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Key comparison BIPM.RI(I)-K4 of the absorbed dose to water standards in ^{60}Co gamma radiation beams of the NIST, USA and of the BIPM

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Abstract

A new key comparison of the standards for absorbed dose to water of the National Institute of Standards and Technology (NIST), USA, and of 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 standards and evaluated as a ratio of the NIST and the BIPM standards for absorbed dose to water, is 1.0019 with a combined standard uncertainty of 5.7 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

An indirect comparison of the primary standards for absorbed dose to water of the National Institute of Standards and Technology (NIST), USA and of the Bureau International des Poids et Mesures (BIPM) was carried out in October 2023 in the ^{60}Co radiation beam at the BIPM. The comparison result is published in the BIPM key comparison database (KCDB 2025) under the reference BIPM.RI(I)-K4. The comparison was carried out after the implementation of the recommendations of the International Commission on Radiation Units and Measurements (ICRU) Report 90 (ICRU 2016) at only the BIPM as the NIST standard is not affected by these recommendations.

The indirect comparison was made using two thimble-type ionization chambers as transfer instruments, both instruments belonging to the NIST. The final results were supplied by the NIST in February 2025.

2. Details of the primary standards and the transfer chambers

The BIPM primary standard, identified as CH7.1, is a graphite-walled parallel-plate cavity ionization chamber positioned at the reference depth in a water phantom (Boutillon and Perroche 1993, Burns and Kessler 2018). The main dimensions are given in Table 1. The primary standard of the NIST for absorbed dose is the Domen water calorimeter described by Domen (1994). Details of the two transfer chambers used for the indirect comparison are given in Table 2.

Table 1. Characteristics of the BIPM primary standard

Dimensions		Standard CH7.1
Cavity	Diameter / mm	45.0
	Thickness / mm	5.147
	Measuring volume / cm^3	6.7942
Electrode	Diameter / mm	41.0
	Thickness / mm	1.027
Wall	Thickness / mm	2.848
	Material	Graphite
	Density / g cm^{-3}	1.85
Voltage applied to outer electrode / V	(both polarities)	80

Table 2. Characteristics of the NIST transfer chambers

Dimensions		Exradin A12[a]	PTW 30013[a]	
Chamber	Outer diameter / mm	7.1	7.0	
	Outer length / mm	26	26	
Electrode	Diameter / mm	1.0	1.1	
	Length / mm	21.6	21.2	
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
Voltage applied [c] / V		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 absorbed dose to water

At the BIPM the absorbed-dose-to-water rate is determined using the primary standard cavity ionization chamber with measuring volume V by the relation

$$\dot{D}_{\mathrm{w,BIPM}} = \frac{I}{\rho_{\mathrm{a}} V} \frac{W}{e} \left(\frac{\mu_{\mathrm{en}}}{\rho}\right)_{\mathrm{w,g}} \bar{s}_{\mathrm{g,a}} \Psi_{\mathrm{w,g}} \beta_{\mathrm{w,g}} \prod k_i \qquad (1)$$

where:

ρ_{a} is the density of air under reference conditions,

I is the ionization current measured by the standard,

W is the average energy spent by an electron of charge e to produce an ion pair in dry air,

$(\mu_{\mathrm{en}}/\rho)_{\mathrm{w,g}}$ is the ratio water-to-graphite of mass energy-absorption coefficients,

$\bar{s}_{\mathrm{g,a}}$ is the ratio of the mean mass stopping powers graphite-to-air,

$\Psi_{\mathrm{w,g}}$ is the photon energy fluence ratio water-to-graphite,

$\beta_{w,g}$ is the absorbed-dose-to-collision-kerma ratio water-to-graphite, and

$\Pi\, k_i$ is the product of the correction factors to be applied to the standard.

The values for the physical constants, the correction factors, the volume of the primary standard entered in equation (1), and the associated uncertainties (Kessler and Burns 2024) are given in Table 3.

Table 3. Physical constants, correction factors and relative standard uncertainties for the BIPM ionometric standard for absorbed-dose-to-water rate [(a)]

Symbol	Parameter / unit	Value	uncertainty [(b)] 100 u_{iA}	100 u_{iB}
Physical constants				
ρ_a	dry air density (0°C, 101.325 kPa) / kg m^{-3}	1.2930	–	0.01
$(\mu_{en}/\rho)_{w,g}$	ratio of mass energy-absorption coefficients	1.1131	–	0.05
W/e	mean energy per charge / J C^{-1}	33.97	–	– [(c)]
$D_{g,air} = s_{g,a}k_{cav}$	product of the ratio of mass stopping powers and cavity perturbation correction	0.9958	0.02	0.13 [(c)]
$\psi_{w,g}$	photon energy fluence ratio	1.0037	0.01	0.07
$\beta_{w,g}$	absorbed-dose-to-collision-kerma ratio	0.9998	0.01	0.01
Correction factors				
k_{env}	envelope of the chamber	0.9993	0.01	0.02
k_{win}	entrance window of the phantom	0.9997	0.01	0.01
k_{rn}	radial non-uniformity	1.0056	0.01	0.03
k_s	saturation	1.0019	0.01	0.02
k_h	humidity	0.9970	–	0.03
Measurement of I/υ				
υ	volume / cm^3	6.7942 [(d)]	–	0.08
I	ionization current (T, P, air compressibility)	–	–	0.02
	short-term reproducibility (including positioning and current measurement) [(e)]		0.02	–
Combined uncertainty of the BIPM determination of absorbed-dose-to-water rate				
quadratic summation			0.04	0.18
combined relative standard uncertainty			0.19	

(a) Details on the determination of absorbed-dose-to-water rate are described by Boutillon and Perroche (1993) and the re-evaluation of the standard is described by Burns and Kessler (2018)

(b) 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

(c) The uncertainty component of 0.13 represents the uncertainty of 0.08 for the product of W/e and the stopping-power ratio $s_{g,a}$, as evaluated for the BIPM and other air-kerma standards for Co-60, and the uncertainty of 0.10 for k_{cav}

(d) Standard CH7.1

(e) Over a period of 3 months

The NIST primary standard is the Domen water calorimeter (Domen 1994). The absorbed dose to water is determined using the equation

$$D_{w,NIST} = \Delta T_w c_w k_{HD} \prod k_i \qquad (2)$$

where:

ΔT_w is the measured temperature rise,

c_w	is the specific heat capacity of water at the calorimeter operating temperature of 22 °C,
k_{HD}	is a correction factor for the heat defect of water, and
$\prod k_i$	is the product of the correction factors applied to the standard.

The absorbed dose to water at the NIST was realized from a series of multiple water calorimeter measurements done using the Domen water calorimeter during the period of 1991 and 1999 (Minniti *et al.* 2006) with a final established absorbed-dose-to-water rate given on the reference date of 1999-06-25. Since then and until 2020, seven reference ionization chambers have been calibrated routinely in this reference beam, establishing direct traceability to the NIST water calorimeter. As the activity of the ^{60}Co source is currently too weak to be able to use the water calorimeter, the reference absorbed-dose-to-water rate $\dot{D}_w$ of the ^{60}Co field is evaluated as the mean value of the absorbed-dose-to-water rates determined using each one of the seven reference chambers. These seven reference chambers were used to calibrate the two transfer chambers used in this key comparison. The uncertainty components for the determination of the absorbed-dose-to-water rate using the water calorimeter in combination with the seven reference chambers (Domen 1994, Minniti *et al* 2006) are shown in Table 4.

Table 4. Physical constants, correction factors and relative standard uncertainties for the NIST standard for absorbed-dose-to-water rate

Symbol	Parameter / unit	Value	uncertainty [a] 100 u_{iA}	100 u_{iB}
Uncertainties associated with the Water Calorimeter				
ΔT_w	temperature rise	–	0.15	0.01
c_w	specific heat capacity of water at 22 °C J / (g °C)	4.1808	–	0.01
k_{HD}	heat defect	1.000	–	0.30
$k_{a,gw}$	beam attenuation in glass wall	1.0000	–	0.10
$k_{a,Lid}$	beam attenuation in calorimeter lid	1.0000	0.05	–
k_{FS}	field size	1.0000	–	0.23
k_{pos}	vessel positioning	1.0000	–	0.02
	water density	–	–	0.02
Determination of $\dot{D}_w$ using the seven reference chambers				
Added uncertainty from a single reference chamber measurement from its calibration against the water calorimeter		–	0.08	0.11
Added uncertainty from a single reference chamber used to determining the absorbed dose to water rate		–	0.05	0.23
Combined uncertainty of the NIST determination of absorbed-dose-to-water rate				
quadratic summation			0.18	0.47
combined uncertainty of $\dot{D}_w$ obtained as the mean value of the 7 reference chambers [b]			0.07	0.47
combined relative standard uncertainty of $\dot{D}_w$			0.47	

(a) 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

(b) In evaluating the combined uncertainty of $\dot{D}_w$, obtained from the mean of the 7 reference chambers, the Type A uncertainties are assumed to be independent while the Type B uncertainties are assumed to be correlated.

Reference conditions

The reference conditions for the absorbed-dose-to-water rate determination at the BIPM are described by Kessler and Burns (2024) and include:

- horizontal radiation beam,
- the distance from the source to the reference plane (centre of the detector) is 1 m,
- the beam size in air at the reference plane is 10 cm × 10 cm square, 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 depth in the water phantom is 5 g cm^{-2}.

The reference conditions at the NIST are the following:

- vertical radiation beam,
- the distance from the source to the reference plane (centre of the detector) is 1 m,
- the beam size in air at the reference plane is 10 cm × 10 cm, the intensity of the radiation field, at a lateral distance of 5 cm from the beam centre, falls to 95 % of the value of the field at the centre of the square field,
- the reference depth in the water phantom is 5 g cm^{-2}.

Reference values

The BIPM reference absorbed-dose-to-water rate, $\dot{D}_{\mathrm{w,BIPM}}$, is taken as the mean of the four measurements made around the period of the comparison, corrected to the reference date of 2023-01-01, 0 h UTC, as is the ionization current of the transfer chambers. The half-life of ^{60}Co used for the decay correction is taken as 5.2711 (8) years (this corresponds to 1925.21 (29) days) (Bé *et al.* 2006).

The value of $\dot{D}_{\mathrm{w,NIST}}$ is given at the reference date of 2023-01-05, 0 h UTC, using the same half-life value to calculate the decay correction.

Beam characteristics

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

Table 5. Characteristics of the ^{60}Co beams at the NIST and the BIPM

^{60}Co beam	Nominal $\dot{D}_{\mathrm{w}}$ / mGy s^{-1}	Source dimensions / mm		Scatter contribution in terms of energy fluence	Field size at 1 m
		diameter	length		
NIST G150	11.8	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 $N_{D,\mathrm{w,lab}}$ for the two transfer chambers given by

$$N_{D,\mathrm{w,lab}} = \dot{D}_{\mathrm{w,lab}} / I_{\mathrm{lab}} \quad (3)$$

where $\dot{D}_{\mathrm{w,lab}}$ is the absorbed-dose-to-water rate and I_{lab} is the 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 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 $N_{D,\mathrm{w,lab}}$ for the transfer chambers are reproduced here.

Positioning

At each laboratory the waterproof chambers were positioned in water with the stem perpendicular to the beam direction and with the appropriate marking on the stem facing the source. No waterproof sleeve was used.

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. Prior to starting the charge measurements, the chambers were pre-irradiated for at least 40 min to a total dose of approximately 10 Gy. The 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, the transfer chambers were pre-irradiated for at least 6 min to a total dose of approximately 4 Gy before any charge measurements were made. The ionization current *I* was calculated from the accumulated electrical charge during a defined time interval measured using a Keithley electrometer, model 6517B. A data set is composed of at least 20 separate radiation exposures, where the ionization current, *I*, measured during each one of these exposures is corrected by the electrical leakage measured before and after each exposure time interval. The relative leakage correction for each chamber was less than 1 part in 10^4.

Ion recombination

Recombination measurements performed at the NIST demonstrated that the recombination correction for these two transfer chambers is negligible. Therefore, no correction for recombination was applied to the measured current. This determination is consistent with the fact that volume recombination is negligible in continuous beams at these low dose rates for these chamber types at this polarizing voltage (Burns and Burns 1993), and the initial recombination loss will have been the same in the two laboratories; a relative uncertainty component of 2 parts in 10^4 is included in Table 8.

Radial non-uniformity correction

No radial non-uniformity correction was applied. At the NIST, the radial non-uniformity of the beam over the section of the transfer chambers is less than 1 part in 10^3. At the BIPM, the correction to the ionization current would be 8 parts in 10^4 for the transfer chambers. A relative uncertainty component of 2 parts in 10^4 is included in Table 8.

Ambient conditions

At each laboratory, the water temperature was measured for each current measurement; it was stable to better than 0.1 °C at the BIPM and 0.2 °C at the NIST.

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 and was in the range from 40 % to 50 %. No correction for humidity was applied to the ionization current measured at either laboratory.

PMMA phantom window

The BIPM uses a horizontal radiation beam, and the thickness of the PMMA front window of the phantom is included as a water-equivalent thickness in g cm^{-2} when positioning the chamber. In addition, the BIPM applies a correction factor k_{pf} = 0.9996 that accounts for the non-equivalence to water of the PMMA window in terms of interaction coefficients. At the NIST, a vertical beam is used and there is no material between the source and the water surface.

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 for each chamber were reproducible to better than 1 part in 10^4. The result of the comparison, $R_{D,\mathrm{w}}$, is expressed in the form

$$R_{D,\mathrm{w}} = N_{D,\mathrm{w,NIST}} / N_{D,\mathrm{w,BIPM}} \quad (4)$$

in which the average value of measurements made at the NIST before and after those made at the BIPM is compared with the average of the measurements made at the BIPM. The results for each chamber are presented in Table 6.

The values $N_{D,\mathrm{w,NIST}}$ measured before and after the measurements at the BIPM give rise to a relative standard deviation for each chamber whose root mean squared (rms) value is taken as a representation of the stability of the transfer instruments. The short-term stability was estimated to be 7 parts in 10^4. Table 8 includes a component of 3 parts in 10^4 for the difference in the comparison results between the two transfer chambers.

Table 6. Results of the comparison of standards for ^{60}Co absorbed dose to water

Transfer Chamber	$N_{D,w,\mathrm{NIST}}$ / Gy µC^{-1}			$N_{D,\mathrm{w,BIPM}}$ / Gy µC^{-1}	$R_{D,\mathrm{w}}$	u_c
	pre-BIPM	post-BIPM	average			
PTW 30013-1815	53.975	54.034	54.004	53.918	1.0016	0.0057
Exradin A12-XA230741	48.163	48.124	48.143	48.041	1.0021	0.0057
Mean values					**1.0019**	**0.0057**

Contributions to the relative standard uncertainty of $N_{D,\mathrm{w,lab}}$ and the combined standard uncertainty u_c for the comparison result $R_{D,\mathrm{w}}$ are presented in Table 7 and Table 8, respectively.

Table 7. Uncertainties associated with the calibration of the transfer chambers

Description of relative standard uncertainty component	BIPM uncertainty		NIST uncertainty	
	$100\ u_{iA}$	$100\ u_{iB}$	$100\ u_{iA}$	$100\ u_{iB}$
Absorbed-dose-to-water rate	0.04	0.18	0.07	0.47
Ionization current for the transfer chambers	0.01	0.02	0.05	0.10
Source to detector distance	0.02	–	–	0.02
Depth in water	0.02	0.06	–	0.20
Short-term reproducibility	0.01	–	–	–
Temperature, pressure	–	–	–	0.05
$N_{D,\mathrm{w,lab}}$	0.05	0.19	0.09	0.52

Table 8. Uncertainties associated with the indirect comparison

Description of relative standard uncertainty component	$100\ u_{iA}$	$100\ u_{iB}$
$N_{D,\mathrm{w,NIST}}/N_{D,\mathrm{w,BIPM}}$	0.10	0.56
Ion recombination	–	0.02
Radial non-uniformity	–	0.02
Stability of the chambers	0.07	–
Different chambers	0.03	–
$R_{D,\mathrm{w}}$	u_c = 0.0057	

The comparison result, taken as the unweighted mean value for the two transfer chambers, is $R_{D,\mathrm{w}} = 1.0019$ with a combined standard uncertainty u_c for the comparison of 0.0057, demonstrating agreement between the two standards for absorbed dose to water.

6. Degrees of equivalence

Following a decision of the CCRI, the BIPM determination of the dosimetric quantity, here $D_{\mathrm{w,BIPM}}$, 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 a combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is the relative difference $D_i = (D_{\mathrm{w}i} - D_{\mathrm{w,BIPM}i}) / D_{\mathrm{w,BIPM}i} = x_i - 1$ and its expanded uncertainty $U_i = 2\ u_i$, which indicates an approximate 95 % confidence level.

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 International Committee of Weights and Measures (CIPM) Mutual Recognition Arrangement (MRA) (1999) and this report. These data are presented graphically in Figure 1.

Note that the data presented in Table 9, while correct at the time of publication of the present report, becomes out-of-date as National Metrology Institutes (NMIs) make new comparisons. In addition, revised validity rules for comparison data have been agreed on 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 (KCDB 2025).

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.

BIPM.RI(I)-K4 – EURAMET.RI(I)-K4.1 – APMP.RI(I)-K4 – EURAMET.RI(I)-K4.2 – EURAMET.RI(I)-K4.3

BIPM.RI(I)-K4

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
LNE-LNHB	-1.9	7.8
METAS	1.1	10.4
PTB	-1.3	7.6
NPL	2.3	14.2
VSL	-3.0	9.6
BEV	-0.3	8.2
GUM	3.0	7.0
ARPANSA	-0.5	10.2
NRC	-0.5	6.8
BFKH	-3.5	9.0
NIM	2.7	7.2
KRISS	-1.4	7.6
NMIJ	-4.8	8.0
NIST	1.9	11.4

EUROMET.RI(I)-K4.1

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
SCK-CEN	-1.5	15.5

APMP.RI(I)-K4

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
DMSc	1.8	10.8
BARC	3.2	11.0
PTKMR-BATAN	2.3	18.8
NRSL/INER	-1.9	8.2
NIS	0.3	14.2

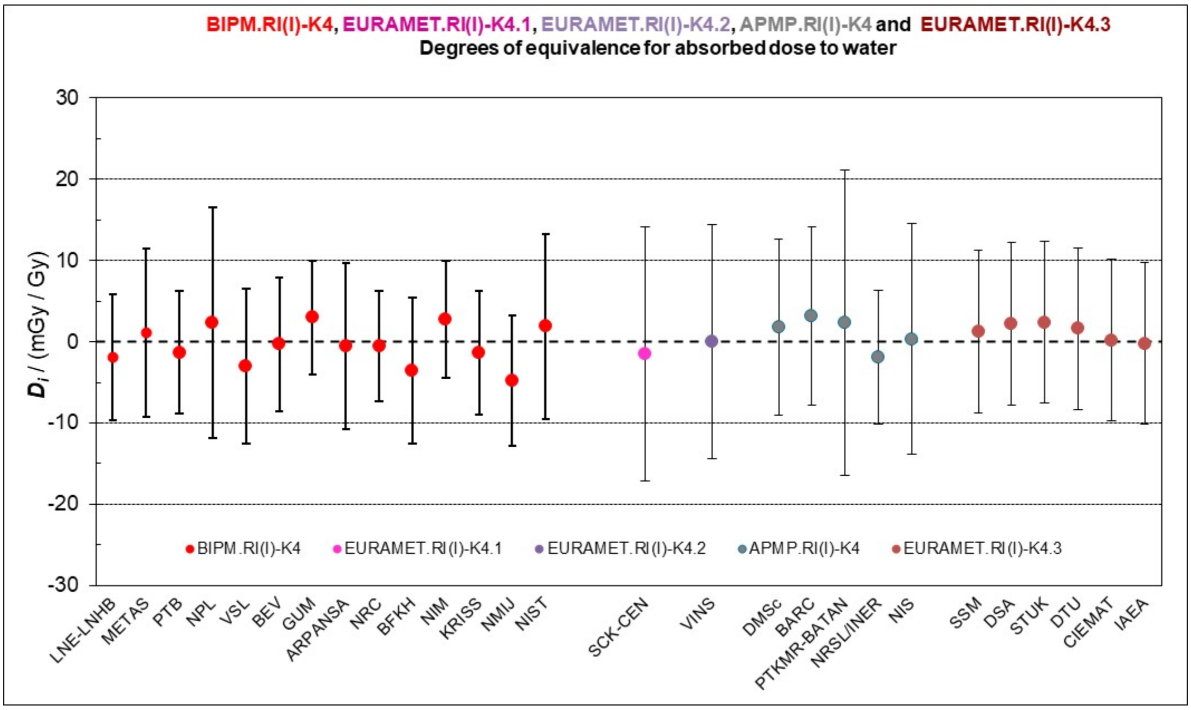
EUROMET.RI(I)-K4.2

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
VINS	0.0	14.3

EURAMET.RI(I)-K4.3

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
SSM	1.2	9.1
DSA	2.2	9.7
STUK	2.4	9.1
DTU	1.6	11.5
CIEMAT	0.2	10.7
IAEA	-0.2	10.3

Figure 1. **Graph of the degrees of equivalence with the KCRV**



7. Conclusions

For the present comparison, made indirectly using transfer instruments, the NIST standard for absorbed dose to water in ^{60}Co gamma radiation compared with the BIPM absorbed dose to water standard gives a comparison result of 1.0019 (57). The NIST standard agrees within the expanded uncertainty with all other NMIs having taken part in the BIPM.RI(I)-K4 ongoing key comparison for absorbed dose to water standards in ^{60}Co gamma-ray beams.

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