PERSONNEL DOSIMETER ANGULAR RESPONSE PROPERTIES AND THE ADOPTION OF ICRU REPORT 39 QUANTITIES

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***Abstract*—A new set of quantities for applied health physics has been proposed by the International Commission on Radiation Units and Measurements with the recommendation that they be based on the ICRU sphere phantom model. The quantities proposed for individual monitoring, which incorporate specific nonisotropic angular response properties, are designed to provide an estimate of an individual's H_E and are the individual dose equivalent, both superficial [effective dose equivalent, $H_s(d)$)] and penetrating [penetrating effective dose equivalent, $H_p(d)$]. Our study of typical dosimeter wearing practices indicated that there were no consistent locations on or angular orientations of dosimeters to the wearer's body. This demonstrated a difficulty in the practical implementation of personnel dosimeters having an angular response approximating $H_p(d)$ for a specifically selected point on a body, rather than the traditionally assumed design goal of dosimeters using an isotropic response. It also indicated that it is important for dosimeters using a $H_p(d)$ response to have an adequate means of mounting the dosimeter to assure the required dosimeter orientation to the body under a wide range of conditions of application. Questions remain as to how the specified ICRU sphere reference phantom (or an approximation thereof) can be used as a practical testing laboratory phantom.**
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INTRODUCTION

THE HUMAN body does not uniformly respond to radiation incident to it at varied angles of exposure as documented in the International Commission on Radiation Units and Measurements Report 25 (ICRU 1976). Many designs of humanoid phantoms were developed to study dose distributions in various organs from external and internal sources of radiation. A number of these are mentioned in the International Commission on Radiological Protection (ICRP) Publication No. 51 (ICRP 1987).

Popular models for estimating the effective dose equivalent (H_E) are the Medical Internal Radiation Dose Committee (MIRD) V phantom (Jones et al. 1973) and the ADAM and EVA phantoms (Kramer and Drexler 1982).

In ICRU Report 19 (1971a), a 30-cm diameter tissue-equivalent sphere (denoted the ICRU sphere) was proposed as a model of the human body for personnel dosimetry purposes. The definition of the dose equivalent quantity did not specifically incorporate angular response factors, and angular response issues were substantially ignored. The ICRU incorporated the concept of Dose Equivalent Index using the ICRU sphere (ICRU 1971b) to help quantify variations in angular response, but it had limited practical use because of several flaws, including nonadditivity.

Personnel dosimeter response studies did not address the issue (NSF 1966; Unruh 1967; ANSI 1972). The dosimetry performance testing standard, ANSI N13.11 (1983), mentioned the need for measuring angular response characteristics; however, this was not implemented as part of the National Voluntary Laboratory Accreditation Program for personnel dosimetry (Gladhill 1986).

While more recent publications on personnel dosimeter response have presented angular response data (Vohra 1982), other publications, particularly those dealing with beta dosimeters, have not (Worley 1982; Sherbini 1985).

A new set of quantities for applied health physics was proposed in ICRU Report 39 (1985) with the recommendation that they be based on the ICRU spherical phantom model. The quantities proposed for individual monitoring, designed to provide an estimate of an individual's H_E, were the individual dose equivalent—both superficial [$H_S(d)$] and penetrating [$H_p(d)$]. These are defined as the dose equivalent in soft tissue below a specified point on the body at a specified depth d.

No specification is given for the angle where radiation is incident on the body or its relationship to an appropriate "specified point" on a body. Additional comments in ICRU Report 39 imply that it should

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apply to a wide range of angles of exposure to the body. It also states that $H_p(10)$-responding dosimeters mounted on the anterior portion of the trunk can be related to H_E for radiations incident anteriorly to laterally (0°–90° relative to normal incidence).

It has been proposed that the ICRU Report 39 quantity for environmental monitoring, the directional dose equivalent [$H'(d)$], is an appropriate quantity for individual monitoring (Grosswendt 1985; Portal 1988). According to ICRU Report 39 definitions, $H'(d)$ can be equal to $H_p(d)$ only under special circumstances: (1) when the values for d are equal; (2) when the specified radial direction for $H'(d)$ intersects the point on the body specified for $H_p(d)$; (3) when the ICRU sphere is specified as the "body" for $H_p(d)$; and (4) when the ICRU sphere is located in an expanded radiation field. Debate continues over the validity of the ICRU Report 39 quantities for applied health physics (Dennis 1988; Dietze 1989).

The validity of the choice of the ICRU sphere as a reference phantom is discussed in ICRU Report 43 (1988) which states ". . . it is evident that the individual's body should be used for the definition of the dose equivalent quantity." The same document recommends a measurement system based on an ICRU sphere phantom and states that the choice of either an anthropomorphic or ICRU sphere phantom is adequate for personnel protection purposes.

ICRU Report 43 shows that $H'(10)$ in the ICRU sphere and $H_p(10)$ in an anthropomorphic phantom, with specified locations symmetrically centered on the abdomen and thorax, give nearly the same response (±15%) for anterior-posterior (AP) and posterior-anterior (PA) parallel beam exposures. The report concludes that a further substitution of $H'(10)$ for $H_p(10)$ is acceptable and that comparisons of the adequacy of $H_p(10)$ as an estimate of H_E can be made by using comparisons of $H'(10)$ to H_E (ICRU 1988).

Recent comparisons of the results of computations based on the MIRD V anthropomorphic and the ICRU sphere phantoms indicated much similarity in responses using the ICRU sphere for $H'(10)$ and the MIRD V anthropomorphic phantom as the "body" for calculating an H_E response. However, there are some substantial differences between these models at lower photon energies and for PA radiation incidence (Grosswendt 1985) with an anteriorly mounted dosimeter, where $H'(10)$ could greatly underestimate H_E.

Studies of male and female anthropomorphic phantom irradiations have shown that >80 keV, $H_p(10)$ (with the dosimeter positioned centrally on the front of the body) agrees well with H_E. However, it is pointed out by Williams that "such conclusions make sense when the dosimeter is pointing towards the source or is rotated with the body in a directional field. If there is a multidirectional field (e.g., isotropic), the value of $H_p(10)$ over- or underestimates the organ dose equivalent by a large amount depending on organ and energy . . . H_E is underestimated by $H_p(10)$ even at high energies when the dosimeter is positioned opposite to the photon entrance surface. All intermediate conditions are also imaginable (Williams et al. 1985)."

DISCUSSION

Dosimetry quantities and phantom types

Due to a lack of data regarding the anthropomorphic phantom response at angles between 0°–90° and 90°–180° relative to normal incidence, it is not known how $H_p(10)$ on the MIRD V phantom, and $H'(10)$ (using an ICRU sphere type of phantom) would compare for other angles of exposure, as well as other specified points for dosimeter location. The uncertainties in the response calculations are not well-defined, and the consequences of substantial changes in the phantom size, shape, or working position are not available.

Exposure conditions having unaligned fields and partial irradiations of the body further complicate these comparisons. Consequently, a comparison of H_E based on the MIRD V phantom to the ICRU sphere-based $H'(d)$ may not be meaningful using presently available data; thus, the ICRU Report 43 substitution of $H'(10)$ for $H_p(10)$ is not adequately supported.

Whether either phantom is superior for representing realistic worker exposure conditions and dosimeter use, remains a question. It seems that neither phantom can be considered the "superior" one for all exposure conditions, and a decision as to which is best could depend on particular conditions (Burlin 1985). Other phantoms widely used for dosimetry testing, such as the ANSI N13.11 polymethylmethacrylate slab phantom (ANSI 1983), may be equally valid.

Influences on dosimeter designs

The main objectives of a radiation protection program are to keep radiation doses received as low as reasonably achievable (ALARA) for the cumulative person-dose equivalent, and below regulatory limits for individuals. Personnel-monitoring programs are used to help guide the ALARA program, to document regulatory compliance, and to help document accidental exposures.

While attempting to support such objectives, the designs of personnel dosimeters are influenced by the desire to achieve many goals simultaneously. Bohm and Ambrosi (1985) identified the following seven objectives for personnel dosimeters: (1) providing information for estimating worker exposure for regulatory compliance; (2) having a very wide dynamic range covering both minimal and life-threatening dose ranges in units relevant for postaccident medical care; (3) indicating the types and energies of the radiations; (4) providing workplace environmental information; (5) providing data for ALARA program coordinators; (6) providing data on the adequacy of workplace designs, work procedures, and personnel training; and (7) providing data for future epidemiological studies, risk and benefit analysis, and medical and legal purposes.

In addition, the design may be influenced by other goals, such as: (1) ruggedness (providing accurate data under extreme environmental conditions); (2) wearability and light weight; (3) incorporating nondosimetry functions, such as a security credential; (4) providing rapid information retrieval with reusable dosimetric elements; (5) providing a permanent record of the dose in the dosimeter while allowing multiple readouts of the dosimeter; and (6) low cost.

Many of these design goals are mutually conflicting. Attempts to satisfy several of these usually involves compromises in the performance of the dosimeter system under various exposure conditions. Thus, when choices are made as to the relative importance of various design goals, poor performance in some of the lower priority goals normally results. Overly broad applications of the device (i.e., serving as a γ, β, n, and criticality dosimeter; as a security badge; and a low cost) can lead to severe compromises. In many cases the use of more than one type of dosimeter, each optimized to serve its special function, is a better choice.

Another significant influence has come from the standards used to test dosimeters. The choice of radiation types, energies, mixtures, exposure conditions, and pass/fail criteria can both directly, and by implication, form a set of dosimeter design priorities for dosimetry services wishing to perform well in such tests. This has been evident in ANSI N13.11 (1983) where considerable emphasis was placed on photon energy response with minor attention paid to angular and beta energy responses. To the technically uninformed, or when expedient, the passing of the standard, alone, was the criteria used to judge the dosimetry system's adequacy for a wide range of applications.

Establishing a suitable personnel dosimeter angular response

Defining what the desired whole-body angular response function to an external radiation field is, will determine what the optimum dosimeter response function should be. Options for the optimum whole-body angular response are: (1) an isotropic angular response function over a given angle of incidence matched to its intended use; (2) an angular response function to match a reference phantom model (i.e., ICRU sphere, MIRD V anthropomorphic phantom) and dosimetric quantities assumed to be appropriate for all personnel being monitored; and (3) for multiple dosimeter use, a response function that overlaps with the response of adjacent dosimeters such that, with proper data manipulation, the angular response factors for a particular phantom model can lead to a satisfactory estimate of H_E.

Design option (1) has the advantage of requiring little concern for the dosimeter's orientation to the body and less sensitivity with respect to its location on the torso. Due to the potential conflicts between the design goals, such a dosimeter may be difficult to design if many ancillary functions (e.g., display of security credential) are desired. In the past, many designers of personnel dosimeters assumed that an isotropic angular response was desirable and lived with the shortcoming of a possible overresponse (Piltingsrud 1971; ANSI 1983; Portal 1988; Bohm and Grosswendt 1989).

Design option (2) has the advantage of resulting in a direct-response correlation with H_E for the designed solid angle of acceptance. Most systems presently in wide-scale use are not of this type. For the successful use of this type of dosimeter, there must be a very specific fixed geometric relationship between the dosimeter and the body. Considering the large varieties of body contours that are encountered and the rapid change the response must have with angle of exposure (for ICRU sphere, see Grosswendt et al. 1988, Table 6), the task of designing a dosimeter as well as its practical application is difficult.

Design option (3) uses multiple dosimeters to achieve angular response goals. Previous approaches to the use of multiple dosimeters on an individual have been vague regarding desirable angular response properties and use of results for a conservative estimate of H_E. Conventional wisdom has been to use the highest reading of an array of whole-body dosimeters, calibrated to measure the ambient dose equivalent $H^*(10)$ (for definition see ICRU 1985), as the estimate of H_E (Hudson 1984; Reece et al. 1985). When interpreting the results of multiple dosimeters, health physicists are confronted with the issue of determining a value of H_E that may have resulted from multiple exposures at several angles of incidence. Each exposure may produce a maximum response (uncorrected for phantom angular response) in a different dosimeter. Yet, each exposure may produce some response in all dosimeters. Applying a phantom angular response correction factor to the individual dosimeter responses is not feasible. Taking the highest dosimeter reading based on a $H^*(10)$ response would generally not underestimate H_E except under certain conditions, such as collimated photon beams with energies >2 MeV, where buildup effects are significant.

Dosimeter placement

Dosimeter placement requirements are influenced by the angular response properties of the dosimeter. The goal of placement should be to avoid an underestimation of H_E without a substantial overestimation, while minimizing the number of dosimeters required on an individual. The ideal placement requires several issues to be addressed: (1) Will the individual be in a fixed geometric relationship to the radiation source, or over what angle to the dosimeter will the source position vary? (2) Will multiple dosimeters be required, considering the total acceptance solid angle of the dosimeter and the required acceptance solid angle of the application? (3) How will the dosimeter response be used to interpret H_E for the individual? (4) Does the dosimeter design and attachment method assure that it will always be in a defined geometric relationship relative to the individual's body? (5) Is a separate dosimeter required to measure dose to an extremity?

Use of multiple dosimeters

To help evaluate the application of multiple dosimeters using $H^*(10)$ responses, possible errors were examined in the estimation of H_E using $H^*(10)$-responding dosimeters at various points on the body, and with various angle of exposure to the body.

Three exposure conditions were examined that used 100-keV photons with a MIRD anthropomorphic phantom, using $H'(10)/H^*(10)$ and $H_E/H'(10)$ values from Grosswendt (1985) and 20-cm transmission factors (representing transmission through the thorax of the phantom) from NBS Handbook No. 138 (NBS 1981).

Using data from Grosswendt (1985), values for $H_E/H^*(10)$ were calculated to be 0.86, 0.41, and 0.67 for incident angles of 0°, 90°, and 180°, respectively. For the sum of unit exposures in the AP and PA directions, H_E = 1.5, and the highest dosimeter indication [$H^*(10)$] was 1.2 (see "A" in Fig. 1).

For left lateral (LLAT) plus right lateral (RLAT) unit exposures, the sum of the two H_E values = 0.82, where the highest dosimeter indication [$H^*(10)$] was 1.2 (see "B" in Fig. 1). For an anteriorly placed dosimeter responding as $H'(10)$, readings may underestimate H_E for equal AP and PA exposures (see "C" in Fig. 1). The total H_E = 1.2 but the total $H'(10)$ = 1.06.

Dosimeters not having an accurate response to radiation incident on their surfaces facing the phantom may reduce or increase the difference between H_E and the highest-indicating dosimeter due to an over- or under-response to backscattered radiation or radiation transmitted through the phantom. Some question remains as to whether it is preferable for a dosimeter to respond to radiation incident on its back (body facing) surface.

Since there does not appear to be a direct correlation to changes of the fraction of backscattered radiation to H_E for body sizes and shapes different from the phantoms used for calibration, a lack of sensitivity to backscattered radiation may have merit in some situations. However, when only one dosimeter is used to estimate H_E, a resulting insensitivity to radiations transmitted through the body may not be desirable, particularly for higher photon energies.

Designing a dosimeter for multiple dosimeter applications

A dosimeter could be specifically designed for multidosimeter applications using a response with a prescribed forward-looking acceptance angle α (Fig. 2) (insensitive to backscattered radiation or radiation transmitted through the body) for all types and energies of radiations to be monitored. It should have sufficient angular response overlap with the adjacent dosimeters

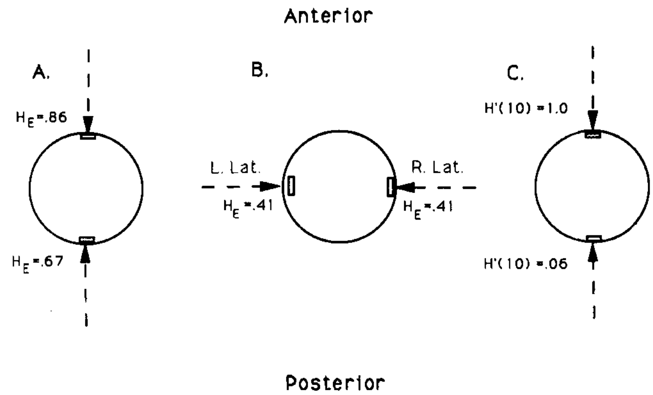

Fig. 1. Multiple exposures to multiple dosimeters. (Phantom attenuation = 20 cm of water. Exposures are unit value.)

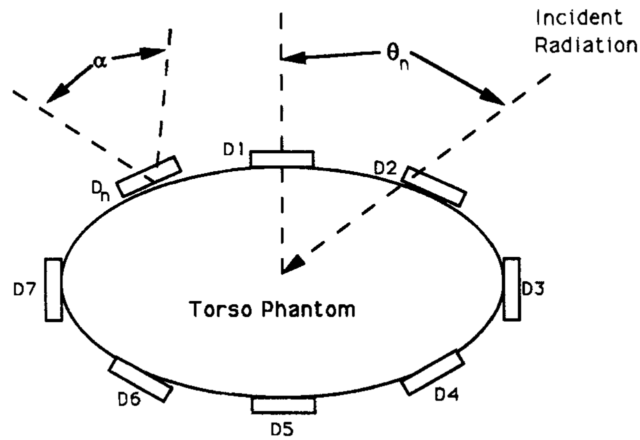

Fig. 2. Use of multiple dosimeters. (α = acceptance angle of dosimeter; θ_n = angle from anterior normal, to torso, to dosimeter.)

such that a relatively smooth indication of H_E is accomplished.

The dosimeters could be calibrated to indicate $H^*(10)$ within their field of view, and angular response correction factors $C_\theta = H_{E,\theta}/H^*(10)$ could be applied for the angles of irradiation of the body as detected by the respective dosimeters placed around the body.

The results of all the corrected dosimeter responses would be summed as:

$$H_E = D_1\ C_{\theta 1} + D_2\ C_{\theta 2} + \cdots + D_n\ C_{\theta n}, \qquad (1)$$

where $D_1 \ldots D_n$ are the responses of the H*(10)-responding dosimeters. It should be noted that as the number of dosimeters increases, the acceptance angle decreases. Also, smaller acceptance angles increase the necessity for well-controlled angular orientations and locations of the dosimeters on the individual. Dosimeter mounting could be a significant factor in creating a practical limit to the number of dosimeters used.

Dosimeter limitations and errors

The design and placement of personnel dosimeters may also be determined by limiting conditions on the total acceptable error in the overall dosimetry process. The limitations associated with the designed performance and placement of the dosimeter, when combined with other sources of error in the dosimeter (i.e., energy response for given radiation types, dose response linearity, and reproducibility; environmental effects such as temperature, humidity, shock, vibration, time between issuance and readout, and reader error) should not exceed the recommendation for an overall measurement uncertainty of 30% for dose equivalent near maximum permissible levels, and up to 300% under 1/10 the maximum permissible levels (ICRU 1971b).

ICRP Publication No. 35 (1985) recommends a limit of 50% error when errors caused by unknown irradiation geometries or ambient conditions are taken into account.

Examples of existing personnel dosimeter designs

The incorporation of several functions into a personnel dosimeter design often complicates the issue of angular response performance. This was seen by examining some dosimeters, most of which were in large-scale use in the past.

Photographic film dosimeter. The first example (Fig. 3) (Scott 1969) is a photographic film dosimeter incorporating many filters and shields to aid in its conversion of film densitometric information to personnel-dose equivalent information. The dosimeter also includes other sensor elements such as neutron activation materials and a LiF thermoluminescent dosimeter (TLD). The data indicating angular response as a function of photon energy shown in Scott (1969) demonstrates that the dosimeter's response is very energy- and angle-dependent. This is related to the very energy-dependent response of the photographic film sensing element and the attempt to correct this by placing one or more filters between the radiation source and the film, each attenuating the incident radiation.

The attenuation coefficients for the filters vary as a function of energy. The resulting ratios of the densitometric information under each filter and an open window are correlated to an incident radiation effective energy, and the response of the dosimeter is then corrected using calibration data.

Fig. 4 shows that the filter elements increase in effective thickness following $1/\cos\theta$. In addition, shadowing by adjacent filters may occur at large angles of incidence. At angles approaching 90°, the dosimeter shows a peaked response as incident radiation is projected under the filters, directly to the film (similar filter arrangements have been used with TLDs with similar effects).

The dosimeter design results in a very uneven angular response with little response at angles greater than ± 30° for photon energies <200 keV. Its angular response appears to decline much more rapidly than that of $H'(10)$. It appears that due to its rear absorbers and poor angular response, this dosimeter would be likely to simulate an $H'(10)$ or an isotropic response only over a very restricted angle of incidence, and would require a very specific angular orientation to the body.

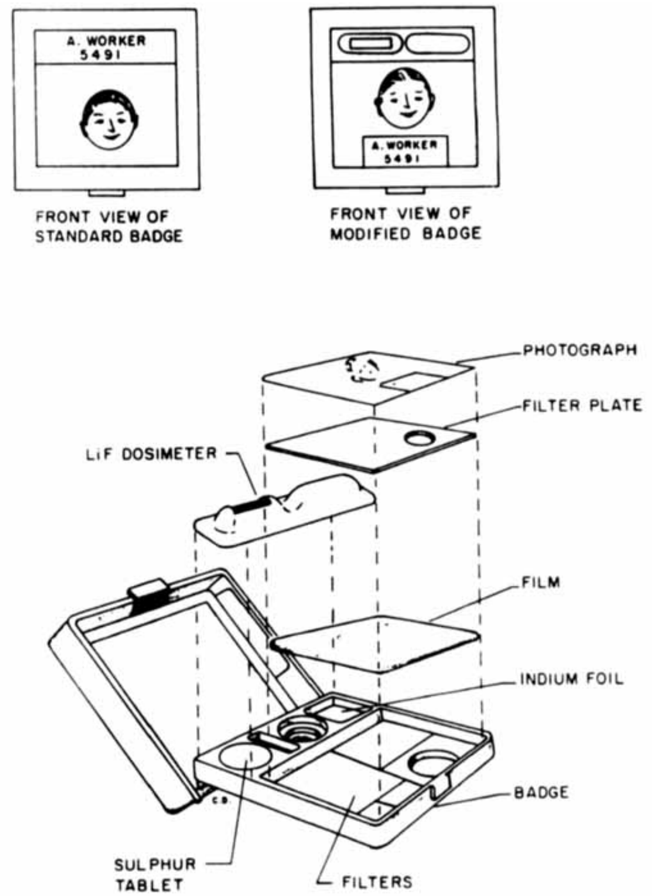

Fig. 3. Exploded view of typical film badge.

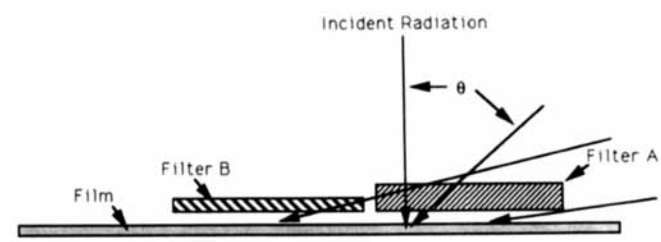

Fig. 4. Geometric effect of filters.

Photosensitive glass dosimeter. The second example (Fig. 5) is a photosensitive glass dosimeter designed for general-purpose applications in a large nuclear facility (Piesch 1968). The phosphate glass sensor element does not have a tissue-equivalent energy response. A spherical tin shell with penetrating holes

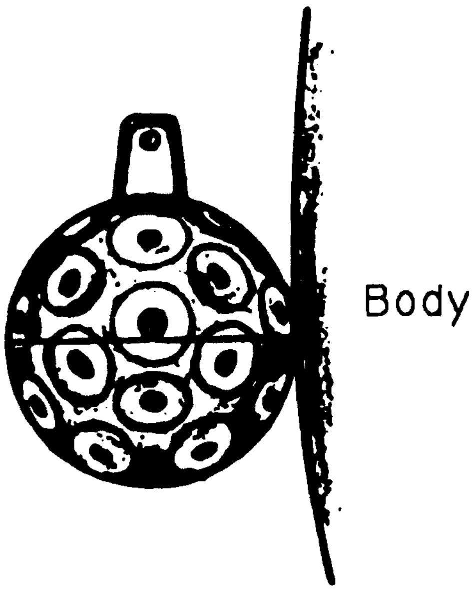

Fig. 5. Isotropic photosensitive glass dosimeter.

distributed equally over its surface is used as an energy correcting filter. The dosimeter response data show a nearly isotropic response for the dosimeter at photon energies >40 keV, in free air. This probably results from the nearly spherical symmetry of the dosimeter's design.

Spherical TLD. The third example is an experimental dosimeter having a LiF TLD 100 sensor in the center of a 1-cm radius polyethylene sphere (Piltingsrud et al. 1971). Its angular response is nearly isotropic for photon radiations >25 keV.

This dosimeter tends to overrespond relative to $H'(10)$ at angles greater than $\pm$ 60° but would require no specific angular orientation to its wearer and would be less sensitive to its location on the anterior torso than a $H'(10)$-responding dosimeter.

Neutron TLD dosimeter. Example four (Fig. 6) is a dosimeter designed for neutron dosimetry using TLD sensors (Hoy 1972). Due to its sensitivity to albedo neutrons and its arrangement of filters, it was designed to be worn on a specific position and with a specific angular orientation to the body. This was accomplished by requiring it to be strapped to the wearer in a specific manner. This specialized attachment method was successful but, along with its large size and weight, resulted in a mixed acceptance by workers.

Analysis of dosimeter designs

The previous examples help illustrate the interaction between angular response, energy response, and mounting position of the dosimeter. Dosimeters requiring detailed filtration measurements to determine the energy response will usually have a poor angular response, partly because the angle of incidence will also change the energy determination. Likewise, a dosimeter designed for a specific nonisotropic angular response will not perform well unless rigidly fixed in place on the body.

The energy vs. angular response can be somewhat decoupled by using a nearly energy-independent dosimeter element. The location and angular orientation vs. angular response may be partially decoupled by using an isotropically responding dosimeter or by properly fixing the position on and orientation of the dosimeter to the body.

These options are difficult to evaluate and their implementation may require compromises in other dosimeter performance characteristics. The angular response properties of personnel dosimeters in use today vary considerably and do not appear to be directly related to dosimeter sensor types. Instead, they appear to be a result of the combination of sensor element responses, interpretation algorithms, and sensor element holder designs. Some of the latest designs incorporating thin sensor elements for improving energy responses to photon and beta particles may display less ideal angular response properties than older, simpler designs (Hofert and Darrigues 1985; Jones et al. 1988).

Effects of dosimeter angular misalignment

The effect of dosimeter angular misalignment to the body may be estimated using Table 6 in Grosswendt et al. (1988) where the ICRU sphere is assumed to be the reference phantom. Assuming a variable misalignment angle α (see Fig. 7) and varied angles of radiation incidence (θ) with an aligned field, the response of a $H'(10)$-responding dosimeter varies widely (Table 1) for 48-keV photons. It is assumed that the dosimeter is not affected by phantom backscatter, nor are shadowing effects of body contours addressed.

Also presented in Table 1 is an anticipated response for a dosimeter having an isotropic response over an angular interval corresponding to the assumed incidence angles, and with no sensitivity to backscatter. The over-response is greater, but there is no under-response. While body motion of an individual may tend to reduce the effects of both α and θ, this would probably not be significant in fixed exposure geometry conditions such as glovebox workers, or situations where short exposure times to high-exposure rate sources occur. It is unlikely that body motion could be relied on as a part of a dosimeters method of use.

Body contour effects

Natural body contours can affect the response of a personnel dosimeter due to both scatter conditions and shielding. For a dosimeter responding as $H_p(d)$ for a standard phantom, the effects of body contours would contribute to the uncertainty of its estimate of H_E due to its use on a variety of body shapes.

The effects of body contours may be minimized by the choice of dosimeter placement and proper use of multiple dosimeters. When using a single dosimeter and when exposure conditions are not fixed, the uncertainty in H_E assignment increases significantly due to

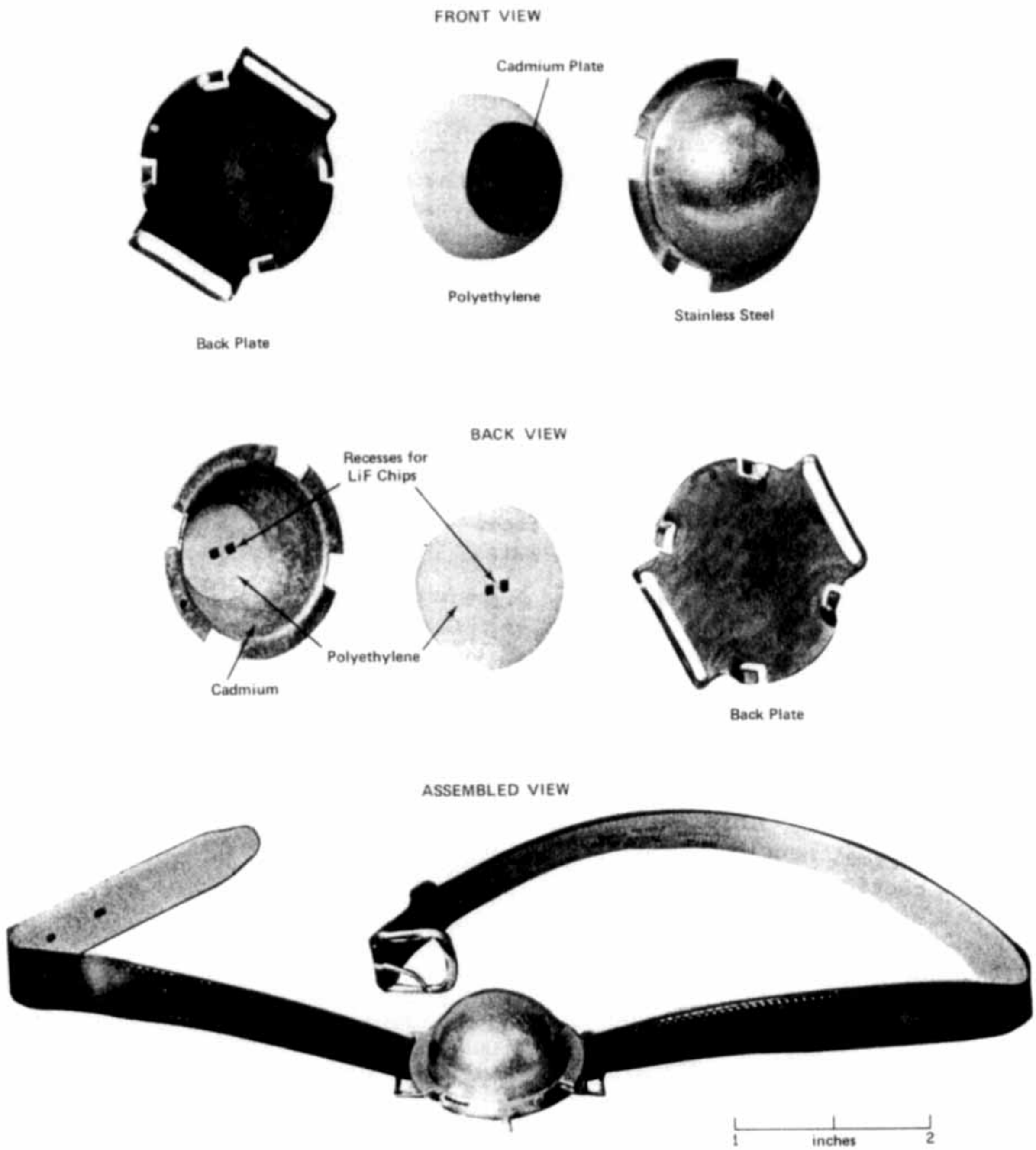

Fig. 6. Thermoluminescent neutron dosimeter badge.

typically poor angular response of dosimeters at larger angles, and to body shielding. This uncertainty can be minimized by using multiple dosimeters and by using a dosimeter displaying an adequate angular response, especially when radiation sources are located below or above the level of the dosimeter.

A study of typical dosimeter placement

To better understand typical dosimeter positioning on users of personnel dosimeters, the authors conducted a brief examination of typical dosimeter locations and angular orientations on personnel in three large institutions, each with professional radiation protection officers overseeing their radiation dosimetry programs. The visits to the facilities were unannounced; thus, they tended to indicate routine wearing of the dosimeters.

During a walk-through of the facilities, all employees encountered who were wearing personnel dosimeters had their dosimeter locations photographed. The photographs showed the wide range of possible loca-

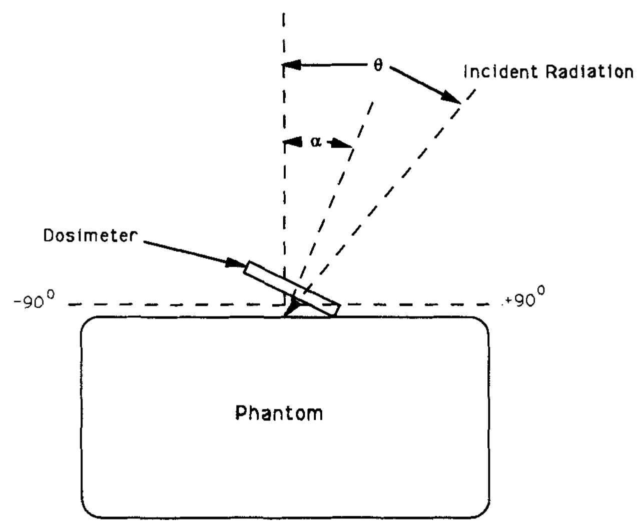

Fig. 7. Dosimeter misalignment to phantom. (α = misalignment angle. θ = angle of incident radiation.)

Table 1. Effects of dosimeter angular misalignment relative to body surface (48-keV photons).

Misalignment angle α (degrees)	Incident radiation angle θ (degrees)	Percent of desired response[a]	
		$H'(10)$ responding dosimeter	Limited isotropic dosimeter
0	+80	100	188
	+60	100	126
	0	100	100
	−30	100	103
	−60	100	125
20	+80	150	188
	+60	117	126
	0	98	100
	−30	91	103
	−60	67	125
40	+80	175	188
	+60	123	126
	0	93	100
	−30	72	103
	−50	44	114
60	+80	185	188
	+60	126	126
	0	79	100
	−30	40	103

[a] $\text{Response} = \dfrac{H(10,\theta - \alpha)/H(10,0°)}{H(10,\theta)/H(10,0°)} \times 100.$

tions and angles of orientation to the body. No dosimeters were worn centered on and plano-parallel to the anterior of the torso. Most of those observed were at extreme positions and angular orientations from plano-parallel to and centered on the anterior of the torso.

The problem of maintaining a fixed relationship of the dosimeter to the body is increased when they are attached to loose-fitting clothing (and to some extent even on tight-fitting clothing) due to initial positioning, body contours, flexing of the means of attachment, and shifting of the clothing on the individual. While this limited study cannot represent the use of all personnel dosimeters, its results are probably typical of personnel dosimetry in medical institutions.

Tests for dosimeter angular response

As part of its certification for use, a personnel dosimeter system is normally tested to evaluate selected performance parameters. The optimum method of testing for angular response properties is not known. Since an accepted testing model will necessarily influence future dosimeter designs, the approach taken can be important.

Many existing dosimetry systems have 10-mm depth angular response properties that are closer to $H'(10)$ than to an isotropic response when the dosimeters are rigidly fixed in a specific orientation to a phantom surface. This is especially true for acceptance angles less than ± 60° from the normal (Hofert and Darrigues 1985). This could make the implementation of an $H'(10)$ response function by a testing program attractive. However, the implementation of a requirement for a fixed position and angular orientation of the dosimeter to the individual may pose substantial problems.

Responsibility for dosimeter positioning

One approach is to adopt $H'(d)$ response criteria and leave problems of dosimeter mounting to the users, assuming that all dosimeters are rigidly fixed to the body. The vendor could be required to state the orientation or range of acceptable orientations to a body required for the device to perform as specified. The user organization would be required to provide a reproducible attachment of the dosimeter to the individual in a specific location. However, this could require a special enforcement effort by the user organization to assure compliance. This is likely to be practical only in organizations where dosimeters are worn only under specific use circumstances with the dosimeter orientation remaining fixed relative to the individual, and where close visual observation of workers is routine.

A second approach is for the testing criteria to allow more than one method, to be applied according to the design and use methods of a particular dosimeter. For dosimeters that are designed to have an angular response simulating $H'(d)$ and having means of attaching the dosimeter securely to a wearer such that it can only be worn in a specified location with a fixed angular orientation to the body, the test could be designed to compare the dosimeter's angular response to that of $H_p(d)$ for a specified point on a specified phantom, or $H'(d)$ for an ICRU sphere phantom.

Such dosimeters could be tested with a fixed orientation to the phantom. Dosimeters not meeting such criteria would be assumed to meet an isotropic response criteria. They could be tested with a variable (random) mounting angle relative to the phantom, thus better simulating its performance under field conditions.

For many dosimeter systems, the relationship between radiation energy determinations and the dosimeter's angular response may result in an incorrect energy determination at nonperpendicular angles of incidence. To adequately account for such properties during testing, the test could include blind variations of both energy and angle of test exposures.

Phantom selection

It is also necessary to choose a practical phantom for use by a testing laboratory. While documents such as ICRU Report 39 have stated that the ICRU sphere is a suitable phantom for calibration of dosimeters measuring $H_p(d)$, much comment has been made concerning the availability of a multielement tissue-equivalent sphere meeting the ICRU criteria, and the practicality of using an ICRU sphere for dosimeter testing (ANSI 1983).

It would be advantageous for the reference phantom used in defining $H_p(d)$ to be a practical one for use in a testing laboratory. Accurate phantom-to-phantom correction factors for the effects of the phantom on the dosimeter's response are difficult to develop and introduce an additional uncertainty into the calibration procedure (ANSI 1983).

Difficulties in the construction and application of an ICRU sphere phantom indicates merit in establishing a working definition of $H_p(d)$ based on a specific point on a specified practical phantom, such as those stated in ANSI N13.11 (ANSI 1983) (a 30 × 30 × 15-cm or 40 × 40 × 15-cm polymethylmethacrylate slab phantom). $H_p(d)$ could be defined as the dose equivalent at a specific depth in the phantom and >10 cm from the edges of the phantom exposure face (to avoid edge effects).

CONCLUSIONS

The angular response of personnel dosimeters is an important characteristic that has not been given adequate attention. The many demands on dosimeter design have made optimal response characteristics more difficult to achieve. Some simpler dosimeter designs conform better to the desired angular response characteristics than more complex designs incorporating elaborate filtration systems, many influenced by the overemphasis on energy response and dosimeter packaging.

The current recommendations of the ICRU leave many questions concerning the adequacy of the new personnel dosimetric quantity $H_p(d)$ for the specification of angular response characteristics. Since it is defined for a specified point on an individual body, a specifically measurable quantity does not exist. Its linkage to $H'(d)$ is weak; it only exists when the $H_p(d)$ body is defined as the ICRU sphere in an expanded radiation field.

If the reference phantom for calibration purposes is specified as the ICRU sphere, there are practical limitations in its construction and its use as a testing laboratory phantom. The means of selecting the measurement point in the body is uncertain, as comparisons of $H'(10)$ to H_E defined using the MIRD V phantom show substantial underestimates of H_E by $H'(10)$ at angles of incidence >90° from an AP exposure. Establishing a working definition of $H_p(d)$ based on a specific point in a specified practical phantom, such as those stated in ANSI N13.11 (ANSI 1983), could help resolve these difficulties.

Typical uses of personnel dosimeters dictate locations on and angular orientations to the body that are not compatible with use criteria for dosimeters having an angular response approximating $H_p(d)$ for a specifically selected point. Difficulties in the practical implementation of personnel dosimeters having an $H_p(d)$ related angular response support the traditionally assumed goal of dosimeters having an isotropic response.

In establishing performance tests, provisions could be made for separate tests for dosimeters having an isotropic response and dosimeters having $H_p(d)$ angular response characteristics, allowing the use of either dosimeter type under appropriate circumstances. Dosimeters tested for a $H_p(d)$ response should demonstrate an adequate means of attaching the dosimeter to the body, assuring the required dosimeter orientation to the body under a wide range of conditions of application.

Disclaimer—Mention of company names or products in the preceding paper does not constitute endorsement by the National Institute for Occupational Safety and Health. The opinions and discussions presented in this article are those of the authors and do not necessarily represent the official position of their employers.

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