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TRAINING COURSE ON DOSIMETRY AND DOSE REDUCTION TECHNIQUES IN DIAGNOSTIC RADIOLOGY

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"DOSE QUANTITIES FOR PROTECTION AGAINST EXTERNAL RADIATIONS"

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Dose Quantities for Protection Against External Radiations

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ABSTRACT

In 1991 the International Commission on Radiological Protection published recommendations (ICRP Publication 60) which contain definitions of some new basic quantities, equivalent dose and effective dose. These definitions are reviewed here along with the operational dose equivalent quantities defined by the International Commission on Radiation Units and Measurement (ICRU) for practical measurements of dose from external radiation in the workplace. The relationships between the limit quantities used for radiological protection and operational quantities are discussed in detail for photons, neutrons and electrons. For photon radiations, the implications of the new ICRP quantities, equivalent dose, H_T, and effective dose, E, are small. The differences between effective dose, E, and the quantity recommended previously in 1977 in ICRP Publication 26 (effective dose equivalent, H_E) for uniform irradiation of the body are less than 10% for most monoenergetic photon energies and irradiation geometries. The operational quantities, defined by ICRU for area and personal monitoring in the workplace, will provide reasonable estimates of E for photon radiations, without underestimation or excessive overestimation. In contrast, for neutron radiations there are more significant implications, because calculations show that E can be between two and four times larger than H_E as defined in ICRP Publication 26 for monoenergetic neutrons up to 2 MeV in various irradiation geometries (although in 1985 ICRP did propose an increase in the value of the quality factor for neutrons, but this recommendation was not adopted in the UK or in other EC countries). In practice, operational quantities will still provide an overestimate of E for most neutron energies and irradiation geometries, and for observed neutron spectra in the workplace. The overestimate is less significant for E than it was for H_E as defined in ICRP Publication 26 for most neutron energies, because the operational quantities have not increased proportionately as a result of the new ICRP recommendations.

The Board recommends that the dose quantities, equivalent dose, H_T, and effective dose, E, defined by ICRP in Publication 60 be adopted as the primary limit quantities in radiological protection. As it is not possible to measure these quantities directly, operational dose equivalent quantities, first defined by ICRU in 1985, should be used for the practical measurement of external radiations in the workplace. Instruments and personal dosemeters should be designed to measure the operational dose equivalent quantities and appropriate type test and calibration procedures should be adopted. Measurements of operational dose equivalent quantities will normally provide an overestimate of primary limit quantities and, in some situations, the overestimate may be excessive. If, as a result, assessed doses are close to limits, measurements of energy spectra and irradiation geometry can be used to obtain a more accurate measure of the limit quantity, effective dose. For measurements of external radiation in the environment from natural or artificial sources, operational dose equivalent quantities will overestimate effective doses to a significant extent, mainly because of the irradiation geometry. In these circumstances measurements of a primary field quantity (eg air kerma or absorbed dose to air) should be carried out and conversion coefficients applied to obtain effective doses.

to be made. However, if a calculation of risk is required in specific circumstances then it would be valid to perform an alternative calculation along the lines suggested in paragraph 32 of ICRP Publication 60, using absorbed dose and RBE values for neutron radiations. These problems have received some considerable attention in dosimetry, and calculations have been performed to estimate the impact of using w_R values recommended by ICRP. At particular neutron energies the effect can appear quite significant, with the numerical value of effective dose being three or four times higher than the numerical value of effective dose equivalent with the quality factor given in ICRP Publication 26. In general, the apparent conceptual problems with the definition of w_R do not have a major impact on area or personal monitoring of ionising radiation, but there are implications for those required to calculate neutron doses. The practical implications of the new ICRP recommendations on dose quantities will be considered in detail later (see paragraphs 38–44).

Effective dose

11 The incidence of stochastic health effects of radiation has been shown to depend on the organ or tissue irradiated. Some organs are more susceptible to radiation damage than others, and have a greater risk of producing cancer or other deleterious effects. ICRP has therefore developed another quantity to reflect the differing risks, which is derived from equivalent dose. Each organ or tissue is weighted according to its observed susceptibility to stochastic health effects* using a tissue weighting factor, w_T. This factor represents the relative contribution of the organ or tissue to the total detriment from stochastic effects, compared to that from uniform irradiation of the whole body. The weighted equivalent dose is called the effective dose, E, and has the units joules per kilogram, with the special name sievert (Sv). It is given by the expression

$$E = \sum_T w_T H_T$$

where H_T is the equivalent dose in tissue or organ T and w_T is the appropriate weighting factor for tissue T. Given the definition of equivalent dose (paragraph 4),

$$E = \sum_T w_T \sum_R w_R D_{T,R}$$

It is assumed by ICRP that w_T values are independent of radiation type and w_R values are independent of tissue, therefore

$$E = \sum_R w_R \sum_T w_T D_{T,R}$$

where $D_{T,R}$ is the mean absorbed dose in tissue or an organ T delivered by radiation R. In both expressions, the radiation R is that incident on the body or emitted by a source within the body.

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*The stochastic effects considered by ICRP include fatal cancers, non-fatal cancers and hereditary effects in all generations. Some of these effects are weighted for their severity and all are weighted according to years of life lost.

12 The tissue weighting factors recommended by ICRP in Publication 60[1] are given in Table 3.

The new quantities, equivalent dose and effective dose, given in ICRP Publication 60 are recommended for use as primary limit quantities in radiological protection against external radiations and for the assessment of risks of radiation exposure. However, much current legislation on radiological protection in the UK refers to limit quantities defined in ICRP Publication 26. Until new regulations are made incorporating the new quantities, it will be necessary to retain the use of the current quantities for many practices.

There are some objections to the use of the new ICRP quantities for calculating doses from neutron radiations, because of apparent dosimetric anomalies. These are not serious enough to warrant special methods for calculating doses from neutron radiations, considering the overall uncertainties in assessing the risks from radiation exposure.

TABLE 3 *ICRP tissue weighting factors*

Tissue or organ	Tissue weighting factor[a], w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05[b,c]

Notes

(a) The values 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.

(b) 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 value or in this additional list constituting the remainder. The latter may also include other tissues or organs selectively irradiated.

(c) 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.

Calculation of effective dose

13 The number of organs and tissues included in the definition of effective dose, E, with a specific weighting factor is twelve, compared to the six organs included in the definition of the previous quantity, effective dose equivalent, H_E. Furthermore a list of ten remainder organs has been specified, and these have been given a weighting factor of 0.05. This contrasts with the previous definition of effective dose equivalent where remainder organs played a larger role with a weighting factor of 0.3, divided amongst five unspecified organs receiving the highest doses, which made H_E strictly non-additive. If note (c) to Table 3 is applied to calculations of E, then it also becomes non-additive, even though this is likely to have little practical significance because of the low numerical value of the weighting factor for remainder organs. The application of the method given in note (c) is not likely to be necessary for most broadbeam whole body exposures to external radiation. However, in some cases, for example, partial body exposures to medical X-rays or to radionuclides in the body, special calculations for remainder organs may be necessary.

External exposures

14 Organ doses from external exposures of the body can be calculated using mathematical phantoms and knowledge of the physics of radiation interactions with matter. Such calculations, which often utilise Monte Carlo simulation of transport mechanisms, can be verified to a limited extent by experimental measurements in physical phantoms. For whole body irradiation the calculation procedure is, in principle, straightforward. The radiation transport equations can be calculated in and around an anthropomorphic mathematical phantom and then used to evaluate organ doses, D_T values. These can then be used to calculate E using the appropriate radiation weighting factors given by ICRP. Some preliminary results of such calculations are given below to evaluate the implications of using E and to examine relationships with operational measurement quantities. The organs can be modelled in a mathematical anthropomorphic phantom used to represent biological reality.

Remainder organs

15 The selection of remainder organs is governed by the definition of w_T given by ICRP [see Table 3, notes (b) and (c)]. There is potential for an element of non-additivity here because it is suggested that remainder tissues should be treated differently in certain circumstances. If a single one of the remainder organs or tissues receives an equivalent dose in excess of that in any of the twelve major organs with specified w_T values, a weighting factor of 0.025 should be applied to that organ and a weighting factor of 0.025 should then be applied to the average dose to the rest of the remainder. For whole body exposure this is not a likely occurrence but for some partial body exposures it could occur. The localised exposure of part of the body for medical purposes is a case in point, because the organ receiving the highest equivalent dose may be a remainder organ—for example, the brain in skull X-rays. Here a calculation of effective dose should follow the ICRP recommendations, including the notes to the tissue weighting factors. Note (b) should not be interpreted as though any tissue or organ can be

added to the list if it is deemed likely to receive a high equivalent dose, or is thought to be susceptible to cancer. Instead, the Board recommends the use of w_T values as stipulated in Publication 60, and awaits further recommendations from ICRP on new organ w_T values as new biological evidence is scrutinised. This should retain the essential additivity of effective dose and ensure a consistent approach.

16 In Publication 61[14] ICRP has recommended that doses to tissues and organs from radionuclides in the body should be computed using the following formula for the committed effective dose, $E(t)$:

$$E(t) = \sum_{T=i}^{T=j} w_T H_T(t) + w_{\text{remainder}} \frac{\sum_{T=k}^{T=l} m_T H_T(t)}{\sum_{T=k}^{T=l} m_T}$$

where $H_T(t)$ is the committed equivalent dose to a tissue or organ, t is the integration time in years following intake*, w_T is the specific weighting factors for each tissue and organ specified by ICRP[1], T_i to T_j (twelve in total), m_T is the mass of the remainder tissues T_k to T_l (ten in total), and $w_{\text{remainder}}$ is the weighting factor assigned to remainder organs. Hence, the remainder organ dose is obtained using a mass weighted averaging technique which gives a true average dose to the set of remainder organs, and this method should also be used for calculating doses from external radiations. It should be noted that this method of averaging can give approximately 90% of the weight to muscle, a tissue not known to be radiosensitive. This means that the quantity $E(t)$ is not necessarily conservative but, due to the low overall weight given to remainder organs (5%), the impact on effective dose calculations is small. If a single remainder organ receives a dose higher than that in an organ with a specific weighting factor, then assigning a weighting factor of 0.025 as specified by ICRP is also likely to introduce only small variations.

17 A full description of how the above procedures are used in calculations of committed equivalent organ doses and committed effective doses from intakes of radionuclides is given in NRPB-R245[15].

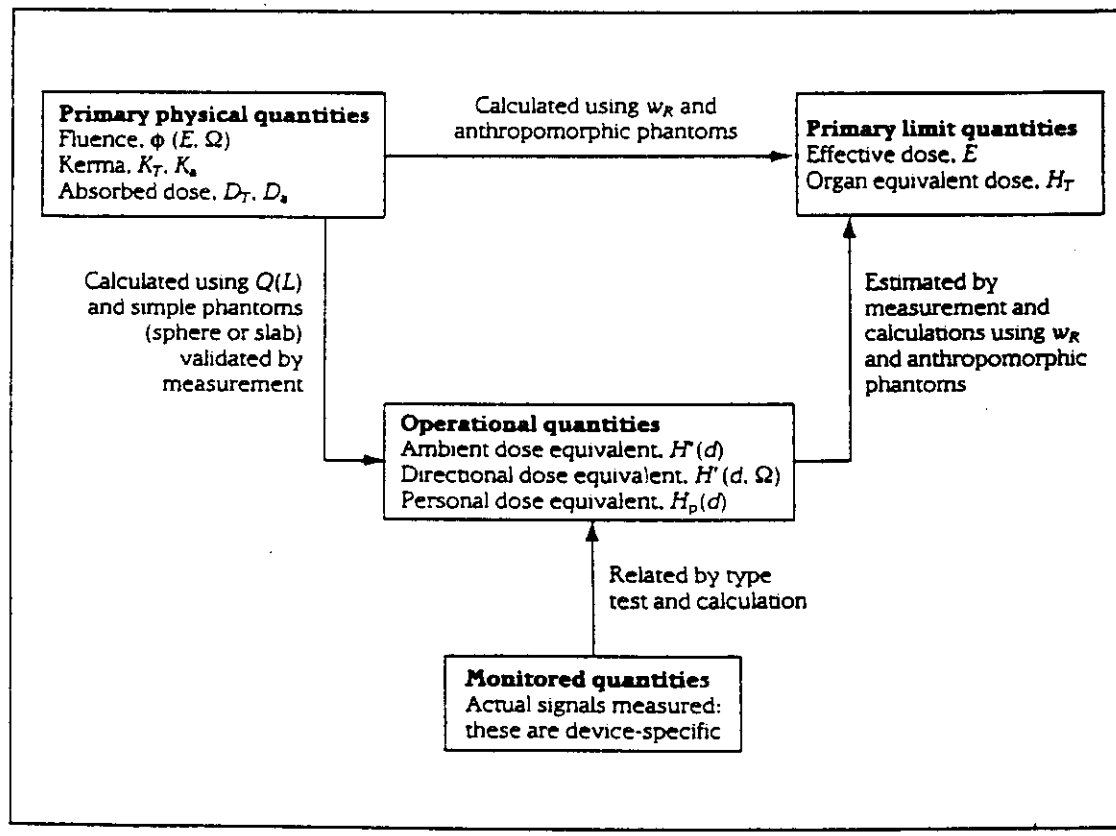
Hierarchy of dosimetric quantities

18 In radiological protection there are a number of dosimetric quantities used for different purposes. The most basic quantities are the physical measurement quantities, such as particle fluence, kerma and absorbed dose. National laboratories keep primary or secondary standards for these quantities and full definitions are given by ICRU in Publication 33[10]. They can be directly related to the risk-based radiological protection quantities defined by ICRP, via calculations in anthropomorphic phantoms using Monte Carlo techniques. Therefore, although the radiological protection limit quantities are not measurable, a measure of

*ICRP recommends t values of 50 years for adults and 70 years for children.

fluence of air kerma in a radiation field can be related to effective dose using calculated conversion coefficients. This was done for the quantities defined in ICRP Publication 26 and results of calculations for the new equivalent and effective dose in ICRP Publication 60 are becoming available. Conversion coefficients for effective dose from air kerma (Sv Gy^{-1}) show significant variations with photon energy in some irradiation geometries. In addition, air kerma can underestimate a radiological protection limit quantity with, for example, conversion coefficients of approximately 1.4 Sv Gy^{-1} in AP (anterior–posterior) irradiation geometries for photon energies below 100 keV. Because of these features in the primary measurement quantities, ICRU has developed operational dose equivalent quantities defined in tissue equivalent phantoms (for area monitoring) and in the body (for personal monitoring). The operational quantities are calculated from the primary field quantities using the Q–L relationships defined by ICRP in tissue equivalent sphere or slab phantoms. Although these quantities are also obtained through calculation they can be verified by measurement, and the quantities measured by monitoring devices can be related to them by type test and calibration data obtained on appropriate phantoms. The operational quantities can then be used to estimate the ICRP equivalent dose and effective dose quantities using the w_R values in an anthropomorphic phantom. This whole process is illustrated in Figure 3 which shows the hierarchy of quantities and the relationships between them, as described above.

FIGURE 3
Relationships between primary limit quantities, physical quantities and operational quantities



RELATIONSHIPS BETWEEN EFFECTIVE DOSE AND EFFECTIVE DOSE EQUIVALENT QUANTITIES

19 The 1990 Recommendations of ICRP contain a change of emphasis in the primary quantity of interest in radiological protection. Equivalent dose is now the absorbed dose averaged over a tissue or organ and weighted for the type of radiation incident on the body, whereas in ICRP Publication 26 the definition of dose equivalent is a point quantity in an organ, obtained by multiplying absorbed dose with a quality factor which depends on the radiation type and energy. This change has implications for dosimetry and is further complicated by the inclusion of more organs in the effective dose quantity defined by ICRP. For penetrating photon radiations the effect of these changes is likely to be small because the weighting factor and the quality factor are numerically the same, and the implications of averaging absorbed dose over an organ, rather than using a point quantity, are insignificant. However, for neutrons there are differences in radiation weighting factors compared with quality factors, and the adoption of an average absorbed dose over an organ, rather than a point quantity, can lead to significant changes, especially as w_R is determined by radiation incident on the body. Equivalent dose is therefore different from dose equivalent, and effective dose is not the same as effective dose equivalent.

20 In 1987 ICRP published[16] the results of a comprehensive evaluation of conversion coefficients for effective dose equivalent from absorbed dose in air. These factors were obtained from extensive Monte Carlo depth dose simulation studies on anthropomorphic phantoms for various orientations of incident radiation fields. These provided a standardised data set for calculating effective dose equivalent and avoided the need for complex phantom modelling. The conversion coefficients were given for photon incident energies ranging from 0.01 to 10 MeV, for neutrons between thermal energies and 20 MeV, and for other external radiations including electrons, protons and muons. With the publication of ICRP Publication 60 and the new quantity effective dose, the data set provided by ICRP Publication 51 is now out of date, and ICRP is undertaking a new review of conversion coefficients in collaboration with ICRU[17]. This is likely to take a few years but, in the meantime, it is possible to review the implications of the new quantities from a selection of published data. For example, Zankl *et al*[18] have published their calculations comparing effective dose and effective dose equivalent for photons and Hollnagel[19] has published results of calculations for neutrons.

Photon radiations

21 Calculations performed by Zankl *et al*[18] use a Monte Carlo code to simulate photon transport in anthropomorphic phantoms 'Adam' and 'Eva'[20] developed from the MIRD phantom, which were the basis of calculations carried out for ICRP Publication 51[16]. These phantoms have organs simulated by simple geometric shapes, such as cylinders, cones or ellipsoids, whose mass and volume agree with data for ICRP reference man[21]. The code follows individual photon histories and uses Oak Ridge cross-sectional data[22] for photoelectric absorption, Compton scattering and pair production. Absorbed doses were calculated by dividing the

total amount of energy deposited in an organ or tissue, by the mass of this organ, assuming that photon energy is deposited at the point of interaction (the kerma approximation). Zankl *et al*[18] present their results as organ and tissue equivalent dose conversion coefficients normalised to air kerma for broad parallel beam irradiations: antero–posterior (AP), postero–anterior (PA), left lateral (Llat), right lateral (Rlat) and full 360° rotation about the phantom axis (Rot). These are then combined with w_T values to give effective dose. The results are reproduced in Table 4 and Figures 4 and 5 present the comparison of effective dose and

TABLE 4 *Conversion coefficients of E (ICRP Publication 60) and H_E (ICRP Publication 26) for photons normalised to air kerma free in air, for parallel whole body irradiations, AP, PA, Llat, Rlat and Rot (360°), taken from Zankl et al*[18]

Photon energy (MeV)	Conversion coefficient (Sv Gy^{-1})									
	AP		PA		Llat		Rlat		Rot	
	E	H_E	E	H_E	E	H_E	E	H_E	E	H_E
0.010	0.0065	0.0071	0.0025	0.0012	0.0017	0.0008	0.0017	0.0008	0.0033	0.0023
0.015	0.040	0.059	0.0058	0.0033	0.0055	0.0077	0.0055	0.0078	0.015	0.021
0.025	0.251	0.336	0.056	0.094	0.043	0.062	0.038	0.059	0.106	0.144
0.035	0.594	0.716	0.237	0.344	0.159	0.199	0.135	0.183	0.299	0.358
0.050	1.111	1.241	0.641	0.801	0.406	0.470	0.344	0.425	0.663	0.722
0.060	1.306	1.430	0.853	1.016	0.532	0.600	0.456	0.544	0.827	0.875
0.070	1.424	1.539	0.981	1.142	0.603	0.669	0.524	0.613	0.938	0.974
0.080	1.433	1.531	1.020	1.162	0.630	0.690	0.551	0.637	0.959	0.988
0.100	1.397	1.467	1.028	1.151	0.643	0.696	0.572	0.649	0.957	0.977
0.150	1.249	1.316	0.966	1.050	0.621	0.664	0.549	0.616	0.891	0.904
0.200	1.172	1.229	0.926	1.003	0.620	0.663	0.552	0.614	0.854	0.862
0.300	1.087	1.136	0.888	0.952	0.614	0.652	0.554	0.616	0.827	0.838
0.500	1.043	1.082	0.880	0.938	0.636	0.668	0.585	0.640	0.810	0.819
1.000	1.005	1.032	0.889	0.933	0.693	0.718	0.652	0.702	0.830	0.831
3.000	0.992	1.015	0.919	0.949	0.802	0.822	0.774	0.812	0.909	0.912
6.000	1.012	1.027	0.932	0.963	0.840	0.863	0.832	0.864	0.932	0.940
10.000	0.978	0.995	0.926	0.957	0.849	0.860	0.848	0.881	0.924	0.928

effective dose equivalent for AP and Rot geometry for the photon energy range from 10 keV to 10 MeV. The table and figures show that conversion coefficients for effective dose are slightly smaller than those for effective dose equivalent, by a few percentage points. The effect is most noticeable at photon energies around 100 keV and less, but there is very little difference at higher energies. For all practical purposes the introduction of effective dose for photon radiations will produce a small change compared to using effective dose equivalent for whole body irradiation, and the numerical differences between the two quantities are due mainly to the changed definition of remainder organs given in ICRP Publication 60.

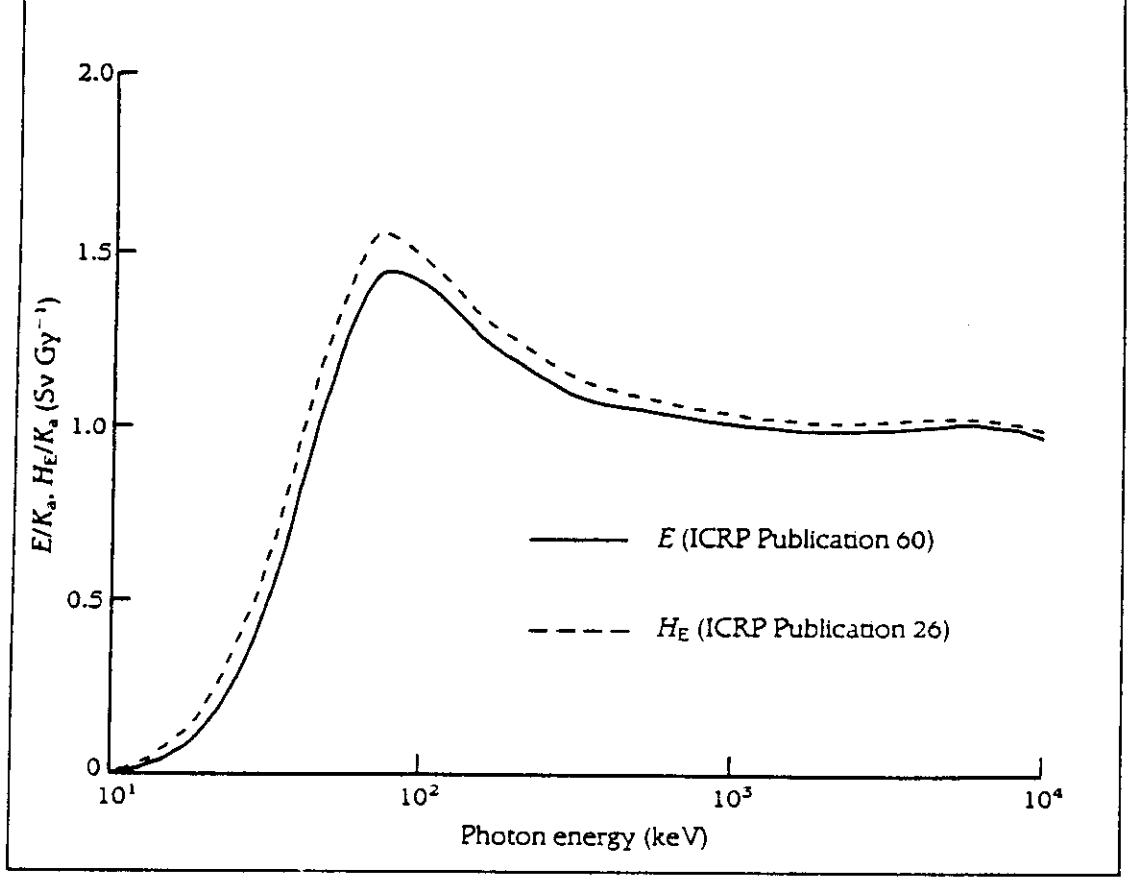


FIGURE 4
Comparison of the quantities H_E (ICRP Publication 26) and E (ICRP Publication 60), normalised to air kerma free in air. Geometry: whole body irradiation, parallel AP

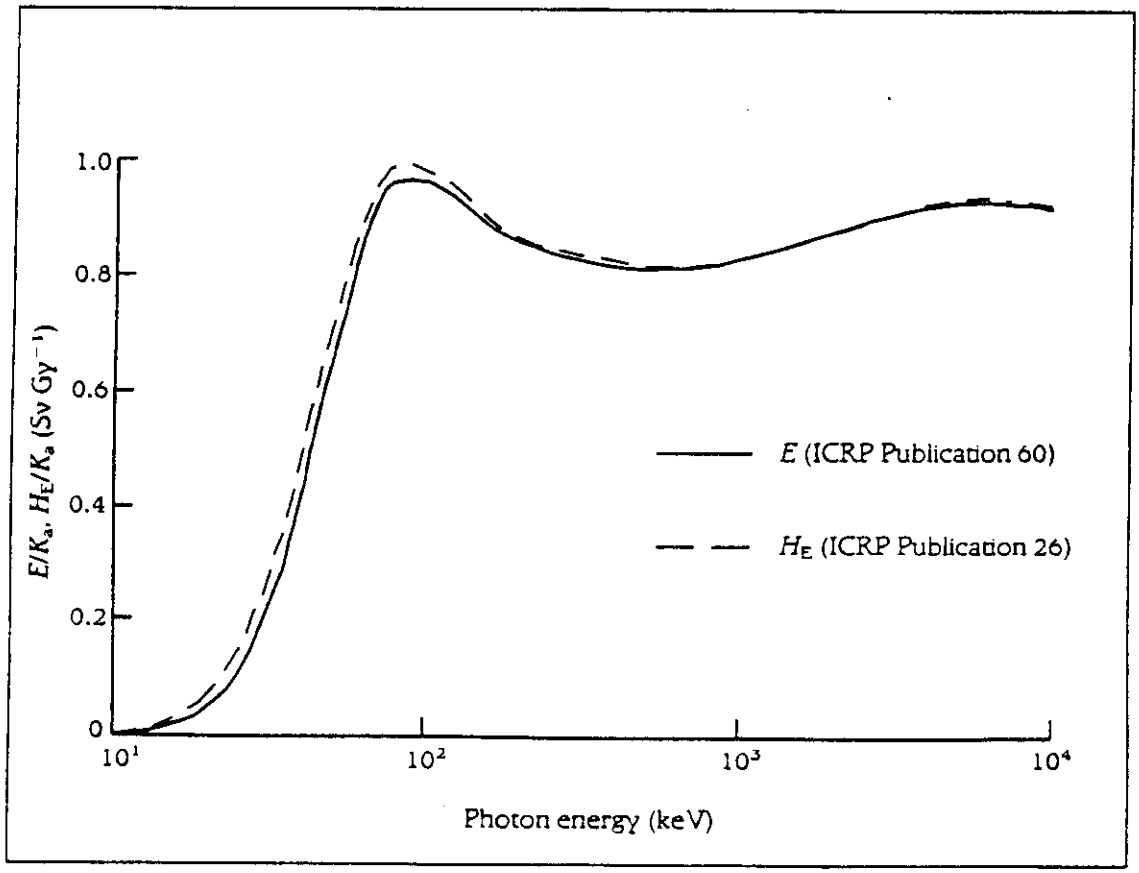


FIGURE 5
Comparison of the quantities H_E (ICRP Publication 26) and E (ICRP Publication 60), normalised to air kerma free in air. Geometry: whole body irradiation, parallel Rot

$H_p(d)$ can be assessed indirectly with a thin, tissue equivalent detector which is worn at the surface of the body and covered with an appropriate thickness of tissue equivalent material. The calibration of the dosemeter is generally performed under simplified conditions on an appropriate phantom.

> The Board recommends that since the quantities equivalent dose and effective dose are, for all practical purposes, impossible to measure, the operational dose equivalent quantities defined by ICRU should be used for monitoring purposes. These quantities will provide a good estimate of the limit quantity effective dose without underestimation or excessive overestimation in most practical circumstances, although there are exceptions.

COMPARISON OF EFFECTIVE DOSE AND OPERATIONAL DOSE EQUIVALENT QUANTITIES

18 The differences between effective dose (ICRP Publication 60)[1] and effective dose equivalent (ICRP Publication 26)[2] for various types of radiation were discussed in paragraphs 19–25. Here the relationship between effective dose and the ICRU operational dose equivalent quantities[5,6] is examined to see whether they provide an adequate measure of effective dose with no underestimation. Recent recommendations from ICRU and ICRP mean that, for photons, there is no change in the sphere quantities, $H^*(10)$, $H'(10, \alpha)$ and $H'(0.07, \alpha)$, and even if a different phantom is used, eg a tissue equivalent slab (30 × 30 × 15 cm), operational quantities will not be very different. For neutron radiations, however, there are some significant differences because of the new Q–L relationship recommended by ICRP in Publication 60.

Photon radiations

Area monitoring quantities

19 The calculations described previously show that the conversion coefficients for effective dose from air kerma are lower than those for effective dose equivalent by a few percentage points. Hence, in broad terms, because the operational dose equivalent quantities were previously overestimating effective dose equivalent[16], the overestimate for the new effective dose will not be very different. This is shown in Figure 7 and Table 6 where conversion coefficients for ambient dose equivalent are compared to those for effective dose in AP, PA and Rot irradiation geometries for photon energies up to 10 MeV. These data have been taken from the conversion coefficients recently calculated by Zankl *et al*[18] for effective dose, which are reproduced in Table 4, and from the conversion coefficients given in Table 10 of ICRP Publication 51[16], for the dose equivalent at a depth in the ICRU sphere. This provides the ratio $E/H^*(10)$ and shows that ambient dose equivalent will give an overestimate of effective dose, even for AP geometry. For photon energies between 60 keV and 10 MeV the mean ratio of $E/H^*(10)$ is 0.85 (range 0.75–0.92) for AP geometry and 0.66 (range 0.48–0.85) for Rot geometry. These values are very close to those obtained for the quantity defined in ICRP Publication

FIGURE 7 *Ratio of effective dose, E, to ambient dose equivalent, H*, for monoenergetic photons up to 10 MeV*

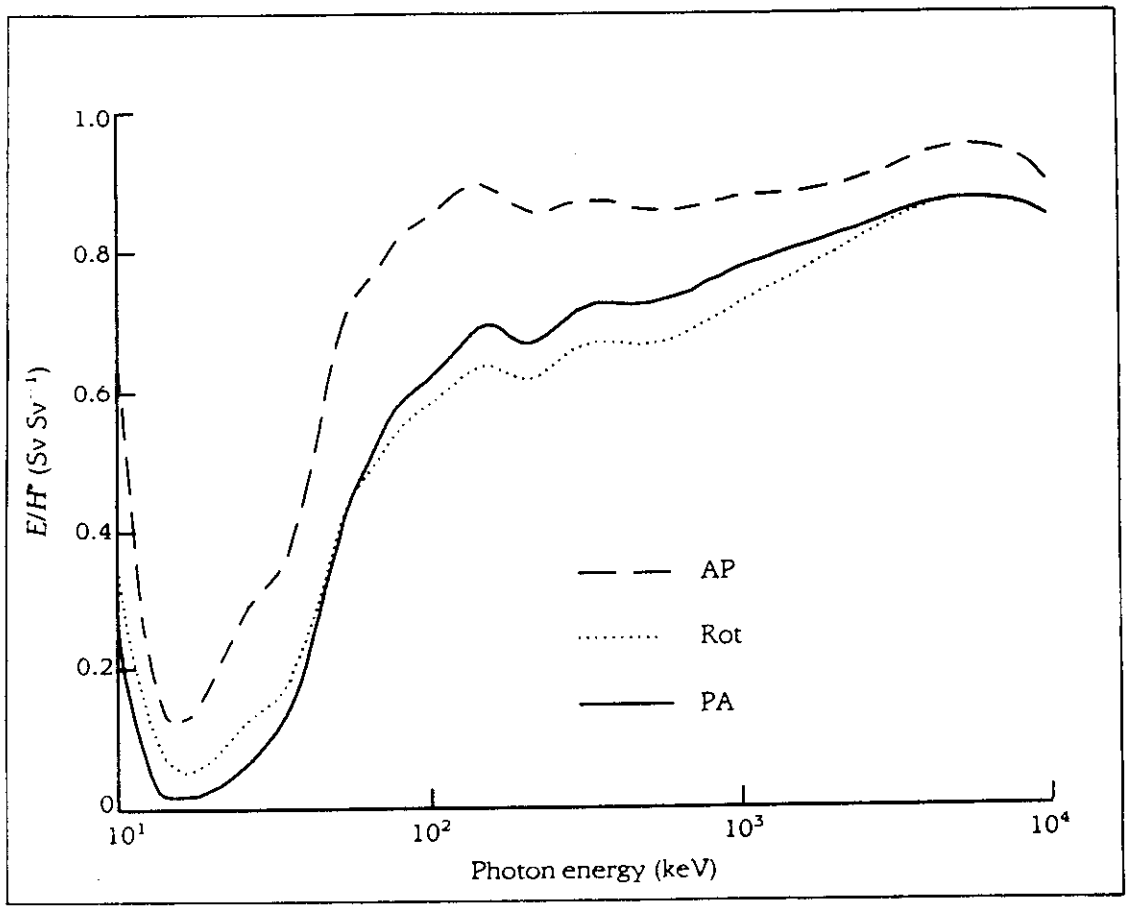


TABLE 6 *Ratio of effective dose to ambient dose equivalent for photon energies up to 10 MeV in irradiation geometries AP, PA and Rot*

Photon energy (MeV)	$E/H^*(10)$ AP	$E/H^*(10)$ PA	$E/H^*(10)$ Rot
$1\ 10^{-2}$	0.65	0.25	0.33
$1.5\ 10^{-2}$	0.15	0.02	0.02
$2.5\ 10^{-2}$	0.30	0.07	0.12
$3.5\ 10^{-2}$	0.47	0.19	0.24
$5\ 10^{-2}$	0.68	0.39	0.41
$6\ 10^{-2}$	0.75	0.49	0.48
$7\ 10^{-2}$	0.82	0.56	0.54
$8\ 10^{-2}$	0.83	0.59	0.55
$1\ 10^{-1}$	0.85	0.62	0.58
$1.5\ 10^{-1}$	0.84	0.70	0.60
$2\ 10^{-1}$	0.85	0.67	0.61
$3\ 10^{-1}$	0.83	0.68	0.63
$5\ 10^{-1}$	0.86	0.73	0.67
1	0.88	0.78	0.72
3	0.89	0.82	0.81
6	0.92	0.85	0.85
10	0.90	0.85	0.85

Note The ratios compiled in this table were calculated from data given by Zankl *et al*[18] and ICRP Publication 51[16].

26. effective dose equivalent. Hence ambient dose equivalent provides an overestimate of effective dose in excess of 15% over a wide range of photon energies and irradiation geometries. For low photon energies (below 60 keV) the overestimate is more significant: at 25 keV, for example, ambient dose equivalent will overestimate effective dose by a factor of three. This has practical implications for monitoring occupational doses in, for example, diagnostic radiology.

40 Conversion coefficients are derived from idealised calculations of dosimetric quantities in anthropomorphic or tissue equivalent phantoms irradiated by monoenergetic radiations, whereas, in reality, workers are exposed to a complex field of radiation energies from different directions. Hence, when conversion coefficients show some apparently undesirable features in relation to limit quantities at particular energies and irradiation geometries, these features may or may not have a practical significance. For photons the influence of practical radiation fields is mostly on the extent of overestimation of limit quantities by operational quantities. If workers are exposed to photons above 60 keV in AP geometry, operational quantities, such as ambient dose equivalent, will give a good estimate of effective dose (within 15%), but when there is a significant low energy photon component, or there is a different radiation field, there can be an overestimate. This overestimate can be between 30% and 50% for typical irradiation geometries above 60 keV but, below this energy, the overestimate can be by factors of two or three or more. An overestimate of a limit quantity is erring on the side of safety and will only be a serious problem when recorded doses approach or exceed dose limits. In these circumstances field measurements, special monitoring programmes and calculations should provide a more accurate assessment of effective dose.

Personal monitoring quantities

41 ICRU has recommended[5] that $H_p(10)$, defined in the body, can be adequately represented by the dose equivalent at 10 mm depth on an appropriate radius in the ICRU tissue equivalent sphere, ie $H'(10)$ the directional dose equivalent. Similarly, $H_p(0.07)$ can be represented by $H'(0.07)$ in the sphere. Some calculations have been carried out on anthropomorphic phantoms to confirm this correspondence between personal and directional dose equivalents and ICRU states that[6], for photons, '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 phantom (the abdomen and thorax) is never greater than 15%'. Recently, for the purpose of calibration and type testing ICRU[8] has included, for practical purposes, $H_p(10)$ in a tissue equivalent 30 × 30 × 15 cm slab, and calculations have been carried out to show the relationship between quantities defined in the body, sphere and slab. These data have been included in some recent technical recommendations from CEC for monitoring individuals[26], and are reproduced in Figure 8 which shows that the quantities have similar values over a wide photon energy range. In practice, this means that $H^*(10)$ can be assumed to be equal to $H'(10, 0)$ and $H_p(10)$ for AP photon irradiation, and hence $E/H_p(10)$ ratios will be very close to the $E/H^*(10)$ ratios shown in Figure 7. At most, the differences in the ratios will be between 5% and 10% [$H_p(10) > H^*(10)$], and this comparison will be considered further in

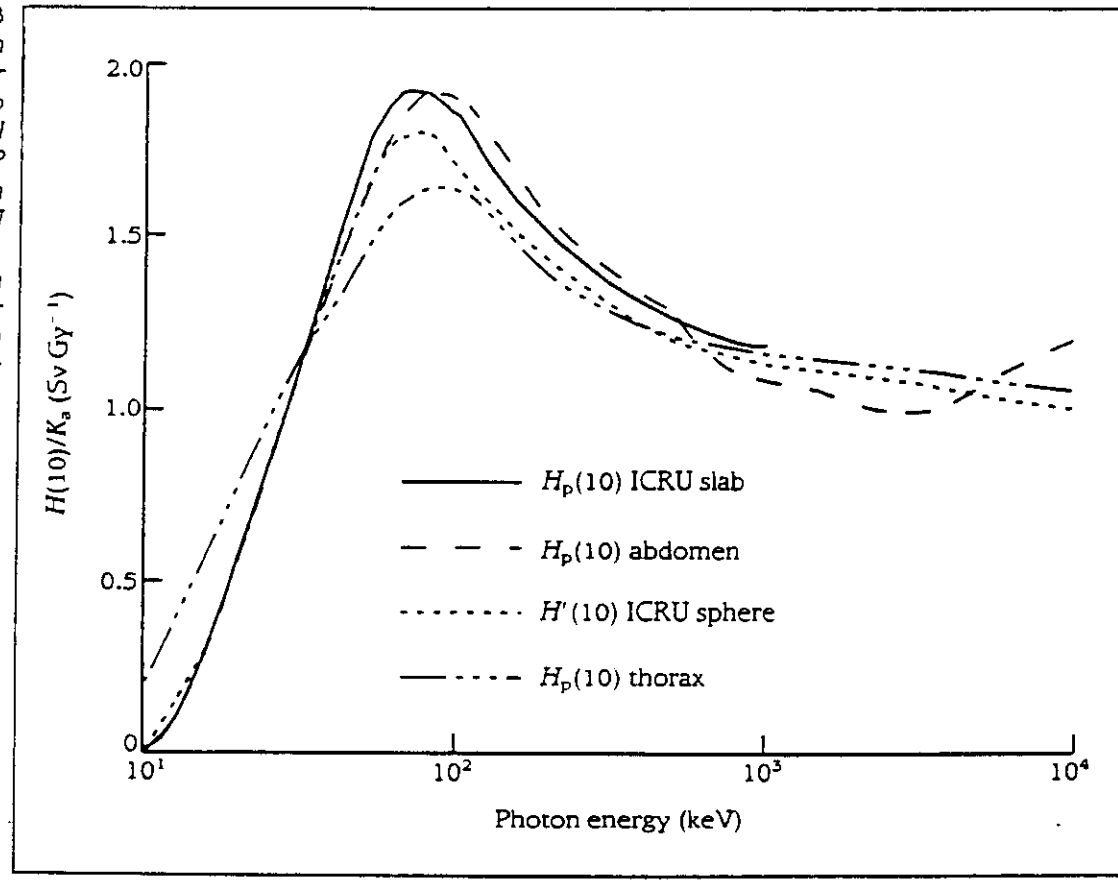


FIGURE 8
Conversion coefficients from air kerma to operational quantities in the AP irradiation geometry. ICRU sphere and slab, compared with coefficients for quantities in an anthropomorphic phantom (Christensen et al[26])

paragraph 53. ICRU[6] has also stated that for photon and neutron radiations, '. . . in almost all situations, the value of $H_p(10)$ is greater than effective dose . . . provided that $H_p(10)$ is measured at an appropriate 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 . . .'. Hence the operational dose equivalent quantities, $H_p(10)$ and $H_p(0.07)$, should provide a good measure of effective dose without any underestimation. Personal dosemeters should therefore be designed to measure the quantities taking account of any requirements of the Health and Safety Executive relating to the approval of dosimetry services in the UK.

Neutron radiations

Area monitoring quantities

42 Previously, ambient dose equivalent, $H^*(10)$, provided a considerable overestimate of effective dose equivalent, H_E, for neutrons[8,16]. In order to verify that operational quantities still provide an overestimate for effective dose, E, data have been compiled from ICRP Publication 51[16], Hollnagel[19], and Schuhmacher and Siebert[27]. Table 7 contains the ratio of conversion coefficients for ambient dose equivalent, $H^*(10)$, and effective dose, E, for AP and Rot irradiation geometries and for neutron energies between thermal and 14 MeV and, for comparison and perspective, the first column shows the ratio $H_E/H^*(10)$ in AP geometry using data from Table D4 of ICRP Publication 51. In Figure 9(a), reproduced from Hollnagel[19], the ratio of effective dose to ambient dose

FIGURE 12
Response of a commonly used Geiger–Müller detector to ambient dose equivalent and air kerma

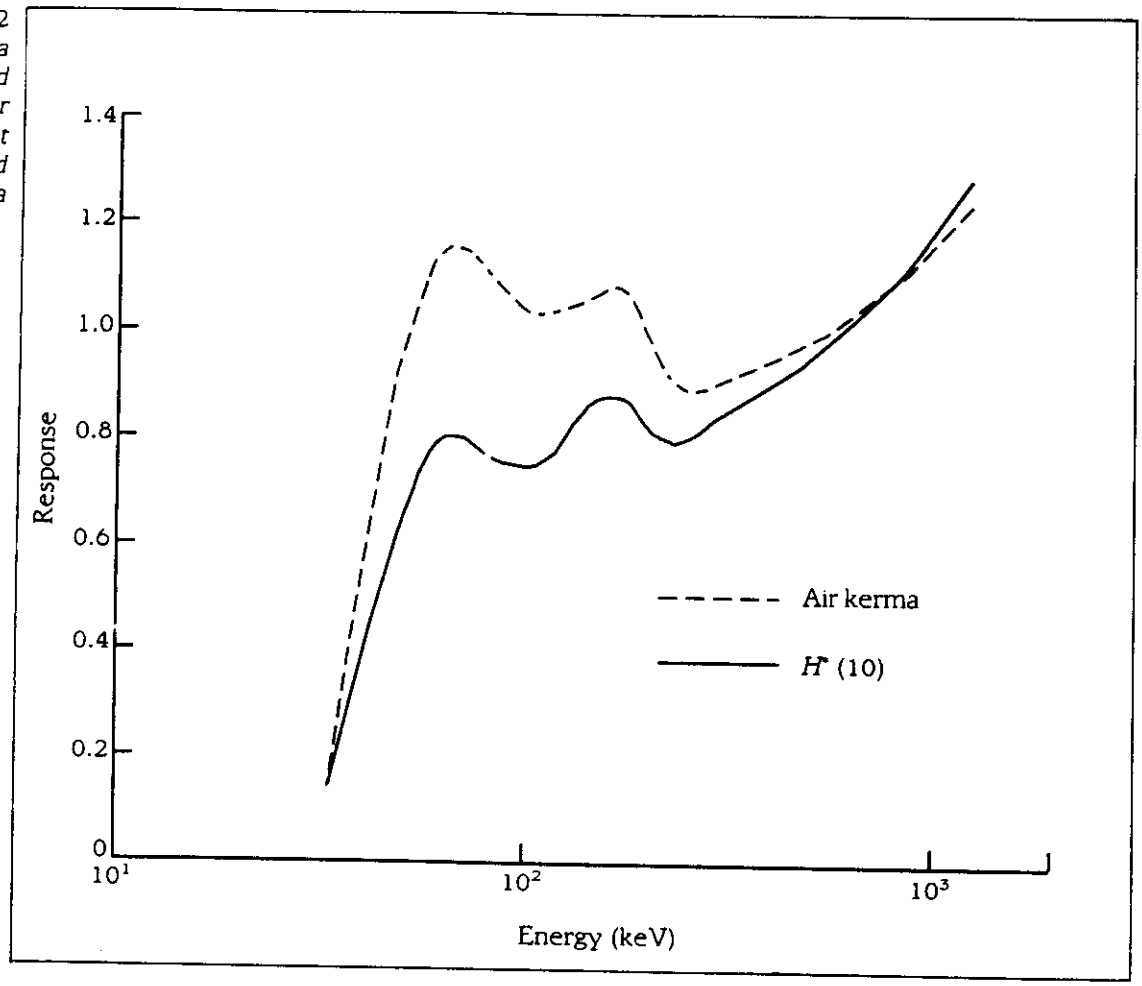
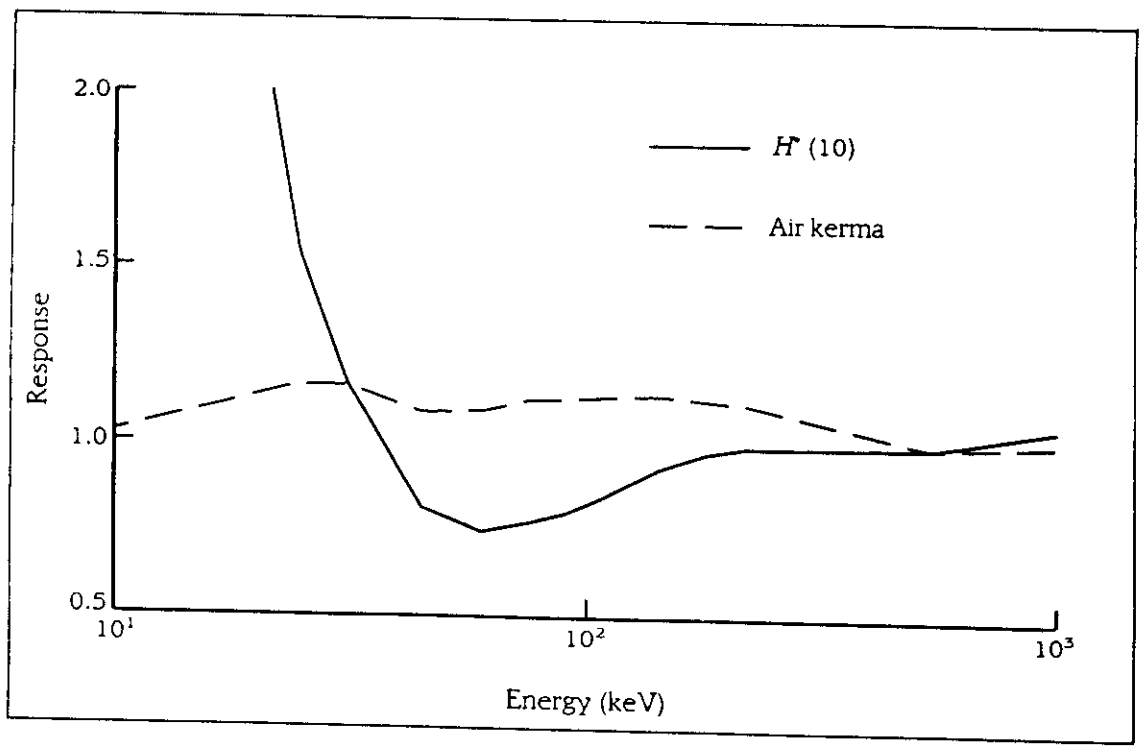


FIGURE 13
Response of a high quality ionisation chamber in terms of air kerma and H (10)*



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