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

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Abstract

A comparison of the standards for air kerma of the Instituto Superior Técnico, Laboratório de Proteção e Segurança Radiológica (IST-LPSR), Portugal and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in December 2015. The comparison result, evaluated as a ratio of the IST-LPSR and the BIPM standards for air kerma, is 1.0026 with a combined standard uncertainty of 1.7×10^{-3}. The results for an indirect comparison made at the same time are consistent with the direct results at the level of 1.1 parts in 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

A comparison of the standards for air kerma of the Instituto Superior Técnico (IST-LPSR), Portugal and of the Bureau International des Poids et Mesures (BIPM) was carried out in December 2015 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2005 (Allisy-Roberts *et al* 2009) published in the BIPM key comparison database (KCDB 2015) under the reference BIPM.RI(I)-K1. The comparison was undertaken using the primary standard of the IST-LPSR. An indirect comparison was also made using a thimble ionization chamber as a transfer instrument. The final results were supplied by the IST-LPSR in May and October 2017.

2. Details of the standards

The IST-LPSR standard CC01 serial number 134 for air kerma is a cylindrical graphite-walled cavity ionization chamber constructed by the Österreichisches Forschungszentrum (ÖFS), Austria. The details of the IST-LPSR standard and the transfer chamber 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 IST-LPSR standard for air kerma and the transfer chamber

IST-LPSR chambers		CCO1-134	NE 2571-2148
Chamber	Outer height / mm	19	26.5
	Outer diameter / mm	18.92	7.0
	Wall thickness / mm	3.98	0.35
Electrode	Diameter / mm	2.015	1.0
	Height / mm	8.970	21.0
Volume	Air cavity / cm^3	1.0161 (1)	0.68
Wall	Materials	High purity moulded graphite ATJ	graphite
	Density	1.80 $g\cdot cm^{-3}$	-
	Impurity	$< 8 \times 10^{-4}$	-
Insulator		PTFE Teflon	PCTFE
Applied voltage	Polarity	250 V (2)	-300 V (3)

(1) measured by the Bundesamt für Eich-und Vermessungswesen (BEV), Austria

(2) both polarities applied at the BIPM; measurements at the IST-LPSR are made using positive polarity with an applied correction k_{pol} = 0.9998 (1)

(3) negative polarity applied to the outer electrode at the BIPM, equivalent to positive polarity applied to the collector at the IST-LPSR

3. Determination of the air kerma

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

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

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 standards and the associated uncertainties for the BIPM (Allisy-Roberts *et al* 2011) and the IST-LPSR standards are also included in Table 2.

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

		BIPM	CH 6.1		IST/LPSR	CC01-134	
		values	uncertainty (1)		values	uncertainty (1)	
			100 u_{iA}	100 u_{iB}		100 u_{iA}	100 u_{iB}
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	0.9989	0.01	0.04	0.9985	–	0.05
$s_{c,a}$	ratio of mass stopping powers	1.0010	–	0.11 (3)	1.0010	–	0.11
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	–	0.02
Correction factors:							
k_g	re-absorption of radiative loss	0.9996	–	0.01	–	–	–
k_s	recombination losses	1.0022	0.01	0.02	1.0024 (4)	0.01	0.01
k_h	humidity	0.9970	–	0.03	0.9970	–	0.03
k_{st}	stem scattering	1.0000	0.01	–	1.0000	0.03	–
k_{wall}	wall attenuation and scattering	1.0011	–	– (5)	1.0220	0.01	0.05
k_{an}	axial non-uniformity	1.0020	–	– (5)	1.0000	–	0.07
k_{rn}	radial non-uniformity	1.0015	–	0.02	1.0002	–	0.02
k_{pol}	polarity	–	–	–	– (6)	–	–
Measurement of I / V							
V	chamber volume / cm^3	6.8855	–	0.08 (5)	1.0161	–	0.10 (7)
I	ionization current / pA		0.01	0.02		0.01	0.02
Relative standard uncertainty							
quadratic summation			0.02	0.15		0.03	0.19
combined uncertainty			**0.15**			**0.19**	

(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 $\bar{s}_{c,a}$ and W/e

(4) Determined at the IST-LPSR

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

(6) At the IST-LPSR, k_{pol} = 0.9998(1)

(7) As determined through dimensional measurements by the BEV

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).

The correction factors for the IST-LPSR standards are described in the previous comparison report (Allisy-Roberts *et al* 2009). Since the last direct comparison, the IST-

LPSR introduced a new value for the stem scattering correction factor which implies a slight increase in the air kerma determination of 3 parts in 10^4 and they changed the correction for ion recombination evaluated using their own determination (see Section 4). The other correction factors and volume determination remain unchanged.

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 IST-LPSR are the same to 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 2015-01-01, 0 h UTC. The half-life of ^{60}Co was taken as 1925.19 days (u = 0.29 days) (Bé *et al* 2006).

The $\dot{K}_{\mathrm{IST\text{-}LPSR}}$ value is the mean of the measurements made over a period from 2015-12-03 until 2016-01-04. By convention it is given at the reference date of 2016-01-01 T 00:00:00 UTC using the same half-life value for ^{60}Co.

Beam characteristics

The characteristics of the BIPM and IST-LPSR beams are given in Table 3.

Table 3. Characteristics of the ^{60}Co beams at the IST-LPSR 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		
IST-LPSR source	0.9	20	-	19 % [(1)]	10 cm × 10 cm
BIPM source	3.3	20	14	21 %	10 cm × 10 cm

(1) taken from Mora *et al* (1999)

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 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

CC01-134

At the BIPM a collecting voltage of 250 V (both polarities) was applied to the outer electrode of the standard at least 30 min before any measurements were made; no correction for polarity was applied. At the IST-LPSR, the same collecting voltage (positive polarity) was applied to the collector of the standard and a correction of 0.9998 (1) is applied to account for the polarity effect. A value of 0.9995 (1) was determined at the BIPM for this chamber.

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At the BIPM a collecting voltage of 300 V (negative polarity) was applied to the outer electrode of the chamber. At the IST-LPSR, the same collecting voltage (positive polarity) was applied to the collector of the chamber; no correction was applied for polarity at either laboratory.

Volume recombination

CC01-134

The correction factor for the IST-LPSR standard for losses due to ion recombination was determined at the BIPM during the previous comparison (Allisy-Roberts *et al* 2009). Using the BIPM determination, the correction factor for ion recombination at 250 V is 1.0020. The IST-LPSR also determined this correction factor. Using the IST-LPSR determination, a correction factor of 1.0024 (1) for ion recombination at 250 V was applied to the IST-LPSR standard in the BIPM beam.

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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. No correction for recombination was applied and a relative uncertainty component of 2×10^{-4} is included in Table 8.

Radial non-uniformity correction

CC01-134

The applied correction factor k_{rn} for the radial non-uniformity of the BIPM beam over the cross-section of the IST-LPSR standard is 1.0002 (1).

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For the transfer chamber, this correction is less than 2×10^{-4} at the BIPM; at the IST-LPSR, this correction would be less than 4×10^{-4}. No radial non-uniformity correction was applied for the indirect comparison and a relative uncertainty component of 2×10^{-4} is included in Table 8.

Charge and leakage measurements

At the IST-LPSR different electrometers are used for the primary standard and the transfer chamber; the primary standard is connected to the PTW UNIDOS, model 10001-10568 and the transfer instrument, to a PTW UNIDOS electrometer, model 10002-20033. At the BIPM, the charge is measured 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. The chambers were pre-irradiated for at least 60 min (≈ 3 Gy) at the IST-LPSR, and for at least 30 min (≈ 6 Gy) at the BIPM before any measurements were made. Leakage current was measured before and after each series of measurements. The ionization current measured for each chamber was corrected for the leakage current; at both laboratories, this correction was less than 2×10^{-4} in relative value.

Ambient conditions

During a series of measurements, the air temperature is measured for each current measurement and was stable to better than 0.01 °C at the BIPM. At the IST-LPSR, the air temperature was stable to better than 0.2 ^{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 IST-LPSR, relative humidity is normally in the range (50 ± 10) %. Consequently, no correction for humidity is applied to the ionization current measured at either laboratory.

5. Results of the comparison

The IST-LPSR primary standard was set-up and measured in the BIPM ^{60}Co beam on two separate occasions. The results were reproducible to better than 1×10^{-4}. The values of the ionization currents measured at the BIPM for the IST-LPSR 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 ^{60}Co source.

Table 4. The experimental results from the IST-LPSR standards in the BIPM beam

IST-LPSR standard	I_+ *and* I_- /pA		I_{mean} / pA
CC01-134	125.8502	-125.7144	125.7823
	125.8511	-125.7137	125.7824
Mean current			125.782

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

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

and is presented in Table 5. The combined standard uncertainty u_c for the comparison result R_K is presented in Table 6.

Table 5. Final result of the IST-LPSR/BIPM comparison of standards for ^{60}Co air kerma

	$\dot{K}_{\mathrm{IST\text{-}LPSR}}$ / Gy s^{-1}	$\dot{K}_{\mathrm{BIPM}}$ / mGy s^{-1}	R_K	u_c
CC01-134	3.3310	3.3223	1.0026	0.0017

Table 6. Uncertainties associated with the comparison result

Relative standard uncertainty	100 u_{iA}	100 u_{iB}
$\dot{K}_{\mathrm{IST\text{-}LPSR}} / \dot{K}_{\mathrm{BIPM}}$	0.04	0.16[a]
Relative standard uncertainty of R_K	0.04	0.16
	$u_c = 0.0017$	

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

The ratio of the values of the air kerma rate determined by the IST-LPSR and the BIPM standards taken from Table 5 is 1.0026 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 IST-LPSR 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.

For the transfer chamber the comparison result is evaluated as the ratio of the calibration coefficients $N_{K,\mathrm{lab}}$ determined at each laboratory. The calibration coefficient is given by

$$N_{K,\mathrm{lab}} = \dot{K}_{\mathrm{lab}} / I_{\mathrm{lab}} \qquad (3)$$

where $\dot{K}_{\mathrm{lab}}$ is the air kerma rate at each lab and I_{lab} is the ionization current of a transfer chamber measured at the IST-LPSR or the BIPM. At the time of the comparison, the IST-LPSR provided a set of calibration coefficients that gave rise to an indirect comparison result 4.7 parts in 10^3 lower than the direct result. Many studies were carried out at the IST-LPSR during 2016 to find the source of this discrepancy. No explanation was found. In 2017, the UNIDOS electrometers were sent to the manufacturer for check and recalibration. Repeated measurements were made and the new calibration coefficients differ from the first set by 3.5×10^{-3}, thereby largely eliminating the discrepancy.

Table 7 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 8.

Table 7. Results of the indirect comparison

Transfer chamber NE 2571-2148	$N_{K,\mathrm{IST\text{-}LPSR}}$ / Gy µC^{-1} pre-BIPM	$N_{K,\mathrm{IST\text{-}LPSR}}$ / Gy µC^{-1} post-BIPM	$N_{K,\mathrm{IST\text{-}LPSR}}$ / Gy µC^{-1} overall mean	$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	R_K	u_c
2015-2016	41.405	41.445	41.425	41.508	0.9980	0.0022
2017*	41.570				1.0015	

* after recalibration of the electrometer

Table 8. Uncertainties associated with the indirect comparison

Transfer chamber	BIPM		IST-LPSR	
Relative standard uncertainty	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
Air kerma rate	0.02	0.15	0.04	0.19
Ionization current for the transfer chambers	0.01	0.02	0.01	0.02
Distance	0.01	–	–	0.10
Reproducibility	0.02	–	0.05	–
Field size	–	–	–	0.03
Temperature and pressure	–	–	–	0.02
$N_{K,\mathrm{lab}}$	0.03	0.15	0.06	0.21
Indirect comparison result	100 $u_{i\mathrm{A}}$		100 $u_{i\mathrm{B}}$	
$N_{K,\mathrm{IST\text{-}LPSR}}$ / $N_{K,\mathrm{BIPM}}$ (1)	0.07		0.20	
Ion recombination	–		0.02	
Radial non-uniformity	–		0.02	
Short-term stability	0.05		–	
$N_{K,\mathrm{IST\text{-}LPSR}}$ / $N_{K,\mathrm{BIPM}}$	u_c = 0.0022			

(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

The calibration coefficients measured at the IST-LPSR before and after the BIPM give rise to an uncertainty of 5 parts in 10^4 for the short-term stability of the chamber. The 2017 result of the indirect comparison taken from Table 7 is 1.0015 with a combined standard uncertainty, u_c, of 0.0022. This result is in agreement with the direct comparison at the level of 1.1 parts in 10^3, which is within the standard uncertainty of the calibration procedure. The result of the direct comparison is used to evaluate the degrees of equivalence for entry in the KCDB.

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 9 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.

Table 9. 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	U_i
	/ (mGy/Gy)	
DMDM	2.5	3.6
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
ENEA-INMRI	-0.1	4.4
NIM	-0.3	5.4
SCK•CEN	2.1	5.2
IST-LPSR	2.6	3.4

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)

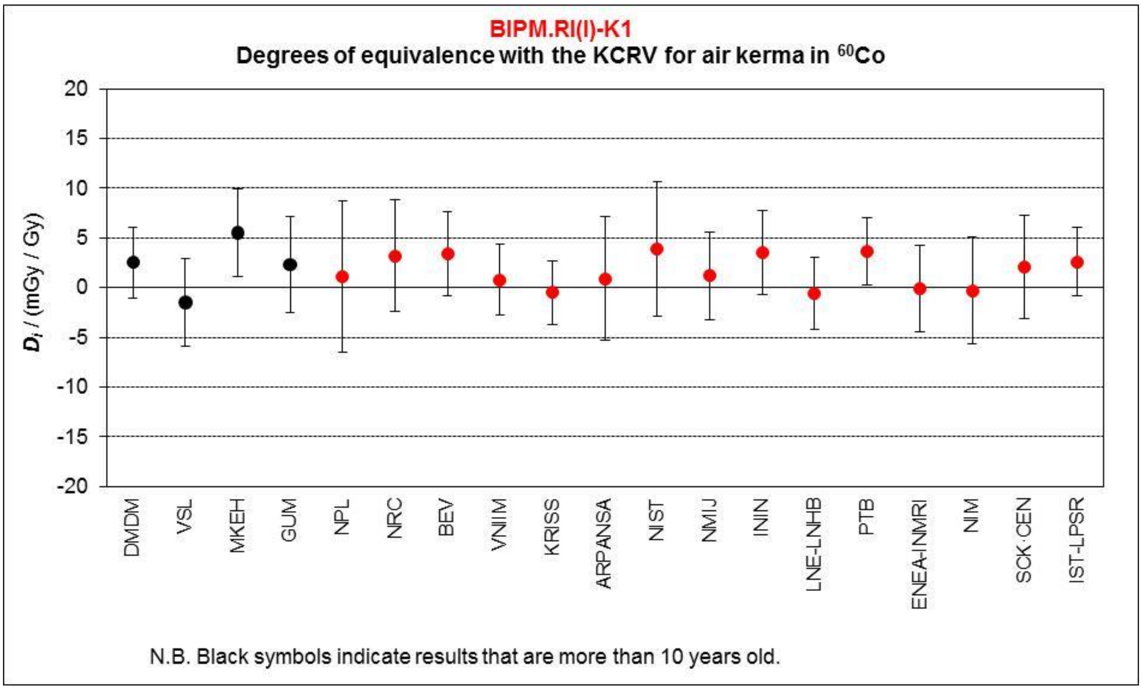
Lab i	D_i	U_i
	/ (mGy/Gy)	
CIEMAT	-1.5	3.9
CMI	-5.8	14.1
SSM	1.0	7.5
STUK	-2.3	7.3
NRPA	5.1	7.1
SMU	5.2	6.5
IAEA	0.0	7.5
HIRCL	4.2	11.9
BIM	-4.5	13.0
METAS	-1.3	4.6
LNMRI	2.4	13.7
CNEA	1.8	10.0

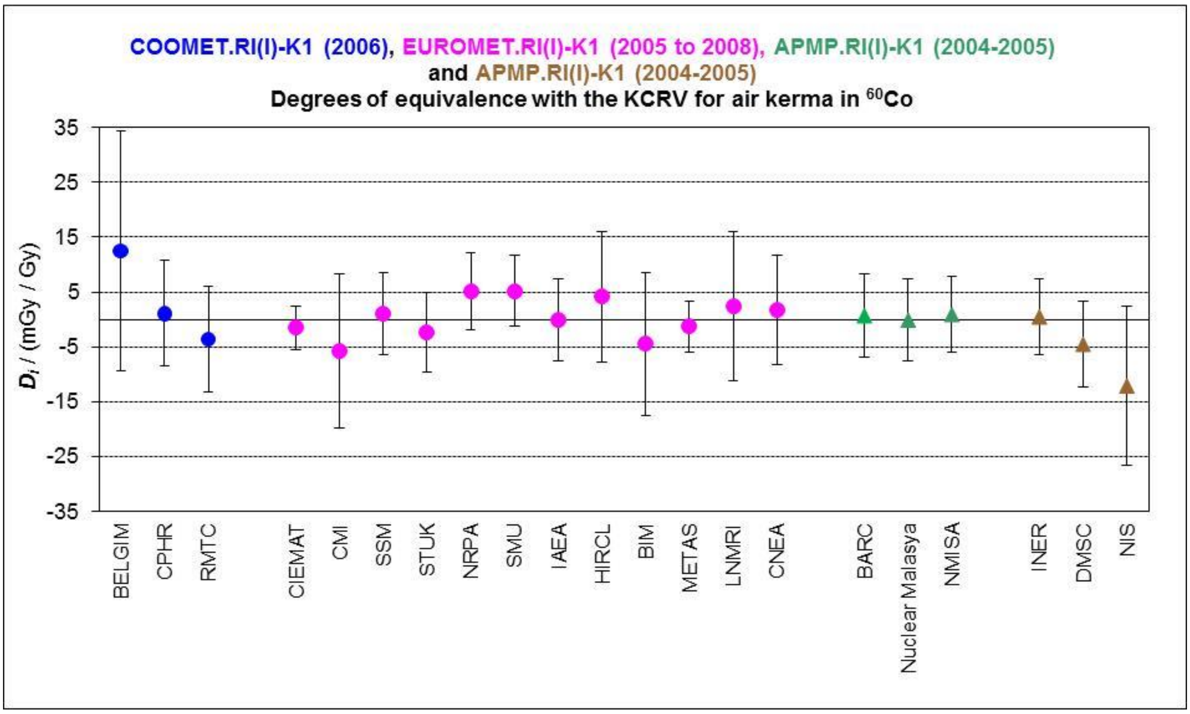
Lab i	D_i	U_i
	/ (mGy/Gy)	
BelGIM	12.5	21.8
CPHR	1.1	9.7
RMTC	-3.6	9.7
BARC	0.7	7.6
Nuclear Malasya	-0.1	7.4
NMISA	0.9	6.9
INER	0.5	6.9
DMSC	-4.5	7.8
NIS	-12.1	14.6

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.

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.

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 IST-LPSR and of the BIPM was made directly in 2004. That comparison result, based on the same primary standard, is 1.0015 (17) when updated for the changes made to the BIPM standard.

For the present comparison, the IST-LPSR standard for air kerma in ^{60}Co gamma radiation compared with the BIPM air-kerma standard gives a comparison result of 1.0026 (17) and so is in agreement within the uncertainties with the previous comparison result. The indirect and direct comparison results are in agreement at the level of 1.1 parts in 10^3, which is within the uncertainty of the calibration procedure.

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