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

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Abstract

A new key comparison of the standards for air kerma of the Główny Urząd Miar (GUM), Poland and the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM during June-July 2020. The comparison result, evaluated as a ratio of the GUM and the BIPM standards for air kerma, is 1.0039 with a combined standard uncertainty of 3 parts in 10^3. The result agrees within the uncertainties with the direct comparison carried out in 2006. 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 Główny Urząd Miar (GUM), Poland, and the Bureau International des Poids et Mesures (BIPM) was carried out during the period June-July 2020 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2006 (Allisy-Roberts *et al.* 2011) published in the BIPM key comparison database (KCDB 2021) under the reference BIPM.RI(I)-K1. The comparison was carried out after the implementation of the recommendations of ICRU Report 90 (ICRU 2016) at both laboratories and the adoption of a second primary standard by the GUM.
The indirect comparison was made using two thimble-type ionization chambers as transfer instruments. The final results were supplied by the GUM in February 2021.

2. Details of the standards and the transfer chambers

The standard for air kerma of the GUM are two graphite-walled cavity ionization chambers referenced as ND 1005, serial number 8303 and IGNAS-IC16A, serial number 001, constructed, respectively, at the Orszagos Mérésügyi Hivatal (now known as the Budapest Főváros Kormányhivatala – BFKH), Budapest, Hungary in 1983 and at the GUM in 2016 (Szymko *et al.* 2019). The main characteristics are given in Table 1. Details of the transfer chambers used for the indirect comparison are also included in Table 1.

Table 1. Characteristics of the GUM standards for air kerma and of the transfer chambers used for the indirect comparison

GUM standards and transfer chambers		ND1005 - 8303	IC16A - 001	NE 2571 - 2676	NE 2561 - 301
Chamber	Outer height / mm	19.0	19.0	24 (inner length)	9.7
	Outer diameter / mm	19.0	19.0	7.0	8.5
	Wall thickness / mm	4.0	4.0	0.36	0.5
Electrode	Diameter / mm	2.0	2.0	1.0	1.7 (hollow)
	Height / mm	10.0	10.0	20.6	6.4
Volume	Air cavity / cm^3	1.013	1.0191	0.7	0.3
Wall	Materials	ultrapure graphite	ultrapure graphite EDM-3	graphite	
	Density	1.71	1.81	1.7	
	Impurity	99.997 %	99.997 %		
Insulator		polyethylene	polyethylene		
Voltage applied to outer electrode / V		+250	+250	+300	+200

The new GUM primary standard IGNAS-IC16A serial number 001 is a graphite-walled cavity ionization chamber constructed at the GUM. The design is similar to the ND1005 constructed at the formerly OMH (Hungary), except the stem diameter (9 mm thicker than the ND1005 stem) and material (different aluminum alloy). The chamber body was assembled from three graphite components: the base, the central electrode, and the cylindrical cap. No glue was used in the assembly, components were tight-fitting. The wall and central electrode are made of ultra-pure graphite.

A high-accuracy coordinate measuring machine was used at the GUM to measure the three components before assembly for the determination of the cavity volume (Szymko *et al*. 2019).

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, Burns and Kessler 2018). The main characteristics are presented in Table 2.

Table 2. Characteristics of the BIPM standard

BIPM standard		CH6.2
Cavity	Diameter / mm	45.010
	Thickness / mm	5.161
	Measuring volume / cm^3	6.8855
Electrode	Diameter / mm	41.029
	Thickness / mm	1.005
Wall	Thickness / mm	2.9
	Material	Graphite
	Density / g cm^{-3}	1.85
Voltage applied to outer electrode / V		± 80

3. Determination of the air kerma

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

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

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 mass stopping powers of graphite and air,
$\prod k_i$	is the product of the correction factors to be applied to the standard.

The air kerma determined at the GUM is the unweighted mean of the results obtained using the two standards.

Physical data and correction factors

The values used for the physical constants, the correction factors, the volume of the primary standards entering in equation (1), and the associated uncertainties are given in Table 3. For the BIPM standards, these values are given in Kessler and Burns 2018.

– *Physical data and wall effect correction factors for the GUM standards*

The ND1005 standard is fully described in the previous comparison report (Allisy-Roberts *et al.* 2011). The correction factors for wall effects and beam non-uniformity (k_{wall}, k_{an} and k_{rn}) for the IC16A standard and the physical constants mass stopping power $s_{\mathrm{c,a}}$, mass energy absorption coefficients $(\mu_{\mathrm{en}}/\rho)_{\mathrm{air,c}}$ and bremsstrahlung losses g_{air} were calculated using the EGSnrc Monte Carlo codes (Rogers *et al.* 2000, Rogers *et al*. 2003):

- CAVRZnrc for the calculation of the factors k_{wall} and k_{an} that correct for the wall effects and the axial non-uniformity of the beam, respectively,
- SPRRZnrc for the mass stopping power ratio calculation, and
- code 'g' for the evaluation of the mass energy absorption coefficient ratio and the mean fraction of electron energy lost in radiative processes.

Default settings for the transport parameters and spectrum files for ^{60}Co that are provided with the codes were used, the number of iterations was set to 10^9 (Szymko *et al*. 2019).

– *Stem scattering for the IC16A*

The correction factor for the stem scatter k_{stem} was determined experimentally by adding a dummy stem of similar dimensions and material. The diameter of the stem is 13.2 mm, 9 mm thicker than the stem of the ND1005 standard; this would explain a correction for the IC16A standard 1.3 parts in 10^3 greater than the one for the ND1005.

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

		BIPM			GUM			
		values	uncertainty (1) 100 u_{iA}	100 u_{iB}	values		uncertainty 100 u_{iA}	100 u_{iB}
Physical Constants								
ρ_{air}	dry air density (2) / kg m^{-3}	1.2930	–	0.01	1.2045		–	0.01
$(\mu_{en}/\rho)_{a.c}$	ratio of mass energy-absorption coefficients	0.9989	0.01	0.04	0.9991		–	0.05
$s_{c.a}$	ratio of mass stopping powers	0.9928	–	0.08 (3)	0.9926		–	0.08 (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	0.0036		–	0.02
Correction factors		**CH6.2**			**ND1005-8303**	**IC16A-001**		
k_g	re-absorption of radiative loss	0.9996	–	0.01	–			
k_s	recombination losses	1.0019	0.01	0.02	1.0022	1.0017	0.01	–
k_{pol}	polarity	– (4)	–	–	0.9986	0.9994	0.03	–
k_h	humidity	0.9970	–	0.03	0.997		–	0.03
k_{st}	stem scattering	1.0000	0.01	–	0.9998	0.9985	0.03	–
k_{wall}	wall attenuation and scattering	1.0011	–	– (5)	1.0206	1.0220	0.01	0.07
k_{an}	axial non-uniformity	1.0020	–	– (5)	1.0002		0.02	0.08
k_{rn}	radial non-uniformity	1.0015	–	0.02	1.0002		0.02	–
Measurement of *I* / *V*								
V	chamber volume / cm^3	6.8855	–	0.08 (5)	1.013	1.0191		0.15 (6)
I	ionization current / pA	–	0.01	0.02			0.02	0.10
Relative standard uncertainty								
quadratic summation			0.02	0.13			0.06	0.23
combined uncertainty			**0.13**				**0.24** (7)	

(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 kPa and 273.15 K and at 101.325 kPa and 293.15 K for the BIPM and the GUM standards, respectively

(3) Combined uncertainty for the product of $s_{c,a}$ and W/e adopted at the BIPM from January 2019 (Burns and Kessler 2018); similarly at the GUM, adopting the recommendations of the ICRU 90

(4) No correction is applied; the mean current measured applying both polarities is used in the determination of *K*

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

(6) Uncertainties for the IC16A standard; the uncertainty for the ND1005 is 0.20

(7) Combined relative uncertainty using the ND1005 standard is 0.27

– *Ion recombination for the GUM standards*

The ion recombination correction factors reported by the GUM at the time of the comparison were 1.0008 (7) and 1.0000 (7) for the ND1005 and the IC16A standards, respectively. These correction factors were evaluated by the GUM using the two-voltage method, as described in the IAEA technical protocol (IAEA 2000). During the direct comparison carried out at the BIPM in 2006 using the ND1005 standard, the ion recombination correction was determined by the BIPM using the Niatel method (Boutillon 1998) described in Allisy-Roberts *et al.* (2011). This method allows to calculate the contribution from the initial and the volume recombination. For these cylindrical-type chambers, the initial recombination represents typically a correction to the measured current of 2 parts in 10^3, being independent of the beam dose rate. Considering the discrepancy observed between the values determined by each laboratory, the GUM re-evaluated this correction using the Niatel method, giving a result similar to the one determined in 2006.

As explained in the IAEA technical protocol, the two-voltage method is based on a linear dependence of the inverse of the measured current and the inverse of the applied voltage, which describes the effect of general recombination in continuous beams. The presence of initial recombination disturbs this linearity, which is not negligible for this chamber type.

The new correction factors shown in Table 2 represent an increase of 1.8 parts in 10^3 of the air kerma and calibration coefficient determinations.

Reference conditions

The reference conditions for the air-kerma determination at the BIPM are described by Kessler and Burns (2018):

– 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 GUM 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 2020-01-01, 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 attenuation coefficient 0.0602 $\mathrm{cm^2\ g^{-1}}$ for ^{60}Co. The half-life of ^{60}Co used for the decay correction was taken as 1925.21 days (u = 0.29 days) (Bé *et al* 2006).

At the GUM, measurements do not refer to an evacuated path length, that is, they are not corrected for air attenuation between source and chambers. The $\dot{K}_{\mathrm{GUM}}$ value is taken as the mean of measurements made around of the period of the comparison. By convention it is given at the reference date of 2020-01-01 using the same half-life value for the decay correction as the BIPM.

Beam characteristics

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

Table 4. Characteristics of the ^{60}Co beams at the GUM 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		
GUM TeraBALT T-100	11.3	20	26.9	21 %	10 cm × 10 cm
BIPM Theratron 1000	6.4	20	14	21 %	10 cm × 10 cm

4. Comparison procedure

The comparison of the GUM and BIPM standards was made indirectly using the calibration coefficients for two transfer chambers given by

$$N_{K,\mathrm{lab}} = \dot{K}_{\mathrm{lab}}/I_{\mathrm{lab}}\ , \tag{2}$$

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

The ionization chambers NE 2571, serial number 2676 and NE 2561, serial number 301, belonging to the GUM, were used as the transfer chambers for this comparison. Their main characteristics are listed in Table 1. These chambers were calibrated at the GUM before and after the measurements at the BIPM.

The experimental method for measurements at the BIPM is described by Kessler and Burns (2018); the essential details for the determination of the calibration coefficients $N_{K,\mathrm{lab}}$ for the transfer chambers 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 300 V and 200 V (positive polarity) was applied to the outer electrode of the NE 2571 and NE 2561 transfer chambers, respectively, at least 40 min before any measurements were made.

Charge and leakage measurements

The charge Q collected by the transfer 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 (~13 Gy). Leakage current was measured before and after each series of measurements. The relative leakage correction was less than 2 parts in 10^4. At the GUM, the charge Q collected by the transfer chambers was measured in the same way as the BIPM using a Keithley electrometer, model 6517A. A pre-irradiation of at least 11 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 part in 10^4.

Radial non-uniformity correction

The correction for the radial non-uniformity of the beam for the transfer chambers is less than 3 parts in 10^4 at the BIPM and a similar correction is appropriate for the GUM beam. No radial non-uniformity correction was applied and a relative uncertainty component of 2 parts in 10^4 is included in Table 6.

Ion recombination

No correction for recombination was applied to the measured current as volume recombination is negligible at a kerma rate of less than 10 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 2 parts in 10^4 is included in Table 6.

Ambient conditions

During a series of measurements, the air temperature is measured for each current measurement and was stable to better than 0.08 °C at the BIPM. At the GUM, the air temperature is measured for each current measurement and was stable to better than 0.4 °C. The ionization current is corrected to the reference conditions of 293.15 K and 101.325 kPa at both laboratories.

At the BIPM, the relative humidity is controlled in the range from 45 % to 55 %. At the GUM, relative humidity is controlled and was in the range from 41 to 51 %. No correction for humidity is applied to the measured ionization current.

5. Results of the comparison

The transfer chambers were set-up and measured in the BIPM ^{60}Co beam on two separate occasions.

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

$$R_K = N_{K,\mathrm{GUM}}/N_{K,\mathrm{BIPM}} \tag{3}$$

in which the average value of measurements made at the GUM before and after those made at the BIPM is compared with the mean of the measurements made at the BIPM. The results for each chamber were reproducible to better than 1 part in 10^4 at both laboratories.

Table 5 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 6. This includes a component of 1 part in 10^4 for the difference in the comparison result between the two transfer chambers.

Some uncertainties in $\dot{K}_{\mathrm{air}}$ that appear in both the BIPM and the GUM determinations (namely air density, *W/e*, μ_{en}/ρ , $\bar{g}$, s_{ca} and k_{h}) cancel when evaluating the uncertainty of the ratio R_K of the GUM and BIPM calibration coefficients.

Table 5. Results of the indirect comparison

Transfer chamber	$N_{K,\mathrm{GUM}}$ / Gy µC^{-1}			$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	R_K	u_{c}
	pre-BIPM	post-BIPM	overall mean			
NE 2571-2676	41.20	41.20	41.20	41.04	1.0038	0.0030
NE 2561-301	95.78	95.84	95.81	95.44	1.0039	0.0030
				Mean value	1.0039	0.0030

Table 6. Uncertainties associated with the indirect comparison

Transfer chamber	BIPM		GUM	
Relative standard uncertainty	100 u_{iA}	100 u_{iB}	100 u_{iA}	100 u_{iB}
Air kerma rate	0.02	0.13	0.06	0.25 [(1)]
Ionization current for the transfer chambers	0.01	0.02	0.08	0.11
Distance	0.01	–	0.01	0.01
Reproducibility	0.01	–	0.01	–
Air density correction	–	–	0.03	0.05
$N_{K,\mathrm{lab}}$	0.03	0.13	0.10	0.28
$N_{K,\mathrm{GUM}}$ / $N_{K,\mathrm{BIPM}}$ [(2)]	0.11		0.27	
Ion recombination	–		0.02	
Radial non-uniformity	–		0.02	
Different chambers	0.01			
$N_{K,\mathrm{GUM}}$ / $N_{K,\mathrm{BIPM}}$	u_c = 0.0030			

(1) Uncertainty considering both standards

(2) 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 mean ratio of the air kerma calibration coefficients of the transfer chambers determined by the GUM and the BIPM taken from Table 5 is 1.0039 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 7 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 Table 7, 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 7. **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 / (mGy/Gy)
NRC	3.2	5.6
VNIIM	0.8	3.6
KRISS	-0.5	3.2
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
BEV	3.0	5.0
GUM	3.9	6.0
ARPANSA	-1.4	5.5

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)
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
LNMRI	2.4	13.7
CNEA	1.8	10.0

BELGIM	12.5	21.8
CPHR	1.1	9.6
RMTC	-3.6	9.6

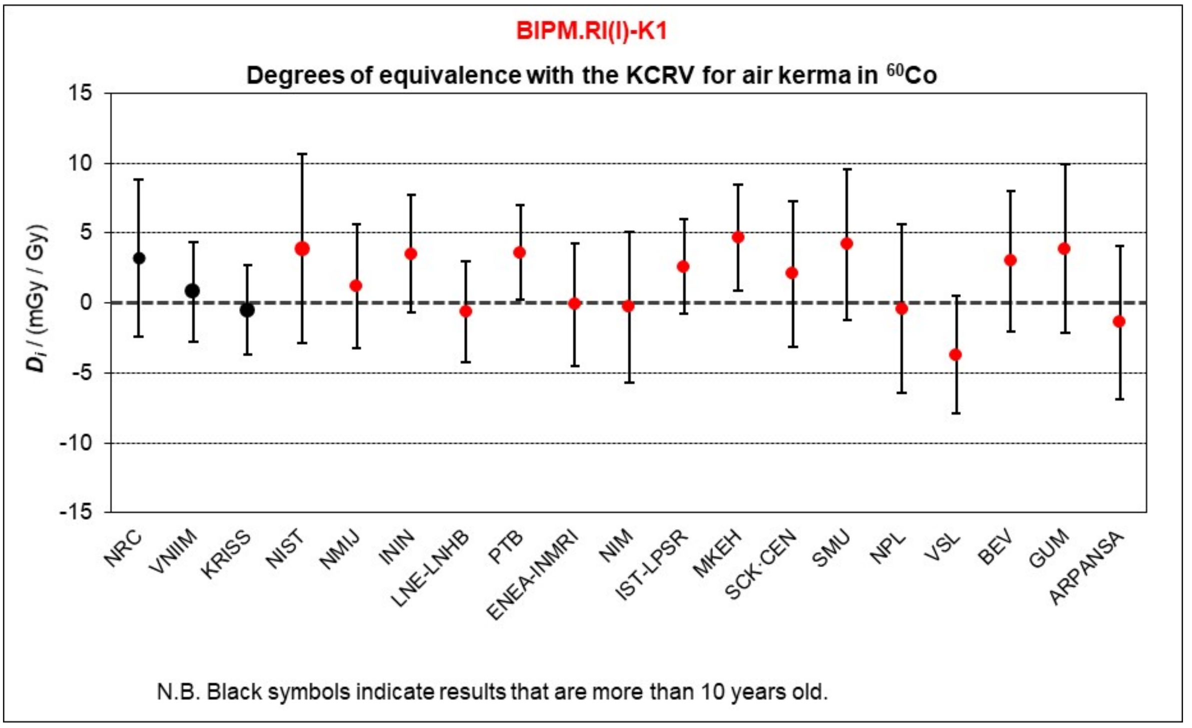
Lab *i*	D_i / (mGy/Gy)	U_i / (mGy/Gy)
BARC	0.7	7.6
Nuclear Malaysia	-0.1	7.4
NMISA	0.9	6.9

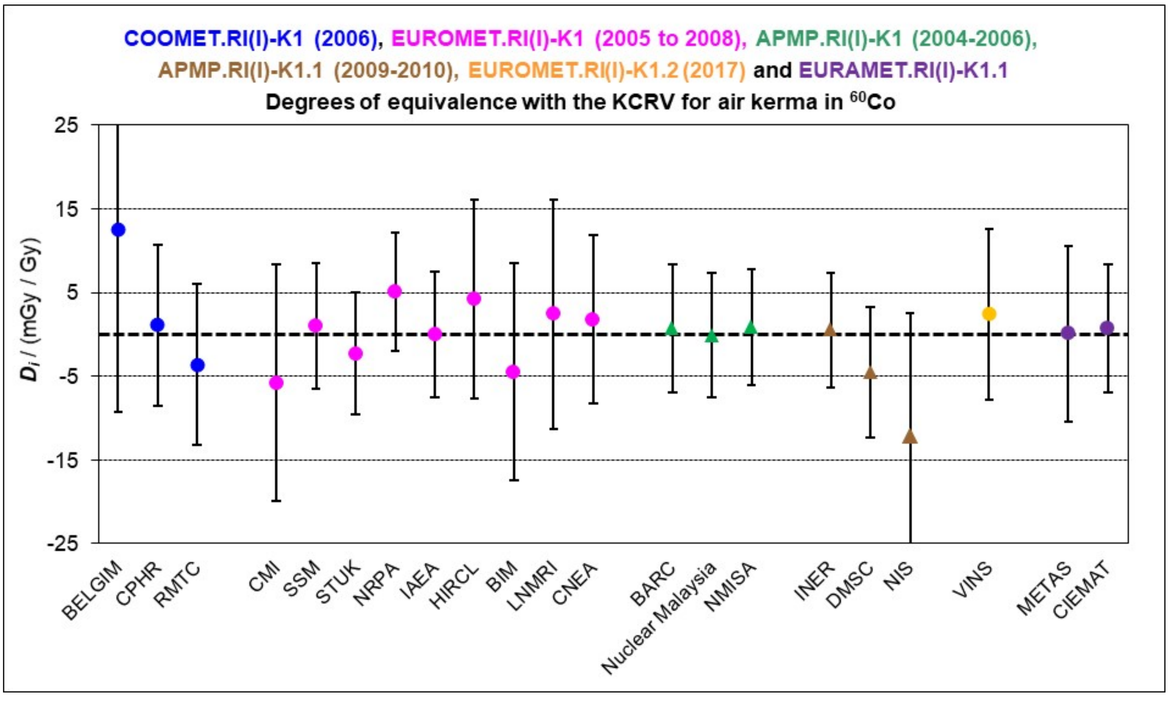
INER	0.5	6.9
DMSC	-4.5	7.8
NIS	-12.1	14.6

METAS	0.1	10.5
CIEMAT	0.7	7.6

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 GUM and of the BIPM was made directly in 2006. The comparison result was 1.0023 (24). As both laboratories adopted the same changes recommended by the ICRU 90 in the determination of air kerma, the comparison result of 2006 should be unchanged.

For the present comparison, the GUM standard for air kerma in ^{60}Co gamma radiation compared with the BIPM air-kerma standard gives a comparison result of 1.0039 (30), in agreement within the uncertainties with the previous comparison result. The GUM 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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