COMPARATIVE STUDY OF RADIATION PROTECTION QUANTITIES FOR NEUTRONS

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INTRODUCTION

Recently, the specified depth dose equivalent H_d has been proposed as the operational dose equivalent quantity for radiation protection measurements for photon, beta and neutron radiation /1/. $H_d(\vartheta)$ can be defined as the dose equivalent at a point at a depth d below the surface of the ICRU spherical phantom. If the point is located on the "reference radius" of the sphere, the angle between the incident monodirectional broad radiation field and the reference radius is termed ϑ.

The aim of this paper is as follows:

a) Partly to present our calculations of H_d as a function of d, ϑ, and the neutron energy E

b) to compare the results with other dose equivalent quantities such as the maximum dose equivalent $\hat{H}$ defined as an energy dependent fluence-to-dose conversion function (FDCF) in ICRU Report 21 /2/, or the effective dose equivalent H_{eff}/3/.

After comparing the energy and directional dependence of H_d and H_{eff} we shall come to the conclusion that H_d is to be questioned as an operational dose equivalent quantity for all exposure situations met with in individual neutron monitoring, since the corresponding ratio of fluence-to-dose conversion factors, $(FDCF)_d/(FDCF)_{eff}$, varies as a function of neutron direction and energy between 3 and 1/336.

c) We therefore propose to extend the concept of H_d by defining an additive dose equivalent quantity

$$H_{sph} = \sum_i g^i H^i \qquad (1)$$

where the upper index i = 1,2,3,.... and where the H^i represent a suitably chosen set of dose equivalent quantities defined within the ICRU sphere. The g^i are suitably chosen constant weighting factors. The ratio of $(FDCF)_{sph}$ to $(FDCF)_{eff}$ varies only between 2 and 1 if the set H comprises five different dose equivalent quantities.

SELECTED RESULTS OF THE H_d CALCULATIONS

The second to fourth columns in the table show $H_d(\vartheta)$ normalized to the fluence of incident neutrons, in units of 10^{-12} Sv cm as a function of neutron energy in eV. A vast body of such data has been computed by means of a recently developed Monte Carlo code and is presented in more detail elsewhere /4/. Here, only the d = 10 mm data are given for ϑ = 0° (frontal or AP incidence), ϑ = 180° (back or PA incidence), and for an isotropic radiation field (ISO).

COMPARISON WITH OTHER DOSE EQUIVALENT QUANTITIES AND DISCUSSION

The remaining columns in the table show $\hat{H}$ as mentioned in Sect. 1 and H_{eff} under the exposure conditions AP (monodirectional broad beam on the front), PA (same on the back), ROT (same with individual continuously rotating about the axis defined by feet and head) and ISO taken from Ref. /5/.

Before comparing and discussing these quantities, calibration procedures for individual dosemeters are briefly recapitulated. The specified-depth dose equivalent H_d is chosen as an example of an operational dose equivalent quantity in the following. The calibration comprises two steps, as shown in Fig. 1. In step (a) the quantity H_d (normalized to the monitor reading) is measured. In step (b) the ICRU sphere is replaced by the anthropomorphic phantom which together with the individual dosemeter forms the "measuring device". If M is the reading of the individual dosemeter (as normalized to the monitor reading), then the calibration factor is generally obtained from $k = H\ /M$.

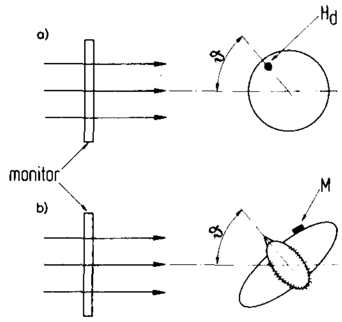

Fig. 1: Experimental arrangement for calibrating individual dosemeters

There are, however, two independent variables which have to be considered: The energy, E, and the direction of incidence, ϑ . An ideal individual dosemeter should satisfy the requirement $k = k(E,\vartheta) = \text{const.}$ for all energies E and all directions ϑ . These calibration problems, particularly if more than one dosemeter is worn by the individual have been discussed in a much more general way elsewhere /6,7/. Here, it is sufficient to emphasize that an operational dose equivalent quantity depends on the energy and the direction of incidence. These dependences for H_{10} are (with respect to the direction only for $\vartheta = 0°$, $180°$) given in the second and third column of the table. If H_{10} is to be an adequate operational quantity, it should have a dependence on E and ϑ roughly similar at least to that of H_{eff}.

Considering the energy dependences shown in the table, H_{10} and $\hat{H}$ can be made conservative estimates of H_{eff}-AP by multiplying them by 1.1 and 1.15, respectively. One then obtains a maximal overresponse of 3.16 and 2.81 for H_{10} and $\hat{H}$, respectively. Such factors may be acceptable in routine area monitoring. For the purpose of discussing individual monitoring, one should note that at E =100 keV

$$\frac{H_{10}(0^{\circ})}{H_{eff}\text{-AP}} = \frac{67.1}{23.7} = 2.83 \qquad (2a)$$

Regarding the directional dependence now by comparing the second and seventh column of the table, one finds $H_{10}(180°)$ to be very much lower than H_{eff}-PA. For E = 1 MeV one finds

$$\frac{H_{10}(180^{\circ})}{H_{eff}\text{-PA}} = \frac{.253}{85.0} = \frac{1}{336} \qquad (2b)$$

Discussing the results of Eqs. (2a, b), H_{10} would give a considerable overall overestimation for exposure of the front side, but a very high underestimation for exposure of the back. We therefore conclude that H_{10} is not an adequate operational dose equivalent quantity for all exposure conditions in individual neutron monitoring.

AN IMPROVED OPERATIONAL QUANTITY H_{sph}

In the preliminary attempt the directional dependence of H_{sph} (see Eq. (1)) was only considered for the directions $\vartheta = 0°$ and $\vartheta = 180°$ of the incident radiation. The reference radius (see Sect. 1) defines a spherical polar coordinate system r,α,β fixed in the ICRU sphere with the polar angle α ($0 \leq \alpha \leq 180°$) and the azimuthal angle β ($0° \leq \beta \leq 360°$). The preliminary choice of the dose equivalent quantities H^i in Eq. (1) is given by the following volume elements in the ICRU-sphere: H^1 corresponds to a point-like volume element at $\alpha = 0°$ and $r = 14$ cm, and this is identical with H_{10} on the reference axis. H^2 is the average in an extended volume element given by 11 cm $\leq r \leq$ 12 cm and $0° \leq \alpha \leq 45°$, H^3 is the average on a thin sperical shell at $r = 14$ cm, H^4 is the average in 11 cm $\leq r \leq$ 12 cm and $135° \leq \alpha \leq 180°$, and H^5 corresponds again to a point-like volume element at $\alpha = 180°$ and $r = 14$ cm. The corresponding factors g_i in Eq. (1) must be so chosen that the energy and directional dependence of H_{sph} match the corresponding dependence of H_{eff}. A preliminary result obtained by a simple trial and error procedure yields $g1 = 0.13$, $g2 = 1.14$, $g3 = 0.16$, $g4 = 0.57$ and $g5 = 0.08$. The ratio $H_{sph} : H_{eff}$ at $\vartheta = 0°$, 180° and all energies listed in the table then satisfy the condition

$$1.0 \leq \frac{H_{sph}}{H_{eff}} \leq 2.1 \qquad (3)$$

This preliminary finding appears to be a remarkable progress in comparison with the poor properties of H_d demonstrated in eqs. (2a, b).

CONCLUSION

The preliminary character of the results in Sect. 4 is again emphasized. In particular it can be expected that in future investigations the extended volume elements for some of the H^i can be replaced by suitably located point-like volume elements. Further, linear programming could be used to obtain an optimal matching of H_{sph} and H_{eff}. It can be expected that an operational quantity could be constructed in the ICRU-sphere which not only has an improved energy dependence for area monitoring, but is also suitable for individual monitoring, since the directional dependence is greatly improved. The price to be paid for this is that one would have to deal with a few points distributed over the volume of the ICRU sphere instead of one single point as in the case of H_d.

From the standpoint of neutron dosimetry, the experiment (a) in Fig. 1 cannot be performed, because no instrument is at present available to measure the dose equivalent. Since this experiment must in any case be replaced by Monte Carlo calculations, H_{eff} as calculated approximately in a standardized anthropomorphic phantom, or any related quantity /7/ would represent an excellent reference dose equivalent quantity. However, the dose equivalent distributions in anthropomorphic phantoms are much more difficult to calculate than in a uniform sphere and the likelehood of errors and uncertainties increases. The authors therefore advocate a solution based on eq. (1).

As for photons, H_{eff} has been rejected on the grounds that it is not measurable. Taking this objection into account, it might be expected that an operational quantity based on eq. (1) turns out to be a reasonable compromise.

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Comparison of Radiation Protection Quantities

E_n	$H_{10}(0^\circ)$	$H_{10}(180^\circ)$	H_{10}-ISO	$\hat{H}$	H_{eff}-AP	H_{eff}-PA	H_{eff}-ROT	H_{eff}-ISO
2.50E-02	8.240	0.055	1.813	10.700	5.480	3.150	3.140	2.450
1.00E+00	10.340	0.123	2.895	10.550	6.940	4.750	4.350	3.330
1.00E+01	7.370	0.100	2.506	10.460	6.980	5.260	4.600	3.510
1.00E+02	6.740	0.182	2.224	10.370	6.740	5.430	4.600	3.500
5.00E+02	5.730	0.117	1.891	10.310	6.290	5.330	4.410	3.350
1.00E+03	5.810	0.146	1.601	10.280	6.110	5.260	4.330	3.260
2.00E+03	5.730	0.146	1.776	9.430	6.210	5.310	4.380	3.320
3.00E+03	6.620	0.195	1.787	9.140	6.280	5.330	4.410	3.350
6.00E+03	6.900	0.117	2.001	9.070	6.380	5.360	4.460	3.390
8.00E+03	7.600	0.125	2.280	9.330	6.430	5.370	4.480	3.410
1.00E+04	8.290	0.212	2.321	9.920	6.460	5.380	4.500	3.420
2.00E+04	13.350	0.107	3.605	16.340	8.990	6.160	5.670	4.370
3.00E+04	19.640	0.159	5.106	22.060	10.890	6.760	6.460	5.040
5.00E+04	32.330	0.206	8.729	32.680	13.900	7.370	7.680	6.030
1.00E+05	67.110	0.185	20.133	57.870	23.700	10.800	12.200	9.660
2.00E+05	128.800	0.283	38.640	99.830	44.670	19.400	22.630	17.900
3.00E+05	164.540	0.200	55.944	135.870	65.950	28.700	33.510	26.400
4.00E+05	221.680	0.186	70.938	168.380	86.790	37.900	44.160	34.700
5.00E+05	222.330	0.200	84.485	198.410	107.000	46.800	54.400	42.700
6.00E+05	257.630	0.264	95.323	230.450	125.720	55.100	63.760	50.000
8.00E+05	331.980	0.268	114.752	284.980	157.440	70.600	81.920	62.900
1.00E+06	375.040	0.253	131.264	326.800	179.000	85.000	94.000	73.300
1.50E+06	338.950	0.903	162.696	376.480	200.770	118.800	118.900	92.500
2.00E+06	352.090	1.626	186.608	396.830	217.800	150.600	140.600	109.000
2.50E+06	352.100	14.203	193.655	405.910	232.000	181.000	160.000	124.000
3.00E+06	402.200	13.850	209.144	409.520	262.100	211.900	184.900	143.000
5.00E+06	439.550	39.267	259.016	408.500	358.000	310.000	270.000	212.000
5.12E+06	451.570	19.990	243.848	408.440	359.500	313.500	273.000	215.000
5.24E+06	360.120	45.798	247.078	408.390	360.890	317.000	276.000	217.000
7.50E+06	439.270	57.723	303.096	407.610	343.800	334.000	292.800	237.600
1.00E+07	492.800	77.121	325.248	408.500	348.000	336.000	302.000	249.000
1.20E+07	528.700	95.953	364.803	412.220	419.900	394.900	356.900	294.000
1.40E+07	561.500	117.469	398.665	416.190	478.200	442.300	400.400	330.000
1.60E+07	575.260	136.967	425.692	420.100	-	-	-	-
1.80E+07	576.570	164.734	438.193	423.840	-	-	-	-
2.00E+07	642.090	181.381	500.830	427.350	-	-	-	-
CF252	350.530	9.680	164.749	340.000	-	-	-	-