 100 keV to 2 MeV	20
	> 2 MeV to 20 MeV	10
	> 20 MeV	5
(See also Figure 1)		
Protons, other than recoil protons, energy > 2 MeV		5
Alpha particles, fission fragments, heavy nuclei		20

1 All values relate to the radiation incident on the body or, for internal sources, emitted from the source.
2 The choice of values for other radiations is discussed in Annex A of ICRP 60.
3 Excluding Auger electrons emitted from nuclei bound to DNA (see paragraph 26 of ICRP 60).

Table 3.2 Tissue weighting factors* [6]

Tissue or organ	Tissue weighting factor, W_T
Gonads	0.20 (0.25)
Bone marrow (red)	0.12 (0.15)
Colon	0.12
Lung	0.12 (0.12)
Stomach	0.12
Bladder	0.05
Breast	0.05 (0.15)
Liver	0.05
Oesophagus	0.05
Thyroid	0.05 (0.03)
Skin	0.01
Bone surface	0.01 (0.03)
Remainder	0.05 (0.30)
WHOLE BODY	1.00 (1.00)

*ICRP 26 values are given in brackets

Table 3.3 Specified Q - L relationships [6]

Unrestricted linear energy transfer,L in water (keV μm^{-1})	**Q(L)***
< 10	1
10 - 100	0.32L - 2.2
> 100	$300/\sqrt{L}$

*With L expressed in keV μm^{-1}

Table 3.4 Dose equivalent at various depths on the principal axis of the ICRU sphere per unit absorbed dose to air in free air for photons incident in a plane parallel beam [8]

Photon energy (MeV)	Conversion coefficient, Sv Gy^{-1} 0.07 mm	10 mm
$1.0\ 10^{-2}$	0.930	0.010
$1.5\ 10^{-2}$	0.974	0.271
$2.0\ 10^{-2}$	1.02	0.601
$3.0\ 10^{-2}$	1.19	1.09
$4.0\ 10^{-2}$	1.38	1.43
$5.0\ 10^{-2}$	1.52	1.63
$6.0\ 10^{-2}$	1.58	1.74
$8.0\ 10^{-2}$	1.59	1.73
$1.0\ 10^{-1}$	1.55	1.65
$1.5\ 10^{-1}$	1.42	1.49
$2.0\ 10^{-1}$	1.34	1.38
$3.0\ 10^{-1}$	1.28	1.31
$4.0\ 10^{-1}$	1.24	1.26
$5.0\ 10^{-1}$	1.21	1.21
$6.0\ 10^{-1}$	1.19	1.19
$8.0\ 10^{-1}$	1.18	1.16
$1.0\ 10^{0}$	1.16	1.14
$1.5\ 10^{0}$	1.15	1.13
$2.0\ 10^{0}$	1.14	1.13
$3.0\ 10^{0}$	1.13	1.12
$4.0\ 10^{0}$	1.13	1.11
$5.0\ 10^{0}$	1.12	1.11
$6.0\ 10^{0}$	1.11	1.10
$8.0\ 10^{0}$	1.11	1.09
$1.0\ 10^{1}$	1.11	1.09

Table 3.5 Dose equivalent per unit fluence at depths of 0.07 mm and 10 mm on the principal axis for neutrons incident in a plane parallel beam on the ICRU sphere [8]

Neutron energy (MeV)	Conversion coefficient, 10^{-12} Sv cm^2 0.07 mm	10 mm
$2.5\ 10^{-8}$	7.20	8.00
$1.0\ 10^{-7}$	5.50	10.4
$1.0\ 10^{-6}$	3.70	11.2
$1.0\ 10^{-5}$	2.80	9.20
$1.0\ 10^{-4}$	2.50	7.10
$1.0\ 10^{-3}$	2.80	6.20
$1.0\ 10^{-2}$	8.90	8.60
$1.0\ 10^{-2}$	18.2	14.6
$5.0\ 10^{-2}$	46.6	35.0
$1.0\ 10^{-1}$	95.0	69.0
$2.0\ 10^{-1}$	168	126
$5.0\ 10^{-1}$	219	258
$1.0\ 10^{0}$	292	340
$1.5\ 10^{0}$	292	362
$2.0\ 10^{0}$	283	352
$3.0\ 10^{0}$	305	380
$4.0\ 10^{0}$	329	409
$5.0\ 10^{0}$	301	378
$6.0\ 10^{0}$	302	383
$7.0\ 10^{0}$	312	403
$8.0\ 10^{0}$	341	417
$1.0\ 10^{1}$	368	446
$1.4\ 10^{1}$	359	520
$1.7\ 10^{1}$	421	610
$2.0\ 10^{1}$	516	650

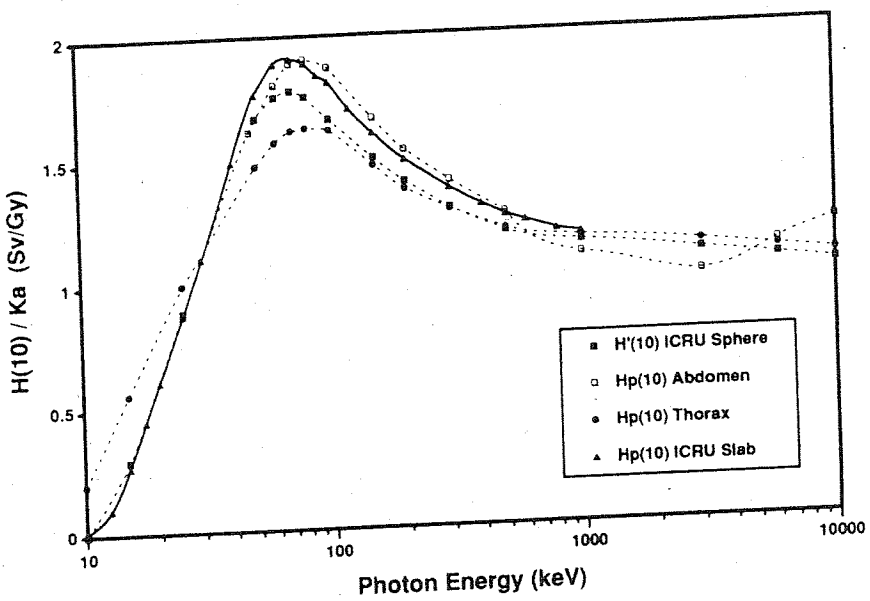


Figure 3.1 Directional dose equivalent, H'(10), and individual dose equivalents $H_p(10)$, in the MIRD-5 phantom [4] and $H_p(10)$ in the tissue equiva lent slab, 30 x 30 x 15 cm, phantom [14], per unit air kerma (in fre air), K, as a function of photon energy; parallel beam from front t back (anterior-posterior, AP)

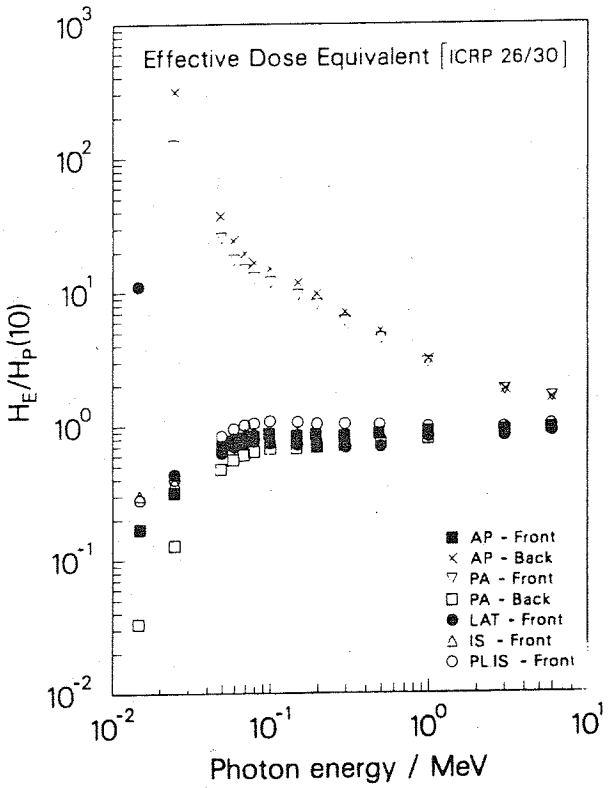


Figure 3.2 Ratio of the effective dose equivalent, H_E, to the personal dose equivalent, penetrating, $H_p(10)$, as a function of photon energy. Two locations for the personal dosemeter are considered: front of the body (Front) and back of the body (Back). $H_p(10)$ is approximated by the dose equivalent at depth 10 mm along the central axis in the ICRU sphere (see text) (ICRP, 1977, 1979). Five geometries are considered in the calculations: AP, broad parallel beam from front to back (anterior-posterior; PA, broad parallel beam from front to back (posterior-anterior); LAT, broad parallel beam from the side (lateral); IS, isotropic field; OL.IS, planar isotropic field, perpendicular to body axis. [4]

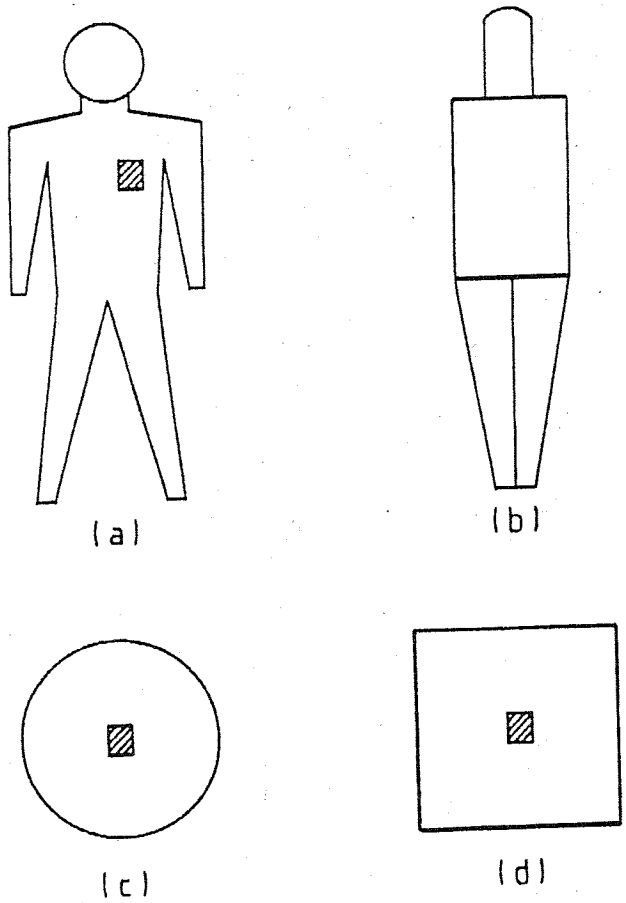


Figure 3.3 Dosemeter and Receptor Combinations

a) Dosemeter worn by a person

b) Anthropomorphic phantom used for the calculation of H_E and $H_p(10)$

c) Dosemeter placed on ICRU sphere for type testing

d) Dosemeter placed on ICRU slab for type testing

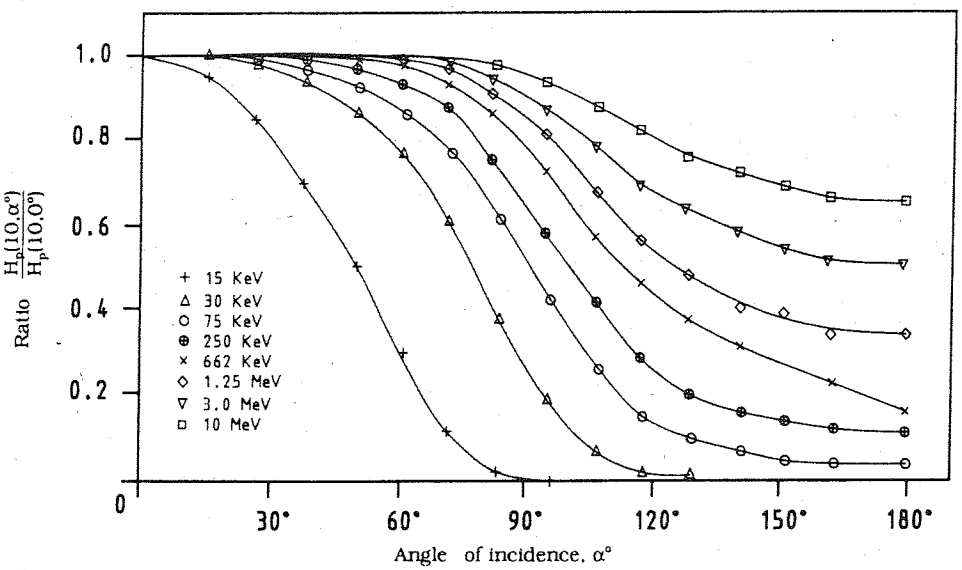


Figure 3.4 Ratio of $H_p(10, \omega°)$ to $H_p(10, 0°)$ against angle of incidence (photons) for the ICRU sphere

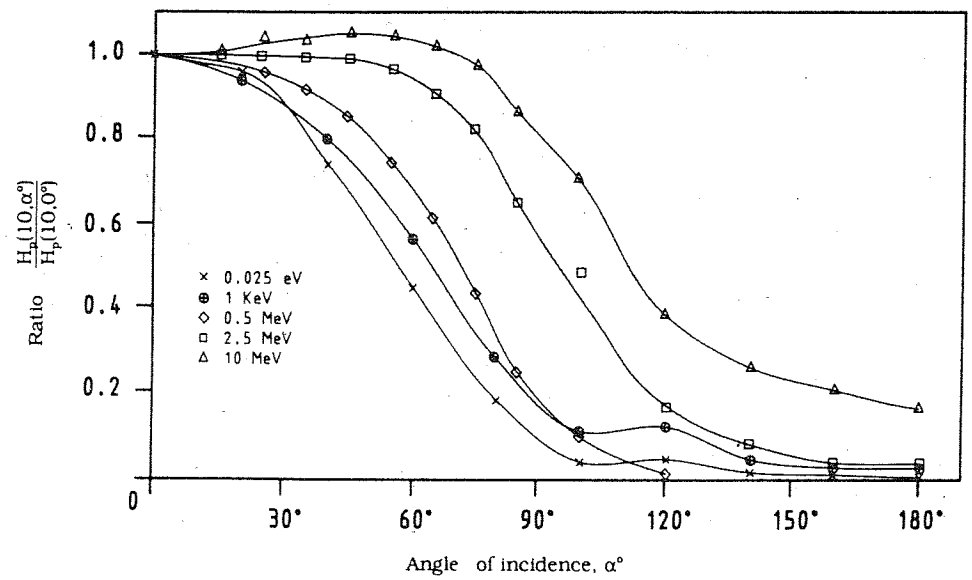


Figure 3.5 Ratio of $H_p(10, \omega°)$ to $H_p(10, 0°)$ against angle of incidence (neutrons) for the ICRU sphere

4. REQUIREMENTS FOR PERSONAL DOSEMETERS

4.1 General

The requirements for personal dosemeters are based on the objectives of individual monitoring (see Chapter 2) and it should be noted that the treatment given here applies to official dosemeters used by approved dosimetry services. General guidance on the basic requirements for personal dosemeters, e.g. in relation to the dose quantities that should be measured, the overall accuracy that should be obtained, and the degree of monitoring that should be exercised, is given by ICRP in Publication 26, 35 and 60 [1, 2, 3], by ICRU in Publication 39, 43 and 47 [4, 5, 6], by IAEA in Safety Series no. 84 [7], and by CEC in its Directive on Basic Safety Standards [8]. The Nuclear Energy Agency (NEA) and the European Radiation Dosimetry Group (EURADOS-CENDOS) have added further guidance on specific problems that have been identified to exist in individual monitoring and have been found to need more clarification [9, 10, 11].

The basic requirements for personal dosemeters are to provide a reliable measurement of the appropriate quantities, i.e. $H_p(0.07)$ and $H_p(10)$ for almost all practical situations, independent of type, energy and incident angle of the radiation and with a prescribed overall accuracy. Additional requirements important from a practical point of view include size, shape, weight and identification of the dosemeters.

In practice, the requirements on accuracy for personal dosemeters can be met by establishing criteria for a number of parameters, influencing the performance of the dosemeter, e.g. its response to radiation type, spectral and directional distribution and environmental influences. This chapter is meant to provide guidance on performance criteria for personal dosemeters for individual monitoring, covering any practical radiation condition involving exposure to beta, gamma and neutron radiations.

4.2 Requirements on Accuracy

Recommendations concerning the acceptable uncertainty in routine individual monitoring are contained in paragraph 109 of ICRP Publication 35 [2]. This states that:

"The uncertainties acceptable in routine monitoring for external radiation should be somewhat less than the investigation level and can best be expressed in relation to the estimates of the annual deep and shallow dose equivalent indices" [now taken to be $H_p(0.07)$ and $H_p(10)$] "that are measured. The uncertainty in the measurements of the annual value of these quantities (or of the upper lim-

its if a cautious interpretation is being conducted) should be reduced as far as reasonably achievable. If these quantities are of the order of the relevant annual limits, the uncertainties should not exceed a factor of 1.5 at the 95% confidence level. Where they amount to less than 10 mSv an uncertainty of a factor of 2 at the 95% confidence level is acceptable. This uncertainty includes errors due to variations in the dosemeter sensitivity with incident energy and direction of incidence, as well as intrinsic errors in the dosemeter and its calibration. It does not include uncertainties in deriving tissue or organ dose equivalents from the dosemeter results."

Although not explicitly stated by ICRP, this is taken to mean that for a large group of workers using a particular dosimetry system, the reported annual doses should fall within the indicated limits of acceptable uncertainties at the 95% confidence level.
The above statement should be taken to mean that the apparent annual dose to an individual ($H_p(0.07)$ and $H_p(10)$) as indicated by a number of practical basic dosemeters, regularly issued during the year and worn on the surface of the body, should not differ from the annual dose equivalent indicated by an ideal dosemeter, worn at the same point, by more then –33% or +50% at the 95% confidence level for doses of the order of the relevant annual limits and –50% or +100% at the 95% confidence level for annual doses below 1/5 of the relevant annual limits (i.e. 4 mSv for $H_p(10)$ and 100 mSv for $H_p(0.07)$). ICRP have recommended that the level of doses, above which recording of the doses is required, the recording level, should be set to 1/10 of the fraction of the annual limit, corresponding to the issuing period used for the dose measurement. This indicates that an absolute uncertainty (in terms of dose) equal to ± 1/10 of the fraction of the relevant annual dose limit, corresponding to the issuing period used, is acceptable, which sets a realistic requirement for the accuracy for the measurement of doses in the lower dose range.

The way ICRP formulate acceptable uncertainties for various dose levels leads to a step function, which provides difficulties when it comes to testing a dosimetry system for accuracy. An alternative method has been proposed [12], smoothing the allowable accuracy interval as a function of dose level. The upper limit is given by

$$H_{u1} = 1.5\,[1 + H_o / (2H_o + H_t)] \qquad (1)$$

and the lower limit by

$$H_{II} = 0 \qquad \text{for } H_t < H_o$$
$$H_{II} = (1 / 1.5)\left[1 - 2H_o / (H_o + H_t)\right] \qquad \text{for } H_t \geq H_o \qquad (2)$$

where H_t is the conventional true dose and H_o is the lowest dose required to be measured, based on the pro rata dose limit, and here set equal to 0.17 mSv and 0.08 mSv for $H_p(10)$ for monthly and two-weekly monitoring periods, respectively, and 4,2 mSv and 1.9 mSv for $H_p(0.07)$ for monthly and two-weekly periods, respectively. The accuracy intervals are presented graphically in Figure 4.1.

It should be noted that to achieve these requirements for *personal beta-ray dosimetry* over the required energy range, i.e. down to 60 keV, then beta-ray detectors of thickness less than 5 mg . cm^{-2} are required. Suitable detectors are now commercially available. These detectors do not have a high sensitivity but the required detection threshold for $H_s(0.07)$, bearing in mind the dose limits for skin, is relatively high i.e. 4 mSv for a monthly issue period. It is stressed that it is important for dosemeters to meet the requirements for the energy threshold even at the expense of the dose threshold since they at least measure the more important higher doses more correctly.
It is accepted that current techniques employed in *personal neutron dosimetry* cannot meet the above requirements and that further development is urgently required in this area. In the meantime, where significant personal neutron doses are concerned personal neutron results should be supported by measurements made with area monitors. Where neutron doses contribute substantially to total doses approaching the dose limits the radiation field should be characterised using more sophisticated equipment such as neutron spectrometers to get information on the neutron spectrum and its angular distribution. This information will allow area specific correction factors to be applied to personal neutron results to obtain more accurate values.

4.3 Analysis of Uncertainties

The overall accuracy of a dosimetry system is determined from the combined effects of a number of systematic and random errors.

The following sources are usually considered to cause systematic uncertainties:
- Energy dependence
- Directional dependence
- Non–linearity of the response
- Fading, dependent on ambient temperature and humidity
- Effects from exposure to light

- Effects from exposure to types of ionising radiations that are not intended to be measured by the dosemeter
- Effects from mechanical shock
- Calibration errors
- Variation in local natural background.

Typical sources of random uncertainties are inhomogeneity of detector sensitivity and zero dose for the batch of dosemeters used and fluctuations in reading parameters including reader sensitivity and background.

The effects from systematic errors often appear with a certain probability distribution and it is recommended by standardising laboratories that systematic uncertainties should be characterised by standard deviations and variances analogous to random uncertainties and that systematic and random uncertainties should be combined by addition in quadrature to obtain a resultant uncertainty for the two types of uncertainties [13, 14, 15].

The combined uncertainty may then be expressed in the form of a standard deviation, S, obtained from:

$$S = \sqrt{\delta_r^2 + \delta_s^2} \qquad (3)$$

where δ_r and δ_s are the resultant random and systematic standard deviations, respectively. δ_r can be determined conventionally from a series of repeated measurements. To obtain a numerical value for δ_s one must evaluate separate standard deviations, $\delta_{s,i}$, for each individual uncertainty from which δ_s then can be obtained according to:

$$\delta_s = \sqrt{\sum_i \delta_{s,i}^2} \qquad (4)$$

By convention it may be assumed that systematic uncertainty distributions follow a rectangular probability distribution from which the standard deviation can be obtained by:

$$\delta_{s,i} = a_i / \sqrt{3} \qquad (5)$$

where a_i is the semi-range of the individual uncertainty of parameter i.

From equations (3), (4) and (5) one gets:

$$S = \sqrt{\delta_r^2 + \frac{1}{3}\sum_i a_i^2} \qquad (6)$$

A special procedure has been proposed for evaluating the uncertainty related to the energy and angular response of a dosemeter (see Section 5.3).

4.4 Performance Criteria

Equation (3) gives the possibility to evaluate a single value of the overall uncertainty of a dosimetry system that can be used for demonstrating compliance with the ICRP overall accuracy requirement, (i.e. an uncertainty interval of –33% and +50% for doses near the dose limits). The equation may also be used to define the performance criteria required to satisfy the ICRP accuracy requirements. An allowable uncertainty limit of –33% and +50% of the dose being measured at the 95% confidence level can be met if:

$$1.96 \mid S \mid \leq 0.5 \times (0.33 + 0.50) \qquad (7)$$

and accordingly from equation (3):

$$S = \sqrt{\delta_r^2 + \delta_s^2} \leq 0.21 \qquad (8)$$

where δ_r and δ_s should be expressed in terms of the performance quotient, $(H_m - H_t)/H_t$, with H_m and H_t indicating measured and conventional true doses, respectively. Thus the acceptance of a system does not imply judgement of specific criteria for each uncertainty parameter, separately, but requires only that the combined effects from the uncertainties are within a certain limit.

In practice, the uncertainties caused by the energy and angular dependence of the response of the dosemeter receive more attention than any other error source, because the effects from all other uncertainty components may be known to be relatively small. It may therefore be convenient to differentiate between the systematic uncertainty component related to the energy and angular responses and characterised by the resultant standard deviation $\delta_{s,(E,\phi)}$ and the uncertainties connected to all other systematic errors and characterised by the resultant standard deviation $\delta_{s(0)}$. By using equation (4) one may get:

$$\delta_s = \sqrt{\delta_{s,(E,\phi)}^2 + \delta_{s,(0)}^2} \qquad (9)$$

and furthermore by using equation (8):

$$\sqrt{\delta_r^2 + \delta^2_{s,(E,\phi)} + \delta^2_{s,(0)}} \leq 0.21 \qquad (10)$$

From equation (10) the maximum allowable value for $\delta_{s,(E,\phi)}$, Δ, can be calculated if δ_r and $\delta_{s,(0)}$ are known. Hence

$$\Delta = \sqrt{0.21^2 - \delta_r^2 - \delta^2_{s,(0)}} \qquad (11)$$

The allowable uncertainty for the combined energy and angular response at a 95% confidence level equals ± 1.96 Δ and the range (± 1.96 Δ) equals ± 0.31.

4.5 Other Requirements

Additional to numerical criteria for the performance of personal dosemeters also criteria important for their practical use as well as economic requirements must be considered. Criteria of this kind are:

- ow cost.
- Low weight. Convenient size and shape. Clips.
- Mechanically strong and dusttight.
- Adaptable to various applications, e.g. measurement of body dose and extremity dose.
- Unambiguous identification.
- Ease of handling.
- Rapid, trouble-free and unambiguous readout. Suited for automatic processing.
- Reliable supplier who can supplement dosemeters over long periods.

In particular for extremity dosemeters attention should be paid to the mechanical strength of the dosemeters and to their resistance to environments with high temperatures and humidity contents as these dosemeters are often used under extreme working conditions.

Where the extremities, e.g. finger tips, come into close proximity to the source, large variations in dose rate occur over the surface of the hand and it is essential upport the detector at the front surface of the finger. Small-size detectors that can be fixed to the finger by means of tape or kept in finger stalls or finger rings are required for this purpose.

References

1. International Commission on Radiological Protection, Recommendations of the ICRP, Publication 26, Ann. ICRP 1 (3) (1977).
2. International Commission on Radiological Protection, "General Principles of Monitoring for Radiation Protection of Workers", Publication 35, Ann. ICRP 9 (4) (1982).
3. International Commission on Radiological Protection, "Recommendations of the International Commission on Radiological Protection", ICRP Publication 60, Ann. ICRP, 21, No. 1-3, (Pergamon Press, Oxford) (1991).
4. International Commission on Radiation Units and Measurements, "Determination of Dose Equivalents Resulting from External Radiation Sources", Report 39 (Bethesda, MD: ICRU Publication) (1985).
5. International Commission on Radiation Units and Measurements, "Determination of Dose Equivalents Resulting from External Radiation Sources - Part 2", Report 43 (Bethesda, MD: ICRU Publication) (1988).
6. International Commission on Radiation Units and Measurements, "Determina-tion of Dose Equivalents Resulting from External Radiation Sources - Part 3", Report 47 (Bethesda, MD: ICRU Publication) (1992).
7. International Atomic Energy Agency, Safety Series No. 84, "Basic Principles for Occupational Radiation Monitoring", IAEA, Vienna (1987).
8. Commission of European Communities, "Council Directive of 15 July 1980 amending the Directives laying down the basic safety standards for the health protection of the general public and workers against the dangers of ionizing radiation", Official Journal of the European Communities L246, 1980 and "Council Directive of 3rd September 1984 amending Directive 80/836/Euratom as regards the basic safety standards for the health protection of the general public and workers against the dangers of ionising radiation", Official Journal of the European Communities, L265, 1984.
9. Nuclear Energy Agency, "Assessment and Recording of Radiation Doses to Workers" (1986).
10. Marshall, T.O., Christensen, P., Julius, H.W. and Smith, J.W., "The Relative Merits of Discriminating and Non-discriminating Dosemeters", Radiation Protection Dosimetry 14 (1), 5 - 10 (1986).
11. Christensen, P., Herbaut, Y. and Marshall, T.O., "Personal Monitoring for Ex-ternal Sources of Beta and Low Energy Photon Radiations", Radiation Protection Dosimetry 18 (4), 241 - 260 (1987).
12. Böhm, J., "Some Remarks on Accuracy and Precision in Individual Monitoring", IAEA Intercomparison for Individual Monitoring, Vienna, 1989, PTB Bericht: PTB-Dos-20, 1991.

13. Bureau International des Poids et Mesures, Working group on the statement of uncertainties (1st meeting), Report to the Comité International des Poids et Mesures, (R. Kaarls, rapporteur), BIPM, Serves, France (1980).
14. National Measurement Accreditation Service (United Kingdom), "The Expression of Uncertainty in Electrical Measurements", Report B3003 (1987).
15. Guidelines for the Expression of the Uncertainty of Measurement in Calibration. Western European Calibration Cooperation WECC Doc. 19-1990.

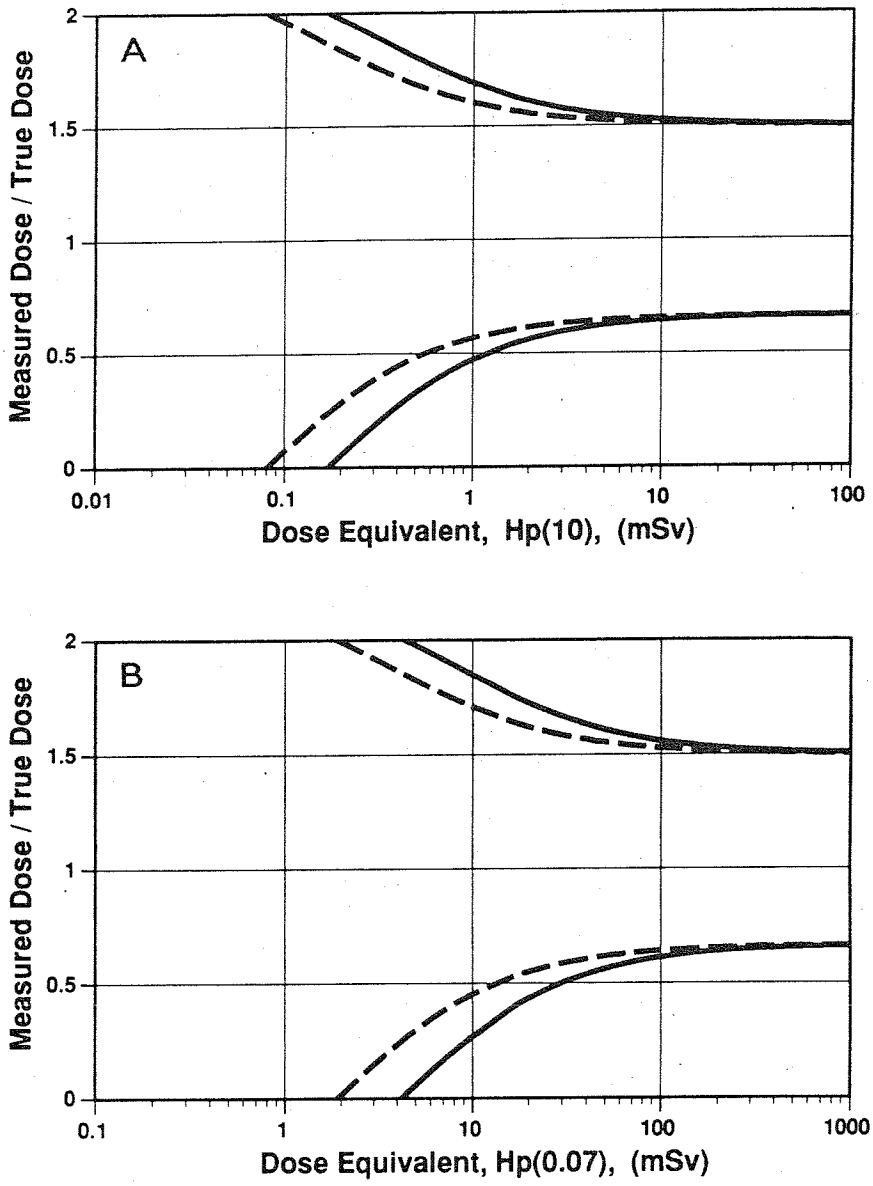


Figure 4.1 Allowable upper and lower limits for the ratio:
Measured dose/Conventional true dose as a function of dose level.
A. Limits for $H_p(10)$; B. Limits for $H_p(0.07)$
Full lines: monthly monitoring periodes
Broken lines: bi-weekly monitoring periods.

5. THE TYPE TESTING OF PERSONAL DOSEMETERS

5.1 General

Having recommended the use of the ICRU operational quantities (see Section 3.2) it is necessary to give some guidance on the type testing and calibration of personal dosemeters for the new quantities.

Type testing involves the calibration of the system under a series of irradiation and storage conditions in order to determine the performance characteristics of the system as a whole and in particular to quantify those sources of random and systematic error given in the beginning of Chapter 4. This largely concerns an investigation into the variation of dosemeter response with the energy and angle of incidence of the radiation beam but it also includes other dosimetric characteristics such as the linearity of dosemeter response, the minimum and maximum measurable doses, the ability to perform satisfactorily in a reasonable range of temperature and humidity conditions, and the ability to cope with high dose rates and pulsed radiation fields. It also includes tests of a more general ture such as the ability to operate satisfactorily in a reasonable range of electric and magnetic fields and the ability to withstand mechanical shock and vibration. The results of type testing are therefore analysed in terms of performance criteria (see Section 4.4).

Routine calibration is carried out at one radiation energy and under a given set of irradiation conditions in order to normalise or standardise the sensitivity of the system. Routine calibration should not be confused with type testing.

5.2 Type Testing for Energy and Angular Response: Basic Concepts

Crucial characteristics of a dosimetry system are its response with respect to radiation energy and angle of incidence (see Section 4.4, second paragraph). The new quantities for individual monitoring, in specifying the measurement of dose equivalent within the body of the wearer, require dosemeters to be type tested on an appropriate phantom to simulate the presence of the person's body. This procedure is adopted with the assumption that if the dosemeter performs adequately on the phantom, it would do likewise on the individual's body (see Figure 3.3).

ne concepts for individual monitoring were initially based on the use of the ICRU sphere [1]. However, for practical reasons (ease of construction, multiple dosemeter calibrations, availability of suitable material, etc.), ICRU have extended the definition of the quantities for individual monitoring to allow use of a 30 cm x 30 cm x 15 cm tissue equivalent slab phantom [2]. This implies for type

testing and calibration purposes that it is assumed that

$H_p(10)_{slab} = H_p(10)_{person}$ and
$H_p(0.07)_{slab} = H_p(0.07)_{person}$

Thus, following the latest ICRU concept, in principle dosemeters should, for the purpose of type testing, be irradiated on a tissue equivalent slab phantom.
Conversion coefficients for the 30 cm x 30 cm x 15 cm tissue equivalent slab phantom are compiled in Table 5.1 [3] for monoenergetic and in Table 5.2 [4.b] for ISO photon reference radiations, "Narrow Spectrum Series" for angles of incidence 0°, 20°, 40° and 60°. Solely for the purpose of comparison, reference is made to similar data for the ICRU sphere listed in Tables 3.4 and 5.4. Specifications for ISO photon reference radiations [5], narrow spectrum series, are given in Table 5.5.
Although the ISO Narrow Spectrum Series is the preferred set of reference radiations, in some circumstances the use of the ISO Wide Spectrum Series may be more appropriate where, for example a higher dose rate is necessary. Conversion coefficients for the ISO Wide Spectrum Series are given for the ICRU tissue equivalent slab in Table 5.3. The specification of the Wide Spectrum Series is given in Table 5.6.

Conversion factors measured for beta radiation are presented in Table 5.7. The use of the computed conversion factors for dosemeters for beta rays is inappropriate (see Section 3.5).

A practical difficulty arises from the fact that ICRU tissue equivalent material cannot be produced exactly. Therefore, ICRU have suggested that, during irradiation of the dosemeters, a 30 x 30 x 15 cm PMMA slab phantom may be used, the backscatter characteristics of which are acceptably close to those of the human trunk for both photon and neutron irradiations. The response of the dosemeter should still be interpreted in terms of the conversion coefficients for the tissue equivalent slab phantom. This procedure effectively calibrates the dosemeters on a tissue equivalent slab even though the dosemeters are irradiated on a PMMA slab. Those who wish to eliminate the small errors introduced by this procedure may either fabricate a slab using a better tissue equivalent material such as MS20 or apply suitable correction factors. It must be noted, however, that these correction factors are dosemeter specific (i.e. depend on the sensitivity of the dosemeter for backscatter radiation from the phantom) and are not simply the ratio of the backscatter fluence rate for the tissue equivalent to the PMMA slab.

It is worth noting that a 30cm x 30cm x 15cm slab phantom consisting of a PMMA skin of a few mm thickness filled with water is a better substitute for ICRU tissue than a PMMA slab. The conversion coefficients for the water slab and the backscatter from it are in fact very close to those for the ICRU tissue slab. It would therefore be accaptable to use the water slab for the type testing of dosemeters for photon radiations using the conversion coefficients given in Tables 5.1, 5.2 and 5.3.

The ICRU have not included neutrons in their latest report [2] neither are there neutron conversion coefficients for use with the tissue equivalent slab. Thus for the time being, as far as the type testing of neutron dosemeters is concerned, there is little or no alternative to fixing them to the ICRU sphere and testing them against the quantity H'(10) using the conversion coefficients given in Table 3.5 and the angular response data given in Figure 3.6.

There is also a need for the development of phantoms for extremity monitoring. These are not so essential for beta-radiation since their range is relatively small but extremity dosemeters must also be capable of measuring gamma-radiation. In this case dosemeters being type tested should be exposed to backscatter, typi-
.l of the extremity concerned, as well as the primary radiation and so there is a need for phantoms for the extremities. In addition the reference doses for these particular phantoms would have to be measured or calculated.

The whole procedure of type testing may be summarised, using, for example, the irradiation of dosemeters to photons for the quantity $H_p(10)$, as follows:

1. Choose the photon energy from the ISO reference radiations given in Table 5.5 or 5.6 and set up the radiation beam together with a monitor chamber (see Figure 5.1a).
2. Design the collimation such that the monitor chamber, the slab and the dosemeters can be completely enveloped by the beam. The slab and the dosemeters should be irradiated at a distance of at least 2 m from the source.
3. In the absence of the slab and dosemeters and for a given indication on the monitor chamber, measure the air kerma (K_a) at the position to be occupied by the center of the front surface of the phantom during the actual irradiations (see Figure 5.1a).
4. Multiply the air kerma by the appropriate conversion coefficient (C) for $H_p(10,\alpha°)$ from Table 5.2 or 5.3. The dose equivalent for $H_p(10,\alpha°)$ is then given by (K_a . C) for a monitor indication of D. Each unit on the monitor chamber thus corresponds to a dose equivalent of (K_a . C) / D for the quantity $H_p(10,\alpha°)$.
5. Place the slab phantom and dosemeter(s) in the beam such that the beam is incident on the dosemeters at angle $\alpha°$ and with the center of the front face of the phantom on the beam axis at the position at which the air kerma was

measured in 3 above (see Figure 5.1b).

6. Choose the dose equivalent (H) to be delivered to the dosemeters. Irradiate the arrangement until the monitor chamber indicates a value of $(H \cdot D) / (K_a \cdot C)$.
7. Process the dosemeters and compare their readings with the conventional true dose equivalent H for $H_p(10,\alpha°)$.

N.B. If a number of dosemeters are irradiated simultaneously in the above manner then a correction for the non-uniform distance to the source may be necessary for those positioned off the beam axis. It is suggested that the phantom be turned at the mid-point of the exposure such that the dosemeters are irradiated at angle $-\alpha°$.

5.3 The Testing for Energy and Angular Response: Interpretation of Results

To determine the responses in a quantitative way tests should be done using the basic concepts given in Section 5.2. The 30 cm x 30 cm x 15 cm PMMA slab phantom, together with the conversion coefficients for the tissue equivalent slab is the vehicle on which the tests are carried out.

Usually performance criteria for the energy and angular response of a dosemeter are specified for each parameter separately, e.g., for the energy response at normal radiation incidence and the angular response at 60 keV or a lower energy. However, as the effects on the uncertainty caused by these two parameters are correlated, the criteria should be specified for both parameters in combination. One approach would be to specify criteria for the angular response and require that these criteria are met for the whole range of energies intended to be monitored. In practice some averaging over different angles of radiation incidence will occur during a monitoring period and it is considered satisfactory to specify criteria only for the mean value of the responses from a number of angles of incidence of the radiation.

The following procedure can be used to determine experimentally the combined energy and angular response of a personal dosemeter (see also Section 4.4).

Energy response curves should be established for both $H_p(0.07)$ and $H_p(10)$ at incident angles of the radiation of 0° and 20°, 40° and 60° from normal. For the angles 20°, 40° and 60° data should be measured for both horizontal and vertical rotation planes except for dosemeters for which it can be predicted that they show equal response for the two rotation planes. Measurements should be made using the reference radiations as specified in ISO standards within the following energy ranges:

	$H_p(0.07)$	$H_p(10)$
Photons	0.010 - 1.5 MeV	0.015 - 1.5. MeV
Beta-rays	0.20 - 3.5 MeV	N.A.
Neutrons	N.A.	thermal - 15 MeV

N.A. = not applicable

The photon and beta ray energies to be included in the measurements should be those listed in Tables 5.5 and 5.7 respectively. Those given in Table 5.6 may be used in some cases for photons.

In a truly isotropic radiation field it would be necessary to weight the results for each angle by the solid angle subtended at the dosemeter. However, in practice the irradiation conditions are more likely to be rotationally isotropic in which case the response at each angle should have equal weighting. Thus for each type of radiation a combined E,ϕ response curve can be constructed by, for each energy E, calculating and plotting the average response [6]:

$$\bar{R}_E = 0.25\,(R_{E,0} + R_{E,20} + R_{E,40} + R_{E,60}) \qquad (1)$$

where $R_{E,\phi}$ is the relative response at energy E and incident angle ϕ obtained from:

$$R_{E,\phi} = \frac{(H_{E,\phi})_m}{(H_{E,\phi})_t}$$

where $(H_{E,\phi})_m$ = the measured dose and $(H_{E,\phi})_t$ = the conventional true values.

If $\bar{R}_E$ is assumed to represent the average response at energy E for the whole range of different angles of incidence of the radiation involved during the monitoring period, the value

$\pm\,|\bar{R}_E - 1|$ may be taken as the uncertainty related to the angular response at energy E.

From equation (10), in Section 4.4, the allowable limits, $\pm\,1.96\,\Delta$, are evaluated for the combined uncertainty (at the 95% confidence level) related to the energy

and angular response of the dosemeter. A dosemeter may therefore be considered to perform satisfactorily if the condition

$$|\bar{R}_E - 1| \leq 1.96\,\Delta \qquad (2)$$

is fulfilled for all the irradiation energies prescribed for the test.

Values of $|\bar{R}_E - 1|$ below 0.40 for three well developed TLD systems have been found for the quantities $H_p(0.07)$ and $H_p(10)$ for the photon energy range 20 keV to 1250 keV [7].

5.4 Type Testing for Other Important Characteristics

Additional to type testing for energy and angular response, there are a number of other important influence quantities, some of which may have particular relevance to certain types of dosemeter. Table 5.8 lists important influence quantities and dosemeter/radiation combinations for which they are relevant. Acceptable uncertainties for the various influence quantities are often given in published documents. However, this is not the approach adopted here. The suitability, or otherwise, of a dosemeter design should be demonstrated by analysing the results of the type tests using formula 10 in Chapter 4. Methods of testing for the influence quantities in Table 5.8 can be found in the literature [8, 9, 10].

References

1. International Commission on Radiation Units and Measurements, "Determina-tion of Dose Equivalents Resulting from External Radiation Sources", ICRU Report 39, Bethesda, MD (1985).
2. International Commission on Radiation Units and Measurements, "Determina-tion of Dose Equivalents Resulting from External Radiation Sources - Part 3", Report 47 (Bethesda, MD: ICRU Publication) (1992).
3. Grosswendt, B., "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., Vol. 35, No. 4, pp 221 - 235 (1991).
4. a) Dimbylow, P.J., Francis, T.M. and Bartlett, D.T., "Calibration of Photon Personal Dosemeters in Terms of the ICRU Operational Quantities: Calculations of Phantom Backscatter and Depth in Dose Distributions", NRPB-R230 (1990).
   b) Iles, W.J. – Private communication.
5. International Organisation for Standardization, "X-ray and Gamma Reference Radiations for Calibrating Dosemeters and Dose Ratemeters and

for Determining their Response as a Function of Photon Energy", ISO 4037 (1979) (presently under revision).

6. Julius, H.W., Christensen, P., Marshall, T.O., "Performance, Requirements and Testing in Individual Monitoring", Rad. Prot. Dosim. Vol. 34, No. 1/4, pp 87-91 (1990).
7. Julius, H.W., Marshall, T.O., Christensen, P., "Type Testing of Personal Dosimeters for Photon Energy and Angular Response" (to be published).
8. International Organisation for Standardization, "Exposure Meters and Dosemeters – General Methods of Testing", ISO 4071 (1978).
9. International Electrotechnical Commission, Draft Standard: "Direct Reading Personal Dose Equivalent and/or Dose Equivalent Rate for X, Gamma and High Energy Beta Radiation", IEC/SC 45B (CO)94 (1989).
10. British Standards Institute, "Electromagnetic Compatibility for Industrial Process Measurements and Central Equivalent"
    Part 1 – General Introduction
    Part 2 – Method of Evaluating Susceptibility to Electrostatic Discharge
    Part 3 – Method of Evaluating Susceptibility to Radiated Electromagnatic Energy
    BS6667 (1985).
11. International Organisation for Standardization, "Reference Beta Radiations for Calibrating Dosemeters and Dose Ratemeters and their Response as a Function of Beta Energy", ISO 6980 (1990).

Table 5.1 Conversion coefficients for the tissue equivalent ICRU, 30 x 30 x 15 cm, slab phantom for $H_p(10)$ and $H_p(0.07)$ for *monoenergetic* photon radiations at angles of 0°, 20°, 40° and 60° (after Grosswendt [3])

	$H_p(10,\alpha)/K_a$				$H_p(0.07,\alpha)/K_a$			
keV	**α = 0°**	**α = 20°**	**α = 40°**	**α = 60°**	**α = 0°**	**α = 20°**	**α = 40°**	**α = 60°**
10.0	0.010	0.007	0.003	0.000	0.951	0.946	0.942	0.919
12.5	0.100	0.090	0.050	0.010	0.964	0.960	0.959	0.946
15.0	0.268	0.245	0.176	0.070	0.986	0.979	0.979	0.960
17.5	0.450	0.422	0.344	0.190	1.006	1.007	1.005	0.988
20.0	0.613	0.586	0.505	0.327	1.040	1.034	1.030	1.021
25.0	0.879	0.861	0.782	0.583	1.123	1.117	1.111	1.088
30.0	1.105	1.088	1.002	0.793	1.227	1.216	1.205	1.157
40.0	1.495	1.464	1.365	1.115	1.441	1.435	1.396	1.326
50.0	1.769	1.718	1.601	1.332	1.629	1.616	1.567	1.456
60.0	1.890	1.860	1.750	1.446	1.720	1.701	1.655	1.531
70.0	1.911	1.884	1.752	1.494	1.741	1.732	1.678	1.558
80.0	1.891	1.878	1.755	1.500	1.719	1.724	1.676	1.568
90.0	1.841	1.826	1.725	1.471	1.694	1.685	1.645	1.555
100.0	1.812	1.769	1.682	1.448	1.670	1.647	1.625	1.528
120.0	1.703	1.696	1.614	1.398	1.604	1.593	1.574	1.489
150.0	1.600	1.587	1.520	1.352	1.515	1.515	1.501	1.441
200.0	1.489	1.482	1.428	1.301	1.424	1.431	1.421	1.390
300.0	1.370	1.363	1.336	1.240	1.338	1.335	1.336	1.329
400.0	1.301	1.295	1.282	1.207	1.278	1.282	1.286	1.290
500.0	1.256	1.252	1.243	1.176	1.240	1.245	1.261	1.262
600.0	1.230	1.226	1.219	1.169	1.218	1.224	1.231	1.244
800.0	1.191	1.189	1.183	1.152	1.190	1.188	1.200	1.219
1000.0	1.175	1.164	1.167	1.137	1.179	1.174	1.183	1.193

Table 5.2 Conversion coefficients for the tissue equivalent ICRU, 30 x 30 x 15 cm, slab phantom for $H_p(10)$ and $H_p(0.07)$ for ISO photon reference radiations, Narrow Spectrum Series (see Table 5.5) at angles of 0°, 20°, 40° and 60° (NRPB [4.b]).

Mean Energy keV	$H_p(10,\alpha)/K_a$				$H_p(0.07,\alpha)/K_a$			
	$\alpha = 0°$	$\alpha = 20°$	$\alpha = 40°$	$\alpha = 60°$	$\alpha = 0°$	$\alpha = 20°$	$\alpha = 40°$	$\alpha = 60°$
9.88	--	--	--	--	0.951	0.946	0.941	0.919
17.4	0.449	0.420	0.342	0.184	1.01	1.01	1.00	0.987
23.1	0.778	0.757	0.678	0.484	1.09	1.08	1.08	1.06
25.2	0.879	0.861	0.782	0.583	1.12	1.12	1.11	1.09
30.9	1.15	1.13	1.04	0.830	1.25	1.24	1.22	1.17
33	1.22	1.20	1.10	0.89	1.29	1.28	1.26	1.23
48	1.68	1.64	1.53	1.26	1.57	1.56	1.52	1.42
65	1.89	1.86	1.74	1.46	1.72	1.71	1.66	1.54
83	1.87	1.85	1.74	1.48	1.71	1.71	1.66	1.56
100	1.80	1.78	1.69	1.45	1.67	1.65	1.62	1.53
118	1.72	1.71	1.63	1.41	1.61	1.60	1.58	1.50
161	1.57	1.55	1.49	1.34	1.49	1.49	1.48	1.43
205	1.48	1.47	1.42	1.30	1.42	1.42	1.41	1.39
8	1.42	1.42	1.38	1.27	1.37	1.38	1.37	1.36
2	1.21	1.21	1.20	1.20	1.21	1.21	1.22	1.23
1250	1.15	1.15	1.15	1.15	1.15	1.15	1.16	1.20

Table 5.3 Conversion coefficients for the tissue equivalent ICRU, 30 x 30 x 15 cm, slab phantom for $H_p(10)$ and $H_p(0.07)$ for ISO photon reference radiations, Wide Spectrum Series see Table 5.6) at angles of 0°, 20°, 40° and 60° (NRPB [4.b]).

Mean Energy keV	$H_p(10,\alpha)/K_a$				$H_p(0.07,\alpha)/K_a$			
	$\alpha = 0°$	$\alpha = 20°$	$\alpha = 40°$	$\alpha = 60°$	$\alpha = 0°$	$\alpha = 20°$	$\alpha = 40°$	$\alpha = 60°$
45	1.518	1.507	1.466	1.375	1.597	1.557	1.453	1.195
58	1.653	1.640	1.593	1.481	1.795	1.759	1.647	1.369
79	1.709	1.701	1.657	1.549	1.870	1.848	1.735	1.472
104	1.651	1.640	1.611	1.519	1.779	1.761	1.668	1.435
134	1.559	1.554	1.536	1.446	1.656	1.642	1.567	1.378
169	1.479	1.481	1.469	1.421	1.557	1.546	1.484	1.332
202	1.427	1.431	1.422	1.390	1.492	1.483	1.430	1.301

Table 5.4 Conversion coefficients [Sv/Gy (K_{air})] for the tissue equivalent ICRU sphere for H'(10) and H'(0.07) for ISO reference radiations, Narrow Spectrum Series (see Table 5.5) at angles of 0°, 20°, 40° and 60° (NRPB [4.a])

Mean Energy keV	$H'(10,\alpha)/K_a$				$H'(0.07,\alpha)/K_a$			
	$\alpha = 0°$	$\alpha = 20°$	$\alpha = 40°$	$\alpha = 60°$	$\alpha = 0°$	$\alpha = 20°$	$\alpha = 40°$	$\alpha = 60°$
9.88	--	--	--	--	0.93	0.92	0.90	0.87
17.4	0.45	0.43	0.34	0.21	0.99	1.00	0.99	0.97
23.1	0.78	0.77	0.69	0.53	1.07	1.08	1.07	1.04
25.2	0.89	0.87	0.80	0.64	1.11	1.11	1.10	1.08
30.9	1.13	1.09	1.03	0.88	1.21	1.21	1.19	1.16
33	1.18	1.14	1.08	0.93	1.24	1.24	1.22	1.19
48	1.56	1.53	1.46	1.28	1.47	1.45	1.42	1.39
65	1.74	1.70	1.63	1.46	1.59	1.56	1.53	1.50
83	1.71	1.67	1.62	1.47	1.58	1.57	1.54	1.51
100	1.64	1.62	1.57	1.44	1.55	1.54	1.52	1.49
118	1.58	1.55	1.52	1.41	1.50	1.49	1.47	1.46
161	1.44	1.43	1.42	1.33	1.39	1.39	1.39	1.40
205	1.37	1.36	1.35	1.29	1.34	1.34	1.35	1.36
248	1.34	1.32	1.31	1.26	1.31	1.31	1.32	1.34
662	1.18	1.19	1.18	1.17	1.19	1.19	1.20	1.23
1250	1.14	1.14	1.13	1.13	1.16	1.16	1.18	1.20

Table 5.5 Specification for ISO photon reference radiations, Narrow Spectrum Series (X-rays and gamma radiations) [5]

FLUORESCENT RADIATIONS

Mean energy (keV)	Tube high voltage (kVp)	Total primary filtration ($g.cm^{-2}$)	Radiator	Secondary filtration ($g.cm^{-2}$)
9.88	60	Al 0.135	Germanium	GaO 0.020
17.4	80	Al 0.27	Molybdenum	Zr 0.035
23.1	100	Al 0.27	Cadmium	Ag 0.053
25.2	100	Al 0.27	Tin	Ag 0.071
30.9	100	Al 0.27	Caesium	TeO_2 0.132

FILTERED X-RAYS

Mean energy)[1]	Resolution R_e (%)	Constant potentional[2] (kV)	Additional filtration[3] Pb (mm)	Sn (mm)	Cu (mm)	1st HVL (mm of copper)	2nd HVL	Homogeneity coefficient
33	30	40	--	--	0.21	0.09	0.12	0.75
48	36	60	--	--	0.6	0.24	0.29	0.83
65	31	80	--	--	2.0	0.59	0.64	0.93
83	28	100	--	--	5.0	1.11	1.2	0.93
100	27	120	--	1.0	5.0	1.73	1.74	0.99
118	36	150	--	2.5	--	2.4	2.58	0.93
163	32	200	1.0	3.0	2.0	3.9	4.29	0.91
205	30	250	3.0	2.0	--	5.2	5.2	1.00
248	34	300	5.0	3.0	--	6.2	--	--

1 The value of the mean energy adopted with a tolerance of ± 3%
2 The constant potential is measured under load
3 The total filtration includes, in each case, the fixed filtration adjusted to 4 mm of Aluminium

GAMMA RADIATIONS

(Mean) Energy -eV)	Gamma source	First HVL Cu (mm)
662	Caesium-137	10.3
1250	Cobalt-60	14.6

Table 5.6 Specifications for ISO photon radiations, Wide Spectrum Series (X-rays and gamma radiations) [5]

Mean energy (keV)[1]	Resolution R_e (%)	Constant potentional[2] (kV)	Additional filtration[3] Pb (mm)	Sn (mm)	Cu (mm)	1st HVL (mm of copper)	2nd HVL	Homogeneity coefficient
45	48	60			0.3	0.18	0.26	0.69
58	54	80			0.5	0.35	0.52	0.67
79	57	110			2.0	0.94	1.16	0.81
104	56	150		1.0		1.86	2.14	0.87
134	58	200		2.0		3.11	3.53	0.88
169	58	250		4.0		4.3	4.38	0.98
202	58	300		6.5		5.0	--	--

1 The value of the mean energy adopted with a tolerance of ± 3%
2 The constant potential is measured under load
3 The total filtration includes, in each case, the fixed filtration adjusted to 4 mm of Aluminium

Table 5.7 Conversion factors for a tissue equivalent slab phantom for $H_p(0.07)$ for beta rays (emitted by standard sources and extended area sources) at angles of 0°, 20°, 40° and 60°, normalized to 0° (see Note)

Nuclide	Distance (cm)	Data normalised to zero degrees 0°	20°	40°	60°
NRPB-data (extended area sources):					
Strontium-90/Yttrium-90	20.0	1.00	1.03	1.10	1.14
Strontium-90/Yttrium-90	30.0	1.00	1.02	1.08	1.09
Thallium-204	20.0	1.00	1.02	1.00	0.82
Thallium-204	30.0	1.00	1.01	0.97	0.80
Promethium-147	15.0	1.00	0.87	0.70	0.48
PTB-data (PTB standards)+:					
Strontium-90/Yttrium-90*					
Type 1	30.0	1.00	1.02	1.10	1.15
Type 2	30.0	1.00	1.02	1.10	1.19
Thallium-204	30.0	1.00	0.97	0.93	0.73
Promethium-147	20.0	1.00	0.95	0.71	

*Type 1: With beam flattening filter
Type 2: Without beam flattening filter
+In compliance with ISO series 1 reference radiations [11]

Note: For beta irradiations it is only necessary to use factors to convert from normal indicence of the radiation to different angles of incidence as the calibration beams of the secondary standard beta units are normally calibrated in units of H(0.07) in tissue.

Table 5.8 Influence and the relevant dosemeter/radiation combinations

Influence quantity	Dosimeter type 1	2	3	4	5	6
Linearity	x	x	x	o	o	x
Zero-dose variations	x	x	x	o	o	x
Fading	x	x	x		o	x
Sensitivity to light	x	x	x		x	
Sensitivity to radiations for which dosemeter not designed	o	o	o		x	o
Effects due to moisture	x	x	x	o	o	x
Effects due to mechanical shock						x
Calibration errors	x	x	x	o	o	x
Dose rate dependence						x
Effects of electrical fields						x
Effects of magnetic fields						x
Effects of pulsed radiation						x
Effects of extreme temperatures	x	x	x	o	o	x

1 = Photographic film dosemeters
2 = Thermoluminescent dosemeters
3 = Radio photoluminescent dosemeters
4 = PADC (CR39) plastic dosemeters
5 = NTA neutron film dosemeters
6 = Electronic personal dosemeter

x = Photon gamma radiation
o = Neutron radiation

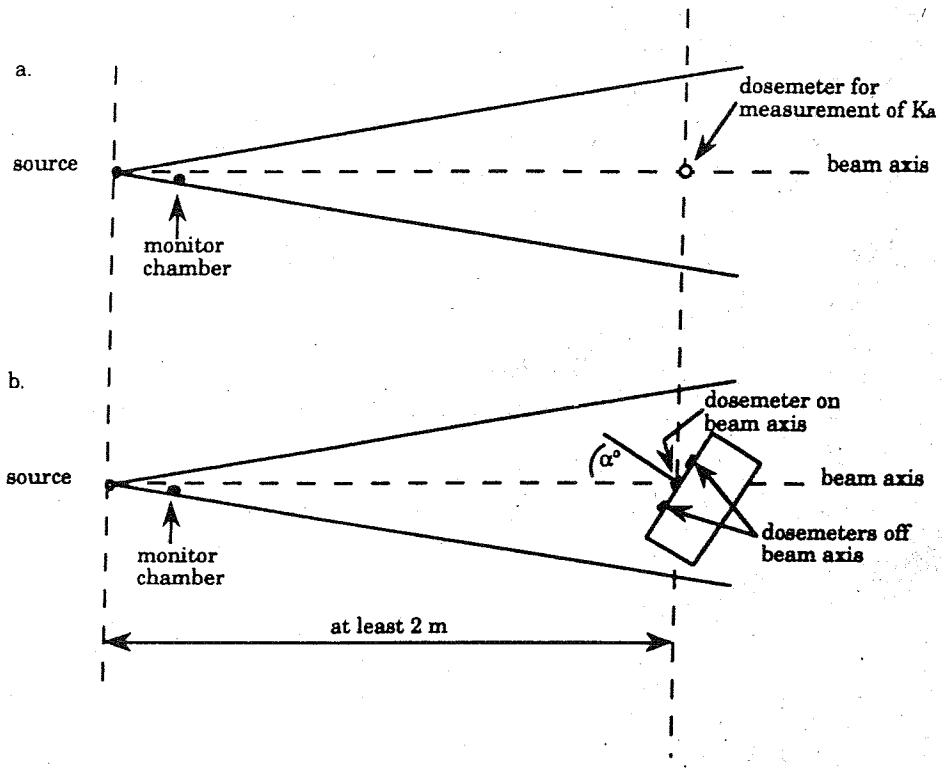


Figure 5.1 Exposure arrangement for dosemeter type testing

6. PERFORMANCE TESTING

6.1 General

In addition to the type testing of a personal dosimetry system, in which the whole performance of the system is carefully analysed in order to verify its capability of meeting the accuracy criteria (see Chapter 5), it is necessary to demonstrate that this standard of performance is maintained continuously. In the following, three categories of testing are described which are carried out regularly for this purpose. Approval performance testing is a means of demonstrating that the overall dosimetric performance standard is maintained, routine testing or calibration is a means by which the sensitivity, precision and accuracy is determined for a single radiation type and energy, usually by using the calibration source, and finally testing connected to the quality assurance (QA) programme must also be included. It should be noted that the initial approval of a dosimetry service by the legal authority should include a combination of type testing and approval performance testing.

6.2 Approval Performance Testing

Performance approval testing is carried out to demonstrate that the required standard of dosimetric performance is maintained. The results should confirm the type testing data.

An approval performance testing programme may be subdivided into different irradiation categories to suit different classes of dosemeter design, i.e. based on the radiation types and energy ranges covered by the dosemeters. Each test may include a range of different energies and angles of incidence of the radiation and an appropriate distribution of doses over the range 0.20 mSv to at least 100 mSv to test the overall performance of the system.
The results of this test should comply with the overall accuracy requirements specified by ICRP so that 95% of the results should fall within the accuracy band defined in Chapter 4 (see also Figure 4.1).

These tests should be carried out at regular intervals, at least annually, by an external test facility and may be used as part of the initial and/or on-going approval for the operation of the services.

6.3 Routine Performance Testing or Calibration

The purpose of routine performance testing is to test the sensitivity, precision and bias of the dosimetry system for measurement of doses at a single energy

usually that of the calibration source, e.g., ^{137}Cs or ^{60}Co gamma rays for photon dosemeters. The precision, as given by the standard deviation of a single measurement, and the bias, i.e., the average deviation of the readings from the conventional true value, should be tested at different dose levels. The results of the tests should at least fulfil the accuracy requirements given in eqv. (1) and (2), Chapter 4 and shown in Figure 4.1. This type of test also serves to normalise the overall sensitivity of the system. Routine performance tests should be repeated at regular intervals, preferably once per month and are normally carried out by the service itself.

6.4 Quality Assurance Testing

A QA programme is an organisation's internal system of procedures and practices which assures the quality of its services. A personal dosimetry service must have and maintain an on-going QA programme involving extensive testing of equipment, calibration facilities, materials and processes. One way of testing the overall quality of the service is to arrange for a "dummy" subscription which should include the entire routine procedure (like a customer's subscription) except that some of the dosemeters receive radiation doses. The dosemeters involved should be exposed to known doses either in the laboratory or by some external test facility. The measured values should be compared with the conventional true values and the results interpreted using the method prescribed in Chapter 4 (see also Figure 4.1).

An alternative – or additional – approach is to participate in national or international intercomparison programmes. Examples of the latter are the programmes run by the CEC, IAEA (International Atomic Energy Agency) and ORNL (Oak Ridge National Laboratories).

7. DOSE RECORD KEEPING AND INFORMATION SYSTEMS

7.1 Objectives and Principles

Dose Record Keeping is the making and keeping of personal dose records for radiation workers. It is an essential part of the process of monitoring the exposure of individuals to radiation and shares in the same objectives (see Chapter 2).
The purpose of record keeping, the nature and scope of the records that are kept, the extent of record keeping systems and the information provided are influenced by local and/or national requirements. In particular, national regulations on registration of personal data and the confidentiality of such data must be taken into account. Apart from demonstrating (the degree of) compliance with legal regulations (dose limits), record keeping may also be used for several additional needs and uses, such as:

- to demonstrate the effectiveness of ALARA
- to provide data for analysis of dose distribution
- to evaluate trends in exposure (possibly as a function of work practices or radiation sources)
- to develop effective monitoring procedures and programmes
- to provide data for medical and/or legal purposes
- to provide data for epidemiological studies.

In principle dose record keeping will be required for workers in category A working conditions, though in view of the objectives described above, it is often considered useful to also keep records of doses received by workers in category B conditions. It is crucial that doses are attributed to the correct individuals.

7.2 Techniques

The techniques of computer-based data processing have shown tremendous improvement during the last decade and both hard- and software have become available at very moderate prices. Therefore, except in the case of small numbers of records, computer-based systems confer a great advantage over the manual processing of records. Either a local (personal computer) or central computer system can be used and the choice will be based not only on national regulatory requirements and cost effectiveness but also on reliability, confidentiality, simplicity of procedures and presentation and compatibility with a national dose depository system.

Because of the availability of "ready-to-go" software packages, especially for p.c.'s, setting up a dose record keeping system may seem a relatively easy thing to do. It should be emphasized, however, that – as experience has demonstrated – there are numerous difficulties and pitfalls

in both programming and developing adequate procedures, which are easily overlooked and which may make satisfactory systems, even at relatively small scale, rather expensive.

It should be borne in mind that keeping individual dose records may never be a purpose in itself, but should serve the protection of the worker. The latter can be achieved only, if all records of an individual can unambiguously be retrieved and combined at any time. Hence, a dose record keeping system is more than just a computer based data storage system, and should rather be a "Dose Record and Information System" (DRIS). When setting up a DRIS, enough thought should be given to its size, structure, accessibility, procedures to control reliable input and output of data, dissemination of information, organisation, staff etc. This is especially important if a DRIS covers more than one establishment (such as a hospital) as is the case – to mention a few examples – with monitoring services operating for several customers [1], with systems serving a number of nuclear power plants [2] and, particularly, with national dose record keeping systems [3]. In all cases it is crucial that a DRIS is informed of up-to-date dose data of the individual worker, which is especially difficult for those workers moving from one employer to another and even more so if they switch from one monitoring service to another.

In view of the latter, it is an advantage if local record keeping systems are linked – in one way or another – to a centralized or national DRIS. Because of increasing cooperation and exchange of personnel between countries, the time may come when this could be extended internationally. This would then require international harmonization of dose record keeping systems and improvement of data communication between countries as well as mutual approval of personnel dosimetry services.

Modern Individual Monitoring Services, in particular the larger ones, having adopted a high degree of automation, often use fully integrated systems linking the dose record keeping to the labelling and issuing of dosemeters and their subsequent dose assessment. Such integrated systems, especially if the dosemeters are labelled with the wearers's name, offer a high degree integrity – and hence quality – of the service being provided.

Besides the effectiveness of the system and quality of the data held, it is highly important that the persons responsible for the system management are trained and competent.

7.3 Dose Record Data

Records should include the results of individual monitoring for both external radiation and internal contamination. More specifically, a dose record can contain up to six kinds of information as follow (see also Section 7.6):

a. Information to identify the individual
b. Measurements of external dose
   - The personal dose equivalent, $H_p(10)$
   - The personal dose equivalent, $H_p(0.07)$
c. Measurements of internal dose, such as
   - The committed dose equivalent (CDE), H_{50} or
   - The committed effective dose equivalent (CEDE), $H_{E,50}$
d. Historical data in summarized form
e. Dates relating to b, c and/or d
f. Text information relating to b, c and/or d.

The ICRP, in Publication 35 [4], state that "the results of monitoring of the workplace are unlikely to be useful in assessing the dose equivalent received by individual workers, unless such an assessment was made at the time as part of the monitoring programme. Substantial amounts of information will be required about the location of these workers and the type of work in hand during the period of monitoring ..... Successful interpretations of the results of monitoring of the workplace in terms of individual exposures may not be possible merely by later perusal of records. The retention of routine records of monitoring of workplaces will thus usually be associated with the demonstration of good standards of house- keeping rather than with the assessment of the exposure of individual workers."

The dose equivalent limit recommended by ICRP, in Publication 26 [5] for stochastic effects relates to the sum of the effective dose equivalent from external exposure during one year and the committed effective dose equivalent from that year's intake of radionuclides. In practice, as is explained in some detail in Chapter 2, the necessary level of protection and compliance with the dose equivalent limits are adequately demonstrated if, for any individual worker, the following conditions are satisfied:

$$\frac{H_p(10) + H_{E,50}}{H_{E,L}} \leq 1 \quad \text{and} \quad \frac{H_p(0.07)}{H_{s,L}} \leq 1$$

where $H_{E,L}$ is the annual limit of the effective dose equivalent or effective dose (50 or 20 mSv) and

$H_{s,L}$ is the annual limit of the dose equivalent in the skin (500 mSv).

It may be convenient, particularly with mixed radiation exposures, to adopt a statement of compliance index (C.I.), using the ratios mentioned above.

Because it is virtually impossible, when evaluating the readings of personal

dosemeters, to distinguish between photon- and beta- radiation, it makes no sense to record (and report) beta doses separately. However, in view of the fact that changes in quality factors for high LET radiation may occur, it may be advisable to treat neutron doses as separate entries.

When a dose assessment is not available for a period when a (classified) radiation worker was (or ought to be) monitored – which may happen when a dosemeter has been damaged or lost or recorded a dose that, on investigation, is declared invalid – the record keeping system should allow the introduction of doses estimated or assessed by an authorised person. These doses may need to be flagged so that they can be distinguished from official dose measurements made by the approved monitoring service.

For those individuals who use extremity dosemeters, separate records of the exposure of each extremity should be kept. In those situations, the assessment of the total exposure of the extremities should be the sum of the readings of the extremity dosemeters in the periods when they were worn and of $H_p(0.07)$ as assessed by the body dosemeters in those periods when extremity dosemeters were not used.

7.4 Reference Levels

A reference level is the predetermined value for any of the quantities that may be encountered in radiation protection programmes which will require a certain course of action to be taken in the event that the value of a quantity exceeds (or is predicted to exceed) this pre-defined level [4].

Reference levels are often values of an effective dose equivalent, but may apply to any other quantity, such as an annual intake. They can then be called derived reference levels.

A reference level is not a limit in itself and the action associated with it may range from just recording the value to intervention.

7.4.1 Recording Level

According to ICRP [4], the recording level is a formally defined value for dose equivalent (or intake) above which a result from a monitoring programme is of sufficient interest to be worth keeping. ICRP has recommended that the recording level for individual monitoring should be based on 1/10 of the fraction of the annual limit, corresponding to the period of time of which the individual monitoring measurement refers (hence, about 0.17 mSv for monthly issuing periods for an annual dose limit of 20 mSv). As a consequence, any reading that is

smaller than the recording level may be discarded and treated as zero in assessing the annual dose equivalent (or intake) for the purpose of radiation protection. Although this may seem realistic, it may not be considered a challenge for the worker and the management to improve radiation safety and strive for lower exposure of the individual, even when this would be Reasonably Achievable. ICRP recognizes that it may be useful to record all dose equivalents above the threshold of detection of the personal dosemeter, but rightly warns against focussing unrealistic attention on to exposures which result in very small risks. With this warning in mind it is suggested that the recording level is taken to be the detection threshold of the dosimetry system.

7.4.2 Reporting Level

Often dosimetry services will regularly notify their customers about their findings for each monitoring period. However, if national regulations permit, a reporting level, i.e. a built in threshold, may be introduced, as a result of which reporting may be optimised by simplifying procedures and/or reducing costs. Below the reporting level it may not be necessary to issue a particular report but to wait until the next summary.

The reporting level, sometimes called the Notification Level, is that value of a dose quantity measured or assessed over a defined period of time at and above which the employer (or his radiation safety representative) is notified in a particular report. This value might approximate to three-tenths of that fraction of the annual limit corresponding to the period of time to which the measurement of assessment refers.

It should be noted that introduction of a reporting level may adversely influence the effectiveness of the monitoring programme. The provision of regular dose reports often motivates the workers for being consequent with their obligations to the dosimetry service.

7.4.3 Investigation Level

According to ICRP (publication 35), an investigation level is a value of dose equivalent (or intake) usually set in relation to a single measurement, rather than to the accumulated dose equivalent (or intake) in one year, above which the result is sufficiently important to justify further investigation. This may be reinforced as a national requirement or otherwise be of sufficient radiological importance to require such action. ICRP have recommended that it is often appropriate to base the investigation level for individual monitoring on 3/10 of that fraction of the relevant annual limit corresponding to the period of time to which the individual monitoring measurement refers.

ICRP put the investigation level in perspective by stating that below the investigation level, the information does not need further study or investigation and, furthermore, that it will often be necessary to change investigation levels, for example as conditions in a workplace change.

7.5 Reporting of Dose Information

7.5.1 General

The reporting of doses to any or all of the following will be required:

- the employer (radiation safety officer/management)
- the radiation worker
- the local safety inspector
- the medical officer
- national legal authorities/inspectorates.

Their needs and therefore the form of the dose report may vary, depending on national regulations, local requirements and personal interests. Local Dose Record and Information Systems will automatically be tuned to local needs. A regional or a national DRIS, however, obviously has to have enough flexibility to satisfy a wide variety of requirements from customers and legal authorities. Often, these requirements are based on ad hoc decisions rather than on formal regulations, not in the least because of the fact that dissemination of information has hardly been touched in the Basic Safety Standards of the European Community, and consequently has not always been dealt with adequately in national legislation.

The process of reporting is usually by printed document or in an urgent situation, by telephone beforehand. Reports would be either summaries of the individual records issued at prescribed intervals (e.g. monthly, quarterly or yearly) or a notification relating to a particular recent entry in the record of a worker or to some recent change in the record status. Reporting levels (see Section 7.4.2) may be applied.

7.5.2 Special Reports

Should a worker ask for a copy of his record, usually through his employer, a simplified or edited version of the full dose record would be appropriate particularly where unrecognisable computer terminology is incorporated in the record transcript. On termination of employment, a summary of the dose record may be requested and given to the worker covering the period of that employment and including any previous dose information transferred from previous employment.

7.5.3 Classification of Data

If it is expected that analyses of doses and statistical studies are likely to be carried out on the recorded data (see Section 7.1), some degree of classification of the data will be necessary. For most purposes, two forms of coding will suffice: one for defining the employers work activity and the other for the occupational category of individual workers. A possible third could be a coding of premises or sites.

In situations where the dose record keeping is linked to a national dose depository, the system of coding will be defined nationally. Even where no national depository exists, there is a strong case for using a system of coding that is common as far as possible with other record keeping services. The principal data classification is that of the employers work activity for which the European NACE system would be applicable [NACE: Nomenclature Générale des Activités Economiques dans les Commu-nautés Européennes, issued by the Statistical Office of the European Communities (SOEC)].

7.5.4 Retention of Dose Data

The retention and future use of personal records will, as ICRP state (Publication 35), be partly a matter for the management in maintaining and improving standards of design and operation, and in achieving and demonstrating compliance with ICRP's recommendations and national regulations. Since the records may also be of use in litigation or for other medico-legal reasons, this will influence the necessary period of retention. Because of the long latent period of some radiation induced diseases, the period must be long, probably at least 30 years. ICRP suggest that the records need not include the original samples, dosemeters, monitoring films etc. from which the data were obtained. Many services, however, will prefer to at least keep films of dosemeters that have received doses equal to and above the investigation level for possible re-evaluation at a later time. Storage of digitized glowcurves of TL dosemeters is possible in principle but requires substantial storage capacity.

7.5.5 Privacy

Services that operate larger scale Dose Record and Information Systems for a (large) number of customers, should realize that they essentially have sensitive information under their control. Measures must be taken to maintain the required confidentiality and to ensure that any use of the data beyond that for the defined record keeping objective, is only for authorised statistical analysis of the kinds listed in Section 7.1.

7.6 Setting up a DRIS

In the following a few suggestions are made for setting up a Dose Record and Information System. The general structure is based on the idea of the DRIS being used by a large scale Individual Monitoring Service (IMS), serving a significant number of customers. It should be obvious that, for smaller services, simpler structures may suffice, but these can easily be derived from the general lay-out.

A general diagram is shown in Figure 7.1. It assumes three different levels:

A. The establishment (employer, customer)

B. The site

C. The individual

The distinction is relevant especially when monitoring services are required to mail various items, such as dosemeters, dose reports and invoices to distinct addresses. A good example is a large hospital, which requires

- the invoice(s) being sent to its central administration,
- the dosemeters and dose reports being sent to each of its departments separately.

It should be clear that the above three levels may blend in to each other, e.g. in the case of a dentist, using only one dosemeter.

Elements which may be included to identify each of the three levels A, B and C are given in Tables 7.1, 7.2 and 7.3 respectively.

Table 7.1 Elements to identify the establishment/employer

#	Entry
A1	Name
A2	Employer code number
A3	Contact
A4	Street and number/PO Box
A5	Postal code
A6	Town
A7	Country
A8	Bank account number
A9	Telephone number
A10	Category of establishment (by code number, see Table 7.4)

Table 7.2 Elements to identify the site

#	Entry
B1	Name
B2	Site code number
B3	Contact
B4	Street and number/PO Box
B5	Postal code
B6	Town
B7	Country
B8	Telephone number
B9	Link to establishment (by code)

Table 7.3 Elements to identify the individual

#	Entry
C1	Full name
C2	A unique number (such as the social security number or a special DRIS number)
C3	Sex
C4	Date of birth
C5	(Link to) employer (possibly in code)
C6	(Link to) site (possibly in code)
C7	Date of commencement of work with present employer
C8	Date of termination of work with present employer
C9	Classification: Employer work activity category
C10	Classification: Worker occupational category (see Table 7.5)

Dose data may include:

#	Entry
C11	$H_p(10)$ (for every issuing period)
C12	$H_p(0.07)$ (for every issuing period)
C13	Neutron component of C11 (for every issuing period)
C14	$H_{E,50}$ (plus additional information on radionuclides within the body)
C15	Dose equivalents to each significantly exposed extremity
C16	Customer entries
C17	Sum of effective dose equivalent and Committed Effective dose for the running calendar year
C18	Cumulation of C17 as from the time the individual entered the DRIS (Euphemistically also called lifetimedose)
C19	Other dosimetry laboratories contributing data to record (in code)

In case the DRIS serves as a national data bank, it should be indicated which approved dosimetry service(s) generate(s) and hold(s) the (detailed) dose records.

For the sake of statistical analysis to find trends in exposure of personnel (see Section 7.5.3) – which is an essential basis for developing radiation protection policy –, it is useful to distinguish between various categories of employers work activities and between various occupational categories of individual workers. In view of the desirability of national and even international harmonization (to improve interpretability of analyses from various countries), possible choices are given in Tables 7.4 and 7.5 respectively.

Table 7.4 Employers work activity categories

#	Entry
01	Hospitals (non university)
02	Hospitals (university)
03	Dentists
04	Veterinary practitioners
05	Private medical practitioners
06	Universities (excluding hospitals and nuclear reactors)
07	Nuclear research reactors
08	Nuclear power stations
09	Nuclear fuel fabrication
10	Nuclear fuel reprocessing
11	Nuclear waste management
12	General industry
13	National and (semi-)government inspectorates
14	Defence
15	Other

Table 7.5 Occupational categories of individual workers

#	Entry
	Medical diagnostic Radiology
01	General diagnostic radiology
02	Cardiology
03	Mammography
04	Surgical radiology
05	Dental radiology
06	Veterinary radiology

Radiation therapy

#	Entry
11	Dermatology
12	Orthovolt therapy
13	Telecurie therapy
14	Megavolt (linac and neutron) therapy
15	Sealed radioactive sources

Unsealed sources, including Nuclear Medicine and Biochemistry

21	Isotope laboratory level C
22	Isotope laboratory level B
23	Isotope laboratory level A
24	In vivo research
25	In vitro research
26	Non-laboratory applications

Non-destructive investigation

1	Fixed units
32	Mobile units

Sealed radioactive sources

41	Fixed sources
42	Mobile sources
43	Calibration sources
44	Food irradiation sources
45	Gas chromatography, fire alarms etc.

Various X-ray units

51	Technical X-ray units 0 - 100 kV
52	Technical X-ray units 100 - 400 kV
53	Technical X-ray units > 400 kV
54	Technical X-ray units in R&D
55	X-ray diffraction units
56	Particle acceleration units
57	Parasitairy X-rays

Non-photon sources

#	Entry
61	Alpha sources
62	Beta sources
63	Neutron sources

Nuclear reactors

71	General operations
72	Waste disposal
73	Transport of nuclear material
74	Enrichment and fuel production
75	Reprocessing
76	Production of radionuclides
77	Radiochemistry

Various activities

81	Maintenance, repair
82	Safety and inspection
83	Nuclear research
84	Radiation research
85	Civil defence
86	Storage of radioactive material

References

1. Kendall, G.M., Kay, P., Saw, G.M.A., Salmon, L., Carter, C.D. and Law, D.V., "The Design and Implementation of the DIRK system for Dosemeter Issue and Record Keeping", National Radiological Protection Board, Report NRPB-R 136, (1983).
2. Julius, H.W., Van der Lugt, G., "A Centralized Radiation Dose Record Keeping System", Proc. 3rd European Congress of the Int. Rad. Prot. Ass., Amsterdam (1975).
3. Kendall, G.M., Greenslade, E. and Young, T.O., "Report of the Working Party of the Central Index of Dose Information", National Radiological Protection Board, Report NRPB-M 92 (1983).
4. International Commission on Radiological Protection, "General Principles of Monitoring for Radiation Protection of Workers", ICRP Publication 35, Ann.

ICRP 9 (4), (Pergamon Press, Oxford) (1982).
5. International Commission on Radiological Protection, "Recommendations of the ICRP", ICRP Publication 26, Ann. ICRP 1 (3), (Pergamon Press, Oxford) (1977).

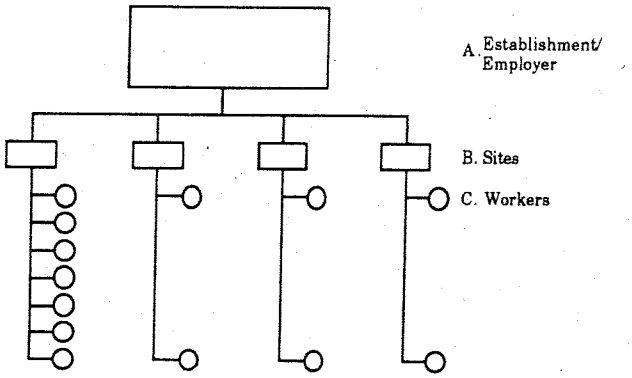


Figure 7.1 General structure of a DRIS

8. ASPECTS OF MANAGEMENT AND ADMINISTRATION

8.1 General

This chapter deals with aspects of general management and administration. All aspects, in some way, play a role in any Individual Monitoring Service (IMS). Their importance may depend, to some extend, on the type and size of the institution, the organisational environment in which it is embedded and whether the service is being operated on a commercial or non-profit basis.

Various aspects of Individual Monitoring are often given insufficient thought or are even overlooked. This seems particularly true for smaller services, where individual monitoring is sometimes considered a simple activity of secondary importance which, when done by in-house personnel, is assumed to be more reliable and effective and is expected significantly cheaper than buying the service from a larger, professional and dedicated institution. One should bear in mind, however, that running a personnel monitoring service requires more than just buying a dosimetry system (i.e. a certain number of dosemeters and the associated equipment to evaluate them) and shipping the dosemeters off to those who need them: The complexity of dosimetric concepts, the technical facilities needed and the problems involved in setting up proper structures for organisation and administration require more scientific knowledge, effort and money than one would expect at first sight.

Details of management, organisation and administration may be related to national legislation and are obviously dependent on local circumstances. Among the latter are:

- the number of dosemeters issued
- the number of customers served
- the categories of dosemeters used (basic, discriminating, neutron, etc.)
- the dosimetric method(s) applied (film, TLD, RPL, track etch, etc.)
- the flexibility as to the lengths of issuing periods
- the level of automation implemented
- etc.

It is clearly not feasible to deal with all possible options and the subject is too extensive to allow for any exhaustive description of details. The information given may, however, serve as a useful checklist which the reader may use in his own way.

8.2 Organisational Structure and Personnel

The Individual Monitoring Service should be independent in character and free from any external influence, e.g. parent organisation or customer, which could adversely affect the quality or impartiality of the service it offers.

The basic organisational structure of an Individual Monitoring Service should contain at least four basic elements, representing:

- Routine dosimetry
- Record keeping
- Administration and finances
- Research and development

Their interrelation is shown in the diagram (Figure 8.1).

Depending on whether the service is largely independent or part of a larger organisation, sub-elements may be distinguished, such as:

- Calibration section
- Mailing centre
- Workshop
- Customer relations section
- Quality control

etc.

It is useful to clearly outline the organisational structure, this being the basis for assigning tasks to staff personnel, smooth communication between staff members and, therefore, effective and efficient operation.

A head of laboratory should be appointed who is technically competent and of recognized stature and experience. He should possess professional or equivalent qualifications appropriate to radiation protection in general and to the radiation dosimetry work of the laboratory in particular. Similar qualifications apply to the deputy head. It is essential that the head be in actual charge of the work of the laboratory. He should have enough adequately trained staff experienced in their specific tasks, such as mechanical and electronic engineering, computer operation, financial administration, clerical work etc. They should be adequately supervised and in general should follow documented procedures (see also Chapter 9).

8.3 The Laboratory Accommodation and Environment

8.3.1 *Spatial Arrangements*

The service should be allocated suitable laboratory accommodation. The spatial arrangements should be such, that enough room is available for equipment, materials and personnel. Weakly or non-directly related activities should prefer-

ably be separated in order to avoid mixing up incoming and outgoing dosemeters and to keep personnel away from unnecessary cross-over noises. It is often useful to carefully sort out ergonomics by detailed analysis of the flow of dosemeters, personnel, materials and other goods. Safe working conditions also need to be considered.

8.3.2 Environmental Conditions

The environmental control must be adequate to ensure that no equipment and dosemeters are subjected to conditions likely to affect their performance. Although strict control of conditions is generally not necessary, reasonably uniform values should be kept for parameters such as temperature (18-23 °C), relative humidity (40-80%RH) and light (700-1000 lux). Dust, undue vibrations and reactive chemical vapours should be avoided as should excessive noise (<35 dBA). One may want to consider more stringent conditions for store rooms.

Special thought should be given to the background radiation level in the laboratory, in particular at locations where dosemeters are kept for significant amounts of time before dispatch or evaluation. This level should never be significantly above normal and preferably about equal to the national average. If dosemeters are stored at locations where radioactive sources may pass by, it is recommended that an alarm monitor be used to prevent the dosemeters from unexpectedly being overexposed. Quantitative information on the radiation level in the storage area (e.g. by using control dosemeters) is essential when net doses are determined by subtraction of the background contribution, which will become more important as the detection threshold of the dosemeters used is lower.

8.3.3 Technical Conditions

Very often the performance of equipment depends on the stability of the electric power. Voltage and AC frequency should stay well within the required specifications of the equipment in use. Clearly, electric and magnetic fields should be low enough as to not affect equipment and dosemeters.

8.3.4 Security

Appropriate attention to aspects of safety is not only of interest for the well being of the personnel, but is also of paramount importance for the continuation of the service as a whole. Fire alarms, fire extinguishers and emergency exits are common in the majority of today's working environments. Special measures need to be considered in order to guarantee that indispensable equipment and dosemeters and particularly invaluable dosimetric data, related to customers, do not get lost.

8.4 Customer Related Issues

Those who use the service of an individual monitoring laboratory often rely, to a large extend, on the experts in the field. This is especially true for smaller customers, such as medical practitioners, dentists and small hospitals, who may have limited knowledge and/or experience in radiation protection and dosimetry matters. In particular new customers are lacking information on the "do's" and "don'ts" in personal dosimetry. They should therefore be provided with adequate information which may include the following:

- Types of dosemeters and their applications (types of radiation, basic, discriminating)
- Issuing periods to chose from
- Where to wear and how to handle dosemeters
- Dosimetric method(s) used
- System of identification of dosemeters and wearers
- Dose record keeping, reporting of results, customer dose entries, accessibility, privacy
- Interpretation of results (quantities, dose limits, natural background, net-dose, lower- and upper limit of detection of the dosimetry system, etc.)
- Issuing and returning procedures
- How to order, change and cancel subscriptions
- Indication on whether the order will be effective until cancellation by the customer or that yearly renewal is required
- Information needed from the customer
- Prices, indicating what they do and do not include, such as: VAT, postage (one way or both ways), charge for lost dosemeters,
- The amount of time to be allowed to make an order (or cancellation) effective
- Mailings should preferably enclose addressed and postaged envelopes
- Information on routine and/or special services provided by the IMS, such as:
  - Immediate reporting by telephone or telex in case of unusually high doses
  - Emergency processing
  - Technical-, scientific-, legal advice and/or assistance (when and how to deal with authorities)

The way the information is provided to the customer and the quality of the presentation will depend on local habits, personal taste, money available, size of the service etc.

It is good to be aware of the fact that some customers consider wearing dosemeters as a "status symbol" (and they may be highly cooperative), while others think that the necessity to be monitored is a nuisance (and they are likely to be highly critical). Most users have in common that

they have difficulties understanding the complexity of both the conceptual dosimetric and the organisational problems involved in individual radiation monitoring. The service may therefore want to be user friendly (which will be for the service's benefit!). Communication between the customer and the service should therefore be simple to handle and the information should be easy to understand, good looking and repetitive.
Even among professional radiation workers there are many who suffer from radiation phobia. No need to say that complaints from customers are to be taken seriously. One should turn customer's complaints into benefit for the service, realizing that the user has a better chance to test its quality under practical conditions.

8.5 Handling and Processing of Dosemeters

It can hardly be emphasised enough that it is essential to strictly follow the proper sequence of procedures that are part of the system. In particular, the flow of incoming and outgoing dosemeters should carefully be kept under control, to make sure that non-evaluated dosemeters will *not* be re-issued.
Experience has shown that, in spite of a seemingly perfect organisational structure of the monitoring service, problems may arise when deviations from the "normal" pattern are encountered. This is especially true for the larger service having adopted a high level of automation, using computers for controlling various processes and for administrative purposes. Both organisation and computer software should be flexible enough to cope with all sorts of anomalies, requiring special actions to be taken. Some typical anomalies are:

- Dosemeters not recovered by the customer
- Dosemeters not returned (or too late)
- Dosemeters lost in the mail
- Identification damaged
- Holder damaged
- Detectors missing or damaged
- Dosemeter contaminated
- Dosemeters irradiated by a type of radiation they are not supposed to measure

8.6 Automation

Automation may, but does not always help to reduce costs, depending on the availability and cost of personnel (see also Section 8.7). Certain parts of the processing chain lend themselves relatively easily to automation, especially if automatic equipment can be bought off the shelf. In-house development of automatic equipment (e.g. for evaluation, identification and/or wrapping of dosemeters) may be necessary, but usually turns out more expensive than expected. (See also Section 8.7). The disadvantage of automation is, that it sometimes reduces and certainly limits the flexibility of the service. On the other hand, automation almost invariably overcomes human errors and mistakes and therefore may con-

tribute significantly to the reliability of the service. Whether and to what extend automation is justifiable, is a trade off between costs and desired quality, taking into account the number and expertise of staff members and the number of dosemeters to be processed.

8.7 Financial Considerations

8.7.1 General

Science and money seldom go hand in hand. Those who are in charge of IMServices should be – and mostly are – scientists who, by nature, are not trained in financial matters which often do not appeal to them. However, a sound financial policy and good bookkeeping practice is a vital aspect of any public service and therefore should be considered an integral part of a smoothly running and reliable IMS. The following may help to improve the understanding of the financial components involved.

8.7.2 Subscription Rates

For the calculation of subscription rates, the following components should be taken into account:

- Running costs
  - Personnel
  - Consumable materials (replacement dosemeters, wrapping materials, envelopes, forms, etc.)
  - Postage
- Building
  - Maintenance
  - Rent
  - Amortization
  - Energy (heating, light, etc.)
  - Cleaning
- Equipment, including computers
  - Maintenance (-contracts)
  - Calibration of irradiation facilities (traceability)
  - Amortization
- Scientific research (facilities, personnel)
- Technical investigations and development (facilities, personnel)
- Software development (facilities, personnel)
- Outside contractors

8.7.3 Capital Investment

It is of vital importance that "up front" money (a reserve budget) be available for investment in scientific research, technical development, replacement of expensive equipment, replacement of dosemeters etc. Financial reserves may also include a buffer, allocated to compensate for fluctuations in the size of the service.

8.8 Scientific Research

As has been explained earlier, individual monitoring requires good knowledge of radiation dosimetry, good understanding of the rather complex dosimetric concepts and extensive experience in dealing with the characteristics and idiosyncrasies of the dosimetric detector materials used in routine monitoring. One should be aware that expertise at a professional level can only be gained and maintained by being involved in scientific research and technical design and development. This implies that it is dangerous to entirely rely on remote research centres, because problems in routine dosimetry often require a scientific approach to be recognized and solved. In reverse, R & D work should be in the closest possible contact with daily practice, in order to make sure that its spin-off can successfully be implemented. Great care should, however, be taken to separate technical development from routine operation of the system. The results of the former should be implemented only after thorough testing.

All this is also essentially true for the smaller services. These, however, may, on one hand, have some difficulties in providing the money for R & D work but, on the other, should make sure that – attractive! – research work should never be in the way of providing dosimetric services at a professional level.

Some subjects of interest for R & D are:

- Dosimetric experiments on:
  - energy dependence for photons, beta radiation and neutrons
  - fading characteristics of detector materials
  - dosemeter design
  - depth dose measurements and (Monte Carlo) calculations
  - calibration of radiation fields
- Technical design and development of:
  - dosemeters
  - read out equipment
  - detector (TL) materials

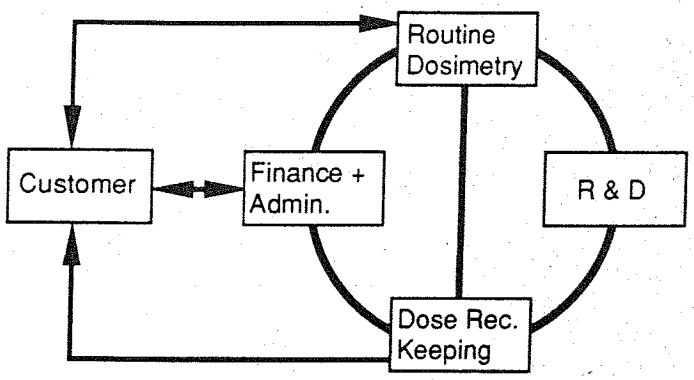


Figure 8.1 Basic structure of an Individual Monitoring Service

9. QUALITY ASSURANCE IN INDIVIDUAL MONITORING

9.1 General

In to-days world there is a growing consciousness of Quality Assurance (QA) and Quality Control (QC). This does not only apply to manufacturing of industrial products, it is equally true for public services. The increasing awareness in our modern societies of the quality of life – and hence of optimal health care and general safety – makes the general public call for "products" of the highest possible quality. Good examples of the latter are the continuously improving safety standards for automobiles, the growing need for quality assurance in medical diagnostic imaging and the optimisation of the working environment. It is therefore strongly recommended that any individual monitoring programme should include a quality assurance programme as an integral part.

In this chapter an attempt is made to roughly outline some aspects that may come into play when QA is applied to routine individual monitoring, a subject which has hardly been dealt with in the professional literature on radiation dosimetry [1]. Although QA is mainly a matter of common sense, the development of a strategy for it, as well as setting the rules for a QA programme and implementing them in the service, requires considerable thought. How to approach the details, depends on the local situation, sometimes on national regulations and often on personal views. The following is intended to provide some useful ideas which, though perhaps rather obvious, may serve as a general guide and help stimulate creativity for those in charge of individual monitoring services.

Expressed in general terms, quality assurance for an IMS means: Careful control of the quality of the service provided, by ensuring that high quality products (dosemeters, reports etc.) are supplied to the customer, and that these are delivered on time at a reasonable price. This requires a system of QC-procedures which have to be developed and followed carefully. Such a system, which essentially touches the entire organisational structure of the service, should contain the following elements:

1. Development, implementation and management of QA
2. Documentation of methods, procedures and test results
3. Quality awareness and training of personnel
4. Acceptance and compliance of newly supplied materials
5. Maintenance and testing of equipment,materials and processes
6. Verification of the calibration facilities
7. Testing of the overall performance of the system

8. Re-typetesting (parts of) the system from time to time

Some of these elements will be discussed in some detail below.

9.2 Development, Implementation and Management of QC

Introduction of a QA programme requires careful analysis of the whole system, starting from the manufacturers of equipment and materials to the customer – the destination of the finished product. One should break down the system in its component parts. Each part is then to be analysed individually, its critical aspects and parameters identified, the operational and financial constraints considered and the procedures developed, documented and introduced. After introduction the procedures have to be reviewed periodically to determine their efficacy and, where necessary, to update them. No need to say that, wherever applicable, QC procedures should comply with national and international standards.

Within the context of this publication it is hardly possible to, in any reasonable detail, deal with strategy and implementation of QA programmes, the subject justifying a book. Figure 9.1 may at least reveal the basic philosophy.

The management, responsible for the QA strategy, should be committed to QA and should make enough financial resources and staff available. They should also be aware that the quality of the end-product, even if the level of automation is high, strongly depends on the involvement of the staff. Some important psychological aspects should be borne in mind:

The need for QA should be justified and the staff should be motivated. It is more stimulating and effective to look for a better future then to critisize the past.

Obvious obstacles are established practices, cultures and values.

It must be borne in mind that the main objective of a balanced cost effective QA/QC programme is to **achieve** and **maintain** and thereby continuously **assure** the quality standard of the service.

9.3 Documentation of Methods, Procedures and Test Results

All methods used and all procedures set up to control the various processes within the service, ought to be well documented. This is considered a "must", when it comes to inspection of the service by official authorities as part of an approval system. Appropriate parts of the documentation should be made available to staff members, preferably tuned to their level and specific needs. This is especially true for operational instructions, of which it may even be useful to have them on display "on the spot".

Not only for official use, but even more so to better understand the behaviour of the parameters that play a role in the chain of dosimetric processes, it is important to carefully document the results of all tests carried out. Analysis of the data collected will, moreover, be of great help in trouble shooting and is essential

to maintain the quality of the service at the highest possible level.

9.4 Quality Awareness and Training of Personnel

The heart of the service depends on the personnel. The management should be aware that they can do their job reliably only when they are adequately trained. Such training should include explanation of

- the basic philosophy and strategy of individual monitoring
- the principles of the methods used
- the technicalities and potential problems of the (part of the) processes they are involved in
- the detailed procedures
- the relation their work has with other parts of the process
- trouble shooting.

Above all, it is important that they are motivated to do the best they can to provide the highest possible performance. An efficient and useful way to do this, is to have staff meetings at regular intervals where the standard of the service can be discussed. Problems should be brought into the open and discussed to arrive at proper solutions. Such an approach provides the best chance to overcome psychological obstacles due to established practices, cultures and values or sensitivity of staff.

9.5 Acceptance and Compliance of Newly Supplied Materials

Every now and then, new supplies of consumable materials will have to be ordered. These should be purchased from a reliable supplier who, on his turn, should be able to verify the quality of his product on the basis of a QA system. Nevertheless, raw materials should be checked before they are put into use, in order to make sure that their quality complies with the specification as agreed with the supplier. Typical examples of useful checks are:

Photographic films: type, emulsion code, energy dependence, sensitivity, contrast index, uniformity.

TL detector materials: energy response, sensitivity, uniformity, fading, light sensitivity.

Chemicals: composition, pureness, identification and expiration dates.

Filmholders: filters (materials, thickness, location in the holder), clips.

Forms: lay-out and typing errors.

9.6 Maintenance and Testing of Equipment, Materials and Processes

Equipment and (dosimetric) materials may change their characteristics as a function of either time or usage.

Obvious examples are found in thermoluminescence dosimetry:

- TL detectors may change in sensitivity e.g. due to variations in heat treatment during readout or annealing, or because of dirt, wear and tear etc. They should be re-calibrated at regular intervals, the length of which should be established experimentally.
- TL readout instruments, although they are reasonably stable these days, need to be checked at least daily and preferably more often using a set of known personal dosemeters. Background signals should be checked regularly, especially when a low detection threshold of the system is claimed.

It has proved to be useful to construct and display a so called Quality Control Process Chart, on which the daily bias from the reference level as well as acceptable intervention and rejection levels are indicated.

In photographic dosimetry, regular tests should be done to check:

- Filmholders for damage, clips, lost filters, contamination etc.
- Densitometers (zero adjust, calibration, light leakage)
- Developer (temperature, replenishing, pH)
- Fixer (temperature, silver content, pH).

The reproducibility of the developing process may be checked by using a sensitometer and by plotting the characteristic curve, derived from sensitometric step densities. It is even better to develop, together with the customer's films, a series of test films, irradiated to cover the entire dose range, and plot the density curve.

9.7 Verification of Calibration Facilities

No individual monitoring service can do without well equipped calibration and monitoring facilities. Various types of radiation sources, capable of producing the kind of radiation beams required for type testing of dosemeters, should be available, as well as adequate measuring equipment to measure radiation fields in the quantities required. The measuring equipment and preferably radioactive sources should be calibrated against the national standard or – if such a standard is not available – by a primary laboratory of another country to ensure traceability. Recalibration should be done at regular intervals (1 - 5 years) or when there is any doubt about the accuracy of the in-house (standard) instruments.

Because the operational quantities, which individual dosemeters are expected to measure, are very difficult to measure, it is common practice to convert the

measured field quantities into $H_p(10)$ and $H_p(0.07)$ using conversion coefficients (see Chapters 3 and 5).
Experts should be aware of any changes that may occur in the values of these coefficients as a result of refinement of their measurement or calculation. The service may want to reassess the response characteristics and evaluate if these changes are significant.

9.8 Testing the Overall Performance of the System

If equipment, materials and all processes are carefully kept under (quality) control, generally speaking the system as a whole should show good performance. The best way, however, to test this is to arrange for a "dummy" subscription which should be run through the entire routine procedure (like a customer's subscription) except for the irradiation. The dosemeters involved should be exposed to exactly known doses either in the laboratory or by some colleague or authorised institute. Real and measured values should be compared and the results interpreted.
An alternative – or additional – method is to participate in national or international intercomparison programmes. Examples of the latter are the programmes run by the CEC, IAEA (International Atomic Energy Agency) and ORNL (Oak Ridge National Laboratories).

References

1. Julius, H.W., "Quality Assurance in Individual Monitoring of Ionizing Radiation", Proc. 5th CEC Seminar on the Radiation Protection Dosemeter Intercomparison Programme, Beta Dosimetry, Bologna (1987).

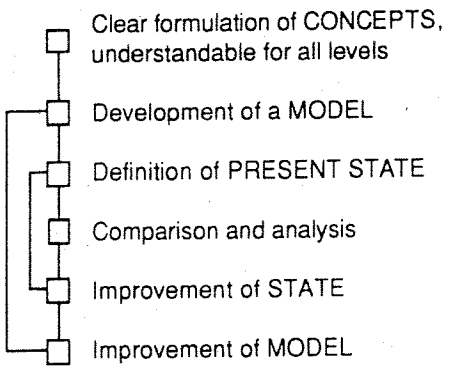
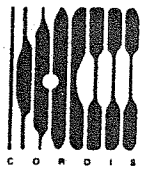


Figure 9.1



The Communities R & D Information Service

(Service d'information de recherche et développement des Communautés)

CORDIS

Un élément vital de votre stratégie de diffusion

CORDIS est un service d'information créé dans le cadre du programme VALUE afin de donner un accès rapide et facile à l'information sur les programmes de recherche de la Communauté européenne. Il s'agit d'un service en ligne gratuit accessible par le centre serveur de la Commission européenne (ECHO) et aussi d'un CD-ROM récemment mis à la disposition du public.

CORDIS offre à la Communauté de recherche et développement européenne:

— un aperçu détaillé et actualisé des activités RDT dans la Communauté européenne, grâce à un ensemble de bases de données et de services associés;

— un accès rapide et aisé à l'information sur les programmes et résultats de la recherche dans la Communauté européenne;

— un service de la Commission en évolution permanente adapté aux besoins de la communauté de recherche et de l'industrie;

— une assistance complète de l'utilisateur incluant la documentation, la formation et les services du bureau d'assistance CORDIS.

Bases de données CORDIS

RTD-Programmes — RTD-Projects — RTD-Partners — RTD-Results
RTD-Publications — RTD-Comdocuments — RTD-Acronyms — RTD-News

Pour que votre programme profite au maximum des services CORDIS:

— informez l'équipe CORDIS de vos initiatives en matière de programmes;

— communiquez régulièrement des informations aux bases de données CORDIS telles que RTD-News, RTD-Publications et RTD-Programmes;

— utilisez les bases de données CORDIS, telles que RTD-Partners, pour la mise en application de votre programme;

— consultez CORDIS pour obtenir les informations les plus récentes sur d'autres programmes proches de vos activités;

— informez vos partenaires des possibilités de CORDIS et de l'importance de leur contribution au service comme des bénéfices qu'ils pourront en retirer;

— contribuez à l'évolution de CORDIS en communiquant au bureau CORDIS vos commentaires sur le service.

Pour plus d'informations sur la communication avec CORDIS, contactez l'équipe CORDIS à la DG XIII:

Bruxelles
M^me^ I. Vounakis
Tél. (+32-2) 299 04 64
Fax (+32-2) 299 04 67

Luxembourg
M. B. Niessen
Tél. (+352) 43 01-33638
Fax (+352) 43 01-34989

Pour obtenir un accès en ligne à CORDIS, veuillez en faire la demande à l'adresse suivante:

Service de la clientèle ECHO
BP 2373
L-1023 Luxembourg
Tél. (+352) 34 98-1240
Fax (+352) 34 98-1248

Si vous êtes déjà un utilisateur ECHO, ayez l'amabilité d'indiquer votre numéro d'utilisateur.

European Commission

EUR 14852 — Radiation protection 73 — Technical recommendations for monitoring individuals occupationally exposed to external radiation

Luxembourg: Office for Official Publications of the European Communities

1994 — VI, 86 pp., fig. — 16.2 x 22.9 cm

Radiation protection series

ISBN 92-826-7364-2

Price (excluding VAT) in Luxembourg: ECU 11.50

These technical recommendations for the monitoring of workers and other persons exposed to external ionizing radiation are providing technical guidance in view of practical applications of dosimetric concepts. The document gives information on the general principles for monitoring individuals as well as requirements for personal dosemeters such as type and performance testing. Also covered are aspects of dose record-keeping systems and administrative problems.

14 15 16 CR-NA-14852-EN-C

NOTICE TO THE READER

All scientific and technical reports published by the Commission of the European Communities are announced in the monthly periodical '**euro abstracts**'. For subscription (1 year: ECU 60) please write to the address below.

Price (excluding VAT) in Luxembourg: ECU 11.50

ISBN 92-826-7364-2

OFFICE FOR OFFICIAL PUBLICATIONS
OF THE EUROPEAN COMMUNITIES

L-2895 Luxembourg

9 789282 673645 >