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

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Abstract

A key comparison of the standards for air kerma of the National Physical Laboratory (NPL), United Kingdom and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in November 2017. The comparison result, based on the calibration coefficients for two transfer chambers and expressed as a ratio of the NPL and the BIPM standards for air kerma, is 0.9996 with a combined standard uncertainty of 3.0×10^{-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 National Physical Laboratory (NPL), United Kingdom, and of the Bureau International des Poids et Mesures (BIPM) was carried out in November 2017 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2007 (Kessler *et al* 2010) published in the BIPM key comparison database (KCDB 2019) under the reference BIPM.RI(I)-K1. The comparison was undertaken using two transfer ionisation chambers type NE 2611A of the NPL. 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 NPL in June 2018.

2. Details of the standards

The primary standard for air kerma of the NPL is a set of two spherical graphite-walled cavity ionization chambers of nominal 5 cm^3 (Bass *et al* 2017). These two chambers replace the previous primary standard, which consisted of three cylindrical graphite-walled cavity ionization chambers of nominal volume 1.5 cm^3.

The details of the NPL standard and the transfer chambers are given 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 NPL standard for air kerma and the transfer chamber

NPL chambers	Nominal values	Primary standard	NE 2611A
Chamber	Inner diameter / mm	21.2	7.5
	Cavity length / mm	-	9.2
	Wall thickness / mm	4.0	0.5
Electrode	Diameter / mm	3.0	1.7
	Length / mm	9.2	6.4
Volume	Air cavity / cm^3	5.0	0.3
Wall	Materials	Graphite	Graphite
	Density / g cm^{-3}	1.7	1.7
Insulator		PEEK [(1)]	---
Applied voltage	Polarity	500 V	200 V [(2)]

[(1)] Polyether ether ketone

[(2)] Negative 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

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

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 (Allisy-Roberts *et al* 2011) are also included in Table 2.

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		values CH 6.1	uncertainty (1) 100 u_{iA}	100 u_{iB}
Physical Constants				
ρ_{air}	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
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
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)

NPL formalism

The air kerma rate is determined at the NPL using the relation

$$\dot{K} = I \cdot N_K \quad (2)$$

where N_K is the air kerma sensitivity coefficient of the standard given by

$$N_K = \frac{1}{\rho_{air} V} \frac{W}{e} \frac{F}{1-\bar{g}} k_h \quad (3)$$

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,
k_h is the correction to 50% relative humidity

and

$$F = F'.k_{\text{an}}.k_{\text{rn}}.k_{\text{stem}}.k_{\text{pol}} \qquad (4)$$

The product $k_{an}.k_{rn}$, the axial and radial non-uniformity correction factors, respectively, are calculated using Monte Carlo.
The factor k_{stem} is the correction for stem scatter for the standard and k_{pol} is the correction for the polarity effect.
F' is the ratio of the dose to the chamber volume in the absence of the chamber, and what is actually measured, the chamber response. Monte Carlo simulations were used to determine *F'*, and is expressed as

$$F' = s_{\text{c,a}}.k_{\text{fl}}.(\mu_{\text{en}}/\rho)_{\text{a,c}}.k_{\text{wall}} \qquad (5)$$

The factor k_{wall} corrects for the photon attenuation and scatter in the wall of the standard and k_{fl} is the fluence perturbation factor that corrects for the perturbation of the electron fluence by the air cavity.

The values used for the physical constants, correction factors and volume of the standards are listed in Table 3, together with the associated uncertainties. The uncertainties associated with the determination of air kerma are listed in Table 4.

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

NPL		values		uncertainty (1)	
		PS5-1	PS5-2	100 u_{iA}	100 u_{iB}
Physical Constants and correction factors					
ρ_{air}	dry air density (2) / kg m^{-3}	1.2046		–	0.01
W/e	mean energy per charge / J C^{-1}	33.97		–	0.15
g_{a}	fraction of energy lost in radiative processes	0.0031		–	0.02
k_h	humidity	0.997		–	0.05
F'	ratio of the dose to the air and dose to the cavity	1.0227	1.0233	0.11	0.18
$k_{an}.k_{rn}$	axial and radial non-uniformity	1.0008		0.14	0.10
k_{stem}	stem scattering	0.9978		0.01	0.05
k_{pol}	polarity effect	1.0001		0.01	–
V	chamber volume / cm^3	4.9164	4.9123	–	0.01
Relative standard uncertainty N_K					
quadratic summation				0.18	0.22
combined uncertainty				**0.28**	

(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 293.15 K

Table 4. Uncertainties associated with the determination of air kerma at the NPL

NPL		uncertainty	
		100 u_{iA}	100 u_{iB}
Correction factors			
N_K	primary standard air kerma sensitivity coefficient	0.18	0.22
k_{elec}	electrometer current calibration	–	0.05
k_{res}	electrometer resolution	–	0.03
k_{ion}	ion recombination	0.05	–
$I_{leakage}$	leakage current	0.05	–
P	pressure	0.02	–
T	temperature	0.04	–
$R_{angular}$	angular response change	0.03	–
R	repeatability	0.05	–
Relative standard uncertainty *K*			
quadratic summation		0.21	0.23
combined uncertainty		**0.31**	

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 the NPL are the same as those at the BIPM.

Reference values

The BIPM reference air-kerma rate $\dot{K}_{\mathrm{BIPM}}$ is taken as the mean of the 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 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 1925.19 days (u = 0.29 days) (Bé *et al* 2006).

The transfer standard calibration coefficients reported by the NPL are based on the average value of $\dot{K}_{NPL}$ determined from measurements made before and after calibration of the transfer chambers using the two cavity ionisation chambers that make up the primary standard.

Beam characteristics

The characteristics of the BIPM and NPL beams are given in Table 5.

Table 5. Characteristics of the ^{60}Co beams at the NPL 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		
NPL source	18.3	20	20	17 %	10 cm × 10 cm
BIPM source	2.6	20	14	21 %	10 cm × 10 cm

4. Comparison procedure

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

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

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

The ionization chambers NE 2611, serial numbers 163 and 134, belonging to the NPL, are the transfer chambers used for this comparison. Their main characteristics are listed in Table 1. These chambers were calibrated at the NPL 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 (negative polarity) was applied to the outer electrode of the NPL transfer chambers at least 40 min before any measurements were made.

Charge and leakage measurements

The charge Q collected by the NPL 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. Leakage current was measured before and after each series of measurements. The relative leakage correction was less than 1×10^{-3}.

At the NPL, the ionisation current I is measured directly using a Keithley electrometer, model 6514. A pre-irradiation exposure of at least 4 Gy was made for each chamber before any measurements. Leakage current was measured before and after each series of measurements. The relative leakage correction was less than 1×10^{-3}.

Radial non-uniformity correction

At the BIPM and the NPL no correction for the non-uniformity of the beam is made as this correction would be less than 1×10^{-4} for the NE 2611 with an uncertainty of 2×10^{-4}.

No radial non-uniformity correction was applied and a relative uncertainty component of 2×10^{-4} is included in Table 7.

Ion recombination

No correction for recombination was applied to the measured current as volume recombination is negligible at a kerma rate of less than 20 mGy s^{-1} for this chamber type at this polarizing voltage, and the initial recombination loss will be the same in the two laboratories; and a relative uncertainty component of 5×10^{-4} is included in Table 7.

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 NPL, the air temperature was stable to better than 0.1^{o}C. The ionization current is corrected to the reference conditions of 293.15 K and 101.325 kPa at both laboratories.
Relative humidity is controlled at (50 ± 5) % at the BIPM. At the NPL, relative humidity is controlled, and calibrations were made in the range 20 to 70 % RH.

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 6 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 7.

Table 6. Results of the indirect comparison

Transfer chamber NE2611A	$N_{K,\mathrm{NPL}}$ / Gy µC^{-1}			$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	R_K	u_c
	pre-BIPM	post-BIPM	overall mean			
sn 134	96.00	95.93	95.965	96.013	0.9995	0.0030
sn 163	94.34	94.30	94.320	94.356	0.9996	0.0030
				Mean value	0.9996	0.0030

Table 7. Uncertainties associated with the indirect comparison

Transfer chamber	BIPM		NPL	
Relative standard uncertainty	100 u_{iA}	100 u_{iB}	100 u_{iA}	100 u_{iB}
Air kerma rate	0.02	0.15	–	0.30
Ionization current for the transfer chambers	0.01	0.02	–	
Distance	0.01	–	–	0.05
Reproducibility	0.01	–	0.05	–
Electrometer calibration	–	–	–	0.05
Electrometer resolution	–	–	–	0.03
Temperature	–	–	0.04	–
Pressure	–	–	0.02	–
$N_{K,\mathrm{lab}}$	0.03	0.15	0.08	0.32

Table 7. (cont)

Indirect comparison result	$100\ u_{i\mathrm{A}}$	$100\ u_{i\mathrm{B}}$
$N_{K,\mathrm{NPL}}$ / $N_{K,\mathrm{BIPM}}$ [(1)]	0.22	0.20
Ion recombination	–	0.05
Radial non-uniformity	–	0.02
Different chambers	0.01	–
$N_{K,\mathrm{NPL}}$ / $N_{K,\mathrm{BIPM}}$	u_c = 0.0030	

(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 the NPL determinations (such as air density, W/e, μ_en/ρ, $\bar{g}$, $\bar{s}_\mathrm{c,a}$ 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 NPL and the BIPM taken from Table 6 is 0.9996 with a combined standard uncertainty, u_c, of 0.0030.

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 $D_i = (K_i - K_{\mathrm{BIPM},i}) / K_{\mathrm{BIPM},i} = x_i - 1$ and its expanded uncertainty $U_i = 2\ u_i$.

The results for D_i and U_i are usually expressed in mGy/Gy. Table 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. These data are presented graphically in Figure 1.

Note that the data presented in Table 8, 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.

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 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

Lab *i*	D_i / (mGy / Gy)	U_i
DMDM	2.5	3.6
GUM	2.3	4.8
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	6.8
NMIJ	1.2	4.4
ININ	3.5	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
NPL	-0.4	6.0
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
CIEMAT	-1.5	4.0
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

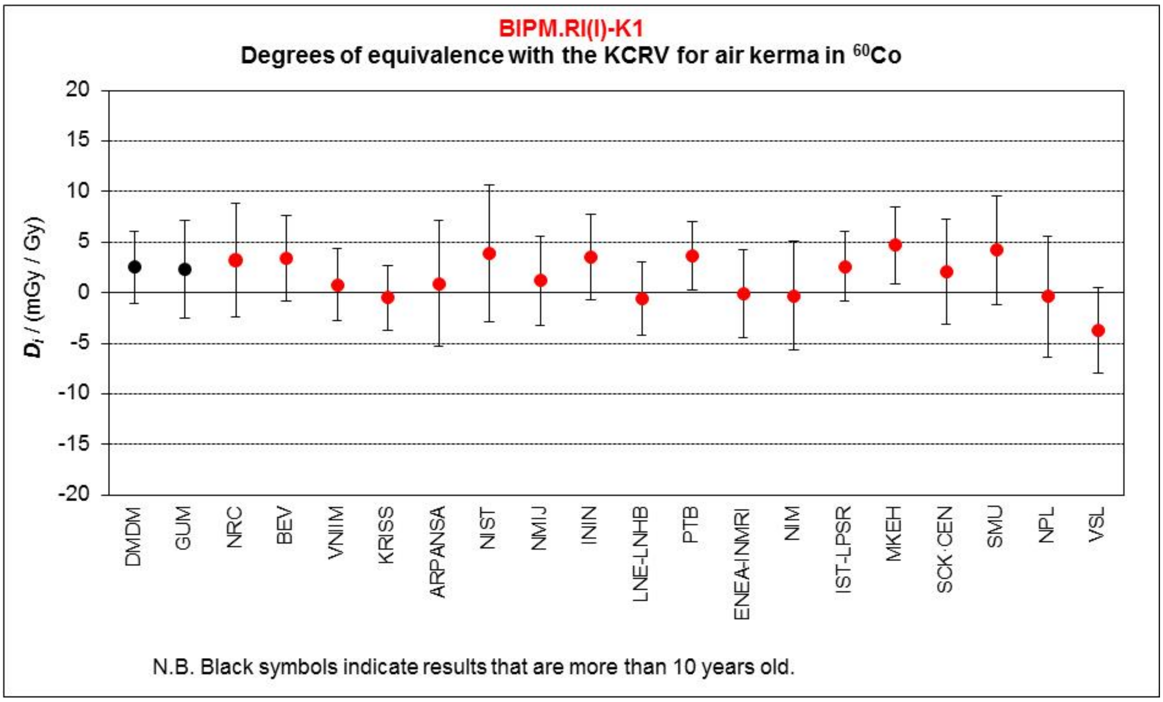
Lab *i*	D_i / (mGy / Gy)	U_i
BELGIM	12.5	21.8
CPHR	1.1	9.6
RMTC	-3.6	9.6

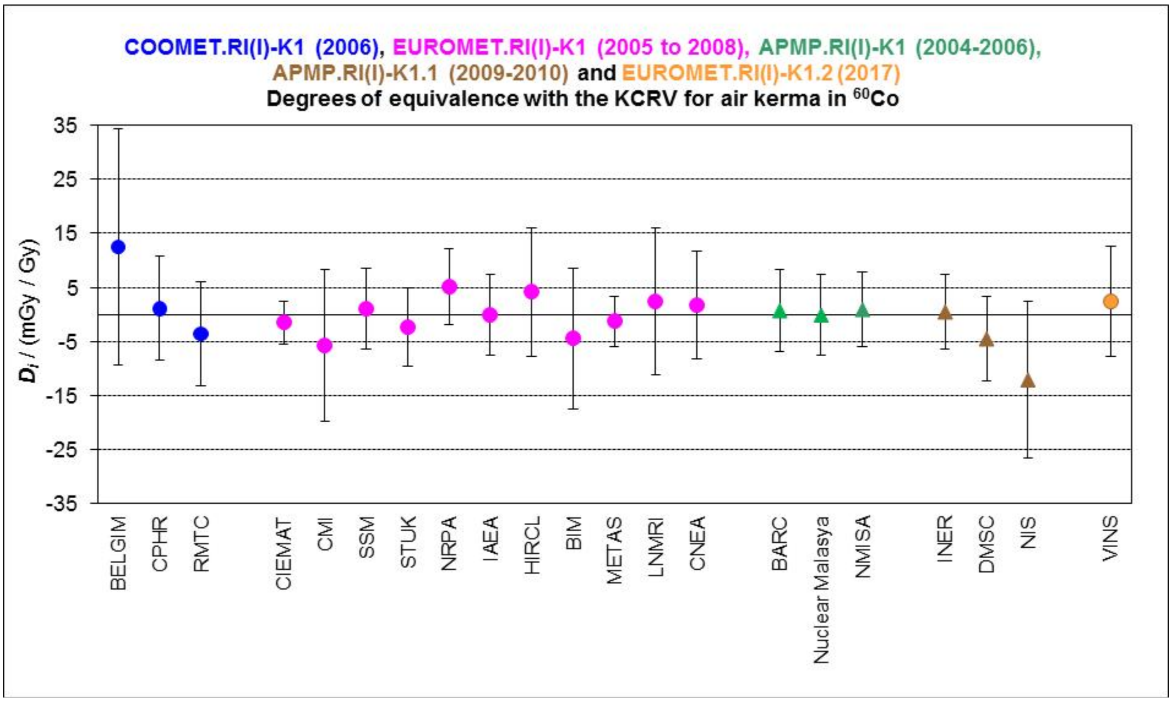
BARC	0.7	7.6
Nuclear Malasya	-0.1	7.4
NMISA	0.9	6.9

INER	0.5	6.9
DMSC	-4.5	7.8
NIS	-12.1	14.6

VINS	2.4	10.2

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 NPL and of the BIPM was made indirectly in 2007. The comparison result, based on a different primary standard for the NPL and the same primary standard for the BIPM, is 1.0011 (38).

For the present comparison, the new NPL standard for air kerma in ^{60}Co gamma radiation compared with the BIPM air-kerma standard gives a comparison result of 0.9996 (30), in agreement within the uncertainties with the previous comparison result. The NPL standard agrees within the expanded uncertainty with all the NMIs having 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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