INFLUENCE OF CHARGED PARTICLE BUILD-UP ON DOSIMETRIC QUANTITIES IN THE SURFACE LAYER OF THE ICRU SPHERICAL PHANTOM

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INTRODUCTION

The specified depth dose equivalent H_d has recently been proposed as the operational quantity for radiation protection measurements for photon, electron and neutron radiation /1/. This quantity would replace the dose equivalent index H_I which has been shown to be a questionable quantity /2/. Both quantities H_d and H_I are secondarily limited quantities and should provide a conservative estimate for the effective dose equivalent H_{eff} defined in /3/. In /3/ H_I has been explicitly suggested as the limiting quantity for external exposure to penetrating radiation, if information on the actual distribution of dose equivalent in the body is lacking.

The depths to be specified for H_d are 70 µm, 3 and 10 mm /1/ below the ICRU sphere surface. At these depths charged particle build-up (CPB) may play an important rôle, as can be inferred from /4/ for photons and seen from /5/ for neutrons. The air surrounding the ICRU sphere may influence the CPB. This is significant for photons /4/ and will be discussed below for neutrons. The influence of the CPB on H_d for photons and neutrons will be studied and implications for the suitability of H_d as the secondarily limited quantity will be discussed.

The CPB is due to the finite range of secondary charged particles (SCP). Its magnitude can be studied by comparing correct calculations of H_d with kerma approximations $H_{d,k}$ where zero range of SCP is assumed.

PHOTON RADIATION

Table 1 displays results of calculations assuming the ICRU sphere in vacuo and irradiated by a broad parallel beam of monoenergetic photons. In order to check the quality of our calculations, $\hat{H}_3$ and $\hat{H}_{10}$, i.e. the maxima on the corresponding shell, are compared with results obtained by /4/. In the last two columns our results for H_I are compared with those of /4/. With the exception of $\hat{H}_3$ for 2 MeV, one finds that our calculations agree for $\hat{H}_3$ and $\hat{H}_{10}$ well within 5 % which we quote as our calculational error. Details of our code can be found in /6/. The results for H_I up to 3 MeV agree within 3 %. At higher energies, however, our results are increasingly higher than those of /4/. In /7/ various calculations of H_I are compared with experimental results. The values of H_I given in /4/ underestimate the experimental and other calculational results above 4 MeV. Our results for H_I at energies above 4 MeV support the values of /8/ as shown in /7/. The ratio of H_3 to its kerma approximation $H_{3,k}$ - second and third column in table 1 - decreases with incident photon energy from 0.96 to 0.08. The trend with energy is due to the increasing range of the secondary electrons. For $H_{10}/H_{10,k}$ - sixth and seventh column - one correspondingly finds values from 0.97 to 0.30. Calculations of H_{eff} by /9/ - not shown in table 1 - show that H_{10} underestimates H_{eff} for frontal irradiation (AP) for all energies above 2 MeV. At 10 MeV

H_{10}/H_{eff}-AP is 0.43. The kerma approximation $H_{10,k}$ is a conservative estimate of H_{eff}-AP. Our results support the suggestion of /3/ that H_I can be used as a conservative estimate of H_{eff}. For the photon energies shown in table 1 the ratio H_I/H_{eff}-AP is found to vary between 1.35 at 0.662 MeV and 1.23 at 10 MeV.

These results clearly show that the influence of CPB on H_3 and H_{10} for high energy photons is considerable. This is important in practical radiation protection. Higher photon energies above 2 MeV occur, for instance, at nuclear reactors, the $^{16}O(n,p)^{16}N$ reaction where ^{16}N emits photons of 6.13 and 7.12 MeV is an example of this.

It is interesting to note in this context that calculations by /4/ for the ICRU phantom in air indicate that H_{10} is then a conservative estimate of H_{eff}-(AP). This is due to the fact that H_{10} then will increase to approximately $H_{10,k}$ since the CPB takes place in air.

NEUTRON RADIATION

A study of CPB for neutrons is given in /5/. There, however, CPB has been examined using a slab phantom and only a surface layer of 5 mm has been examined. In table 2 the ratios of H_d to $H_{d,k}$ are intercompared. The values in /5/ have been read from a graph which displays smoothed curves. Our values /6/ have not been smoothed and contain calculational errors of up to 7 %. With the exception of the values for 0.07 mm at 5 MeV, and for 3 mm at 20 MeV, the agreement is quite satisfactory. The influence of CPB is considerable only for d = 0.07 mm.

The quantity H_d also depends on the direction of the incident neutrons (see e.g. /10/). It is interesting to study the influence of CPB on the "ear effect" (i.e. the fact that for certain incident radiations the maximum of the dose equivalent distribution within the ICRU sphere occurs at 90° instead of 0°, see e.g. /4/). The magnitude of CPB is again studied by comparing H_d with $H_{d,k}$. The effect which is most pronounced at d = 0.07 mm is shown in table 3. The data clearly exhibit an "ear effect" which is also observed for photons /4/. The sharp drop for angles above 90° (back half of sphere) is typical of neutrons and not seen in photon fields. The CPB increases with energy and decreases with angle. This effect was observed to be less pronounced for d = 3 mm and E_n = 14 and 20 MeV. Similar results given in /11/ do not show the ear effect since the subdivison of the phantom was not sufficiently fine.

These results given in tables 2 and 3 show that with the exception of 20 MeV neutrons, the CPB influences $H_{0.07}$ only. This CPB effect, however, would not disappear if the ICRU sphere were embedded in air, since the hydrogen content of even moist air is negligible as compared with that of the phantom which contains 10.1 % H by weight.

Returning to the question of the suitability of H_d as a secondarily limited quantiy, we give in /10/ a detailed comparison of H_{10} at zero degrees with H_{eff}-AP as a function of energy. From our data given in /10/ and /6/ it can be seen that H_d (for d = 0.07, 3 and 10 mm) is a conservative estimate of H_{eff}-AP for $E_n \geq 8$ keV, if the ICRU sphere is in vacuo. This result is practically unaffected by embedding the sphere in air.

CONCLUSION

In calculating H_3 and H_{10} the CPB is not negligible for photon irradiation with energies $E_\gamma \geq 2$ MeV. This influence could be remedied e.g. by specifying greater depths (d ≈ 2 - 4 cm) for those high energies. In calibrating dosimeters therefore CPB necessitates careful considerations. In practical applications measurements with and without build-up layers (1 - 3 g/cm^2) should be made and the higher reading be used.

The CPB in the ICRU phantom for neutron radiation is only of significance for d = 70 µm and energies $E_n \geq 5$ MeV, and for 3 and 10 mm at 20 MeV. In contrast to photons, the surrounding air would not remedy the problem. However, since all H_d (d = .07, 3 and 10 mm) for $E_n \geq 8$ keV are conservative estimates of H_{eff}-AP, no problem is caused by CPB.

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Table 1
Intercomparison of various fluence to dose equivalent conversion factors (pSv cm^2) as function of photon energy E_γ (MeV); (a) corresponds to ref. /4/

E_γ	$H_{3,K}$	H_3	$\hat{H}_3$	$\hat{H}_3$(a)	$H_{10,K}$	H_{10}	$\hat{H}_{10}$	$\hat{H}_{10}$(a)	H_I	H_I(a)
.662	3.64	3.48	3.89	3.77	3.62	3.51	3.87	3.78	3.9	3.82
1.25	6.16	5.06	6.34	6.39	6.08	6.34	6.34	6.19	6.4	6.19
2.0	8.53	4.59	7.85	8.64	8.43	8.36	8.84	9.02	8.8	9.02
3.0	11.3	3.93	10.5	11.1	11.2	9.86	11.3	11.6	11.6	11.6
5.0	16.5	3.82	14.4	15.1	16.3	9.59	15.1	15.7	16.8	16.2
7.0	22.4	3.80	17.8	18.0	22.5	9.79	19.5	19.6	22.0	19.9
10.0	30.7	3.78	22.8	23.6	30.8	10.2	25.6	24.9	29.7	25.9
15.0	48.4	3.78	31.7	-	48.1	14.2	34.8	-	66.5	-

Table 2
Ratio H_d to its KERMA approximation as a function of neutron energy E_n (MeV) and depth d (mm) as given by /5/ and the authors /6/

d	Ref.	E_n /MeV			
mm		5	10	14	20
0.07	/5/	0.42	0.69	0.69	0.77
	/6/	0.67	0.69	0.73	0.71
3.0	/5/	1.00	1.00	1.00	0.97
	/6/	0.98	1.02	1.00	0.87
10.0	/6/	1.03	1.04	1.03	0.88

Table 3
Fluence to specified depth dose conversion factors (pSv cm^2), in kerma approximation and correct as function of neutron energy E_n (MeV) and angle (degree)

Angular Range	E_n/MeV							
	5		10		14		20	
	$H_{0.07,k}$	$H_{0.07}$	$H_{0.07,k}$	$H_{0.07}$	$H_{0.07,k}$	$H_{0.07}$	$H_{0.07,k}$	$H_{0.07}$
0°-10°	380	254	457	303	537	389	715	507
10°-20°	{ 386	{ 268	455	300	529	388	741	526
20°-30°			455	304	539	396	746	533
30°-50°	391	289	463	323	543	412	745	541
50°-70°	406	331	476	364	560	450	765	576
70°-90°	429	387	500	416	591	507	813	640
90°-110°	267	262	350	314	431	392	625	518