Key comparison BIPM.RI(I)-K1 of the air-kerma standards of VSL, The Netherlands, and the BIPM in ^{60}Co gamma radiation

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Abstract

A key comparison of the standards for air kerma of VSL, Dutch Metrology Institute, The Netherlands (VSL) and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in December 2017. The comparison result, based on the calibration coefficients for two transfer chambers and expressed as a ratio of the VSL and the BIPM standards for air kerma, is 0.9963 with a combined standard uncertainty of 2.1×10^{-3}. The results are analysed and presented in terms of degrees of equivalence, suitable for entry in the BIPM key comparison database.

1. Introduction

An indirect comparison of the standards for air kerma of the VSL, Dutch Metrology Institute, The Netherlands, and of the Bureau International des Poids et Mesures (BIPM) was carried out in December 2017 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2005 (Kessler *et al* 2010) published in the BIPM key comparison database (KCDB 2018) under the reference BIPM.RI(I)-K1. The comparison was undertaken using two transfer ionisation chambers type NE 2611A and NE 2571 of the VSL. The result of the comparison is given in terms of the mean ratio of the calibration coefficients of these transfer instruments determined at the two laboratories. The final results were supplied by the VSL in June 2018.

2. Details of the standards

The primary standard for air kerma of the VSL is a graphite-walled spherical cavity ionization chamber of volume 5 cm^3 described by Hofmeester (1975). The main characteristics of the standard are given in Table 1. Details of the transfer chambers used for the indirect comparison are also included 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 VSL standard for air kerma and the transfer chamber

VSL chambers	Nominal values	5cc spherical	NE 2611A	NE 2571
Chamber	Outer diameter / mm	28.9	8.5	7.0
	Outer height / mm	-	9.7	24 (inner length)
	Wall thickness / mm	4	0.5	0.36
Electrode	Diameter / mm	3.5	1.7	1.0
	Length / mm	8	6.4	20.6
Volume	Air cavity / cm^3	4.845	0.3	0.7
Wall	Materials	graphite	graphite	
	Density / g cm^{-3}	1.79	1.7	
Applied voltage	V	250	200 [(1)]	300 [(1)]

[(1)] Positive polarity applied to the outer electrode at both laboratories

3. Determination of the air kerma

BIPM formalism

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

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

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,

$(\mu_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$ 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 VSL standard, the corresponding data are also presented in Table 2.

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

		BIPM	**CH 6.1**		**VSL**	**5cc**	
		values	uncertainty [(1)]		values	uncertainty [(1)]	
			100 u_{iA}	100 u_{iB}		100 u_{iA}	100 u_{iB}
Physical Constants							
ρ_{air}	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	0.9989	0.01	0.04	0.999	–	0.05
$s_{c,a}$	ratio of mass stopping powers	1.0010	–	0.11 [(3)]	1.0006	–	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	0.0031	–	0.02	0.0032	–	0.03
Correction factors:							
k_g	re-absorption of radiative loss	0.9996	–	0.01	–	–	–
k_s	recombination losses	1.0022	0.01	0.02	1.0031	–	0.01
k_h	humidity	0.9970	–	0.03	0.9970	–	0.03
k_{st}	stem scattering	1.0000	0.01	–	0.9990	–	0.05
k_{wall}	wall attenuation and scattering	1.0011	–	– [(4)]	1.0214	–	0.08
k_{an}	axial non-uniformity	1.0020	–	– [(4)]	1.0000	–	0.09
k_{rn}	radial non-uniformity	1.0015	–	0.02	1.0000	–	0.02
Measurement of I / V							
V	chamber volume / cm^3	6.8855	–	0.08 [(4)]	4.845	–	0.10
I	ionization current / pA		0.01	0.02		0.01	0.02
Relative standard uncertainty							
quadratic summation			0.02	0.15		0.01	0.21
combined uncertainty			**0.15**			**0.21**	

[(1)] Expressed as one standard deviation
u_{iA} represents the type A relative standard uncertainty estimated by statistical methods,
u_{iB} 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 $s_{c,a}$ 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)

Correction factors for the VSL standard

– *Recombination loss (k_s)*

At VSL the correction factor for recombination losses was determined using the method described by Boutillon (1998).

– *Stem scattering (k_{st})*

The correction for stem scatter for the standard determined using a dummy stem is 0.9990 with a relative standard uncertainty of 5 parts in 10^4 (Hofmeester 1975).

– *Attenuation and scattering in the chamber wall (k_{wall}) and axial non-uniformity (k_{an})*

The effect of attenuation and scatter in the graphite wall of the standard and the axial non-uniformity correction were determined at VSL using the Penelope Monte Carlo code. Simulations were validated with measurements for a range of chamber wall thicknesses and chamber orientations. This method is described by van Dijk (2007).

– *Polarity effect (k_{pol})*

At VSL, only positive polarity to the outer electrode is applied and a correction factor of 0.9999(1) is introduced to account for the polarity effect.

– *Volume determination*

The standard 5cc is a spherical graphite-walled cavity ionization chamber constructed by the RIV (Bilthoven, the Nederlands) and its effective volume was determined with mercury and was reported as 4.845(5) cm^3 (Hofmeester 1975).

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.

The reference conditions at VSL are the same as those at the BIPM.

Reference values

The BIPM reference air-kerma rate $\dot{K}_{BIPM}$ is taken as the mean of the four measurements made around the period of the comparison. The $\dot{K}_{BIPM}$ values refer to an evacuated path length between source and standard corrected to the reference date of 2017-01-01, 0 h UTC. The correction for air attenuation between source and standard uses the ambient air density at the time of the measurement and the air mass attenuation coefficient 0.0602 $cm^2\ g^{-1}$ for ^{60}Co. The half-life of ^{60}Co was taken as 1925.21 days (u = 0.29 days) (Bé *et al* 2006).
At the VSL, the reference air-kerma rate $\dot{K}_{VSL}$ was determined within 2 days of the transfer chambers measurements. The $\dot{K}_{VSL}$ value refers to an evacuated path length between source and standard corrected to the reference date of 2018-01-01, 0 h UTC. At the VSL the half life of ^{60}Co was taken to be 1925.5 days (IAEA TECDOC619). The correction for air attenuation between source and standard uses the ambient air density at the time of the measurement and the air mass attenuation coefficient 0.0570 $cm^2\ g^{-1}$ for ^{60}Co.

Beam characteristics

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

Table 3. Characteristics of the ^{60}Co beams at VSL and the BIPM

^{60}Co beam	Nominal $\dot{K}$ / mGy s^{-1}	Source dimensions / mm		Scatter contribution in terms of energy fluence	Field size at 1 m
		diameter	length		
VSL source	7.1	20.3	29.9	Not evaluated	10 cm × 10 cm
BIPM source	2.6	20	14	21 %	10 cm × 10 cm

4. Comparison procedure

The comparison of the VSL and BIPM standards was made indirectly using the calibration coefficients $N_{K,\mathrm{lab}}$ for the two transfer chambers given by:

$$N_{K,\mathrm{lab}} = \dot{K}_{\mathrm{lab}} / I_{\mathrm{lab}} \tag{6}$$

where $\dot{K}_{\mathrm{lab}}$ is the air kerma rate and I_{lab} is the ionization current of a transfer chamber measured at the VSL or the BIPM. The current is corrected for the effects and influences described in this section.

The ionization chambers NE 2611, serial number 120, and NE 2571, serial number 3235, belonging to the VSL, are the transfer chambers used for this comparison. Their main characteristics are listed in Table 1. These chambers were calibrated at the VSL before and after the measurements at the BIPM.

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

Positioning

At each laboratory the chambers were positioned with the stem perpendicular to the beam direction and with the appropriate marking on the stem facing the source.

Applied voltage and polarity

A collecting voltage of 200 V and 300 V (positive polarity) was applied to the outer electrode of VSL NE 2611 and NE 2571 transfer chambers, respectively, at least 40 min before any measurements were made.

Charge and leakage measurements

The charge Q collected by the VSL chambers was measured at the BIPM using a Keithley electrometer, model 642. The source was exposed during the entire measurement series and the charge was collected for the appropriate, electronically controlled, time interval. A pre-irradiation was made for at least 40 min before any measurements. The leakage current was measured before and after each series of measurements. The relative leakage correction was less than 5×10^{-4}. At the VSL the transfer chambers were measured with a Keithley 6517A. The chambers were pre-irradiated for at least 30 minutes. At the VSL the relative leakage correction was less than 1×10^{-3}.

Radial non-uniformity correction

No correction for the non-uniformity of the beam was made as this correction would be similar at both laboratories. At the BIPM, this correction is less than 3×10^{-4}. A relative uncertainty component of 2×10^{-4} is included in Table 5.

Ion recombination

No correction for recombination was applied to the measured current as volume recombination is negligible at a kerma rate of less than 15 mGy s^{-1} for this chamber type at this polarizing voltage, and the initial recombination loss will be the same in the two laboratories; a relative uncertainty component of 5×10^{-4} is included in Table 5.

Ambient conditions

During a series of measurements, the air temperature is measured for each current measurement and was stable to better than 0.03 °C at the BIPM. At the VSL, the air temperature was stable to better than 0.05 ^{o}C. The ionization current is corrected to the reference conditions of 293.15 K and 101.325 kPa at both laboratories. The relative humidity is controlled at (50 ± 5) % at both laboratories.

5. Results of the comparison

The transfer chambers were set-up and measured in the BIPM ^{60}Co beam on two separate occasions. The results were reproducible to better than 1×10^{-4}. Table 4 lists the relevant values of N_K at the stated reference conditions (293.15 K and 101.325 kPa) and the final results of the indirect comparison. The uncertainties associated with the calibration of the transfer chambers are presented in Table 5.

Table 4. Results of the indirect comparison

Transfer chamber	$N_{K,\mathrm{VSL}}$ / Gy µC^{-1}			$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	R_K	u_c
	pre-BIPM	post-BIPM	overall mean			
NE 2611 sn 120	94.702	94.700	94.701	95.083	0.9960	0.0021
NE 2571 sn 3235	41.147	41.165	41.156	41.299	0.9965	0.0021
				Mean value	0.9963	0.0021

Table 5. Uncertainties associated with the indirect comparison

Transfer chamber	BIPM		VSL	
Relative standard uncertainty	100 u_{iA}	100 u_{iB}	100 u_{iA}	100 u_{iB}
Air kerma rate	0.02	0.15	0.01	0.21
Ionization current for the transfer chambers	0.01	0.02	0.01	0.04
Distance	0.01	–		0.02
Reproducibility	0.01	–	0.01	
$N_{K,\mathrm{lab}}$	0.03	0.15	0.02	0.22
Indirect comparison result	100 u_{iA}		100 u_{iB}	
$N_{K,\mathrm{VSL}}$ / $N_{K,\mathrm{BIPM}}$ (1)	0.03		0.19	
Ion recombination	–		0.05	
Radial non-uniformity	–		0.02	
Different chambers	0.03		–	
$N_{K,\mathrm{VSL}}$ / $N_{K,\mathrm{BIPM}}$	$u_c = 0.0021$			

(1) The combined standard uncertainty of the comparison result takes into account correlation in the type B uncertainties associated with the physical constants and the humidity correction

Some of the uncertainties in $\dot{K}$ that appear in both the BIPM and VSL determinations (such as air density, W/e, μ_{en}/ρ, $\bar{g}$, $\bar{s}_{c,a}$ and k_h) cancel each other when evaluating the uncertainty of R_K.

The mean ratio of the air kerma calibration coefficients of the transfer chambers determined by the VSL and the BIPM taken from Table 4 is 0.9963 with a combined standard uncertainty, u_c, of 0.0021.

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 x_i with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is the relative difference $D_i = (K_i - K_{BIPM,i}) / K_{BIPM,i} = x_i - 1$ and its expanded uncertainty $U_i = 2\,u_i$.

The results for D_i and U_i are usually expressed in mGy/Gy. Table 6 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. These data are presented graphically in Figure 1 which includes the linked results of the corresponding regional key comparisons COOMET.RI(I)-K1, EUROMET.RI(I)-K1, APMP.RI(I)-K1 and APMP.RI(I)-K1. For clarity, the RMO comparisons are plotted in the second graph.

When required, the degree of equivalence between two laboratories *i* and *j* can be evaluated as the difference $D_{ij} = D_i - D_j = x_i - x_j$ and its expanded uncertainty $U_{ij} = 2\,u_{ij}$, both expressed in mGy/Gy. In evaluating u_{ij}, account should be taken of correlation between u_i and u_j. Following the advice of the CCRI(I) in 2011, results for D_{ij} and U_{ij} are no longer published in the KCDB.

Table 6. 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. The tables are formatted as they appear in the BIPM key comparison database

BIPM.RI(I)-K1

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
DMDM	2.5	3.6
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
ENEA-INMRI	-0.1	4.4
NIM	-0.3	5.4
IST-LPSR	2.6	3.4
MKEH	4.7	3.8

SCK•CEN	**2.1**	5.2
SMU	**4.2**	5.4
VSL	**-3.7**	4.2

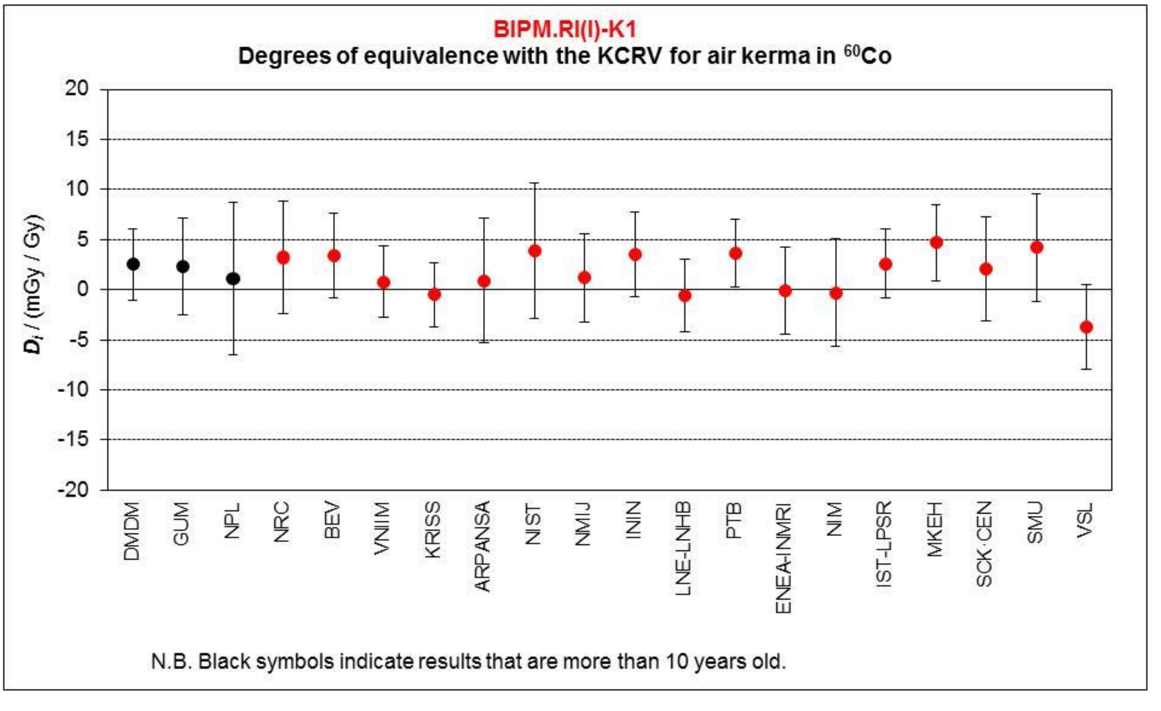
COOMET.RI(I)-K1 (2006) – EURAMET.RI(I)-K1 (2005 to 2008) –
APMP.RI(I)-K1 (2004 to 2006) – APMP.RI(I)-K1.1 (2009 to 2012) – EURAMET.RI(I)-K1.2 (2017)

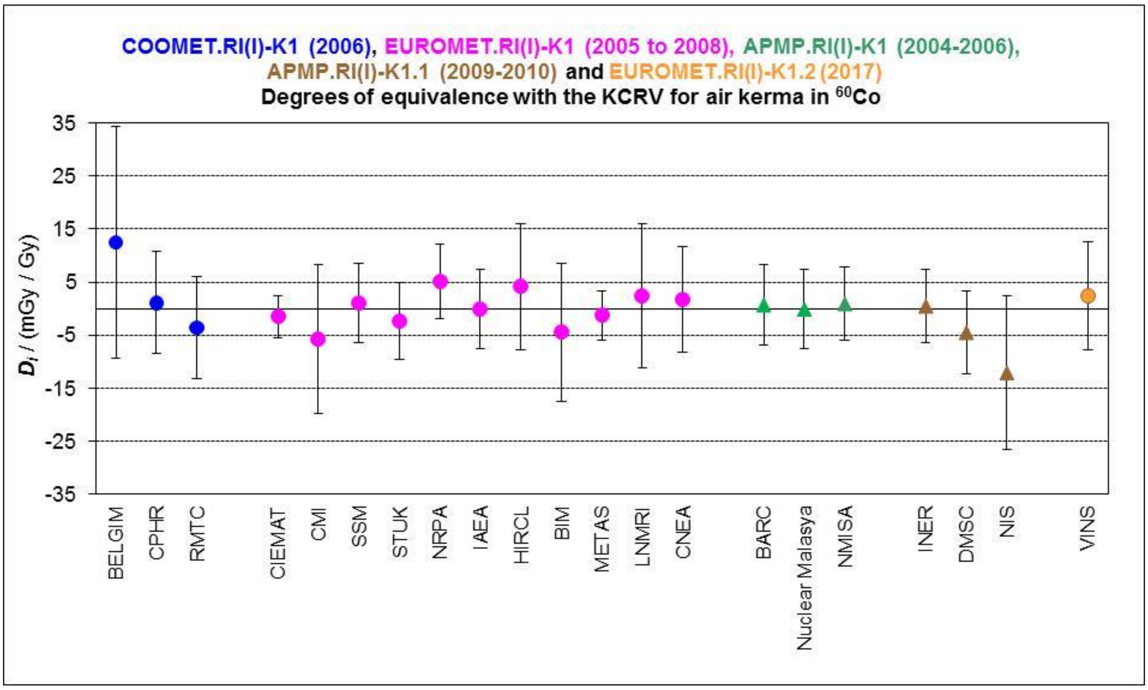
Lab *i*	***D*ᵢ / (mGy/Gy)**	***U*ᵢ / (mGy/Gy)**
CIEMAT	**-1.5**	3.9
CMI	**-5.8**	14.1
SSM	**1.0**	7.5
STUK	**-2.3**	7.3
NRPA	**5.1**	7.1
IAEA	**0.0**	7.5
HIRCL	**4.2**	11.9
BIM	**-4.5**	13.0
METAS	**-1.3**	4.6
LNMRI	**2.4**	13.7
CNEA	**1.8**	10.0

Lab *i*	***D*ᵢ / (mGy/Gy)**	***U*ᵢ / (mGy/Gy)**
BelGIM	**12.5**	21.8
CPHR	**1.1**	9.7
RMTC	**-3.6**	9.7
BARC	**0.7**	**7.6**
Nuclear Malasya	**-0.1**	**7.4**
NMISA	**0.9**	**6.9**
INER	**0.5**	6.9
DMSC	**-4.5**	7.8
NIS	**-12.1**	14.6
VINS	**2.4**	10.2

Note that the data presented in Table 10, while correct at the time of publication of the present report, become out-of-date as NMIs carry out new comparisons. The formal results under the CIPM MRA are those available in the key comparison database.

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 VSL and the BIPM was made indirectly in 2005. The comparison result was 0.9985 (22).

For the present comparison, the VSL standard for air kerma in ^{60}Co gamma radiation compared with the BIPM air-kerma standard gives a comparison result of 0.9963 (21).

In 2005, the VSL result was based on the average of the air kerma rate taken over 5 years, whereas for the present comparison the result is based on the air kerma rate measured during the calibration of the transfer chamber. If the same procedure is applied to the 2005 comparison, the result would decrease by 1.5×10^{-3}, which is in better agreement with the present result.

The VSL standard agrees within the expanded uncertainty with all the NMIs that have taken part in the BIPM.RI(I)-K1 ongoing key comparison for air kerma standards in ^{60}Co gamma-ray beam.

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