Re-establishment of the air kerma and ambient dose equivalent standards for the BIPM protection-level ^{60}Co beam

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Abstract

The air kerma and ambient dose equivalent standards for the protection-level ^{60}Co beam have been re-established following the repositioning of the irradiator and modifications to the beam. Details concerning the standards and the new uncertainty budgets are described in this report with their implications for dosimetry comparisons and calibrations.

Introduction

In 1986, experimental determinations were made of the ambient dose equivalent rate $\dot{H}^*$ and the air kerma rate $\dot{K}$ for the protection-level ^{60}Co γ-ray beam and the ratio H^*/K was derived from these results. The measurements were performed at a distance of 3.483 m from the source using a wide, back-directed beam from the irradiator. At this distance, the collimator defined a circular field 740 mm in diameter [1]. To accommodate a new ^{60}Co therapy-level source in the same laboratory, the protection-level irradiator was displaced and in its new location the back-directed beam is no longer available. The forward beam from this source was used for reference air kerma measurements at 1.120 m [2]. A larger collimator was fitted to the forward beam to best reproduce the original measurement conditions for the back-directed beam at 3.483 m. In this new beam, the ambient dose equivalent has been re-established from air kerma measurements at 1.120 m and 3.483 m, making use of the ratio H^*/K determined previously [1].

Experimental arrangement

The activity of the protection-level ^{60}Co source was approximately 0.8 TBq on 1 January 2005. The source has small dimensions and is located on a fine cylindrical mounting of about 8 mm diameter inside a lead-protected housing with internal cube-side dimension of about 25 cm. The beam is horizontal and the original collimator for the forward-directed beam defined a field size 90 mm in diameter at 1.120 m, the reference distance for air kerma measurements. With the same collimator, the field size at 3.483 m, the distance used for the determination of ambient dose equivalent, was 280 mm in diameter rather than the 740 mm diameter used for the experimental determination of $\dot{H}^*$ in the back-directed beam. In order to reproduce the larger diameter beam, a new lead collimator was machined. Consequently, the new conditions of measurement are as given in Table 1.

A new calibration bench was installed, together with a translation table to position both the BIPM standard for reference air kerma measurements and a transfer chamber for calibration at the appropriate distance. The BIPM standard is a graphite-walled cavity chamber and is described in [2].

To define the beam axis, radial profile measurements were made at three different distances (0.920 m, 1.120 m and 1.420 m). For these measurements, a spherical chamber (Shonka 4) was positioned on the translation table, which allowed automatic lateral displacements of 10.0 (1) mm. With the beam axis so defined, final radial profile measurements were made at the reference distance for air kerma (1.120 m) to determine radial non-uniformity corrections and the increased field size using the new collimator.

Table 1. Conditions of measurement in 2005

Source activity (01-01-05) (approximate value)	0.8 TBq
Source dimensions	
diameter	5 mm
length	6 mm
Determination of air kerma	
distance from source to reference plane	1120 mm
beam diameter in the reference plane	257 mm
Determination of ambient dose equivalent	
distance from source to reference plane	3483 mm
beam diameter in the reference plane	800 mm

Reference air kerma determination

The air kerma rate is given by

$$\dot{K} = \frac{I}{m}\frac{W}{e}\frac{1}{1-\bar{g}}\left(\frac{\mu_{en}}{\rho}\right)_{a,c} \bar{s}_{\mathrm{c,a}} \prod k_i \qquad , \tag{1}$$

where

I/m is the ionization current measured by the standard per mass of air,
W is the average energy spent by an electron of charge e to produce an ion pair in dry air,
$\bar{g}$ is the fraction of electron energy lost to bremsstrahlung in air,
$(\mu_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$ is the ratio of the mean mass energy-absorption coefficients of air and graphite,
$\bar{s}_{\mathrm{c,a}}$ is the ratio of the mean stopping powers of graphite and air,
$\prod k_i$ is the product of the correction factors to be applied to the standard.

The values of the physical constants and correction factors entering in the determination of the air kerma rate are given in Table 2 together with their relative standard uncertainties for two BIPM standards. The values for standard CH2 are described in [2]. The standard CH5-2 is nominally identical to CH2. The factors k_{at} and k_{s} that correct for photon attenuation and scattering in the chamber wall, respectively, were re-evaluated for CH5-2 to take into account the slightly different front wall thickness. The factor k_{rn} that corrects for the radial non-uniformity of the beam was calculated from the radial profile measured after the change of the collimator.

Table 2. Physical constants and correction factors entering in the determination of air kerma rate and their estimated relative standard uncertainties in the BIPM ^{60}Co beam.

		$\dot{K}$ at 1.120 m		100 × relative uncertainty [(a)] for CH2		$\dot{K}$ at 3.483 m	100 × relative uncertainty [(a)] for CH5-2	
				100 s_i	100 u_i		100 s_i	100 u_i
Physical constants								
dry air density / kg·m^{-3} [(b)]		1.2930		–	0.01	1.2930	–	0.01
$(\mu_{en}/\rho)_{a,c}$		0.9985		–	0.05	0.9985	–	0.05
$\bar{s}_{c,a}$		1.0003		–	} 0.11	1.0003	–	} 0.11
W/e / (J·C^{-1})		33.97		–		33.97	–	
$\bar{g}$		0.0032		–	0.02	0.0032	–	0.02
Correction factors		CH2	CH5-2			CH5-2		
k_s	recombination losses	1.0014	1.0014	0.01	0.01	1.0014	0.01	0.01
k_h	humidity	0.9970	0.9970	–	0.03	0.9970		0.03
k_{st}	stem scattering	1.0000	1.0000	0.01	–	1.0000	0.01	-
k_{at}	wall attenuation	1.0388	1.0390	0.01	0.04	1.0390	0.01	0.04
k_{sc}	wall scattering	0.9735	0.9734	0.01	0.07	0.9734	0.01	0.07
k_{CEP}	mean origin of electrons	0.9925	0.9925	–	0.01	0.9925	–	0.01
k_{an}	axial non-uniformity	0.9968	0.9968	–	0.07	0.9990	–	0.07
k_{rn}	radial non-uniformity	1.0003	1.0003	0.01	0.02	1.0002	0.01	0.02
V	volume / cm^3	6.8116	6.8344	0.01	0.03 [(c)]	6.8344	0.01	0.10
I	ionization current / pA [(b)]			0.01	0.02		0.10	0.02
Uncertainty								
	quadratic summation			0.03	0.17		0.10	0.20
	combined uncertainty			0.17			0.22	

[(a)] Expressed as one standard uncertainty.
s_i represents the relative standard Type A uncertainty, estimated by statistical methods;
u_i represents the relative standard Type B uncertainty, estimated by other means.
[(b)] At 101.325 kPa and 273.15 K.
[(c)] u_i is 0.10 × 10^{-2} for CH5-2, and the combined uncertainty is 0.20 × 10^{-2}

The value of the ionization current measured at 3.483 m with the BIPM standard is only 0.4 pA, with a relative standard uncertainty of 1 × 10^{-3} for the mean of a series of 30 measurements. As the current is so low at this distance, the reference measurements to demonstrate the long-term stability of the air kerma determination have always been made at 1.120 m.

To date, the two BIPM standards, CH2 and CH5-2, have been used for these reference measurements. The mean, decay-corrected air kerma rate determinations between 2003 and 2005 are shown in Table 3. The results demonstrate the stability for each standard at the level of, at most, two parts in 10^4. The slight deviation from unity of the ratio of the two air kerma determinations is likely to be due to a difference in the volume determinations.

As chamber CH2 has been used since 1970 as the reference standard for this beam, the periodic determinations of $\dot{K}$ at 1.120 m are made with this chamber. With the new beam installed in 2003, the overall mean value for the air kerma rate is 10.097 μGy s^{-1} (reference date 1 January 2005) with a relative statistical standard uncertainty of 5 × 10^{-5}.

Table 3. Reference air kerma rate determinations at 1.120 m

Year	CH2 $\dot{K}$ / µGy s^{-1}	CH5-2 $\dot{K}$ / µGy s^{-1}	$\dot{K}_{CH2}/\dot{K}_{CH5-2}$
2003	10.096 (1)	10.091 (1)	1.0005 (1)
2004	10.096 (1)	10.092 (1)	1.0004 (1)
2005	10.098 (1)	–	–

The uncertainties given in parentheses represent the statistical standard uncertainty of each value.

Conversion to reference ambient dose equivalent

The ambient dose equivalent is derived from the air kerma determined at 3.483 m and the ratio H^*/K determined previously by experiment [1].

A series of measurements was made in 2003 using the BIPM standard CH5-2 and the results are given in Table 4.

Table 4. Air kerma rate and ambient dose equivalent rate for 2003

air kerma rate at 3.483 m $\dot{K}$ / µGy s^{-1}	experimental ratio ($\dot{H}^*/\dot{K}$)/ (Sv Gy^{-1})	ambient dose equivalent rate $\dot{H}^*$ / µSv s^{-1}
1.358 (3)	1.143 (2)	1.552 (5)

The uncertainties given in parentheses represent the combined standard uncertainty of each value.

However, as the ionization currents measured at this reference distance mitigate against a good statistical reproducibility, and since the standard CH5-2 is normally used as the ^{137}Cs reference standard, it was decided to revert to the previous method to determine the reference air kerma, namely the use of standard CH2 at 1.120 m.

The air kerma rate at 3.483 m is obtained by applying the ratio $\dot{K}_{3.483}/\dot{K}_{1.120}$ derived from a series of air kerma determinations made using the standard CH5-2 at these two distances. Finally, the ambient dose equivalent rate is obtained by making use of the experimental ratio $\dot{H}^*/\dot{K}$ at 3.483 m;

$$\dot{H}^* = \dot{K}_{1.120}\left(\dot{K}_{3.483}/\dot{K}_{1.120}\right)\left(\dot{H}^*/\dot{K}\right)_{3.483} \qquad (2)$$

Reference values for 2005 are given in Table 5. The uncertainties represent the combined standard uncertainties.

Table 5. Reference air kerma rate and ambient dose equivalent rate for 2005

$\dot{K}$ / µGy.s^{-1} (*)	$\dot{K}_{1120}/\dot{K}_{3483}$	($\dot{H}^{*}/\dot{K}$)/ (Sv Gy^{-1})	$\dot{H}^{*}$ / µSv s^{-1}
10.097 (17)	9.670 (15)	1.143 (2)	1.193 (4)

(*) mean of $\dot{K}$ measured at 1.120 m using CH2, between 2003 and 2005 (see Table 3).
The uncertainties given in parentheses represent the combined standard uncertainty of each value.

Calibration of secondary standards

Three NMI secondary standards have been calibrated since the re-establishment of the ambient dose equivalent rate. Each of these had also been calibrated prior to the relocation of the ^{60}Co irradiator.

Table 6 gives the calibration coefficients obtained for these NMIs chambers before and after the source relocation. The pre- and post-calibration coefficients are in agreement within the measurement uncertainties.

Table 6. Calibration coefficients for secondary standards calibrated before and after the relocation of the ^{60}Co irradiator

NMI secondary standard	N_{H^*} / µSv nC^{-1} New calibration	N_{H^*} / µSv nC^{-1} Previous calibration
NE 2575	57.23 (20)	57.21 (20)
LS 01	28.22 (10)	28.25 (11)
HS 01	27.84 (10)	27.87 (11)

The uncertainties given in parentheses represent the combined standard uncertainty of each value.

Conclusion

Since the relocation of the ^{60}Co irradiator used for protection-level dosimetry comparisons and calibrations, the ambient dose equivalent standard has been re-established for the protection-level ^{60}Co beam. Although the combined relative standard uncertainty of 4×10^{-3} is a slight increase on the previous value due to the low air kerma rate at the reference distance for ambient dose equivalent, this is not significant in the context of radiation protection.

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References

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