Key comparison BIPM.RI(I)-K1 of the air-kerma standards of the PTB, Germany and the BIPM in ^{60}Co 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 ^{60}Co 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 1.0036 with a combined standard uncertainty of 1.7×10^{-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 ^{60}Co 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)-K1. The comparison was undertaken using four primary standards 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 standards HRK-3/1, HRK-3/2, HRK-2/1 and HRK-2/2 were used for the present comparison and the main characteristics of the standards are listed in Table 1. The BIPM primary standard is a parallel-plate graphite cavity ionization chamber with a volume of about 6.8 cm^3 (Boutillon *et al* 1973, Burns *et al* 2007).

Table 1. Characteristics of the PTB standards for air kerma

	HRK-3/1	HRK-3/2	HRK-2/1	HRK-2/2
Shape	Parallel plate		cylindrical	
Dimensions				
Outer height / mm	8.5		24	
Outer diameter / mm	48		14	
Inner height / mm	4.5		20	
Inner diameter / mm	44		10	
Wall thickness / mm	2		2	
Graphite wall density / g cm^{-3}	1.775		1.775	
Electrode diameter / mm	40		2	
Electrode height / mm	0.5		16	
Air cavity volume / cm^3	6.1380	6.1004	1.5190	1.5157
Applied voltage (both polarities) / V	100		200	

3. Determination of the air kerma

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

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

where

ρ_{air} is the density of air under reference conditions,

I is the ionization current under the same conditions,

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,

$(\mu_{\text{en}}/\rho)_{\text{a,c}}$ is the ratio of the mean mass energy-absorption coefficients of air and graphite,

$\bar{s}_{\text{c,a}}$ 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) are given in Table 2.

The correction factors entering in equation (1), the volume of the primary standard and the associated uncertainties for the BIPM standard are also included in Table 2 (Allisy-Roberts *et al* 2011). For the PTB standards, these data are presented in Table 3.

Table 2. Physical constants and correction factors with their relative standard uncertainties of the BIPM standard for the ^{60}Co radiation beam at the BIPM

		BIPM		
		value	uncertainty (1)	
			100 s_i	100 u_i
Physical Constants				
ρ_a	dry air density (2) / kg m^{-3}	1.2930	–	0.01
$(\mu_{en}/\rho)_{a,c}$	ratio of mass energy-absorption coefficients	0.9989	0.01	0.04
$s_{c,a}$	ratio of mass stopping powers	1.0010	–	0.11 (3)
W/e	mean energy per charge / J C^{-1}	33.97	–	
g_a	fraction of energy lost in radiative processes	0.0031	–	0.02
Correction factors:				
k_g	re-absorption of radiative loss	0.9996	–	0.01
k_s	recombination losses	1.0022	0.01	0.02
k_h	humidity	0.9970	–	0.03
k_{st}	stem scattering	1.0000	0.01	–
k_{wall}	wall attenuation and scattering	1.0011	–	– (4)
k_{an}	axial non-uniformity	1.0020	–	– (4)
k_{rn}	radial non-uniformity	1.0015	–	0.02
k_{pol}	polarity	---	–	–
Measurement of I / V				
V	chamber volume / cm^3	6.8855	–	0.08 (4)
I	ionization current / pA	---	0.01	0.02
Relative standard uncertainty				
quadratic summation			0.02	0.15
combined uncertainty			**0.15**	

(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) The uncertainties for k_{wall} and k_{an} are included in the determination of the effective volume (Burns *et al* 2007)

The correction factors for the BIPM standards were re-evaluated in 2007 and the changes to the air-kerma rate determination arise from the results of Monte Carlo calculations of correction factors for the standard, a re-evaluation of the correction factor for saturation and a new evaluation of the air volume of the standard 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 1.0054 and a reduction of the relative standard uncertainty of this determination to 1.5 parts in 10^3. A full description of the changes to the standard is given by Burns *et al* (2007).

Table 3. Physical constants and correction factors with their relative standard uncertainties of the PTB standard for the ^{60}Co radiation beam at the BIPM

		PTB			
		value		uncertainty (1)	
				100 s_i	100 u_i
Physical Constants					
ρ_a	dry air density (2) / kg m^{-3}	1.2930		–	0.01
$(\mu_{en}/\rho)_{a,c}$	ratio of mass energy-absorption coefficients	0.9985		–	0.05
$s_{c,a}$	ratio of mass stopping powers	1.0010		–	0.11 (3)
W/e	mean energy per charge / J C^{-1}	33.97		–	
g_a	fraction of energy lost in radiative processes	0.0032		–	0.02
Correction factors:		HRK3	HRK2		
k_s	recombination losses	1.0011	1.0022	0.05	0.05
k_h	humidity	0.9970			0.03
k_{st}	stem scattering	0.9992	0.9982	0.05	
k_{wall}	wall attenuation and scattering	1.0004	1.0134	0.01	0.05
k_{an}	axial non-uniformity	1.0015	1.0002	0.03	0.05
k_{rn}	radial non-uniformity	1.0015	1.0002		0.02
k_{pol}	polarity	---			
Measurement of I / V					
$V_{HRK-3/1}$	chamber volume / cm^3	6.1380		0.08	---
$V_{HRK-3/2}$	chamber volume / cm^3	6.1004		(4)	---
$V_{HRK-2/1}$	chamber volume / cm^3		1.5190	(4)	---
$V_{HRK-2/2}$	chamber volume / cm^3		1.5157	(4)	---
I	ionization current / pA	---		0.01	0.02
Relative standard uncertainty for HRK-3					
quadratic summation				0.11	0.16
combined uncertainty (5)				**0.19**	

(1) Uncertainties for the HRK3 standards, 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) The volume uncertainties for the HRK-3/2, HRK-2/1 and HRK-2/2 standards are 0.10, 0.03 and 0.08, respectively.

(5) The combined uncertainties for the HRK-3/2, HRK-2/1 and HRK-2/2 standards are 0.20, 0.18 and 0.19, respectively.

The correction factors for the PTB standards are described in the previous comparison report (Allisy-Roberts *et al* 2005). No change to the standards has been made since the last direct comparison. The radial non-uniformity corrections applied to the PTB standards were evaluated for the BIPM ^{60}Co beam; the corrections for recombination loss for the BIPM ^{60}Co beam were 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 10 cm × 10 cm, defined by the photon fluence rate at the centre of each side of the square being 50 % of the photon fluence rate at the centre of the square.

Reference values

The BIPM reference air-kerma rate $\dot{K}_{\text{BIPM}}$ is taken as the mean of the four measurements made around the period of the comparison. The $\dot{K}_{\text{BIPM}}$ 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 ^{60}Co was taken as 1925.21 days (u = 0.29 days) (Bé *et al* 2006).

Beam characteristics

The characteristics of the BIPM and PTB beams are given in Table 4.

Table 4. Characteristics of the ^{60}Co beams at the PTB and the BIPM

^{60}Co beam	Nominal $\dot{K}$ / mGy s^{-1} (2014-01-01)	Source dimensions / mm		Scatter contribution in terms of energy fluence	Field size at 1 m
		diameter	length		
PTB source	18.08	20.3	29.9	25 %	10 cm × 10 cm
BIPM source	3.8	20	14	21 %	10 cm × 10 cm

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 each chamber was positioned in the reference plane at 1 m from the source.

Applied voltage and polarity

A collecting voltage of 100 V and 200 V (both polarities) was applied to the outer electrode of the HRK3 and HRK2 standards, respectively, at least 40 min before any measurements were made.

Charge and leakage measurements

The charge Q collected by the PTB chambers was measured at the BIPM using a Keithley electrometer, model 642. 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 ionization current measured for the standard was corrected for the leakage current. This correction was, in relative value, less than 2×10^{-4} for the HRK3 standards and around 7×10^{-4} for the HRK2 standards.

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. Results of the comparison

Each PTB standard was set-up and measured in the BIPM ^{60}Co beam on two separate occasions. The results for each chamber were reproducible to better than 1×10^{-4}. The values of the ionization currents measured at the BIPM for the PTB standards are given in Table 5. They have been normalized to standard temperature and pressure and corrected to the reference date for the decay of the ^{60}Co source.

Table 5. The experimental results from the PTB standards in the BIPM beam

PTB standard	I_+ *and* I_- /pA		I_{mean} / pA
HRK3-1	886.10	-885.78	885.94
	886.12	-885.77	885.94
Mean current			885.94
HRK3-2	880.87	-880.72	880.80
	880.79	-880.55	880.67
Mean current			880.73
HRK2-1	216.79	-216.59	216.69
	216.78	-216.59	216.68
Mean current			216.69
HRK2-2	216.42	-216.22	216.32
	216.44	-216.20	216.32
Mean current			216.32

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 6. The combined standard uncertainty u_c for the comparison result R_K is presented in Table 7.

Table 6. Final result of the PTB/BIPM comparison of standards for ^{60}Co air kerma

	$\dot{K}_{\mathrm{PTB}}$ / mGy s^{-1}	$\dot{K}_{\mathrm{BIPM}}$ / mGy s^{-1}	R_K	u_{c}
HRK3-1	3.8050	3.7898	1.0040	0.0017
HRK3-2	3.8059		1.0042	0.0017
HRK2-1	3.7998		1.0026	0.0017

HRK2-2	3.8016		1.0031	0.0017

Table 7. Uncertainties associated with the comparison result

Relative standard uncertainty	100 s_i	100 u_i
$\dot{K}_{PTB} / \dot{K}_{BIPM}$	0.11	0.12[a]
Different standards σ_{tr}	0.04	-
Relative standard uncertainty of R_K	0.12	0.12
	u_c = 0.17	

[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 6 is 1.0036 with a combined standard uncertainty, u_c, of 0.0017. Some of the uncertainties in $\dot{K}$ that appear in both the BIPM and the PTB determinations (such as air density, *W/e*, μ_{en}/ρ, $\bar{g}$, $\bar{s}_{c,a}$ and k_h) cancel when evaluating the uncertainty of R_K.

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

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 8 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.

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, D_{ij}, between any pair of NMIs, *i* and *j*, is thus expressed as the difference

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

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

$$u_{ij}{}^{2} = u_{c,i}{}^{2} + u_{c,j}{}^{2} - \sum_{k}\left(f_{k}u_{k,\mathrm{corr}}\right)_{i}^{2} - \sum_{k}\left(f_{k}u_{k,\mathrm{corr}}\right)_{j}^{2} \quad (6)$$

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.

Table 8. 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

BIPM.RI(I)-K1 - COOMET.RI(I)-K1 (2006) - EURAMET.RI(I)-K1 (2005 to 2008) – APMP.RI(I)-K1 (2004 to 2006)

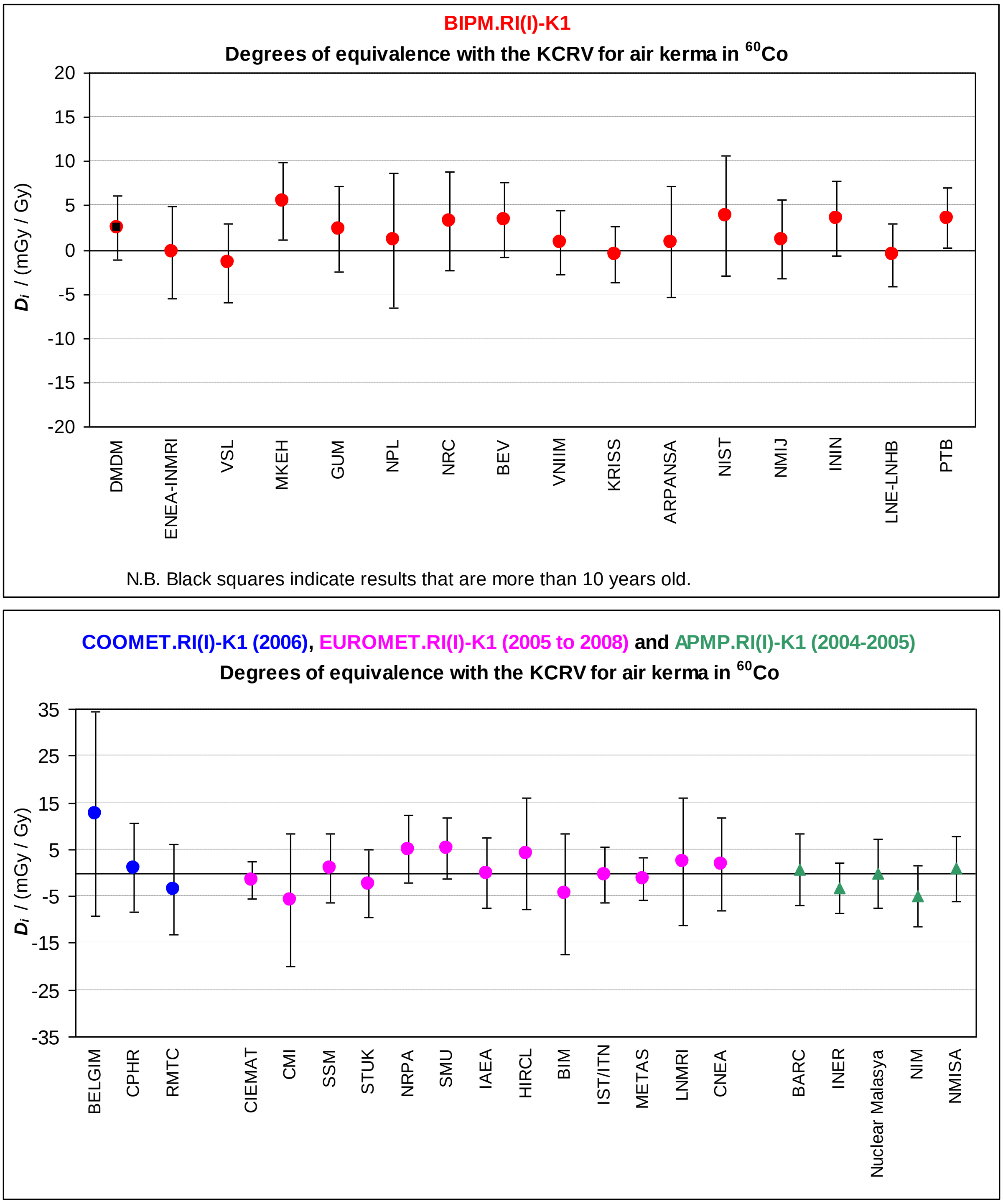
Lab i	D_i / (mGy/Gy)	U_i / (mGy/Gy)
DMDM	2.5	3.6
ENEA-INMRI	-0.3	5.2
VSL	-1.5	4.4
MKEH	5.5	4.4
GUM	2.3	4.8
NPL	1.1	7.6
NRC	3.2	5.6
BEV	3.4	4.2
VNIIM	0.8	3.6
KRISS	-0.5	3.2
ARPANSA	0.9	6.2
NIST	3.9	6.4
NMIJ	1.2	4.4
ININ	3.6	4.2
LNE-LNHB	-0.6	3.6
PTB	3.6	3.4

BelGIM	12.5	21.8
CPHR	1.1	9.7
RMTC	-3.6	9.7

Lab i	D_i / (mGy/Gy)	U_i / (mGy/Gy)
CIEMAT	-1.5	3.9
CMI	-5.8	14.1
SSM	1.0	7.5
STUK	-2.3	7.3
NRPA	5.1	7.1
SMU	5.2	6.5
IAEA	0.0	7.5
HIRCL	4.2	11.9
BIM	-4.5	13.0
IST/ITN	-0.4	6.0
METAS	-1.3	4.6
LNMRI	2.4	13.7
CNEA	1.8	10.0

BARC	0.7	7.6
INER	-3.2	5.4
Nuclear Malasya	-0.1	7.4
NIM	-4.9	6.6
NMISA	0.9	6.9

Figure 1. Graph of degrees of equivalence with the KCRV



7. Conclusion

The previous comparison of the air-kerma standards for ^{60}Co gamma radiation of the PTB and of the BIPM was made directly in 2000. The comparison result, based on the PTB primary standards HRK1, HRK2-1 and HRK3-1, is 1.0045 (18) 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 ^{60}Co gamma radiation compared with the BIPM air-kerma standard gives a comparison result of 1.0036 (17) and so is in agreement within the uncertainties with the previous comparison result.

References

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