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Laboratori Nazionali di Frascati

Submitted to Radiation Protection Dosimetry

LNF–94/008 (P)
20 Gennaio 1994

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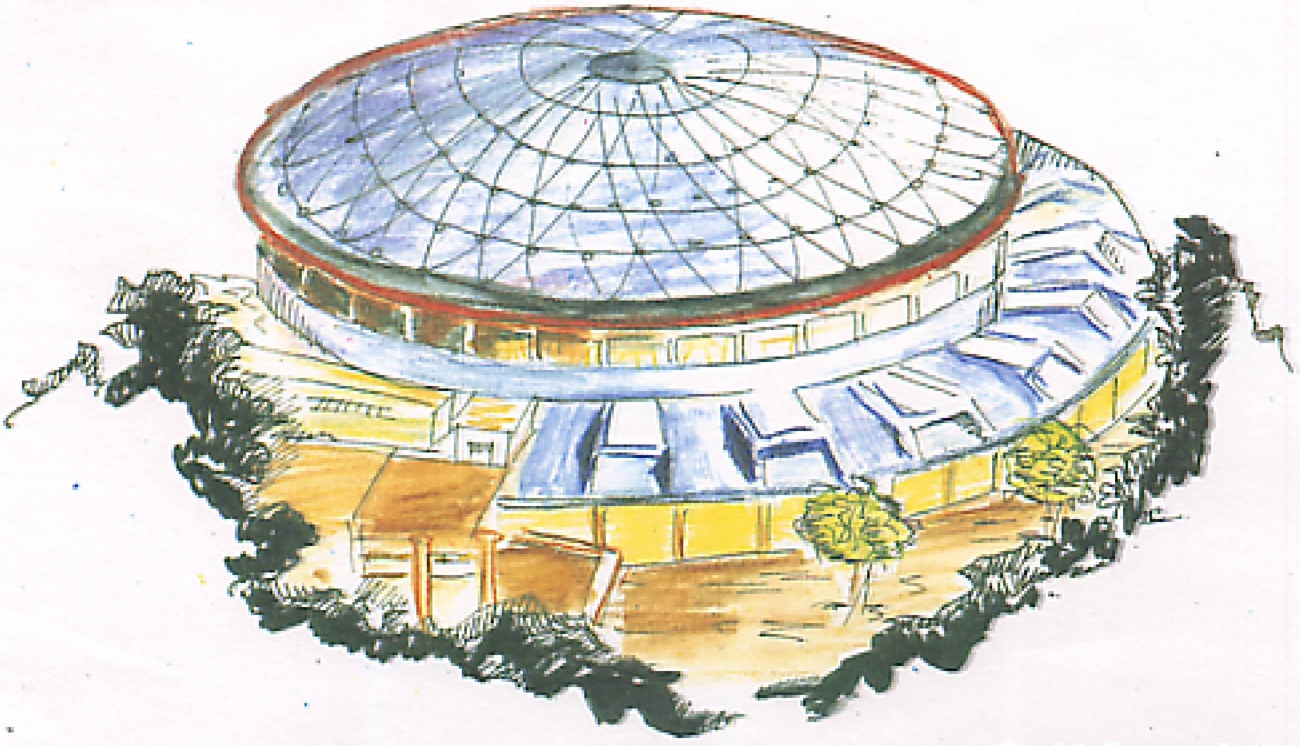
PACS.: 28.80



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LNF-94/008 (P)
20 Gennaio 1994

On the conversion coefficients from fluence to ambient dose equivalent

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Abstract

The conversion coefficients from photon fluence (or other physical quantities) to ambient dose equivalent recommended by ICRU in the Report 47 are overestimated in the energy range 4–10 MeV, since derived from calculations carried out with the ICRU sphere in air. Such a procedure is clearly contradictory with the definition of the ambient dose equivalent given by ICRU itself.

In this paper, the values of the conversion coefficients consistently evaluated by Monte Carlo calculations using the FLUKA code, are presented.

The resulting ambient dose equivalent is shown not to be conservative with respect to the effective dose equivalent when the photon energy exceeds about 3 MeV.

1 Introduction

Values of conversion coefficients from photon fluence to ambient dose equivalent, $H^*(10)/\phi$, have been given by ICRU in the Report 47 [1]. They are based on Monte Carlo calculations for parallel beams of monoenergetic photons from 10 keV to 10 MeV incident on a 30 cm diameter ICRU sphere [2, 3, 4, 5, 6, 7, 8]. All these calculations have been performed before the publication of the ICRU Report 39 [9], when the quantity ambient dose equivalent was defined and introduced in the operational practice for environmental and area monitoring. The results of the calculations were usually expressed in terms of various radiological quantities, including the dose equivalent at 10 mm depth. However it should be pointed out that the dose equivalent at 10 mm depth given by the above mentioned authors was not always the central axis value.

Usually dose equivalent values have been computed as the sum of two contributions: the dose equivalent when the ICRU sphere is in vacuo and the dose equivalent from scattered photons and the corresponding electrons and positrons produced in an air column in front of the sphere [6]. The dimensions of the air column were such to attain full electronic equilibrium. It has been assumed that, at 10 mm depth, secondary electrons are in equilibrium with the primary photons and that the ambient dose equivalent, H*(10), equals tissue kerma minus bremsstrahlung losses. According to ICRU Report 47, this should be in practice a good approximation for photons energies up to about 3 MeV, while at higher energies, the increasingly incomplete equilibrium should be partly compensated by secondary electrons that originate in an accelerator target or in the air, and that accompany the incident photon beam.

Conversion coefficients from fluence to dose equivalent on the principal axis at a depth of 10 mm for photons incident in various geometry on the ICRU sphere, have been also given by ICRP in the Publication 51 [10], as averages of the results of two Monte Carlo calculations [4, 7]. ICRP did not use the term ambient dose equivalent in the Publication 51.

The ambient dose equivalent, H*(10), at a point in a radiation field, is actually the dose equivalent that would be produced by the corresponding aligned and expanded field, in the ICRU sphere at a depth, 10 mm, on the radius opposing the direction of the aligned field [9, 1].

The fluence and its energy distribution in an aligned and expanded field have the same values throughout the volume of interest as in the actual field at the point of reference and the fluence is unidirectional.

When the ICRU sphere is in air, the radiation field incident on its surface is not at all aligned and expanded, due to the radiation scattered or produced in air. In order to match the definition of H*(10), the ICRU sphere has to be in vacuo.

The authors of the Monte Carlo calculations quoted by ICRU and ICRP have taken into account the attenuation of the primary beam in the cylinder of air in front of the sphere by normalizing all their results to unit fluence of the primary beam at the centre of the sphere. No correction was introduced for the radiation scattered or produced in air and incident "not aligned" on the sphere. In this way they clearly overestimated the ambient dose equivalent, since the effect of the air on the primary beam was taken into account incorrectly. The attenuation was in fact neglected, but its effects were not (i.e. production of secondaries).

As a consequence, the conversion coefficients recommended by ICRU and ICRP are overestimated at the highest energies and not in agreement with the definition of ambient dose equivalent.

The additivity of radiation components is another important point which is worthwhile to discuss a bit further. One of the main justifications claimed by the International Commissions for the introduction of the quantity ambient dose equivalent was additivity indeed. But, if the conversion coefficients had to be computed with a suitable air layer in front of the phantom in order to attain full electronic equilibrium, it would be clear that the additivity would be spoiled too because of the different thicknesses required at different energies. The ambient dose equivalent would be close to the deep dose equivalent when air thickness was optimized.

Of course, in practice, the radiation field at the point of reference may include also the radiation scattered by air or originated in accelerator targets or in the air itself, as suggested by ICRU. However, according to the definition, in the calculations of the ambient dose equivalent, these radiation components have to be aligned and expanded throughout the volume of interest too. The fluence incident on the ICRU sphere must be the same throughout all points of its surface and has to be unidirectional. The proper ambient dose equivalent should be computed folding the incident fluence, both uncollided and secondary components, with suitable conversion coefficients calculated according to the above prescriptions, that is with a monoenergetic beam in vacuo.

In conclusion the ICRU definition provides a tool for the calculation of the conversion coefficients from physical quantities (i.e. particle fluence) to ambient dose equivalent. According to the definition, in the calculation, the ICRU sphere cannot be placed in a cylinder of air of variable thickness for photons [1] or in vacuo for electrons [11], at pleasure of the authors.

2 Monte Carlo calculations

This paper presents the results of calculations performed in order to evaluate correctly the conversion coefficients from photon fluence to ambient dose equivalent in the energy range 10 keV to 10 MeV.

According to the ICRU Report 39, the geometry considered in the calculations was very simple. A 30 cm diameter sphere of unit density tissue, as defined by ICRU (H, 10.1% by weight; C, 11.1%; N, 2.6%; O, 76.2%), was exposed in vacuo to a parallel photon beam expanded throughout its volume.

The FLUKA Monte Carlo code [12] has been used for all calculations presented in this paper. FLUKA is a general purpose transport code originally developed at CERN for high energy shielding calculations which has been substantially improved in the last years in Milan [13, 14, 15]. The electromagnetic part of the code (EMF) was developed since 1988 starting from EGS4 and includes significant improvements. Developments which are relevant for the presented calculations are the bremsstrahlung model [15] now based on the most recent tabulations of Berger and Seltzer [16], and where the emitted photon angular distribution is accurately described (it has been introduced for e^+, e^- after pair creation too), the advanced electron transport algorithm [14] and the inclusion of Hartree-Fock atomic inelastic form factors when simulating Compton scattering [15].

Details about the physics improvements and the ability of the FLUKA code to simulate electron-photon transport are discussed elsewhere [14, 15, 17].

The energy deposited in the ICRU sphere has been scored as function of depth and radius in a R-Z binning cylindrical structure along the principal axis. Different grids have been selected according to the depth: 0.2 cm longitudinal bins were used up to 2 cm, 1 cm ones for larger depths. The radial bin was always taken to be 1 cm. The values of $H^*(10)/\phi$ have been averaged over the depth 0.9-1.1 cm. The value of R (1 cm) was a compromise between accuracy and CPU saving. However, some tests performed with smaller radii (R=0.5 cm; R=0.1 cm) at the test energies of 600 keV and 10 MeV, have shown no significant difference, within the statistical uncertainties, when compared to the R=1 cm results. It was assumed that an electron deposits its energy at the point of interaction at electron energies less than 50 keV (i.e. ranges $\leq 4.3\cdot 10^{-3}$ g/cm^2 in tissue). The cut-off energy for photons was 1 keV.

A special algorithm has been used when generating the primary photons to "concentrate" artificially the incident particles on the sphere axis in order to improve statistics (see Appendix A).

The statistical uncertainties were estimated by doing all calculations in several batches and computing the standard deviation of the average. The total number of histories was large enough to keep the standard error on the conversion coefficients below few %.

3 Discussion of the results

The present results are quoted in terms of ambient dose equivalent per unit incident fluence. In our case, since the beam is normally incident, fluence is simply given by the number of incident photons divided by the cross sectional area of the sphere.

The results are summarized in tab. 1 over the energy range 10 keV to 10 MeV. Statistical uncertainties on each value (standard error in %) are presented in brackets following the value. Comparisons with the data adopted in the ICRU Report 47, in the ICRP Publication 51 (AP geometry), and with results of calculations made with EGS3 for a broad parallel beam of photons incident on a 30-cm-thick semi-infinite slab of ICRU tissue [18] are also presented in tab. 1. In this last case, the comparison is made, for the sake of simplicity, assuming the values of the dose equivalent at a depth of 0.8-1.0 cm.

The very good agreement between our results and the conversion coefficients suggested by ICRU up to about 3 MeV must be pointed out. The kerma approximation applied to the sphere in air, as adopted by the authors to whom ICRU referred, does not introduce significant errors below this energy. However, at higher energies, the contribution to the dose equivalent from air scatter, as already demonstrated [6], becomes predominant with respect to the dose equivalent when the sphere is in vacuo. However, as previously discussed, an ICRU sphere sitting in an air medium does not comply with the definition of ambient dose equivalent.

The differences between our results and those of EGS3 reflect the differences in the phantoms and in the geometry considered and possibly the many improvements of the FLUKA code with respect to the now superseded EGS3 code. Anyway, the two calculations give very similar results also at energies higher than 3 MeV, the phantom being located in vacuo in both cases.

In order to make fully clear the reasons for the differences found with the respect to the ICRU data, calculations have been also performed with the ICRU sphere sitting in an air medium, for an energy of the initially parallel beam of 10 MeV. According to ref. [6], in order to have secondary electron equilibrium, the sphere was placed in a cylinder of air of 500 cm radius and 4000 cm length. The energy deposited has been scored in the same R-Z binning histogram used in the vacuo case. Moreover the energy deposited has been scored for both cases (in vacuo and in air) also along directions perpendicular to central axis, with the aim to confirm the so called "ears effect" or "equator effect", observed by some authors [4, 6]. These terms refer to the dose maxima which occur, for certain photon energies, on the periphery of the sphere in vacuo when irradiated by unidirectional parallel beams. The attenuation of the primary beam in air

Tab. 1 Comparison of the results of the present calculations to the data of ICRU Report 47 and of other calculations. All the conversion coefficients $H^*(10)/\phi$ are expressed in pSv·cm^2. Standard errors (in %) are reported in brackets.

E (MeV)	This work	ICRU 47	ICRP 51	EGS3 [18]
0.01	0.082 (1.2)	0.077	0.0769	
0.015	0.84 ($\leq$ 1.0)	0.85	0.846	0.914
0.02	1.04 ($\leq$ 1.0)	1.00	1.01	1.07
0.03	0.81 (1.4)	0.79	0.785	0.816
0.04	0.61 (1.8)	0.63	0.614	0.655
0.05	0.51 (2.5)	0.54	0.526	0.586
0.06	0.51 (2.4)	0.50	0.504	0.555
0.08	0.56 (1.4)	0.53	0.532	0.618
0.1	0.62 (3.0)	0.61	0.611	0.720
0.15	0.87 (1.6)	0.89	0.890	
0.2	1.23 (1.2)	1.20	1.18	1.39
0.3	1.81 (1.4)	1.80	1.81	1.99
0.4	2.36 (2.1)	2.38	2.38	2.63
0.5	2.78 ($\leq$ 1.0)	2.93	2.89	3.18
0.6	3.46 (2.0)	3.44	3.38	3.62
0.8	4.29 (1.4)	4.38	4.29	4.66
1.0	5.18 (1.5)	5.2	5.11	5.49
1.5	6.92 (1.5)	7.0	6.92	
2.0	8.25 (1.3)	8.6	8.48	8.64
3.0	10.4 (2.0)	11.2	11.1	11.0
4.0	10.7 (2.4)	13.6	13.3	10.9
5.0	10.4 (1.6)	15.7	15.4	10.2
6.0	9.57 ($\leq$ 1.0)	17.9	17.4	9.77
8.0	9.10 (1.7)	22.3	21.2	8.82
10.0	8.76 ($\leq$ 1.0)	26.4	25.2	8.50

has been corrected like in the quoted references, by normalizing the results to the uncollided fluence at the sphere entrance surface.

The results so obtained are shown in fig. 1, where the dose equivalents in the directions investigated are shown when the sphere is in vacuo and in air.

Some conclusions can be drawn from fig. 1. When the sphere is in air, the dose equivalent at a depth of 10 mm along the axis opposing the direction of the primary beam is about a factor 3 higher than in vacuo. This explains the difference at the higher energies between the conversion coefficients recommended by ICRU and the results of our calculations. When the sphere is in vacuo, the dose equivalent at a depth of 10 mm along the axis opposing the direction of the primary beam is about a factor 3 lower than at 90° ("ears effect"). The inclusion of air scatter does not seem able to eliminate completely the ears effects at depths lower than about 2 cm.

The ears effect is just a consequence of the different build-up effect occuring in the considered directions, because of the geometry of the target. From this point of view, the ICRU sphere appears to be a quite unsuitable phantom.

The values of $H^*(10)/\phi$ correctly calculated at energies higher than 3 MeV are increasingly lower than the dose maxima. At 4 MeV this ratio is equal to about 0.8 which decreases to 0.36 at 10 MeV. Moreover, in the energy range 4-10 MeV, $H^*(10)$ does not appear to be conservative with respect to the effective dose equivalent ex ICRP Publication 51, as shown in tab. 2, and likely with respect to the effective dose ex ICRP Publication 60 [19] too. Anyway a meaningful comparison can be carried out only if, both risk and monitoring quantities, are calculated in the same convention.

However these arguments do not seem sufficient to justify the misuse of its own definition made by ICRU when recommending fluence-to-ambient-dose-equivalent conversion coefficients. Rather, the validity of the introduction of the quantity ambient dose equivalent, or of the ICRU sphere itself, ought to be questioned.

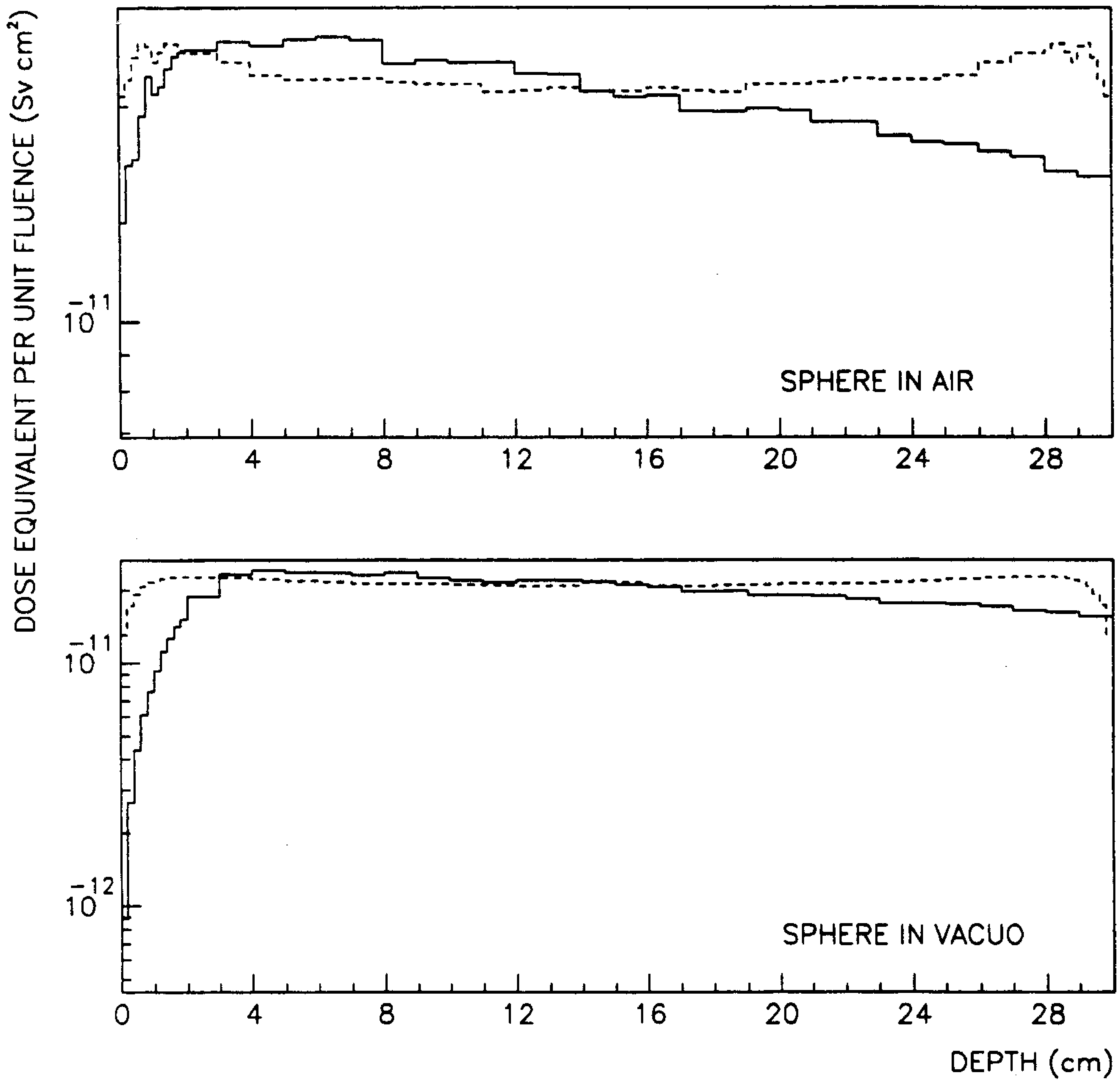

Fig.1 Dose equivalent per unit photon fluence as a function of the depth when the ICRU sphere is in air and in vacuo. The solid lines give the dose equivalent along the central axis whereas the dashed lines give the dose equivalent at 90°.

Tab. 2 Conversion coefficients from photon fluence to ambient dose equivalent (this work) and to effective dose equivalent (ICRP 51) in the energy range 3-10 MeV, expressed in pSv·cm^2.

E (MeV)	This work	ICRP 51
3	10.4	10.2
4	10.7	12.5
5	10.4	14.7
6	9.57	16.7
8	9.10	20.8
10	8.76	24.7

4 Conclusions

In conclusion, not only the conversion coefficients from photon fluence to ambient dose equivalent given in ICRU Report 47 are not appropriate in the energy range 4-10 MeV, but the quantity ambient dose equivalent, as defined in the ICRU Report 39, cannot be used for operational radiation protection purposes whenever the photon energy exceeds about 3 MeV, that is for almost all practical situations involving medical and research electron accelerators.

Appendix A: primary beam sampling

The unbiased probability distribution for the radial coordinate of a uniform parallel beam over $[0, R]$ is:

$$P(r)dr = \frac{2rdr}{R^2}$$

and the cumulative probability distribution:

$$I(r) = \int_0^r P(r')dr' = \frac{r^2}{R^2}$$

Proper sampling could be accomplished by setting:

$$\rho = I(r) = \frac{r^2}{R^2}$$

and solving for r:

$$r = R\sqrt{\rho}$$

where ρ is a uniformly distributed random number on $[0, 1]$. However the "natural" distribution is uncovenient whenever the interesting quantities have to be computed around the axis, since most of the time is spent in simulating photons at large radii where the area is larger, which are likely to contribute very little to the desired result.

In order to overcome this limitation it can be worthwhile to sample from different distributions, possibly more peaked on the axis, and to apply suitable corrections to the results. Let us sample from:

$$P^*(r)dr = R^{\alpha-1}\frac{1-\alpha}{r^\alpha}dr \qquad 0 < \alpha < 1$$

with corresponding cumulative distribution:

$$I^*(r) = \frac{r^{1-\alpha}}{R^{1-\alpha}}$$

which can be solved for r:

$$r = R\rho^{\frac{1}{1-\alpha}}$$

This distribution is clearly peaked on the axis. An unbiased result can be obtained if a suitable r-dependent "weight" is applied to particles selected according to this method. It is straightforward to show that such a "weight" is given by the ratio of the unbiased to the biased probability distributions:

$$w(r) = \frac{P(r)}{P^*(r)} = \frac{2}{1-\alpha}\frac{r^{1+\alpha}}{R^{1+\alpha}}$$

The minimum weight a particle can take is of course 0 for particles produced exactly on the axis, while the maximum weight is given by:

$$w_{max} = w(R) = \frac{2}{1-\alpha}$$

Statistics is improved with respect to the "natural" distribution for particles with $r<r_1$, while it is decreased for particles with $r>r_1$, with r_1 given by:

$$w(r_1) = 1$$

that is:

$$r_1 = R(\frac{1-\alpha}{2})^{\frac{1}{1+\alpha}}$$

No particular investigation has been carried out about the α value. For the present calculations the value $\alpha = \frac{1}{2}$ has been adopted. With this choice one can get $w_{max} = 4$ and $r_1 = \frac{R}{2.52}$. The limited weight range, $[0, 4]$, and the r_1 figure (5.95 cm for R=15 cm) are both suitable for the presented calculations. In principle r_1 should be chosen in such a way to improve statistics for photons at radii enough small to be able to significantly contribute to the energy deposition in the volume of interest. The CPU saving obtained by means of this simple variance reduction technique were large, particularly for the calculations performed with the equilibrium air layer (R=500 cm) where "natural" calculations would have required unmanageable computer times.

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