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

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Abstract

A comparison of the standards for air kerma of the Hungarian Trade Licensing Office (MKEH), Hungary and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in March 2016. The comparison result, evaluated as a ratio of the MKEH and the BIPM standards for air kerma, is 1.0047 with a combined standard uncertainty of 1.9×10^{-3}. The results for an indirect comparison made at the same time are consistent with the direct results at the level of 2.6 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 new comparison of the standards for air kerma of the Hungarian Trade Licensing Office (MKEH)[a], Hungary and of the Bureau International des Poids et Mesures (BIPM) was carried out in March 2016 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2006 (Kessler *et al* 2006) published in the BIPM key comparison database (KCDB 2017) under the reference BIPM.RI(I)-K1. The comparison was undertaken using two primary standards of the MKEH. An indirect comparison was also made using a thimble ionization chamber as a transfer instrument. Final comments on the report were received from the MKEH in October 2017.

2. Details of the standards

The MKEH standard for air kerma is a set of three nominally identical cavity ionization chambers constructed at the MKEH (type ND 1005, serial number 7707, 7708 and 7714) in

[a] Since the comparison was made, the name of the MKEH has changed to Budapest Főváros Kormányhivatala (BFKH)

1977. Two of these standards were used for the present comparison and their main characteristics are given in Table 1, as well as the details of the transfer chamber.

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 MKEH standard for air kerma and the transfer chamber

MKEH chambers		ND 1005 - 7707	ND 1005 - 7708	NE 2561 - 084
Chamber	Outer height / mm	19	19	8.5 mm
	Outer diameter / mm	19	19	17.5 mm
	Wall thickness / mm	4	4	0.5 mm
Electrode	Diameter / mm	2	2	1.7 mm
	Height / mm	8.97	8.97	6.4 mm
Volume	Air cavity / cm^3	1.0182	1.0227	0.3 cm^3
Wall	Materials	Ultra-pure graphite EK51 Ringsdorf		graphite
	Density	1.75		–
	Impurity	impurities less than 1.5×10^{-4}		–
Insulator		PTFE Teflon		–
Applied voltage	Polarity	250 V (1)		200 V (2)

(1) both polarities

(2) positive polarity applied to the outer electrode

3. Determination of the air kerma

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

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

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,

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

$\bar{s}_{c,a}$ 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 MKEH standards are also included in Table 2.

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

		BIPM	CH 6.1		MKEH	ND 1005	
		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)]	1.0007	–	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	1.0019	0.01	0.01
k_h	humidity	0.9970	–	0.03	0.9970	–	0.03
k_{st}	stem scattering	1.0000	0.01	–	0.9998	0.05	
k_{wall}	wall attenuation and scattering	1.0011	–	– [(4)]	1.0216	0.01	0.07
k_{an}	axial non-uniformity	1.0020	–	– [(4)]	0.9998	0.04	0.08
k_{rn}	radial non-uniformity	1.0015	–	0.02	1.0002	–	0.02
k_{pol}	polarity	–	–	–	–	–	–
Measurement of I / V							
V	chamber volume / cm^3	6.8855	–	0.08 [(4)]	[(5)]	0.10	0.05
I	ionization current / pA		0.01	0.02		0.01	0.02
Relative standard uncertainty							
quadratic summation			0.02	0.15		0.12	0.17
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 reference temperature 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)

(5) See Table 1

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 MKEH standards are described in the previous comparison report (Kessler *et al* 2006). No change to the standards has been made since the last direct comparison.

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.

At the MKEH, the reference distance is 0.9 m and a circular field of diameter 11.3 cm (Table 3).

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 2016-01-01, 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 $\mathrm{cm}^2\ \mathrm{g}^{-1}$ for ^{60}Co. The half-life of ^{60}Co was taken as 1925.19 days (u = 0.29 days) (Bé *et al* 2006).

Beam characteristics

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

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

^{60}Co beam	Nominal $\dot{K}$ / mGy s^{-1} (2016-01-01)	Source dimensions / mm		Scatter contribution in terms of energy fluence	Field size at reference distance
		diameter	length		
MKEH source	2.4	20	20	25%	11.3 cm diameter
BIPM source	2.9	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 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

ND 1005

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 MKEH, the same collecting voltage (positive polarity) was applied to the collector of the standard; the polarity effect measured at the

MKEH is negligible and assumed to be unity. A value of 0.9995 (1) was determined at the BIPM for both standards.

NE 2561

At both laboratories a collecting voltage of 200 V (positive polarity) was applied to the outer electrode of the chamber; no corrections was applied for polarity at either laboratory.

Volume recombination

ND 1005

The correction factor for the MKEH standard for losses due to ion recombination was determined at the BIPM during the previous comparison (Kessler *et al* 2006). A correction factor of 1.0019 (1) for ion recombination at 250 V was applied to the MKEH standard in the BIPM beam.

NE 2561

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

ND 1005

The correction factor k_{rn} for the radial non-uniformity of the BIPM beam over the cross-section of the MKEH standards is estimated to be 1.0002 (1).

NE 2561

For the transfer chamber, this correction is less than 1×10^{-4} at the BIPM and at the MKEH, this correction is 1.0003; no radial non-uniformity correction was applied and a relative uncertainty component of 2×10^{-4} is included in Table 8.

Charge and leakage measurements

The charge Q collected for each chamber is measured at the BIPM using a Keithley electrometer, model 642. The chambers were pre-irradiated for at least 30 min (≈ 5 Gy) before any measurements were made. The ionization current measured was corrected for the leakage current; this correction, in relative value, was less than 1×10^{-4} for the primary standards and around 3×10^{-4} for the transfer chamber.

At the MKEH the charge is measured using a Keithley electrometer, model 19517/705. The chambers were pre-irradiated for at least 40 min before any measurements were made. The ionization current measured was corrected for the leakage current; this correction, in relative value, was less than 1×10^{-4} for the primary standards and less than 5×10^{-4} for the transfer chamber.

Ambient conditions

During a series of measurements, the air temperature is measured for each current measurement; at both laboratories, the temperature was stable to better than 0.01 °C. The ionization currents are normalized to the reference temperature (293.15 K for the transfer chamber) and 101.325 kPa at both laboratories.

Relative humidity is controlled at (50 ± 5) % at the BIPM. At the MKEH, 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 MKEH primary standards 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}. The values of the ionization currents measured at the BIPM for the MKEH standards 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 MKEH standards in the BIPM beam

MKEH standard	I_+ *and* I_- /pA		I_{mean} / pA	I_{mean} / pA
ND 1005 - 7707	110.96	-110.84	110.90	110.89
	110.94	-110.82	110.88	
ND 1005 - 7708	111.44	-111.34	111.39	111.39
	111.44	-111.33	111.39	

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

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

and is presented in Table 5.

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

ND 1005	$\dot{K}_{\mathrm{MKEH}}$ / mGy s^{-1}	$\dot{K}_{\mathrm{BIPM}}$ / mGy s^{-1}	R_K	u_c
7707	2.9266	2.9132	1.0046	0.0019
7708	2.9267		1.0047	

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

Table 6. Uncertainties associated with the comparison result

Relative standard uncertainty	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
$\dot{K}_{\mathrm{MKEH}} / \dot{K}_{\mathrm{BIPM}}$	0.12	0.14[a]
Relative standard uncertainty of R_K	0.12	0.14
	u_c = 0.19	

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

The mean ratio of the values of the air kerma rate determined by the MKEH and the BIPM standards taken from Table 5 is 1.0047 with a combined standard uncertainty, u_c, of 0.0019. Some of the uncertainties in $\dot{K}$ that appear in both the BIPM and the MKEH 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

$$N_{K,\mathrm{lab}} = \dot{K}_{\mathrm{lab}} / I_{\mathrm{lab}} \tag{3}$$

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 MKEH or the BIPM. 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	$N_{K,\mathrm{MKEH}}$ / Gy µC^{-1} pre-BIPM	$N_{K,\mathrm{MKEH}}$ / Gy µC^{-1} post-BIPM	$N_{K,\mathrm{MKEH}}$ / Gy µC^{-1} overall mean	$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	R_K	u_c
NE 2561-84	94.02	94.04	94.03	93.83	1.0021	0.0020

Table 8. Uncertainties associated with the indirect comparison

Transfer chamber	BIPM		MKEH	
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	0.12	0.17
Ionization current for the transfer chambers	0.01	0.02	0.03	0.05
Distance	0.01	–	–	0.02
Short-term stability	0.02	–	–	–
$N_{K,\mathrm{lab}}$	0.03	0.15	0.12	0.18
Indirect comparison result	100 $u_{i\mathrm{A}}$		100 $u_{i\mathrm{B}}$	
$N_{K,\mathrm{MKEH}}$ / $N_{K,\mathrm{BIPM}}$ (1)	0.13		0.16	
Ion recombination	–		0.02	
Radial non-uniformity	–		0.02	
$N_{K,\mathrm{MKEH}}$ / $N_{K,\mathrm{BIPM}}$	u_c = 0.0020			

(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 values $N_{K,\mathrm{MKEH}}$ measured for the NE 2561 before and after the measurements at the BIPM give rise to a relative standard uncertainty of 2 parts in 10^4, taken as a representation of the stability of the transfer chamber. The result of the indirect comparison taken from Table 7 is 1.0021 with a combined standard uncertainty, u_c, of 0.0020. This result is in agreement with the direct comparison at the level of 2.6 parts in 10^3, which is slightly higher than 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.

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.

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

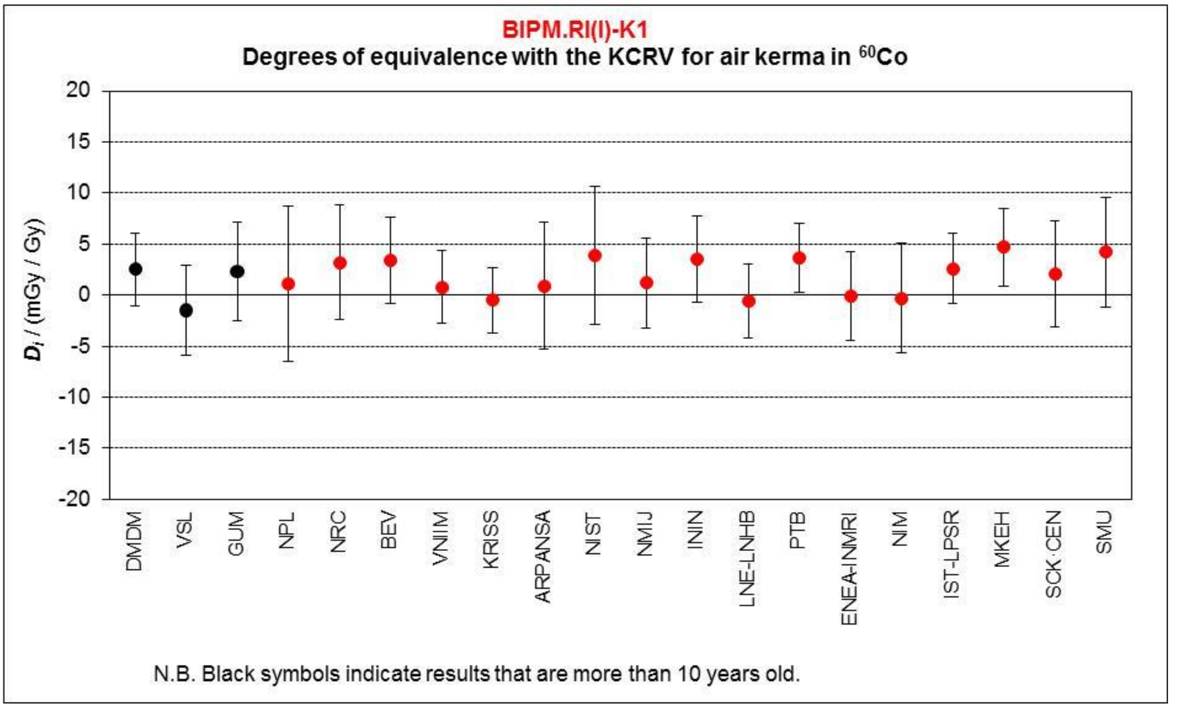
Lab *i*	D_i	U_i
	/ (mGy/Gy)	
DMDM	2.5	3.6
VSL	-1.5	4.4
GUM	2.3	4.8
NPL	1.1	7.6
NRC	3.2	5.6
BEV	3.4	4.2
VNIIM	0.8	3.6
KRISS	-0.5	3.2
ARPANSA	0.9	6.2
NIST	3.9	6.4
NMIJ	1.2	4.4
ININ	3.6	4.2
LNE-LNHB	-0.6	3.6
PTB	3.6	3.4
ENEA-INMRI	-0.1	4.4
NIM	-0.3	5.4
IST-LPSR	2.6	3.4
SCK•CEN	2.1	5.2
SMU	4.2	5.4
MKEH	4.7	3.8

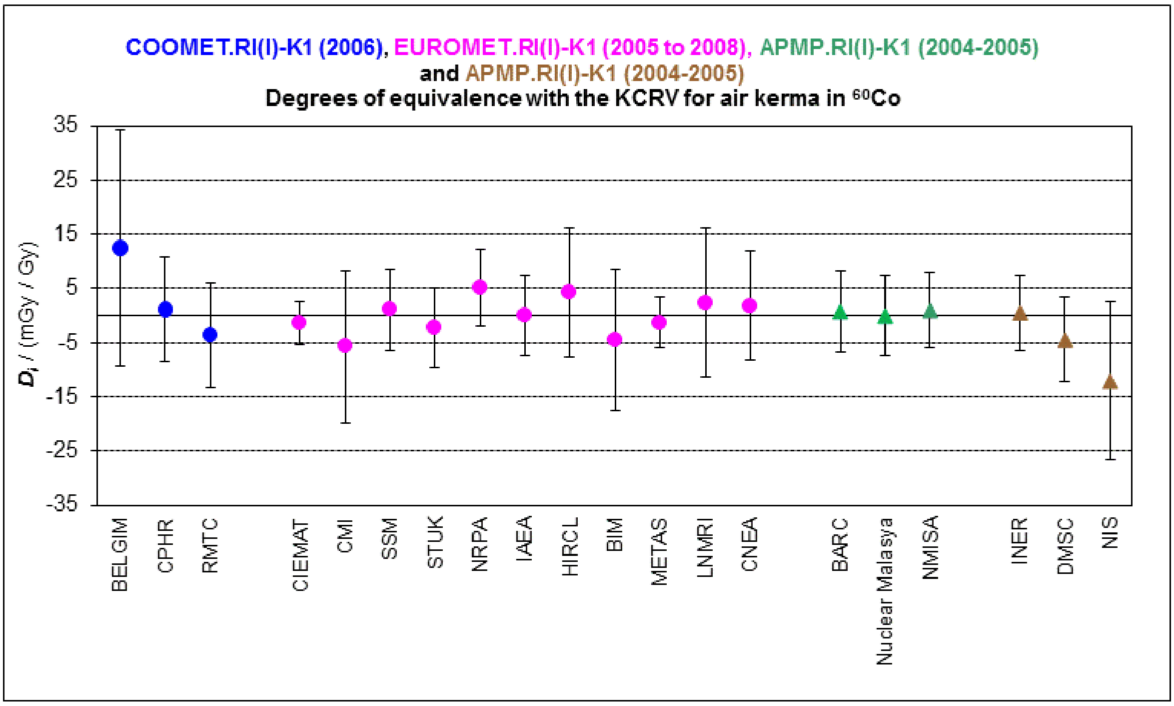
COOMET.RI(I)-K1 (2006) – EURAMET.RI(I)-K1 (2005 to 2008) – APMP.RI(I)-K1 (2004 to 2006) – APMP.RI(I)-K1.1 (2009 to 2012)

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

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 MKEH and of the BIPM was made directly in 2006 using the BIPM Picker beam. The comparison result, based on the same primary standards, is 1.0055 (18) when updated for the changes made to the BIPM standard. At that time, supplementary measurements were made using the CIS Bio beam, adopted as the BIPM reference beam in 2007. The comparison result using the latter beam is 1.0046(19).

For the present comparison, the MKEH standard for air kerma in ^{60}Co gamma radiation compared with the BIPM air-kerma standard gives a comparison result of 1.0047 (19) 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 2.6 parts in 10^3, which is within the expanded standard uncertainty of the calibration procedure.

References

Allisy-Roberts P J, Burns D and Kessler C 2011 Measuring conditions and uncertainties for the comparison and calibration of national dosimetric standards at the BIPM *Rapport BIPM-11/04*

Allisy P J, Burns D and Andreo P 2009 International framework of traceability for radiation dosimetry quantities *Metrologia* **46(2)** S1-S8

Bé M-M, Chisté V, Dulieu C, Browne E, Baglin C, Chechev V, Kuzmenco N, Helmer R, Kondev F, MacMahon D and Lee K B 2006 Table of Radionuclides (Vol. 3 – A = 3 to 244) *Monographie BIPM-5*.

Boutillon M and Niatel M T 1973 Study of a graphite cavity chamber for absolute measurements of ^{60}Co gamma rays *Metrologia* **9** 139-146

Burns D, Allisy P J and Kessler C 2007 Re-evaluation of the BIPM international standard for air kerma in ^{60}Co gamma radiation *Metrologia* **44** L53-L56

CCEMRI 1985 *Comité Consultatif pour les Étalons de Mesures des Rayonnements Ionisants*, Constantes physiques pour les étalons de mesure de rayonnement, 1985, *CCEMRI Section (I)* **11** R45

CIPM MRA 1999 *Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes*, International Committee for Weights and Measures, 1999, 45 pp. http://www.bipm.org/en/cipm-mra/cipm-mra-documents/

KCDB 2015 BIPM Key Comparison Database KCDB ^{60}Co air kerma comparisons BIPM.RI(I)-K1

Kessler C, Roger P, Burns D, Allisy-Roberts P J, Machula G and Rabus H 2006 Comparison of the standards for air kerma of the OMH and the BIPM for ^{60}Co gamma radiation *Rapport BIPM-06/07*