Key comparison BIPM.RI(I)-K1 of the air-kerma standards of the NIST, USA, 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 National Institute of Standards and Technology (NIST), USA, and the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in October 2023. The comparison result, based on the calibration coefficients for two transfer chambers and expressed as a ratio of the NIST and the BIPM standards for air kerma, is 1.0044 with a combined standard uncertainty of 3.4 parts in 10^3. The result agrees within the uncertainties with the indirect comparison carried out in 2011, when updated with the changes implemented to the standards at each laboratory. 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 Institute of Standards and Technology (NIST), USA, and the Bureau International des Poids et Mesures (BIPM) was carried out in October 2023 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2011 (Kessler *et al.* 2013) published in the BIPM key comparison database (KCDB 2025) under the reference BIPM.RI(I)-K1. The comparison was carried out after the implementation of the recommendations of the ICRU Report 90 (ICRU 2016) at both laboratories.

The indirect comparison was made using two thimble-type ionization chambers as transfer instruments. The final results were supplied by the NIST in September 2024 and the final version of the report in January 2025.

2. Details of the standards and the transfer chambers

The NIST ^{60}Co air-kerma standard consists of two graphite spherical cavity ionization chambers identified as St-01 and St-10, with volumes of 1 cm^3 and 10 cm^3, respectively, as described by Minniti *et al.* (2006).

The BIPM primary standard, identified as CH6.2, is a graphite-walled parallel-plate cavity ionization chamber described in Boutillon *et al.* (1973), Burns *et al.* (2007), and Burns and Kessler (2018). The main characteristics of the BIPM and NIST primary standards are given in Table 1. Details of the transfer chambers used for the indirect comparison are given in Table 2.

Table 1. Characteristics of the BIPM and the NIST standards

Dimensions		BIPM Standard	NIST Standards	
		CH6.2	St-01	St-10
Cavity	Diameter / mm	45.01	12.7	26.8
	Thickness / mm	5.16	–	–
	Measuring volume / cm^3	6.8749	1.1309	10.069
Electrode	Shape	disc	cylindrical	cylindrical
	Diameter / mm	41.03	1.016	1.0
	Thickness / mm	1.005	–	–
Wall	Thickness / mm	2.90	3.980	3.755
	Material	graphite	graphite	graphite
	Density / g cm^{-3}	1.85	1.73	1.72
Voltage applied / V		± 80 to outer electrode	-300 to outer electrode	

Table 2. Characteristics of the NIST transfer chambers

Nominal values		Exradin A12 [a]	PTW 30013 [a]	
Chamber	Outer diameter / mm	7.1	7.0	
	Outer length / mm	26	23.6	
Electrode	Diameter / mm	1.0	1.1	
	Length / mm	21.6	21.0	
Cavity	Nominal volume / cm^3	0.6 [b]	0.6	
Wall	Thickness / mm	0.5	0.335	0.09
	Material	C552 air equivalent plastic	PMMA	graphite
	Density / g cm^{-3}	1.76	1.19	1.85
Buildup Caps	Thickness/ mm	2.9	4.7	
Voltage applied / V [c]		300	300	

[a] Certain commercial equipment, instruments, and materials are identified in this work in order to specify adequately the experimental procedure. Such identification does not imply recommendation nor endorsement by the NIST nor does it imply that the material or equipment identified is the best available for the purposes described in this work

[b] Manufacturer states 0.64 cm^3

[c] At the BIPM a negative polarizing voltage -300 V is applied to the outer electrode; at the NIST, a positive polarizing volage +300 V is applied to the inner electrode

3. Determination of the air kerma

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

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

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 mass 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, the correction factors, the volume of the primary standards entered into equation (1), and the associated uncertainties are given in Table 3a and Table 3b. For the BIPM standards, these values are given in Kessler and Burns (2024).

Table 3a. Physical constants, correction factors and relative standard uncertainty components of the BIPM standard for the ^{60}Co radiation beam at the BIPM

BIPM		Values CH6.2	uncertainty (1)	
			100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
Physical Constants				
ρ_{air}	dry air density (2) / kg m^{-3}	1.2930	–	0.01
$(\mu_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$	ratio of mass energy-absorption coefficients	0.9989	0.01	0.04
$s_{\mathrm{c,a}}$	ratio of mass stopping powers	0.9928	–	0.08 (3,4)
W/e	mean energy per charge / J C^{-1}	33.97		
$\bar{g}$	fraction of energy lost in radiative processes	0.0031	–	0.02
Correction factors				
k_{h}	relative humidity	0.9970	–	0.03
k_{g}	re-absorption of radiative loss	0.9996	–	0.01
k_{s}	recombination losses	1.0019	0.01	0.02
k_{st}	stem scattering	1.0000	0.01	–
k_{wall}	wall attenuation and scattering	1.0011	–	– (5)
k_{an}	axial non-uniformity	1.0020	–	– (5)
k_{rn}	radial non-uniformity	1.0015	–	0.02
Measurement of *I* / *V*				
V	chamber volume / cm^3	6.8749	–	0.08 (5)
I	ionization current / pA	–	0.01	0.02
Relative standard uncertainty				
quadratic summation			0.02	0.13
combined uncertainty			**0.13**	

(1) Expressed as one standard deviation:
$u_{i\mathrm{A}}$ represents the type A relative standard uncertainty estimated by statistical methods,
$u_{i\mathrm{B}}$ represents the type B relative standard uncertainty estimated by other means

(2) At 101.325 kPa and 273.15 K

(3) Combined uncertainty for the product of $s_{\mathrm{c,a}}$ and W/e adopted from ICRU Report 90 recommendations (ICRU 2016)

(4) Adopted from January 2019 (Burns and Kessler 2018)

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

Table 3b. Physical constants, correction factors and relative standard uncertainty components of the NIST standards for the ^{60}Co radiation beam at the NIST

NIST		values St-01	uncertainty (1)		values St-10	uncertainty (1)	
			100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$		100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
Physical Constants							
ρ_{air}	dry air density (2) / kg m^{-3}	1.2930	–	0.02	1.2930	–	0.02
$(\mu_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$	ratio of mass energy-absorption coefficients	0.9990	–	0.04	0.9990	–	0.04
$s_{\mathrm{c,a}}$	ratio of mass stopping powers	0.9926	–	0.08 (3)	0.9926	–	0.08 (3)
W/e	mean energy per charge / J C^{-1}	33.97			33.97		
$\bar{g}$	fraction of energy lost in radiative processes	0.0033	–	0.03	0.0033	–	0.03
Correction factors and uncertainty components							
k_{h}	relative humidity	0.9971	–	0.06	0.9971	–	0.06
k_{s}	recombination losses	1.0022	0.01	0.05	1.0019	0.05	0.10
k_{st}	stem scattering	0.9982	–	0.05	0.9992	–	0.05
k_{wall}	wall attenuation and scattering	1.0207	–	0.17	1.0236	–	0.17
k_{an}	axial non-uniformity	1.0000	–	0.02	1.0000	–	0.05
k_{rn}	radial non-uniformity	1.0000	–	0.01	1.0000	–	0.01
k_{TP}	air density	–	–	0.03	–	–	0.03
Measurement of *I* / *V*							
V	chamber volume / cm^3	1.1309	0.10	0.10	10.069	0.16	0.10
I	ionization current / pA	–	0.10	0.10	–	0.06	0.10
t	time / s	–	–	0.05	–	–	0.05
d	distance/ m	–	–	0.02	–	–	0.02
Relative standard uncertainty							
quadratic summation			0.14	0.27		0.18	0.28
combined uncertainty			**0.30**			**0.34**	
combined uncertainty(4)			**0.30**				

(1) Expressed as one standard deviation:
$u_{i\mathrm{A}}$ represents the type A relative standard uncertainty estimated by statistical methods,
$u_{i\mathrm{B}}$ represents the type B relative standard uncertainty estimated by other means

(2) At 101.325 kPa and 273.15 K

(3) Combined uncertainty for the product of $s_{\mathrm{c,a}}$ and W/e adopted from ICRU Report 90 recommendations (ICRU 2016)

(4) The combined uncertainties of St-01 and St-10 account for correlation in the type B uncertainties

Reference conditions

The reference conditions for the air-kerma determination at the BIPM are described by Kessler and Burns (2024): the distance from source to reference plane is 1 m and 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 NIST are 1 m from source to reference plane and a square field of 10 cm x 10 cm, defined by the photon fluence rate at the center of each side of the square being 95 % of the photon fluence rate at the center of the square.

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 2023-01-01, 0 h UTC. The correction for air attenuation between source and standard used the ambient air density at the time of the measurement and the air attenuation coefficient 0.0602 $\mathrm{cm}^2\ \mathrm{g}^{-1}$ 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 NIST, no air attenuation correction was applied and the reference value $\dot{K}_{\mathrm{NIST}}$ is given at the reference date of 2023-01-01, 0 h UTC using the same half-life value.

Beam characteristics

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

Table 4. Characteristics of the ^{60}Co beams at the NIST 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		
NIST	11.7	32.2	60.9	– [a]	10 cm × 10 cm
BIPM Theratron 1000	4.3	20	14	21 %	10 cm × 10 cm

[a] Not determined

4. Comparison procedure

The comparison of the NIST 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 corrected ionization current of a transfer chamber measured at the NIST or the BIPM. The current is corrected for the effects and influences described in this section.

The ionization chambers PTW 30013 serial number 1815, and Exradin A12 serial number XA230741, belonging to the NIST, were the transfer chambers used for this comparison. Their main characteristics are listed in Table 2. These chambers were calibrated at the NIST before being sent to the BIPM and again three months after measurements were made at the BIPM.

The experimental method for measurements at the BIPM is described by Kessler and Burns (2024); 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. The uncertainty listed in Table 6 is obtained by estimating the reproducibility of the chamber positioning.

Applied voltage and polarity

At the NIST, a collecting voltage of 300 V, positive polarity, was applied to the collector of the transfer chambers at least 30 min before any measurements were made. At the BIPM, the voltage was applied to the outer electrode of the chamber; to produce the same electric field inside the sensitive volume of the chambers, the same collecting voltage, but negative polarity, was applied at least 40 min before the measurements.

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 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 (~10 Gy). Measurements were done with the build-up caps that belong to each chamber listed in Table 2 and supplied with the transfer chambers sent by the NIST. Leakage current was measured before and after each series of measurements. The leakage correction, estimated as the ratio of the leakage current relative to the ionization current, was less than 1 part in 10^4. At the NIST, a pre-irradiation was made for 30 min before any measurements. The ionization current I was calculated from the accumulated electrical charge during a defined time interval measured using an electrometer Keithley model 6517B. A data set is composed of at least 20 irradiation measurements, each of which is corrected by leakage measured before and after the irradiation measurement. The relative leakage correction for each chamber 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 NIST beam. No radial non-uniformity correction was applied and a relative uncertainty component of 2 parts in 10^4 is included in Table 7.

Ion recombination

Recombination measurements performed at NIST demonstrated that the recombination correction for these 2 transfer chambers is negligible. Because of this, no correction for recombination was applied to the measured current. This determination is consistent with the fact that volume recombination is negligible for continuous beams for these chamber types at this polarizing voltage (Burns and Burns 1993), 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 7.

Ambient conditions

During a series of measurements, the air temperature was measured for each current measurement and was stable to better than 0.05 °C at the BIPM. At the NIST, the air temperature was also measured for each current measurement and was stable to better than 0.2 °C. The ionization current was 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 NIST, relative humidity is controlled in the range from 40 % to 50 %; no correction for humidity was applied to the ionization current measured (Seltzer and Bergstrom 2003).

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 2 parts in 10^4.

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

$$R_K = N_{K,\mathrm{NIST}}/N_{K,\mathrm{BIPM}} \qquad (3)$$

in which the average value of measurements made at the NIST before and after those made at the BIPM is compared with the mean of the measurements made at the BIPM.

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 at each laboratory and with the indirect comparison are presented in Table 6 and Table 7, respectively.

The values $N_{K,\mathrm{NIST}}$ measured before and after the measurements at the BIPM give rise to a relative standard deviation for each chamber, whose r.m.s. value is taken as a representation of the stability of the transfer instruments. The short-term stability was estimated to be less than 1 part in 10^4. Table 7 includes a component of 3 parts in 10^4 for the difference in the comparison results between the two transfer chambers.

Table 5. Results of the indirect comparison

Transfer chamber	$N_{K,\mathrm{NIST}}$/ Gy µC^{-1}			$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	R_K	u_c
	pre-BIPM	post-BIPM	overall mean			
Exradin A12	43.722	43.723	43.722	43.517	1.0047	0.0034
PTW 30013	49.336	49.335	49.335	49.135	1.0041	0.0034
				Mean value	1.0044	0.0034

Table 6. Uncertainties associated with the transfer chamber calibration

	BIPM		NIST	
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	0.13	0.11	0.28
Ionization current (BIPM) or Charge (NIST)	0.01	0.02	0.10	0.10
Time	–	–	–	0.05
Source to Detector Distance	0.01	–	–	0.02
Positioning	–	–	–	0.02
Reproducibility	0.02	–	–	–
Air density	–	–	–	0.03
Relative humidity	–	–	–	0.06
Decay correction	–	–	–	0.01
$N_{K,\mathrm{lab}}$	0.03	0.13	0.15	0.31

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

The mean ratio of the air-kerma calibration coefficients of the transfer chambers determined by the NIST and the BIPM taken from Table 5 is 1.0044 with a combined standard uncertainty, u_c, of 0.0034.

Table 7. Uncertainties associated with the indirect comparison

Relative standard uncertainty	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
$N_{K,\mathrm{NIST}}$ / $N_{K,\mathrm{BIPM}}$ ⁽¹⁾	0.15	0.30
Ion recombination	–	0.02
Radial non-uniformity	–	0.02
Stability of the chambers	0.01	–
Different chambers	0.03	–
R_K	$u_c = 0.0034$	

⁽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

6. Degrees of equivalence

Following a decision of the CCRI(I), the BIPM determination of the dosimetric quantity, here K_{BIPM}, is taken as the key comparison reference value (KCRV) (Allisy *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, becomes out-of-date as NMIs make new comparisons. In addition, revised validity rules for comparison data have been agreed by the CCRI(I) so that any results older than 15 years are no longer considered valid and are removed from the KCDB. The formal results under the CIPM MRA are those available in the key comparison database.

7. Conclusion

The previous comparison of the air-kerma standards for ^{60}Co gamma radiation of the NIST and the BIPM was made indirectly in 2011. That comparison result was 1.0039 (34). Since the previous comparison, both laboratories implemented some changes in the standards following the recommendations of the ICRU 90. For the NIST and for the BIPM, this resulted in a reduction of 8 parts in 10^3 and 8.3 parts in 10^3 in the determination of air kerma, respectively. Adopting these changes, the 2011 comparison result becomes 1.0042 (34), in close agreement with the new comparison result of 1.0044 (34).

The NIST 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 beams.

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	U_i
	/ (mGy/Gy)	
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/ITN	**2.6**	3.4
SCK-CEN	**2.1**	5.2
SMU	**4.2**	5.4
NPL	**-0.4**	6.0
VSL	**-3.4**	4.2
BEV	**3.0**	5.0
GUM	**3.9**	6.0
ARPANSA	**-1.4**	5.4
NRC	**2.2**	4.4
BFKH	**2.9**	4.4
NMIJ	**1.3**	4.4
KRISS	**0.6**	3.6
NIST	**4.4**	6.8

APMP.RI(I)-K1.1 (2009 to 2012)

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
DMSC	**-4.5**	8.8
NIS	**-12.1**	15.0

EURAMET.RI(I)-K1.1 (2013-2015)

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
METAS	**0.1**	10.5

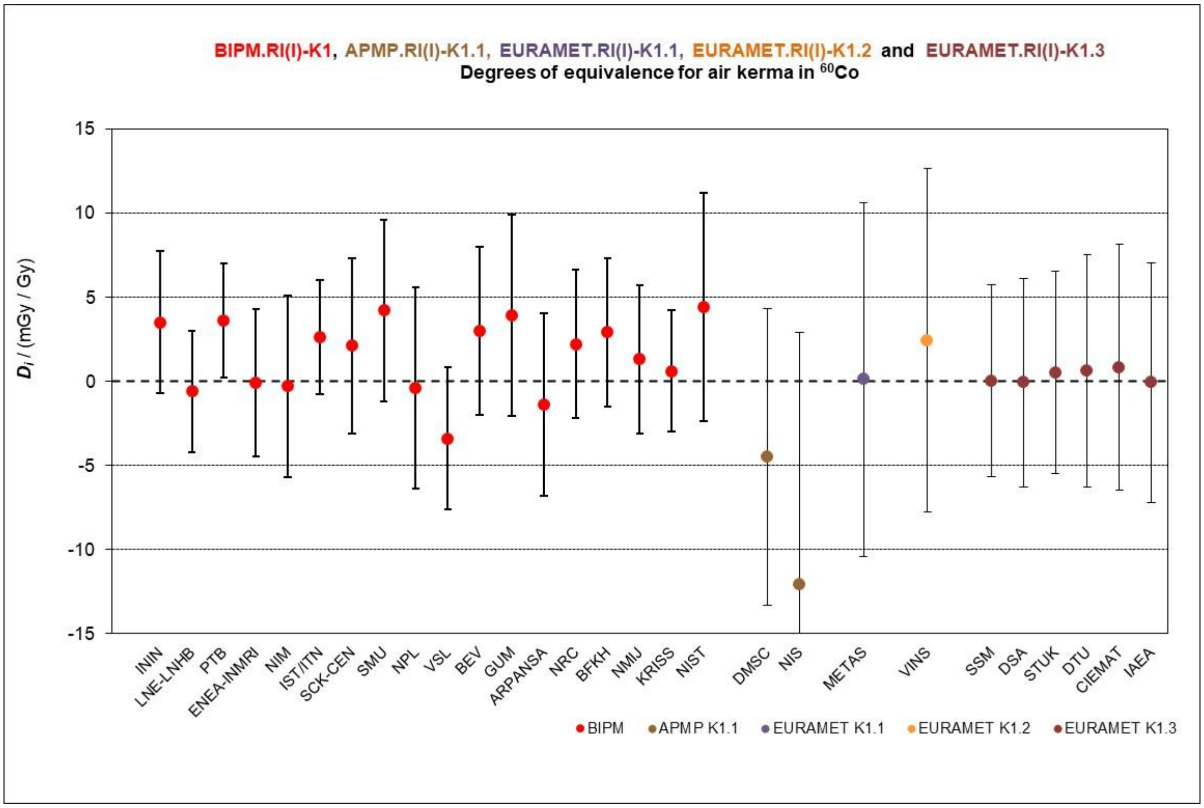
EURAMET.RI(I)-K1.2 (2017)

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
VINS	**2.4**	10.2

EURAMET.RI(I)-K1.3 (2022)

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
SSM	**0.0**	5.7
DSA	**-0.1**	6.2
STUK	**0.5**	6.0
DTU	**0.6**	6.9
CIEMAT	**0.8**	7.3
IAEA	**-0.1**	7.1

Figure 1. Graph of degrees of equivalence with the KCRV



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