CIPM MRA
Comparison reports

BIPM.RI(I)-K4 (LNE-LNHB 2026)

Measurement of absorbed dose to water for Cobalt 60

KEY COMPARISON

© 2026, C. Kessler *et al*

This report is published by the BIPM.

Original content from this Report may be used under the terms of the Creative Commons Attribution 4.0 International (CC BY 4.0) Licence.

Any further distribution of this Report must be cited as:
C. Kessler *et al* 2026 *CIPM MRA Comparison reports* **06018**

https://doi.org/10.59161/NRZC7758

The CIPM MRA Comparison reports are made available under the Creative Commons Attribution International licence:
Attribution 4.0 International (CC BY 4.0)



By using this Report, you accept to be bound by the terms of this licence
(https://creativecommons.org/licenses/by/4.0/).

Distribution – you may distribute the Report according to the stipulations below.

Attribution – you must cite the Report.

Adaptations – you must cite the original Report, identify changes to the original and add the following text: This is an adaptation of an original Report by the Author(s). The opinions expressed and arguments employed in this adaptation should not be reported as representing the views of the Authors.

Translations – you must cite the original Report, identify changes to the original and add the following text: In the event of any discrepancy between the original work and the translation, only the text of the original Report should be considered valid.

Third-party material – the licence does not apply to third-party material in the Report. If using such material, you are responsible for obtaining permission from the third-party and of any claims of infringement.

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

C. Kessler[1], F. Delaunay[2], S. Bondiguel[2]

[1]Bureau International des Poids et Mesures, F-92312 Sèvres Cedex

[2] CEA-LIST Laboratoire National Henri Becquerel, CEA Saclay, 91191 Gif-sur-Yvette, France

Abstract

A new indirect key comparison of the standards for absorbed dose to water of the Laboratoire National de Métrologie et d'Essais – Laboratoire National Henri Becquerel (LNE-LNHB), France, and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in June 2026. The comparison result, based on the calibration coefficients for two transfer chambers and evaluated as a ratio of the LNE-LNHB and the BIPM standards for absorbed dose to water, is 1.0004 with a combined standard uncertainty of 3.6 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

An indirect comparison of the primary standards for absorbed dose to water of the Laboratoire National de Métrologie et d'Essais – Laboratoire National Henri Becquerel (LNE-LNHB), France and of the Bureau International des Poids et Mesures (BIPM) was carried out in June 2026 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2013 (Kessler *et al.* 2013) published in the BIPM key comparison database (KCDB 2026) 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 the BIPM.

The indirect comparison was made using two thimble-type ionization chambers as transfer chambers, both instruments belonging to the LNE-LNHB. The final results were supplied by the LNE-LNHB in July 2026.

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 LNE-LNHB for absorbed dose to water is a graphite calorimeter (Ostrowsky and Daures 2008, Delaunay *et al.* 2014).

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		BIPM standard CH7.1
Cavity	Diameter / mm	45.0
	Thickness / mm	5.147
	Measuring volume / cm^3	6.7942
Electrode	Shape	disc
	Diameter / mm	41.0
	Thickness / mm	1.027
Wall	Thickness / mm	2.85
	Material	graphite
	Density / g cm^{-3}	1.85
Voltage applied to outer electrode / V		± 80

Table 2. Characteristics of the LNE-LNHB transfer chambers

Nominal values		PTW 30013	
Chamber	Outer diameter / mm	7.0	
	Outer length / mm	23.6	
Electrode	Diameter / mm	1.1	
	Length / mm	21.2	
Cavity	Nominal volume / cm^3	0.6	
Wall	Thickness / mm	0.335	0.09
	Material	PMMA	graphite
	Density / g cm^{-3}	1.19	1.85
Voltage applied to outer electrode / V		+ 300	

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 under the same conditions,
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 of mass energy-absorption coefficients water-to-graphite,
$\bar{s}_{\mathrm{g,a}}$ is the ratio of the mean mass stopping powers for electrons in graphite and air,
$\Psi_{\mathrm{w,g}}$ is the photon energy fluence ratio water-to-graphite,
$\beta_{\mathrm{w,g}}$ 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 [1]

Symbol	Parameter / unit	Value	uncertainty [2]	
			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	–	– [3]
$D_{g,air} = s_{g,a}k_{cav}$	product of the ratio of mass stopping powers and cavity perturbation correction	0.9958	0.02	0.13 [3]
$\psi_{w,g}$	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	ion recombination	1.0019	0.01	0.02
k_h	humidity	0.9970	–	0.03
Measurement of I / V				
V	volume / cm^3	6.7942 [4]	–	0.08
I	ionization current (T, P, air compressibility)	–	–	0.02
	short-term reproducibility (including positioning and current measurement) [5]		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	

[1] 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)

[2] 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

[3] 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 ^{60}Co, and the uncertainty of 0.10 for k_{cav}

[4] Standard CH7.1

[5] Over a period of 3 months

At the time of the previous comparison, conducted in 2013, the LNE-LNHB determination of the absorbed-dose-to-water rate in ^{60}Co beam (Alcyon irradiator) was based on both graphite and water calorimetry. As described in the corresponding comparison report (Kessler *et al.* 2013), the mean value of the results obtained using the two methods was used as the reference value.

In 2014, the LNE-LNHB re-evaluated the graphite-to-water absorbed-dose conversion factor $[D_w(V)/D_{core}]_{MC}$ using Monte Carlo simulations. In 2017, the LNE-LNHB adopted the revised primary standard graphite calorimeter as the national standard for the determination of absorbed dose to water, resulting in an increase of 1.8 parts in 10^3 in the determination of D_w with a relative standard uncertainty of 2.5 parts in 10^3. Based on this revised method, a set of several reference thimble-type ionization chambers (NE 2571 and PTW 30013) was calibrated periodically in terms of absorbed dose to water.

In 2024, a new ^{60}Co irradiator (GammaBeam X200) was adopted as the reference radiation beam. The absorbed-dose-to-water rate was then determined ionometrically using the reference ionization chambers that had been calibrated against the graphite calorimeter in the previous irradiation facility. The uncertainties associated with the determination of the absorbed-dose-to-water rate are given in Table 4.

Table 4. Determination of absorbed-dose-to-water rate and the relative standard uncertainties for the LNHB standard

Symbol	Parameter	uncertainty [1]	
		100 u_{iA}	100 u_{iB}
Graphite calorimeter (Alcyon ^{60}Co beam)			
$\dot{D}_{\mathrm{core}}$	absorbed dose in the core	0.01	0.02
$\left[\frac{D_{\mathrm{w}}(V)}{D_{\mathrm{core}}}\right]_{\mathrm{MC}}$	Monte Carlo dose ratio	0.09	0.20
$k_{\mathrm{prof}}(V)$	radial non-uniformity	0.01	0.02
k_i	impurities	–	0.10
k_{asym}	front/back asymmetry	0.01	–
k_{t}	decay correction	–	0.01
Combined uncertainty of the determination of absorbed-dose-to-water rate *(Alcyon beam)*			
quadratic summation		0.09	0.23
combined relative standard uncertainty $\dot{D}_{\mathrm{w}}$		0.25	
Ionization chamber calibration (Alcyon ^{60}Co beam)			
I	current	0.03	0.09
k_{TP}	temperature and pressure correction	–	0.04
k_{pol}	polarity effect	0.02	0.02
ks	ion recombination	0.02	0.02
$k$rn	radial non-uniformity	0.05	0.02
	distance	–	0.01
	depth	–	0.04
Combined uncertainty of the determination of chamber calibration			
quadratic summation		0.11	0.25
combined relative standard uncertainty $N_{D,\mathrm{w}}$		0.28	
Ionization chambers (GammaBeam ^{60}Co beam) [2]			
Combined uncertainty of the determination of absorbed-dose-to-water rate *(GammaBeam)*			
combined relative standard uncertainty $\dot{D}_{\mathrm{w}}$		0.29 [3]	

[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] Similar uncertainty budget as the one for the Alcyon beam

[3] The combined standard uncertainty is calculated from measurements using different reference ionization chambers and removing correlations

Reference conditions

The reference conditions for the absorbed-dose-to-water rate determination at the BIPM (Kessler and Burns 2024) and at the LNE-LNHB are the following:

- horizontal radiation beam,
- the distance from the source to the reference plane at the BIPM is 1 m and at the LNE-LNHB is 1.6 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} at the BIPM and 5 cm (0.4 cm PMMA and 4.6 cm water at 20 °C) at the LNE-LNHB.

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 2026-01-01, 0 h UTC. The half-life of ^{60}Co used for the decay correction is taken as 1925.23 days (u = 0.29 days) (https://www.lnhb.fr/nuclides/Co-60_tables.pdf).

The value of $\dot{D}_{\mathrm{w,LNE-LNHB}}$ is given at the reference date of 2026-06-01, 0 h UTC, using the same half-life value to calculate the decay correction. The absorbed-dose-to-water rate values $\dot{D}_{\mathrm{w}}$ determined at each laboratory are given at the corresponding reference dates in Table 5.

The ionization currents measured using the transfer chambers are decay corrected to the corresponding reference dates adopted by each laboratory.

Beam characteristics

The characteristics of the BIPM and LNE-LNHB beams are given in Table 5.

Table 5. Characteristics of the ^{60}Co beams at the LNE-LNHB 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 reference distance
		diameter	length		
LNE-LNHB GammaBeam X200	2.1	20	18	21 %	10 cm × 10 cm
BIPM Theratron 1000	2.9	20	14	21 %	10 cm × 10 cm

4. Comparison procedure

The comparison of the LNE-LNHB and BIPM standards was made indirectly using the calibration coefficients $N_{D,\mathrm{w,lab}}$ for the two transfer chambers given by

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

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 LNE-LNHB or at the BIPM. The current is corrected for the effects and influences described in this section.

The two transfer chambers used for this comparison were PTW 30013, serial numbers 8859 and 8860, both belonging to the LNE-LNHB. Their main characteristics are listed in Table 2. These chambers were calibrated at the LNE-LNHB before and 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 chambers were positioned in water, with the stem perpendicular to the beam direction and with the appropriate marking on the stem facing the source.

Applied voltage and polarity

At both laboratories, a polarizing voltage of 300 V (positive polarity) was applied to the outer electrode of the LNE-LNHB transfer chambers, at least 40 min before any measurements were made. No corrections were applied by either laboratory for polarity.

Charge and leakage measurements

The charge Q collected by the LNE-LNHB 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. The measurements were corrected by the mean leakage current 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 LNE-LNHB, a pre-irradiation was made for 40 min before any measurements. The ionization current I was measured using a Keithley electrometer, model 642. The relative leakage correction for each chamber was less than 1 part in 10^4.

Ion recombination

Volume recombination is negligible for continuous beams at the present dose rates and for the applied polarizing voltage, and the initial recombination loss will be the same in the two laboratories; consequently, no correction was applied and a relative uncertainty component of 2 parts in 10^4 is included in Table 8.

Radial non-uniformity correction

The LNE-LNHB calibration coefficients are corrected for the radial non-uniformity of the beam; for consistency, the BIPM also applied the mentioned correction to the ionization current. The correction factor applied, estimated to be the same at both laboratories, is 1.0008; the corresponding relative standard uncertainties are included in Table 7.

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 0.6 °C at the LNE-LNHB.

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 LNE-LNHB, the relative humidity is controlled in the range from 30 % to 70 %; no correction for humidity was applied to the ionization current measured.

PMMA phantom window

Both laboratories use a horizontal radiation beam. At the BIPM, 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.

5. Results of the comparison

The PTW 30013 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

$$R_{D,\mathrm{w}} = N_{D,\mathrm{w,LNE\text{-}LNHB}} / N_{D,\mathrm{w,BIPM}} \tag{3}$$

in which the average value of measurements made at the LNE-LNHB 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.

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.

The values $N_{D,\mathrm{w,LNE\text{-}LNHB}}$ 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 chambers. The short-term stability was estimated to be 1 part in 10^4. Table 8 includes a component of 1 part 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	$N_{D,\mathrm{w,LNE\text{-}LNHB}}$ / Gy μC^{-1}			$N_{D,\mathrm{w,BIPM}}$ / Gy μC^{-1}	$R_{D,\mathrm{w}}$	u_c
	pre-BIPM	post-BIPM	average			
PTW 30013-8859	53.709	53.725	53.717	53.702	1.0003	0.0036
PTW 30013-8860	53.630	53.660	53.645	53.624	1.0004	0.0036
Mean values					**1.0004**	**0.0036**

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

Description of relative standard uncertainty component	BIPM uncertainty		LNE-LNHB uncertainty	
	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
Absorbed-dose-to-water rate	0.04	0.18	–	0.29
Ionization current for the transfer chambers	0.01	0.02	0.04	0.04
Source to detector distance	0.02	–	–	0.01
Depth in water	0.02	0.06	–	0.04
Short-term reproducibility	0.01	–	–	–
Radial non-uniformity	–	0.02	0.05	0.02
Temperature, pressure	–	–	–	0.02
$N_{D,\mathrm{w,lab}}$	0.05	0.19	0.06	0.29

Table 8. Uncertainties associated with the indirect comparison

Description of relative standard uncertainty component	100 u_{iA}	100 u_{iB}
$N_{D,w,\text{LNE-LNHB}}/N_{D,w,\text{BIPM}}$	0.08	0.35
Ion recombination	–	0.02
Stability of the chambers	0.01	–
Different chambers	0.01	–
Combined standard uncertainty u_c of $R_{D,w}$	$u_c = 0.0036$	

The comparison result, taken as the unweighted mean value for the two transfer chambers, is $R_{D,w} = 1.0004$ with a combined standard uncertainty u_c for the comparison of 0.0036, 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 $D_{w,BIPM}$, is taken as the key comparison reference value (KCRV) (Allisy *et al.* 2009). It follows that for each National Metrology Institute (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 $D_i = (D_{wi} - D_{w,BIPMi})/ D_{w,BIPMi} = x_i - 1$ 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 BIPM key comparison database (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 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.

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 – EURAMET.RI(I)-K4.2 – EURAMET.RI(I)-K4.3

BIPM.RI(I)-K4

Lab *i*	D_i	U_i
	I (mGy / Gy)	
METAS	1.1	10.4
PTB	-1.3	7.6
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
NPL	-0.2	13.4
LNE-LNHB	0.4	7.2

EURAMET.RI(I)-K4.1

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

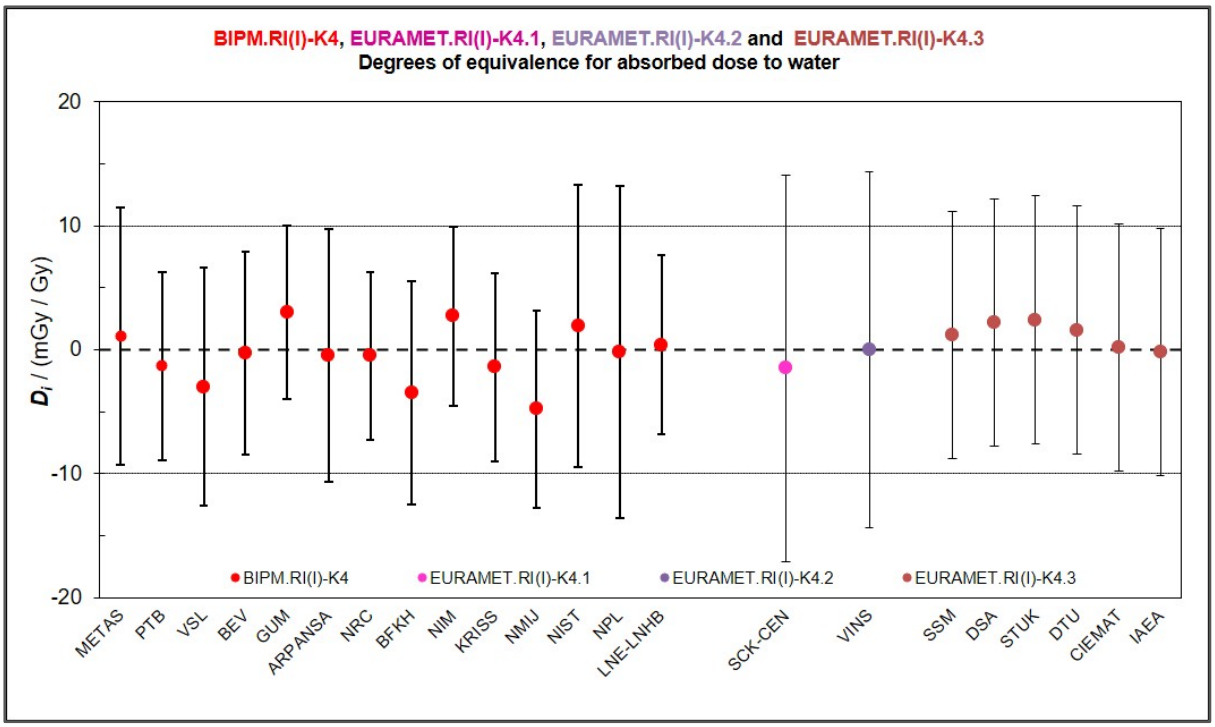
EURAMET.RI(I)-K4.2

Lab *i*	D_i	U_i
	I (mGy / Gy)	
VINS	0.0	14.4

EURAMET.RI(I)-K4.3

Lab *i*	D_i	U_i
	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

The previous comparison of the LNE-LNHB and BIPM standards for absorbed dose to water in a ^{60}Co beam was made in 2013 at the BIPM using two transfer chambers. The result of the indirect comparison was 0.9971 (39).

Since the previous comparison, the BIPM has implemented some changes in the standard following the recommendations of the ICRU 90, resulting in a reduction of 1 part in 10^3 in the determination of absorbed dose to water; the LNHB also revised the primary standard and the changes adopted represent an increase of 1.8 parts in 10^3 in the determination of absorbed dose to water. Considering the revised values, the 2013 comparison result becomes 0.9999 (37).

For the present comparison, made indirectly using transfer chambers, the LNE-LNHB 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 1.0004 (36), in close agreement with the previous comparison result. The LNE-LNHB 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.

References

Allisy P J, Burns D T and Andreo P 2009 International framework of traceability for radiation dosimetry quantities *Metrologia* **46(2)** S1-S8 (DOI 10.1088/0026-1394/46/2/S01).

Boutillon M and Perroche A-M 1993 Ionometric determination of absorbed dose to water for cobalt-60 gamma rays *Phys Med Bio* **38** 439-454 (DOI 10.1088/0031-9155/38/3/010).

Burns D and Kessler C 2018 Re-evaluation of the BIPM international dosimetry standards on adoption of the recommendations of ICRU Report 90 *Metrologia* **55** R21-R26 (DOI 10.1088/1681-7575/aacb01).

CIPM MRA: *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 CIPM MRA.

Delaunay F, Gouriou J, Daures J, Le Roy M, Ostrowsky A, Rapp B and Sorel S 2014 New standards of absorbed dose to water under reference conditions by graphite calorimetry for ^{60}Co and high-energy x-rays at LNE-LNHB *Metrologia* **51(5)** (DOI 10.1088/0026-1394/51/5/552).

ICRU 2016 Key data for ionizing-radiation dosimetry: Measurement standards and applications J. ICRU 14 Report 90 (Oxford University Press).

KCDB 2026 BIPM key comparison database ^{60}Co absorbed dose to water comparisons BIPM.RI(I)-K4.

Kessler C, Burns D T, Delaunay F and Donois M 2013 Key comparison BIPM.RI(I)-K4 of the absorbed dose to water standards of the LNE–LNHB, France and the BIPM in ^{60}Co gamma radiation *Metrologia* **50** *Tech. Supp.* 06019 (DOI 10.1088/0026-1394/50/1A/06019).

Kessler C and Burns D 2024 Measuring conditions and uncertainties for the comparison and calibration of national dosimetric standards at the BIPM *Rapport* BIPM-24/04.

Ostrowsky A and Daures J 2008 The construction of the graphite calorimeter GR-9 at LNE-LNHB Report CEA-R-6184 (https://inis.iaea.org/records/x9e6n-g8a18).