Key comparison BIPM.RI(I)-K5 of the air kerma standards of the PTB, Germany and the BIPM in ^{137}Cs gamma radiation

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Abstract

A direct comparison of the standards for air kerma of the Physikalisch-Technische Bundesanstalt (PTB), Germany and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{137}Cs radiation beam of the BIPM in March 2014. The comparison result, evaluated as a ratio of the PTB and the BIPM standards for air kerma, is 1.0024 with a combined standard uncertainty of 2.7×10^{-3}. The results are analysed and presented in terms of degrees of equivalence for entry in the BIPM key comparison database.

1. Introduction

A direct comparison of the standards for air kerma of the Physikalisch-Technische Bundesanstalt (PTB), Germany and of the Bureau International des Poids et Mesures (BIPM) was carried out in March 2014 in the ^{137}Cs radiation beam at the BIPM to update the previous comparison result of 2000 (Allisy-Roberts *et al* 2005) published in the BIPM key comparison database (KCDB 2014) under the reference BIPM.RI(I)-K5. The comparison was undertaken using the primary standard HRK-3 of the PTB.

2. Details of the standards

The PTB standard for air kerma is comprised of six graphite-walled cavity ionization chambers of different size and shape, each with a graphite inner electrode, constructed at the PTB. The standard HRK-3/1 was used for the present comparison and the main characteristics of the standard are listed in Table 1.
The BIPM standard is a parallel-plate graphite cavity ionization chamber with a volume of about 6.8 cm^3 as described by Boutillon *et al* (1973) and Boutillon *et al* (1996) and the results of recent evaluations of calculated correction factors and new volume estimations are described by Kessler *et al* (2009).

Table 1. Characteristics of the PTB standard for air kerma

	HRK-3/1
Shape	Parallel plate
Dimensions	
Outer height / mm	8.5
Outer diameter / mm	48
Inner height / mm	4.5
Inner diameter / mm	44
Wall thickness / mm	2
Graphite wall density / g cm^{-3}	1.775
Electrode diameter / mm	40
Electrode height / mm	0.5
Air cavity volume / cm^3	6.1380
Applied voltage (both polarities) / V	100

3. Determination of the air kerma

For a cavity chamber with measuring volume *V*, the air-kerma rate is determined by the relation

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

where

I/m is the ionization current per unit mass of air measured by the standard,
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 by bremsstrahlung production 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.

Physical data and correction factors

The values used for the physical constants, recommended by the Consultative Committee for Ionizing Radiation (CCEMRI 1985), the correction factors entering in equation (1), the volume of the primary standard and the associated uncertainties for the BIPM are given in Table 2 (Allisy-Roberts *et al* 2011). For the PTB standard, the corresponding data are also included in Table 2.

Table 2. Physical constants and correction factors with their estimated relative uncertainties of the BIPM and PTB standards for the ^{137}Cs radiation beam at the BIPM

Standard		BIPM value	uncertainty (1) 100 s_i	uncertainty (1) 100 u_i	PTB value	uncertainty (1) 100 s_i	uncertainty (1) 100 u_i
Physical Constants							
ρ_a	dry air density (2) / kg m^{-3}	1.2930	–	0.01	1.2930	–	0.01
$(\mu_{en}/\rho)_{a,c}$	ratio of mass energy-absorption coefficients	0.9990		0.05	0.9990		0.05
$s_{c,a}$	ratio of mass stopping powers	1.0104	–	0.11 (3)	1.0104	–	0.11 (3)
W/e	mean energy per charge / J C^{-1}	33.97	–		33.97	–	
g_a	fraction of energy lost in radiative processes	0.0012	–	0.02	0.0012	–	0.02
Correction factors:		**CH5-1**			**HRK3/1**		
k_s	recombination losses	1.0018	0.01	0.02	1.0011	0.05	0.05
k_h	humidity	0.9970	–	0.03	0.9970	–	0.03
k_{st}	stem scattering	0.9998	0.01	–	0.9989	0.05	–
k_{wall}	wall attenuation and scattering	1.0002	0.01	(4)	0.9980	0.01	0.05
k_{an}	axial non-uniformity	1.0018	–	0.04	1.0018	0.04	0.05
k_{rn}	radial non-uniformity	1.0011	0.01	0.10	1.0011	0.01	0.10
Measurement of I / υ							
υ	chamber volume / cm^3	6.7967 (6)	–	0.08	6.1380	0.08	–
I_{leak}	leakage correction (5)		–	–		–	0.20
I	ionization current		0.02	0.02		0.06	0.02
Relative standard uncertainty							
	quadratic summation		0.03	0.19		0.13	0.27
	combined uncertainty		**0.19**			**0.30**	

(1) Expressed as one standard deviation
s_i represents the type A relative standard uncertainty estimated by statistical methods,
u_i represents the type B relative standard uncertainty estimated by other means

(2) At 101 325 Pa and 273.15 K

(3) Combined uncertainty for the product of $\bar{s}_{c,a}$ and W/e

(4) Uncertainties included in the uncertainty of the chamber effective volume

(5) Uncertainty due to the leakage correction for the PTB standard, as explained in Section 4

(6) For standard CH5-1, the measured volume 6.8028 cm^3 reduced by the factor 1.0009 (Burns *et al* 2007).

The correction factors for the BIPM standards were re-evaluated in 2009 and the changes to the air-kerma rate determination arise from the results of Monte Carlo calculations of correction factors for the standards, a re-evaluation of the correction factor for saturation and a new evaluation of the air volume of the standards using an experimental chamber of variable volume. The combined effect of these changes is an increase in the BIPM determination of air kerma by the factor 1.0030 for the ^{137}Cs radiation protection beam, and a reduction of the relative standard uncertainty of this determination to 1.9 parts in 10^3 (Kessler *et al* 2009 and Burns *et al* 2007).

The correction factors for the PTB standards are described in the previous comparison report (Allisy-Roberts *et al* 2005). No change to the standard has been made since the last direct comparison. The radial non-uniformity correction applied to the PTB standard was evaluated for the BIPM ^{137}Cs beam; the correction for recombination loss for the BIPM ^{137}Cs beam was calculated using the PTB determination.

Reference conditions

The reference conditions for the air-kerma determination at the BIPM are described by Allisy-Roberts *et al* (2011):

- the distance from source to reference plane is 1 m,
- the field size in air at the reference plane is 20 cm diameter.

Reference values

The BIPM reference air-kerma rate $\dot{K}_{\mathrm{BIPM}}$ is taken as the mean of four measurements made around the period of the comparison. The $\dot{K}_{\mathrm{BIPM}}$ values refer to an evacuated path length between source and standard corrected to the reference date of 2014-01-01, 0 h UTC. The half-life of ^{137}Cs was taken as 10 976 days (u = 30 days) (Bé *et al* 2006). The correction for air attenuation between source and standard uses the ambient air density at the time of the measurement and the air attenuation coefficient 0.080 cm^2 g^{-1} for ^{137}Cs.

Beam characteristics

The characteristics of the BIPM and PTB beams are given in Table 3.

Table 3. Characteristics of the ^{137}Cs beams at the PTB and the BIPM

^{137}Cs beam	Nominal $\dot{K}$ (2014-01-01)	Scatter contribution in terms of energy fluence	Field size
PTB source[(1)]	160 µGy s^{-1}	not evaluated	25.9 cm ϕ at 1 m
BIPM source	14 µGy s^{-1}	30 %	20 cm ϕ at 1 m

(1) At the PTB seven Cs-137-sources of different activities combined with different sized collimators are in use. The numbers shown in the table are those of the source no. 18 with the highest activity and the largest collimator no. 6.

4. Experimental method

The experimental method for measurements at the BIPM is described by Allisy-Roberts *et al* (2011); the essential details of the measurements are reproduced here.

Positioning

The centre of the chamber was positioned in the reference plane of the beam at 1 m from the source.

Applied voltage and polarity

A collecting voltage of 100 V (both polarities) was applied to the outer electrode of the HRK3 standard at least 40 min before any measurements were made.

Charge and leakage measurements

The charge Q collected by the PTB chambers was measured using a Keithley electrometer, model 642 of the BIPM. The source is exposed during the entire measurement series and the charge is collected for the appropriate, electronically controlled, time interval. A pre-irradiation was made for at least 40 min before any measurements. The measured current values are given in Table 4. Leakage current was measured before and after each series of measurements. The leakage current was varying, in relative value, from 1×10^{-3} to 3.4×10^{-3} (the measured leakage currents are also given in Table 4). Correcting by leakage, the relative standard deviation of the mean ionization current is 1.1×10^{-3}. Interestingly, this value reduces to 7×10^{-5} when the leakage correction is removed. While this might indicate that the leakage correction should not be applied, the comparison result was evaluated following the standard BIPM procedure of applying the measured leakage correction. On the basis that the comparison result would be higher by 2.6 parts in 10^3 if no leakage correction was applied (see Table 4), an additional relative standard uncertainty of 2 parts in 10^3 is included in Table 2.

Ambient conditions

During a series of measurements at the BIPM, the air temperature is recorded for each current measurement and was stable to better than 0.1 K. Relative humidity is controlled at (50 ± 5) %. No correction for humidity is applied to the ionization current measured.

5. Result of the comparison

The PTB standard was set-up and measured in the BIPM ^{137}Cs beam on three separate occasions. The values of the ionization current and leakage measured at the BIPM for the PTB standard are given in Table 4. They have been normalized to standard temperature and pressure and corrected to the reference date for the decay of the ^{137}Cs source.

Table 4. The experimental results from the PTB standard in the BIPM beam

HRK3/1	Measured current / pA leakage correction applied			Measured current / pA no leakage correction applied		
	$(I_{measured} - I_{leak})$		$I_{mean,corr}$	$I_{measured}$		I_{mean}
I I_{leak}	-3.3341 -0.0040	3.3341 0.0046	3.3341	-3.3381	3.3387	3.3384
I I_{leak}	-3.3265 -0.0113	3.3286 0.0111	3.3276	-3.3379	3.3397	3.3388
I I_{leak}	-3.3282 -0.0092	3.3277 0.0124	3.3280	-3.3375	3.3401	3.3388
Mean current			3.3299	Mean current		3.3387
St. dev. %			0.11	St. dev. %		0.007

The result of the comparison, R_K, is expressed in the form

$$R_K = \dot{K}_{\mathrm{PTB}} / \dot{K}_{\mathrm{BIPM}} \qquad (2)$$

and is presented in Table 5, where $\dot{K}_{\mathrm{PTB}}$ was calculated from the current determined with the leakage correction applied. The combined standard uncertainty u_c for the comparison result R_K is presented in Table 6, where some of the uncertainties that appear in both the BIPM and the PTB determinations (air density, W/e, μ_{en}/ρ, $\bar{g}$, $\bar{s}_{c,a}$ and k_h) cancel when evaluating u_c.

Table 5. Final result of the PTB/BIPM comparison of standards for ^{137}Cs air kerma

$\dot{K}_{\mathrm{PTB}}$ / µGy s^{-1}	$\dot{K}_{\mathrm{BIPM}}$ / µGy s^{-1}	R_K	u_c
14.373	14.339	1.0024	0.0027

Table 6. Uncertainties associated with the comparison result

Relative standard uncertainty	BIPM		PTB	
	100 s_i	100 u_i	100 s_i	100 u_i
Air kerma determination $\dot{K}$	0.03	0.19	0.13	0.27
Relative standard uncertainty of R_K	100 s_i		100 u_i	
	0.13		0.24 [a]	
	0.27			

[a] Takes account of correlation in type B uncertainties.

The mean ratio of the values of the air kerma rate determined by the PTB and the BIPM standards taken from Table 5 is 1.0024 with a combined standard uncertainty, u_c, of 0.0027.

6. Degrees of equivalence

Comparison of a given NMI with the key comparison reference value

Following a decision of the CCRI, the BIPM determination of the dosimetric quantity, here K_{BIPM}, is taken as the key comparison reference value (KCRV) (Allisy-Roberts *et al* 2009). It follows that for each NMI i having a BIPM comparison result $R_{K,i}$ (denoted x_i in the KCDB) with combined standard uncertainty, u_i, the degree of equivalence with respect to the reference value is given by a pair of terms:

the relative difference $$D_i = (K_i - K_{\mathrm{BIPM},i})/ K_{\mathrm{BIPM},i} = R_{K,i} - 1, \quad (3)$$

where K_i is the value determined using the NMI standard during the comparison, and

the expanded uncertainty (k = 2) of this difference, $$U_i = 2\, u_i. \quad (4)$$

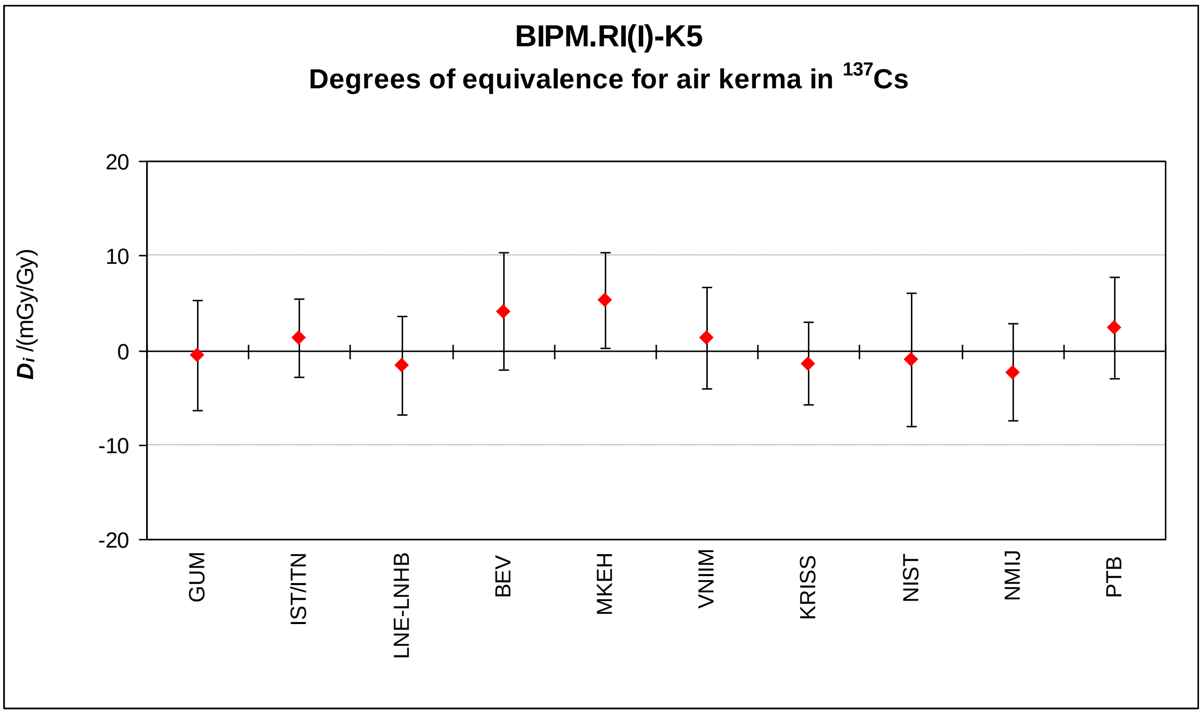
The results for D_i and U_i are expressed in mGy/Gy. Table 7 gives the values for D_i and U_i for each NMI, i, taken from the KCDB of the CIPM MRA (1999) and this report, using equations (3) and (4). These data are presented graphically in Figure 1.

Table 7. **Degrees of equivalence**

For each laboratory *i*, the degree of equivalence with respect to the key comparison reference value is the difference D_i and its expanded uncertainty U_i. Tables formatted as they appear in the BIPM key comparison database

Lab *i*	D_i / (mGy/Gy)	U_i
GUM	-0.5	5.8
IST/ITN	1.3	4.2
LNE-LNHB	-1.6	5.2
BEV	4.1	6.2
MKEH	5.3	5.0
VNIIM	1.3	5.4
KRISS	-1.4	4.4
NIST	-1.0	7.0
NMIJ	-2.3	5.2
PTB	2.4	5.4

Figure 1. **Graph of degrees of equivalence with the KCRV**



Comparison of any two NMIs with each other

The degree of equivalence between any pair of national measurement standards, when required, is expressed in terms of the difference between the two comparison results and the expanded uncertainty of this difference; consequently, it is independent of the choice of key comparison reference value.

The degree of equivalence between any pair of NMIs, *i* and *j*, is thus expressed as the difference

$$D_{ij} = D_i - D_j = R_i - R_j \qquad (5)$$

and the expanded uncertainty ($k = 2$) of this difference, $U_{ij} = 2\,u_{ij}$, where

$$u_{ij}{}^2 = u_{c,i}{}^2 + u_{c,j}{}^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_i^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_j^2 \tag{6}$$

and the final two terms are used to take into account correlation between the primary standards, notably that arising from the physical constants and correction factors for similar types of standard.

Note that the data presented in the table, while correct at the time of publication of the present report, become out-of-date as NMIs make new comparisons. The formal results under the CIPM MRA are those available in the key comparison database.

7. Conclusion

The previous comparison of the air-kerma standards for ^{137}Cs gamma radiation of the PTB and the BIPM was made directly in 2000. The comparison result, based on the PTB primary standards HRK1 and HRK3-1, is 1.0034 (28) when updated in the key comparison database for the changes made to the BIPM standard.
For the present comparison, the PTB standard for air kerma in ^{137}Cs gamma radiation compared with the BIPM air-kerma standard gives a comparison result of 1.0024 (27) and so is in agreement within the uncertainties with the previous comparison result and with the KCRV.

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