INDIVIDUAL MONITORING FOR EXTERNAL RADIATION, SOME CONCEPTUAL AND PRACTICAL ASPECTS

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INTRODUCTION

Statistics show that, at least in the Western world, each member of the public is, on average, subjected to one X-ray examination per year. It is recognized that radiation doses due to the medical application of ionizing radiation are far from negligible but also that the benefits gained are significant, often life saving. Although reference values are presently being considered, dose limits do not exist for patients and doses are assessed only on an ad hoc basis.

For those, however, who professionally deal with sources of ionizing radiation the situation is quite different. For this category of workers a system of dose limitations has long ago been developed and includes the measurement of the actual exposure of the individual worker. In 1982 the International Commission on Radiological Protection (ICRP) state, in Publication 35 (1), 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." Indeed, monitoring of workers constitutes an integral part of radiological protection. The main objectives of individual monitoring and some of the benefits that may accrue from it are:

- demonstration of compliance with legal requirements and regulations
- provision of information for the evaluation of the dose received by an individual in the event of an accidental exposure
- demonstration of good working practices and the adequacy of supervision and training which will motivate workers to reduce their exposures to the lowest possible level
- information on collective doses as a useful tool for risk-benefit analyses.

In 1991 ICRP (2) recommended a concise system of radiological protection, including dose limits for workers. This system formed the basis for the safety standards of international organizations such as the IAEA and the European Union from which national regulations are derived.

PRIMARY AND OPERATIONAL QUANTITIES IN INDIVIDUAL MONITORING

The ICRP system of dose limits (2) is based on the concept of effective dose, E. E is the sum of the weighted doses in all tissues and organs of the body as given by the expression

$$E = \sum_T w_T \cdot H_T \qquad (1)$$

where H_T is the equivalent dose in tissue or organ T and w_T is the weighting factor for tissue T. The equivalent dose in tissue T is given by

$$H_T = \sum_R w_R \cdot D_{T,R} \qquad (2)$$

where w_R is the radiation weighting factor and $D_{T,R}$ is the absorbed dose averaged over the tissue or organ T due to radiation R. Values for w_T and w_R are given in ICRP Report 60 (2).

The purpose of this *primary quantity*, E, (also called the *protection or limiting quantity*) is to provide a measure of detriment from stochastic effects for non-uniform irradiation of the body which could be equated to the detriment for uniform irradiation (3). Although it was recognized that the risk associated with a given exposure would vary – by up to a factor of about 10 – with the age and sex of the individual exposed, only one set of values for w_T (derived from averages for a population of workers) has been recommended by ICRP as being appropriate for the protection of any worker regardless of these sources of variability (2, 3). It is clear that effective dose, although in concept applicable to individuals, corresponds to an expectation of average detriment and therefore is, in practice, assumed to be applicable to an average population of workers.

In most national and international regulations annual dose limits are also given in terms of the primary quantity and are taken to apply to the individual concerned. Therefore, in principle, E (formerly H_E the effective dose equivalent (3)) is the quantity that should be determined in radiation protection dosimetry. However, this requires detailed knowledge of the equivalent dose in various organs and tissues in the body, and thus the quantity is difficult to assess and impossible to measure directly. For this reason ICRU, in 1985, introduced in Report 39 (4) the concept of *operational quantities* which was further elaborated in ICRU Reports 43 and 47 (5, 6). Presently, for individual monitoring the operational quantity is the *personal dose equivalent, $H_p(d)$*. This quantity is defined as the dose equivalent in soft tissue (ICRU 4-element composition) at an appropriate depth, d, below a specified point on the body (6) (usually taken to be the point at which the dosemeter is worn). For weakly penetrating and strongly penetrating radiations the recommended depths are 0.07 mm and 10 mm respectively (notations: $H_p(0.07)$ and $H_p(10)$).

The concept of personal dose equivalent has been created to provide a quantity considered to be metrologically sound and able to give a reasonable estimate of the protection quantity. In ICRU Report 43 (5) it was shown that, for uniform irradiation of the body, $H_p(10)$ could be considered a satisfactory representative of the effective dose equivalent, H_E (3), overestimating this (former) protection quantity by only some 20% for photon radiations of 50 keV and greater. In essence, this is also true for the effective dose, E, as introduced by ICRP in 1991 (2). For lower photon energies the overestimate, however, is significant and may be as high as a factor of 5 at 15 keV. (It is useful to note that practical dosemeters tend to underestimate $H_p(10)$ in this energy region and therefore may give a better estimate of E, see below).
The definition of $H_p(10)$ implies that, for a given orientation of an individual in a given radiation field, this quantity is multi-valued, it being dependent on the individual concerned, i.e. on the individual's size and shape (influencing, by scattering and attenuation, the dose equivalent at the depth d) and on the "specified point on the body" where the dosemeter is worn. These variations may, however, not be judged important in the context of the much larger variations in detriment resulting from sex and age.

It is worth noting that, as far as practical measurements are concerned, many current dosemeters do not strictly measure the dose equivalent in the adjacent tissues because they often use non tissue equivalent detectors covered with filters of various materials in combination with algorithms applied to match the calibration quantities under calibration conditions. Also, significant variations in dosemeter readings may occur due to variations in the separation of dosemeter and body and resulting from differences in the energy and angle characteristics of the radiation backscattered from the body (7). These variations, however, critically depend on the dosemeter design.

DOSIMETRIC REQUIREMENTS FOR PERSONAL DOSEMETERS

Personal dosemeters should be capable of providing reliable measurements of the appropriate quantities $H_p(0.07)$ and $H_p(10)$. ICRP (1) requires that in individual monitoring the maximum error in the measurement of a dose at the level of the annual dose limit should not exceed a factor of 1.5 at the 95% confidence level. This means that the measured dose should be within the interval of –33% and +50% of the conventional true value of the quantity of interest (8, 9, 10). Hence, if S is the standard deviation of the measurement,

$$1.96\ |S| \leq 0.5\ (0.33 + 0.50) \rightarrow S \leq 0.212 \qquad (3)$$

Here S is supposed to include all errors – both random and systematic – in the dosimetry system. If δ_r and δ_s are the resultant random and systematic standard deviations respectively then S can be obtained from:

$$S = (\delta_r^2 + \delta_s^2)^{1/2} \qquad (4)$$

Following the convention, δ_s can be calculated by assuming that systematic uncertainties follow a rectangular probability distribution (8, 9).
Among the systematic errors, the variation in the response of the dosemeter as a function of photon-energy and angle of incidence is the most important, the remaining systematic errors usually being relatively small.

The corresponding error and its relative standard deviation, ($\delta_{E,\phi}$), obviously depends on the design of the dosemeter, which includes the choice of the detector material(s), the filters used and the housing.
Hence (4) can be rewritten as:

$$S = \sqrt{\delta_r^2 + \delta_s^2 + \delta_{E,\phi}^2} \leq 0.212 \qquad (5)$$

where δ_r and δ_S are the relative standard deviations of the resultant random and remaining systematic errors

respectively.

By Equation (5) the performance criteria for personnel dosimetry systems are expressed in general terms, without specifically limiting the uncertainties of any of the parameters involved. This approach leaves some freedom with respect to the physical and technical characteristics of the dosimetry system used. If, for example, the radiation energy and angular dependence is small, relatively large random errors can be tolerated, and vice versa. This implies that if, for a particular dosimetry system, the relative standard deviations due to the overall random error (δ_r) and the remaining systematic error (δ_s) are known, the maximum allowable value, Δ, for the dosemeter design error ($\delta_{E,\phi}$) can be determined. For example, if $\delta_r = 0.06$ and $\delta_s = 0.04$, then $(\delta_{E,\phi})_{max} = \Delta = 0.20$ (10).

TYPE TESTING OF PERSONAL DOSEMETERS: THE PHANTOM PROBLEM

Type testing is the determination of the dosemeter response characteristics under laboratory conditions that come reasonably close to real life situations. E.g., when testing for $H_p(10)$ for photon radiation, a personal dosemeter is irradiated on a phantom under standardized laboratory irradiation conditions (8, 11) and its response as a function of radiation energy and angle of incidence, $R_{E,\phi}$, is compared to the dose at a depth of 10 mm in the phantom. $H_p(10)_{phantom}$ can be calculated from air kerma measurements (phantom absent) by multiplying K_a by $C(E,\phi)$, the conversion coefficient for energy E and angle of incidence ϕ (8, 12, 13). Ideally

$$R_{E,\phi} = H_p(10)_{phantom} = C(E,\phi)\, K_a \qquad (6)$$

Although the concept of operational quantities would suggest a straight forward recipe for type testing of personal dosemeters, this is not true. ICRU gave some hints in Report 39 (4): "The calibration of the dosemeters is done under simplified conventional conditions at the depth d in an appropriate phantom. For dosemeters to be worn on the trunk, a suitable phantom is the ICRU sphere" (30 cm in diameter and consisting of ICRU tissue). However, not only is it impossible to fabricate ICRU tissue, also there are several practical problems in the manufacture and use of spherical phantoms. Therefore, taking into account extensive discussion on this topic, ICRU gave further guidance in Report 47 (6): After indicating that "the calibration of dosemeters is generally performed under simplified conditions on an appropriate phantom", various phantoms in use are listed and, for the reason that "it is .... desirable to achieve uniformity in calibration procedures", the 30 x 30 x 15 cm PMMA phantom is recommended. The report also extends the definition of the operational quantities for individual monitoring to include the dose equivalent at a depth d in a phantom made of ICRU tissue, and states: "The quantity to be used for calibration is therefore $H_p(10)$ in a phantom having the composition of ICRU tissue, and the same size and shape as the calibration phantom". This "is the dose equivalent at the depth d below the point where the dosemeter is to be calibrated".
As was done earlier for the ICRU sphere, coefficients were calculated to convert air kerma to $H_p(10)$ at various depths (including 10 mm) in the ICRU slab and phantoms of different shapes and materials for various angles of incidence of the radiation (12, 13, 14). Detailed type testing procedures have also been published (8, 15).

As mentioned above, PMMA has been suggested and even recommended (6) as a satisfactory surrogate for ICRU tissue material. Although PMMA is cheap and easily available, it has the disadvantage that it produces dosimetric complications resulting from differences in absorption and backscatter as compared to tissue. It is important to be aware of these complications, especially because the interpretation of type test results in terms of performance criteria (8, 15) is a crucial part of the official approval of a dosimetry system for individual monitoring. In view of this the concept of using PMMA phantoms in conjunction with PMMA related dosimetric reference data for the purpose of type testing (and/or for the design) of personal dosemeter is a very dangerous one, for various reasons: Dosemeters designed to correctly measure the dose in the ICRU tissue slab phantom may, when type tested on a PMMA phantom, show a relative response as a function of photon energy and angle of radiation incidence different from $H_p(10)$ in PMMA and, as a result, may not comply with the officially required performance criteria and hence not be approved. Alternatively, dosemeters with relatively poor response characteristics in terms of $H_p(10)$ in tissue, might show fortuitous agreement with the results of tests made on a PMMA phantom.

One might indeed wonder whether a dosemeter which is designed to correctly measure the dose in a PMMA phantom (in order to make it pass the test) can be expected to, as intended, correctly measure the dose in soft

tissue. The fact that, between 25 and 70 keV, $H_p(10)$ in PMMA is about 20% higher than $H_p(10)$ in tissue (7) may find some compensation by the increased fluence (some 10 to 15%) at the PMMA phantom surface. This compensation, however, only applies to dosemeters that are sensitive to and able to correctly measure the dose from backscattered radiation. Clearly a dosemeter, which is entirely insensitive to backscatter (hence does not respond to the presence of a phantom or an individual at all), designed to correctly measure $H_p(10)$ in PMMA and successfully tested on a PMMA phantom will, when worn by a person, be in error by some 20% in the photon energy range between 25 and 70 keV (important in diagnostic radiology). Factors meant to correct for the larger contribution of backscatter radiation, produced by PMMA (15, 16), are not generally applicable because such corrections strongly depend on the design of the dosemeter.

From the above it may be concluded that, from both a conceptual and a practical point of view, the PMMA slab phantom can be considered unsuitable (7). This seems to be gradually becoming recognized. ISO is in the process of adopting a better substitute for the ICRU tissue slab, i.e. a water filled PMMA phantom of the same dimensions (30 cm x 30 cm x 15 cm) the front wall of which is thin, 2.5 mm, while the remaining walls are 10 mm thick (17). Backscatter properties of this phantom are very close to (i.e. less then 3% different from) those of the ICRU tissue slab. $H_p(10)$ in the latter will still be the reference quantity. This will certainly help to dissolve the confusion which still remains in the minds of many who run an individual dosimetry service. It will, however, not solve the still remaining problem of type testing dosemeters for angular responses at angles larger than 60 degrees (7).

TYPE TESTING FOR PHOTON ENERGY AND ANGULAR RESPONSE

In the case of type testing of personal dosemeters for photon-energy and angular dependence it is recommended (8) to determine the energy response for both $H_p(0.07)$ and $H_p(10)$ at four angles of incidence: 0° (normal incidence), 20°, 40° and 60°. Irradiations should be made on a suitable phantom (preferably the 30 x 30 x 15 cm water filled PMMA ISO slab (17)) using the narrow spectrum reference radiations as specified by ISO (8, 11). A combined energy and angular response can be calculated and plotted by, for each energy E, averaging the response over all angles of radiation incidence. The resulting average response, $\overline{R}_E$, then becomes:

$$\overline{R}_E = 0.25 \left(R_{E,0} + R_{E,20} + R_{E,40} + R_{E,60} \right) \tag{7}$$

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

$$R_{E,\phi} = \frac{\left(H_{E,\phi}\right)_m}{\left(H_{E,\phi}\right)_t} \tag{8}$$

where $\left(H_{E,\phi}\right)_m$ = the measured dose and $\left(H_{E,\phi}\right)_t$ = the conventional true value. $\left(H_{E,\phi}\right)_t$ should, when type testing for $H_p(0.07)$ and $H_p(10)$, be taken to be the dose equivalents at depths of 7 mg.cm^{-2} and 1000 mg.cm^{-2} respectively in the ICRU tissue equivalent slab phantom (*not* in the ISO phantom, which only serves the purpose of creating realistic back scatter conditions!). In Equation (7) the responses at each angle are weighted equally, which is assumed to be acceptable in practical situations where irradiation conditions are likely to be two dimensional rotationally isotropic (18).

The average uncertainty related to the angular response at energy E is represented by $| \overline{R}_E - 1 |$.

If, as indicated above, the maximum allowable value of $(\delta_{E,\phi})$, i.e. $(\delta_{E,\phi})_{max} = \Delta$, due to variations in the combined energy and angular response is calculated according to Equation (5) then the performance requirement for $\overline{R}_E$ becomes:

$$| \overline{R}_E - 1 | \leq 1.96 \Delta \tag{9}$$

for all energies between 15 keV and 1.25 MeV.

A typical example of the response for $H_p(10)$ for various photon energies and angles of incidence of a TLD (LiF) based personal dosemeter (10) is given in Figure 1.

SHOULD AN INDIVIDUAL DOSEMETER BE SENSITIVE TO BACKSCATTER?

At first sight effective dose, as defined by ICRP in Publication 60 (2), would seem – and is usually considered – to be an individual oriented quantity. Not true: Even if it were possible to obtain the equivalent doses in the organs of the individual concerned, the next step would be to weight these values using tissue weighting factors as given by ICRP. These factors, however, are – as mentioned earlier – population values averaged over sex and age. E therefore cannot be assessed for a given individual. Conceptually, E is more related to a mathematical model (such as the anthropomorphic models ADAM and EVA as used in Monte Carlo (MCNP) calculations), with population averaged weighting factors. Both from a fundamental and a practical point of view it is clearly illogical to have a multi-valued individual related quantity, $H_p(10)$, as an estimator of a single-valued, sex and age dependent quantity (7).

If one were to attempt to estimate an individual specific value of effective dose from a measurement of personal dose equivalent, it would at least be required that variations in E, caused by differences in H_T resulting from differences in shape and/or size of the individual, are reflected in similar changes in $H_p(10)$ and (for the purpose of measurement) in the reading of the dosemeter worn on the surface of the body. However, it is generally to be expected that $H_p(10)$, as well as the radiation field at the surface of the body and therefore – possibly – the reading of the dosemeter, will increase with increased size of the individual, owing to increased backscatter, whereas the equivalent dose to organs is expected to decrease owing to greater attenuation of the radiation within the body. Furthermore, E includes in its formulation the term $0.05\ H_T$ for the female breast, which can neither be reflected in $H_p(10)$ for the male nor in the reading of a dosemeter (assuming that the latter is not different for female and male workers). Consequently, the answer to the question: "Should a personal dosemeter be sensitive to backscatter? " is: No. This is not meant to imply that personal dosemeters should *not at all* be sensitive to backscatter, which would be difficult to realize in practice. It just indicates that there is no point in expending a great deal of effort to design personal dosemeters capable of responding to or measuring radiation backscattered from the wearers body.

It would, in fact, seem more straight forward to design dosemeters to assess $H_p(10)$ in the ISO water filled slab phantom, irrespective whether they will or will not be responding to backscatter. It can be assumed that such dosemeters, when worn at an appropriate position on a person, would measure $H_p(10)$ with sufficient accuracy to provide an estimate of E as good as $H_p(10)$ does (or better). If they were also performance tested on this type of phantom, difficulties in interpreting the results would also disappear. Moreover, when justified by the magnitude of the exposure and provided information on the energy and angular distribution of the radiation concerned is available, corrections can be made to the reading of the dosemeter to improve the assessment of $H_p(10)$. Further corrections, based on the relationship between $H_p(10)$ and E for the actual radiation condition, could then be applied to obtain a better assessment of E. Final effort could then still, in principle, be made to correct the assessed value of detriment knowing details of the individual exposed.

It has been suggested (7) that a more direct estimate of E from a dosemeter reading should be considered at some future stage. Arguments against this approach, e.g. that this is only valid if the field is uniform, are also applicable to the utility of $H_p(10)$. Where the field is non-uniform. e.g. resulting from the wearing of lead aprons, ICRP states (2) that more extensive measurements may need to be made. Here more than one dosemeter is frequently worn and the estimate is made of E, not of $H_p(10)$ which can have no meaning for a multi-badged person.

Following this suggestion, dosemeters might be designed to have an air kerma response matching that of E, rather than of $H_p(10)$. This means that the relative response of a dosemeter as a function of energy and angle of incidence, $R_{E,\phi}$, should follow as closely as possible the relation

$$R_{E,\phi} = C(E,\phi)\, K_a \tag{10}$$

where

$$C(E,\phi) = E\,(E,\phi)_{Adam(or\ Eva)} / K_a. \tag{11}$$

The fact that many (if not most) TLD based dosemeters, used today, show a severe underresponse relative to $H_p(10)$ at low (photon) energies and therefore compensate for the fact that $H_p(10)$ gives a significant overestimate of E in this energy region, seems to support this idea.
Type testing of dosemeters could be performed on a standard phantom (e.g. a water-filled thin walled PMMA elliptical cylinder may be preferred) the backscatter characteristics of which are adequately similar to the mathematical models (ADAM, EVA.). The field quantity used to determine the response characteristics

would be unchanged, i.e. air kerma for photons. Difficulties arising because of inappropriate wearing positions are no different from those currently for $H_p(10)$.

DOSE RECORD KEEPING

Often the concepts and physical aspects of personal dosimetry gain more attention than the recording, reporting and analysis of the data obtained. It should be borne in mind, however, that proper recording of radiation doses is an equally essential part of the process of individual monitoring and shares in the same objectives.

Specific objectives of dose record keeping are (19):

- to inform the workers and the management on occupationally received doses to, e.g. optimize operations and to demonstrate the effectiveness of ALARA.
- to prevent overexposure of individuals, particularly important for outside workers.
- to provide data for analysis of dose distributions and for evaluation of trends, on the basis of which radiation protection procedures and monitoring programs can be developed and, if necessary, improved.
- to provide data for legal and medical purposes
- to provide data for epidemiological studies.

From the above it will be clear that a dose record keeping system serves a broader goal than just satisfying the local, regional or national legal authorities. It should rather be a Dose Registration and Information System (DRIS) (8,19), to be used as a multi-purpose tool in radiation protection. For the larger Individual Monitoring Services dose record keeping systems are often integrated in an overall automated management system.

It should be emphasized that a DRIS– if properly set up – contains information that can be used as a tool for assessing the performance of a personnel dosimetry service by statistical analysis of measuring results, especially those at low doses (see below).

Within the European Communities, co-operation and exchange of personnel between countries is increasing as a result of an on-going integration of the member states. This will enforce the need for international data communication by means of computer networks. The latter is even explicitly mentioned in the CEC Directive 90/641, which deals with the "operational protection of outside workers exposed to the risk of ionizing radiation during their activities in controlled areas" (20). These developments emphasize the necessity for international harmonization of dose record keeping systems and categorization of the data they contain. Such harmonization is of vital importance to solve the problems related to significant differences in the way international bodies – CEC, UNSCEAR, NEA, WHO – approach statistical analyses of occupational exposures.

Because of the availability of relative user friendly data base management systems, setting up a dose record keeping system may seem relatively easy. It should, however, be emphasized that numerous difficulties can be encountered in both programming and in developing adequate procedures. Special attention should be given to size, structure, accessibility, dissemination of information, organization and quality assurance procedures. This is especially important if a DRIS covers a wide range of customers (e.g. hospitals, nuclear power plants, military installations etc.) and even more so if the system operates as a National Dose Registration and Information System (NDRIS). For the latter it is crucial to keep the dose information up-to-date which, however, may be difficult if workers move from one employer to another or if they switch from one monitoring service to another.

Because it is of paramount importance that the effectiveness of the system, the quality of the recorded data and the confidentiality are guaranteed, the persons responsible for the system need to be well trained and competent.

STATISTICAL ANALYSIS OF ROUTINE MONITORING DATA

As stated above, statistical analysis of the dose data stored in a DRIS is a useful tool for quality control, especially for the performance at low dose levels. Regular analysis of the dose distributions can show the stability of both the dosemeters and the measuring equipment (21). Depending on the population monitored, often the majority of the workers will not receive any occupational dose at all. This means that the frequency distribution of the occupational dose (i.e. the measured dose minus the contribution due to natural background) will show its maximum at 0.00 mSv, i.e. the modal dose is 0.00 mSv. Due to variations in the natural background from place to place and due to intrinsic variations in the dosimetry system, the dose distribution will have a gauss like shape, which will be slightly skewed to a somewhat higher level, due to real occupational doses. An example is given in Figure 2, in which data taken from the TNO individual monitoring service are plotted. The width of the dose distribution should be in agreement with independently obtained information on variations in the natural background and noise of the dosimetry system. Consequently variations in the position of the modal dose or in the width of the dose distribution are indicators for possible

problems with the dosimetry systems at very low dose levels. Using more advanced techniques the various contributions to the width of the distribution can be traced, giving an indication where to look for the source of problems, which allows for fine tuning of the system.

QUALITY ASSESSMENT IN INDIVIDUAL MONITORING: THE ULTIMATE PROOF

Quality Assurance (QA) and Quality Control (QC) are more and more becoming integral parts of our societies. Originally QA and QC mainly applied to the manufacturing of industrial products, to-day also public services are required to provide high quality products for a reasonable price. This can be guaranteed only by developing and implementing a QA/QC program that is tailor made and touches the entire organizational and technical structure of the service in question. Some of the basic elements of such a program, applied to Individual Monitoring Services (IMS), have been published (8). These should be considered complementary to more general requirements as published by ISO (22).

A QA/QC program involves every single step in the process of providing dosemeters to the customer, reading and evaluating the dosemeters returned and reporting the results. It is, however, very useful to in addition test the overall performance (dosimetric, organizational, administrative and financial) of the IMS as well as the postal service. This is done at TNO since 1987, by creating a "QA-subscription" for three "dummy" customers to whom dosemeters are assigned: 10 on a bi-weekly, 6 on a four-weekly and 6 on a quarterly basis respectively (21, 23). These dosemeters are randomly chosen, indistinguishable from those for the regular customers, and mailed to the private address of a member of the staff. Subsequently all dosemeters are taken back to the laboratory. Of each set 2 dosemeters are stored in a lead pig, 2 are placed in the IMS processing area and 2 are irradiated to 2.00 mSv ^{60}Co gamma radiation. The 4 remaining dosemeters from the bi-weekly set are, in duplicate, irradiated to 0.20 and 12.00 mSv respectively. At the end of each issuing period the related dosemeters are taken back home and returned to the laboratory by regular mail. Evaluation of the dosemeters and reporting of the results follow the standard (highly automated) procedures. Copies of the reports are sent to the responsible staff members.

Statistical analysis of the results of the QA-subscriptions gives both the accuracy and the precision of the dosimetry system under routine conditions. Figure 3 shows, as an example, the results of the dosemeters of the biweekly QA-subscription which were irradiated to 2.00 mSv. In the figure the statistical parameters for each year are given. Here avg denotes the average, std the standard deviation in the individual values, Hm/Ht the quotient of the measured dose and the conventional true dose and std/Ht the relative standard deviation in the measured values. The annual average of Hm/Ht ranges from 0.99 to 1.03. The relative standard deviation in the individual dose assessments ranges from 7% in early years to 4% in the more recent years.

Applying regression analysis on the standard deviation for all five dose levels used, results in a value for the relative standard deviation over a broad dose range. In 1994 this relative standard deviation was 4.1% (correlation coefficient 0.999) (23).

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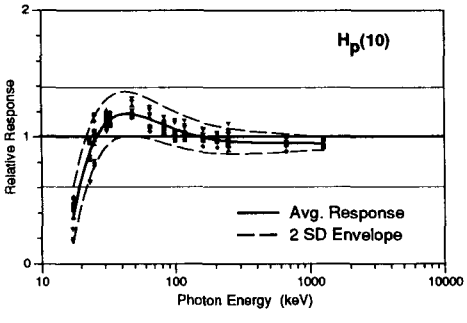

Figure 1. Combined photon energy and angular response data for $H_p(10)$ of a LiF based personal dosemeter.

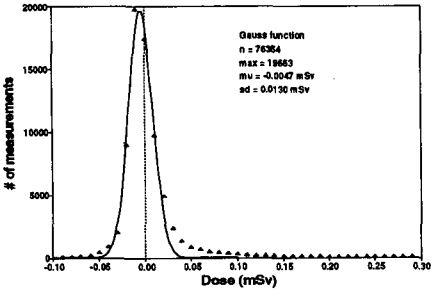

Figure 2. Distribution of net occupational doses, taken from the TNO IMS

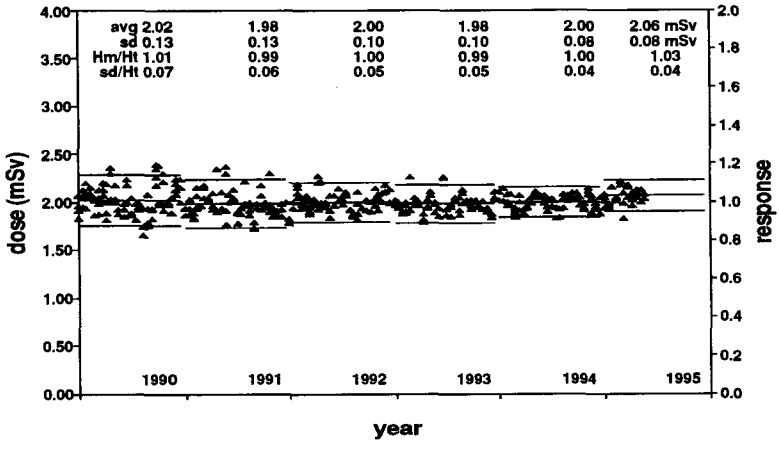

Figure 3. Results of the TNO IMS QA subscription dosemeters, irradiated to 2.00 mSv. The solid lines represent the average and the confidence limits.