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BIPM.RI(I)-K4 (NPL 2025)

Measurement of absorbed dose to water for Cobalt 60

KEY COMPARISON

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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 NPL, United Kingdom and of the BIPM

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Abstract

A new key comparison of the standards for absorbed dose to water of the National Physical Laboratory (NPL), United Kingdom, and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in September 2025. The comparison result, based on the calibration coefficients for two transfer chambers and evaluated as a ratio of the NPL and the BIPM standards for absorbed dose to water, is 0.9998 with a combined standard uncertainty of 6.7 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 Physical Laboratory (NPL), United Kingdom and of the Bureau International des Poids et Mesures (BIPM) was carried out in September 2025 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2017 (Kessler *et al.* 2019) published in the BIPM key comparison database (KCDB 2026) under the reference BIPM.RI(I)-K4. The 2025 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 both laboratories.

The 2025 indirect comparison was made using two thimble-type ionization chambers as transfer chambers, both instruments belonging to the NPL. The final results were supplied by the NPL in December 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 NPL for absorbed dose is a graphite calorimeter described by Sander *et al.* (2017). The NPL uses the scaling dose ratio method to derive the absorbed dose to water from its calorimetric determination of absorbed dose to graphite (Nutbrown *et al.* 2002).

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 NPL transfer chambers**

Dimensions		NE 2611A / NPL 2611
Chamber	Cavity diameter / mm	7.35
	Cavity length / mm	9.22
Electrode	Diameter / mm	1.76
	Length / mm	6.35
Cavity	Nominal volume / cm^3	0.325
Wall	Thickness / mm	0.5
	Material	Graphite
	Density / g cm^{-3}	1.80
Voltage applied to the outer electrode / V		-200

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

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

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 of mass energy-absorption coefficients water-to-graphite,

$\bar{s}_{\mathrm{g,a}}$ 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,

$\beta_{\mathrm{w,g}}$ 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	saturation	1.0019	0.01	0.02
k_h	humidity	0.9970	–	0.03
Measurement of I/υ				
υ	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

The NPL primary standard is a graphite calorimeter, described by Sander *et al.* (2017) and in the previous comparison report (Kessler *et al.* 2019). The calorimeter is operated in quasi-adiabatic mode, and the sensitivity of the calorimeter to ionising radiation energy absorbed in the graphite core is calculated from voltage and resistance measurements traceable to NPL standards. The absorbed dose to water is determined from measurements of the absorbed dose to graphite.

The absorbed dose to graphite, $D_{g,ref}$, at the reference point (equivalent to 5 g cm^{-2} depth in water) in a homogeneous, cylindrical, pure graphite phantom (with the shape of the calorimeter components and their sizes scaled in terms of electron density) is given by

$$D_{g,ref} = (E^{rad}/m_{core,eff})k_{imp}k_{gap}k_{z,cal}k_{d,cal}k_{rn,cal}k_{an,cal} \quad (2)$$

where:

E^{rad} is the energy absorbed in the calorimeter core from ionizing radiation only (Seuntjens and Duane 2009),

$m_{core, eff}$ is the effective mass of the graphite core including all non-graphite materials,

k_{imp} is the Monte Carlo (MC) calculated impurity correction factor, calculated as the dose ratio $D_{core,gaps}$ / $D_{core,all}$, where $D_{core,gaps}$ is the dose to the core with all non-graphite materials in the calorimeter substituted with pure graphite (no impurities) with mass density of the core graphite and scaled in terms of electron density, and $D_{core,all}$ is the dose to the core in the real calorimeter,

k_{gap} is the MC calculated compensated vacuum gap correction factor, calculated as the dose ratio $D_{core,nogaps}$ / $D_{core,gaps}$, where $D_{core,nogaps}$ is the dose to the core with all vacuum gaps in the pure graphite calorimeter geometry substituted with pure graphite ensuring the mass-thickness (in terms of electron density) of material upstream of the graphite core remains unchanged, and $D_{core, gaps}$ is defined as above,

$k_{z,cal}$ is the inverse square correction factor for the difference in distance between the ^{60}Co source to the reference plane and the ^{60}Co source to the measurement plane (centre of calorimeter core),

$k_{d,cal}$ is the correction factor for the difference in the desired reference depth in graphite and that achievable in the measurement setup,

$k_{rn,cal}$ is the correction factor for the radial non-uniformity of the ^{60}Co beam over the calorimeter core, and

$k_{an,cal}$ is the correction factor for the axial non-uniformity of the ^{60}Co beam over the calorimeter core. The decrease of absorbed dose with depth at the water-equivalent depth of 5 g cm^{-2} is approximately linear and, as the calorimeter core extends only 5 mm along the beam axis, no correction is made for the non-uniformity of absorbed dose along the beam axis.

The previously applied thermistor lead resistance correction factor $k_{lead\ res,th}$ in Sander *et al.* (2017) and Kessler *et al.* (2019) was removed from Equation (2) in this report and deemed to be more appropriate to be included in the uncertainty budget (see Table 5, item ‘Electrical calibrations’).The main characteristics of the NPL calorimeter are shown in Table 4.

Table 4. Characteristics of the NPL graphite calorimeter

Component	Characteristic	Value
Core	Diameter / mm	19.984
	Thickness / mm	5.005
	Effective mass / g	2.9572
	Graphite density / g cm^{-3}	1.878
Gap widths	Gap between core and inner front jacket / mm	0.768
	Gap between inner and outer front jacket / mm	0.769
	Gap between outer front jacket and outer front mantle / mm	0.822
Water-equivalent depth	Mid-plane of core to front of phantom (excl. build-up) / g cm^{-2}	1.5558
Cylindrical outer graphite phantom	Diameter / cm	32
	Height (excl. build-up) / cm	8.26
Cylindrical build-up plate	Diameter / cm	23
	Height / cm	2.08
	Graphite density (mean) / g cm^{-3}	1.841

Note: All the calorimeter components were constructed from a single block of graphite. The build-up plates, however, were constructed from a different type of graphite with the density stated in the table

The NPL reference standard chambers

The NPL uses a set of three reference standard ionization chambers, two manufactured by Nuclear Enterprises of type NE 2611A, serial numbers 202 and 204, and one manufactured by NPL of type NPL 2611, serial number 1010, to maintain and transfer absorbed dose to graphite (Pearce *et al.* 2011). The main characteristics of these reference standard chambers are the same as those for the transfer chambers listed in Table 2. The reference standard chambers are set up in a cuboidal graphite phantom and calibrated against the calorimeter.

The dose to graphite at the reference point in the graphite phantom (i.e. at the centre of the thimble chamber inside the graphite phantom), D_g, measured at 5.0426 g cm^{-2} water-equivalent depth in terms of electron density is given by

$$D_g = D_{g,ref}\, k_{geom} \quad (3)$$

where:

$D_{g,ref}$ is the absorbed dose to graphite at the reference point in the graphite core of the calorimeter (water-equivalent depth of 5 g cm^{-2}) and

k_{geom} is the MC calculated configuration correction factor for the combined effect of

(a) the difference between the geometries of the cylindrical calorimeter and the cuboidal graphite phantom, which is used to calibrate NPL's reference standard chambers, resulting in different scatter contributions at the reference point, and

(b) the difference in depth of the reference points for the calorimeter (5 g cm^{-2}) and the graphite phantom (5.0426 g cm^{-2}).

k_{geom} corrects $D_{g,ref}$ to the measurement point of the reference standard chamber in the graphite phantom, where the chamber is not at exactly 5 g cm^{-2} water-equivalent depth.

The reference standard chamber calibration coefficient, $N_{Dg,NPLref\ cham}$, in terms of absorbed dose to graphite per unit electric charge produced in the thimble chamber inside the graphite phantom is obtained from the relation

$$N_{Dg,\ NPL\ ref\ cham} = D_g / (Q_{g,\ NPL\ ref\ cham}\, k_{elec}\, k_{ion}\, k_{z,cham}\, k_{rn,cham}\, k_{Tp}) \quad (4)$$

where:

D_g is the absorbed dose to graphite at the reference point in the graphite phantom (equivalent to 5.0426 g cm^{-2} water-equivalent depth),

$Q_{g,\ NPL\ ref\ cham}$ is the electric charge, measured at a relative humidity in the range 20 % to 70 %, with the reference standard chamber in the graphite phantom,

k_{elec} is the electrometer correction factor,

k_{ion} is the correction factor for ion recombination in the reference standard chamber,

$k_{z,\ cham}$ is the inverse square correction factor for the difference in distance between the ^{60}Co source to the reference plane and the ^{60}Co source to the measurement plane (centre of reference standard chamber),

$k_{rn,\ cham}$ is the correction factor for the radial non-uniformity of the ^{60}Co beam over the reference standard chamber in the graphite phantom and

k_{Tp} is the factor to correct from ambient temperature T and pressure p to standard temperature and pressure.

Conversion to absorbed dose to water from absorbed dose to graphite

At the NPL, the reference standard chamber calibration coefficient, $N_{Dw,NPLref\ cham}$, in terms of absorbed dose to water at the reference depth of 5 g cm^{-2} in water has been obtained from the reference standard chamber calibration coefficient, $N_{D\mathrm{g,NPLref\ cham}}$, in terms of absorbed dose to graphite at the reference point (see Equation 4) by using the scaling dose ratio method and the formalism described by Nutbrown *et al.* (2002)

$$N_{D\mathrm{w,\ NPL\ ref\ cham}} = N_{D\mathrm{g,\ NPL\ ref\ cham}}(N_\mathrm{w}/N_\mathrm{g}) \tag{5}$$

where:

N_w / N_g is the conversion factor of the reference standard chamber calibration coefficient from graphite to water at the reference point.

The uncertainty components for the determination of the absorbed-dose-to-water using the graphite calorimeter in combination with the reference standard chambers are shown in Table 5.

Changes to the physical constants and correction factors adopted at the NPL since the previous comparison in 2017

The recommendations of ICRU Report 90 (ICRU 2016) were implemented at the NPL in 2019. Additionally, a refined analysis of the measured specific heat capacity of the pure graphite used for the calorimeter core was carried out. This work also resulted in the introduction of a specific heat capacity correction factor (see Table 5, including footnotes (2) and (3)).

The thermistor calibration correction factor, which was included in the previous data analysis but not explicitly mentioned in the previous comparison report (Kessler *et al.* 2019), and also the previously applied thermistor lead resistance correction factor were both reviewed and deemed to be more appropriate to be included in the uncertainty budget (see item 'Electrical calibrations'), rather than applied as separate correction factors.

The re-evaluations mentioned above represent a reduction in the determination of absorbed dose to water of 3.3 parts in 10^3 between 2017 and 2024.

In 2023, a new ^{60}Co source was installed at NPL in the existing irradiator housing. This resulted in revised measured radial beam non-uniformity correction factors for both the calorimeter and the reference standard chambers in the graphite phantom.

Reference conditions

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

- 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 NPL are the same as the BIPM conditions.

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 2025-01-01, 0 h UTC. The ionization current measured using the transfer chambers is decay corrected to the same reference date. The half-life of ^{60}Co used for the decay correction is taken as 5.2710 (8) years (this corresponds to 1925.19 (29) days) (Bé *et al.* 2006).

The value of $\dot{D}_\mathrm{w,NPL}$ is given at the reference date of 2025-07-23, 0 h UTC, using the same half-life value to calculate the decay correction.

Table 5. Physical constants, correction factors and relative standard uncertainties for the NPL standard for absorbed-dose-to-water

Symbol	Parameter / unit	Value	uncertainty 100 u_{iA}	100 u_{iB}
Calorimetry				
$m_{core,eff}$	Effective mass of the core / g	2.9572	<0.01	0.01
$k_{z,cal}$	Inverse square correction for source-to-core distance	1.0000	–	0.10
$k_{d,cal}$	Reference depth in graphite	1.0000	<0.01	<0.01
$k_{rn,cal}$	Radial beam non-uniformity correction for the calorimeter	0.9986	–	0.03
$k_{an,cal}$	Axial beam non-uniformity correction for the calorimeter	1.0000	–	0.01
	Core alignment on beam axis	–	–	<0.01
Monte Carlo considerations				
$k_{gap} \times k_{imp} \times k_{geom}$	Product of MC calculated factors [(1)]	1.0056	0.10	0.10
	Source and calorimeter geometry modelling	–	–	0.10
	MC self-consistency, transport parameters	–	–	0.10
Electrical calibrations				
	Electronics and thermistor calibrations	–	0.20	0.08
Heat capacity				
c_p	Specific heat capacity of core graphite sample [(2)] / J kg^{-1} K^{-1}	716.28	0.28	0.08
k_c	Specific heat capacity correction factor [(3)]	0.9971	–	0.10
Calorimeter measurements				
	Calorimeter data analysis	–	–	0.16
	Repeatability of calorimetry results	–	0.10	–
Reference standard chamber measurements				
k_{elec}	Electrometer calibration	–	–	0.10
	Electrometer resolution	–	–	0.03
k_{ion}	Ion recombination	1.0014	–	0.03
$k_{z,cham}$	Inverse square correction for source-to-chamber distance	1.0000	–	0.10
$k_{rn,cham}$	Radial beam non-uniformity correction for the ion chamber	0.9991	–	0.01
T	Air temperature / K	293.15	–	0.06
p	Air pressure / kPa	101.33	–	0.05
RH	Relative humidity	–	–	0.10
	Ion chamber repeatability	–	0.03	–
Graphite to water conversion				
N_w / N_g	Conversion of absorbed dose from graphite to water [(4)]	1.1270	0.25	0.23
Combined uncertainty of the NPL determination of $N_{Dw, \text{NPL ref cham}}$				
quadratic summation			0.45	0.42
combined relative standard uncertainty			0.62	

(1) Monte Carlo calculated correction factors for the effects of the vacuum gaps in the calorimeter, the non-graphite impurities in the core and the difference between the geometries of the calorimeter and the graphite phantom for the reference standard chamber measurements, including differences in the water-equivalent depths of the reference points

(2) The specific heat capacity of a sample of graphite manufactured from the same batch as the calorimeter core at T = 25 °C.

(3) The correction factor applied to take into account the effect on the temperature rise of the graphite due to the differing values of heat capacity of the non-graphite components within the core, i.e. the thermistors and epoxy glue

(4) See Nutbrown *et al.* (2002) for the numerical value of the graphite to water conversion factor for the ^{60}Co beam quality The type A and B uncertainties are those shown in Pearce *et al.* (2011). These uncertainties are currently reported by the NPL for the ^{60}Co beam quality as well as all clinical linac MV photon beam qualities for absorbed dose to water calibrations

Beam characteristics

The characteristics of the BIPM and NPL beams are given in Table 6.

Table 6. Characteristics of the ^{60}Co beams at the NPL and the BIPM

^{60}Co beam	Nominal $\dot{D}_w$ / mGy s^{-1}	Source dimensions / mm		Scatter contribution in terms of energy fluence	Field size at 1 m
		diameter	length		
NPL Theratron 780-C	17.7	20	20	17 %	10 cm × 10 cm
BIPM Theratron 1000	3.3	20	14	21 %	10 cm × 10 cm

4. Comparison procedure

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

$$N_{D,\mathrm{w,lab}} = \dot{D}_{\mathrm{w,lab}} / I_{\mathrm{lab}} \tag{6}$$

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

The transfer chambers used for this comparison were NE 2611A, serial number 203 and NPL 2611, serial number 1007, both belonging to the NPL. Their main characteristics are listed in Table 2. These chambers were calibrated at the NPL 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 inside the sleeve provided by the NPL, with the stem perpendicular to the beam direction and with the appropriate marking on the stem facing the source.

Applied voltage and polarity

At the NPL and at the BIPM, a polarizing voltage of 200 V (negative polarity) was applied to the outer electrode (wall) of the transfer chambers. At the NPL, this was applied at least 10 minutes before any measurements were made. At the BIPM, the polarizing voltage was applied at least 40 minutes before any measurements were made. No corrections were applied by either laboratory for polarity.

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 minutes to a total dose of approximately 10 Gy. The measurements were corrected by the mean leakage current measured before and after each series of measurements. The measured leakage currents were around 20 fA for NE 2611A-203 and 3 fA for NPL 2611-1007. The leakage correction, estimated as the ratio of the leakage current relative to the ionization current, was 6 parts in 10^4

and less than 1 part in 10^4 for the NE 2611A-203 and the NPL 2611-1007 transfer chambers, respectively.
At the NPL, each transfer chamber was pre-irradiated for at least 5 minutes to a total dose of approximately 5 Gy. This was followed by a measurement of the leakage current. Finally, with the source exposed, the ionization current I was sampled once per second for a total of 300 s using a Keithley electrometer, model 6517A. The relative leakage correction for each transfer chamber was less than 4 parts in 10^4.

Ion recombination

At the NPL, the measured currents are usually corrected for ion recombination (the correction applied at the NPL to the measured currents was 1.0014). However, for these chamber types, 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 3 parts in 10^4 is included in Table 9.

Radial non-uniformity correction

No radial non-uniformity correction was applied. At the NPL, 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 2 parts in 10^4 for the transfer chambers. A relative uncertainty component of 2 parts in 10^4 is included in Table 9.

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 NPL.

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 NPL, relative humidity is controlled and was in the range from 50 % to 65 %. No correction for humidity was applied to the ionization current measured at either laboratory.

PMMA phantom window

Both laboratories use 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.
The waterproof PMMA sleeve supplied by the NPL was used at both laboratories and, consequently, no correction for the influence of the sleeve was necessary at either laboratory.

5. Results of the comparison

The NE 2611A-203 and the NPL 2611-1007 transfer chambers were set up and measured in the BIPM ^{60}Co beam on three and two separate occasions, respectively. The results for each chamber were reproducible to better than 2 parts in 10^4. The result of the comparison, $R_{D,\text{w}}$, is expressed in the form

$$R_{D,\text{w}} = N_{D,\text{w,NPL}}/N_{D,\text{w,BIPM}} \tag{7}$$

in which the average value of measurements made at the NPL 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 7.

The values $N_{D,\mathrm{w,NPL}}$ 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 2 parts in 10^4. Table 9 includes a component of 3 parts in 10^4 for the difference in the comparison results between the two transfer chambers.

Table 7. Results of the comparison of standards for ^{60}Co absorbed dose to water

Transfer Chamber	$N_{D,\mathrm{w,NPL}}$ [(1)] / Gy µC^{-1}			$N_{D,\mathrm{w,BIPM}}$ / Gy µC^{-1}	$R_{D,\mathrm{w}}$	u_c
	pre-BIPM	post-BIPM	average			
NE 2611A-203	103.91	103.87	103.89	103.89	1.0000	0.0068
NPL 2611-1007	102.05	102.05	102.05	102.10	0.9995	0.0068
Mean values					**0.9998**	**0.0068**

(1) The $N_{D,\mathrm{w,NPL}}$ values provided by the NPL included an ion recombination correction that has been removed in accordance with Section 4

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 8 and Table 9, respectively.

Table 8. Uncertainties associated with the calibration of the transfer chambers

Description of relative standard uncertainty component	BIPM uncertainty		NPL 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	–	–
Reference chamber calibration coefficient in terms of absorbed dose to water	–	–	0.45	0.42
Ionization current for the reference standard chambers	–	–	0.05	0.13 (1)
Ionization current for the transfer chambers	0.01	0.02	0.07	– (2)
Source to detector distance	0.02	–	–	–
Depth in water	0.02	0.06	–	–
Short-term reproducibility	0.02	–	0.03	–
$N_{D,\mathrm{w,lab}}$	0.05	0.19	0.46	0.44

(1) Including uncertainties for the electrometer calibration and resolution (0.10), and for T and p corrections (0.08)

(2) Type B uncertainty already accounted for in the type B uncertainty for the ionization current measurements with the reference standard chambers. For the calibration at the NPL, the reference and transfer chambers were used sequentially in the same water phantom. The same electrometer, barometer and temperature probe were used for the measurements, resulting in correlated uncertainties.

Table 9. Uncertainties associated with the indirect comparison

Description of relative standard uncertainty component	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
$N_{D,\mathrm{w,NPL}}/N_{D,\mathrm{w,BIPM}}$	0.46	0.48
Ion recombination	–	0.03
Radial non-uniformity	–	0.02
Stability of the chambers	0.02	–
Different chambers	0.03	–
$R_{D,\mathrm{w}}$	u_c = 0.0067	

The comparison result, taken as the unweighted mean value for the two transfer chambers, is $R_{D,\mathrm{w}}$ = 0.9998 with a combined standard uncertainty u_c for the comparison of 0.0067, 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 10 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 10, 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 2026).

Table 10. 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
	/ (mGy / Gy)	
LNE-LNHB	-1.9	7.8
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

EURAMET.RI(I)-K4.1

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

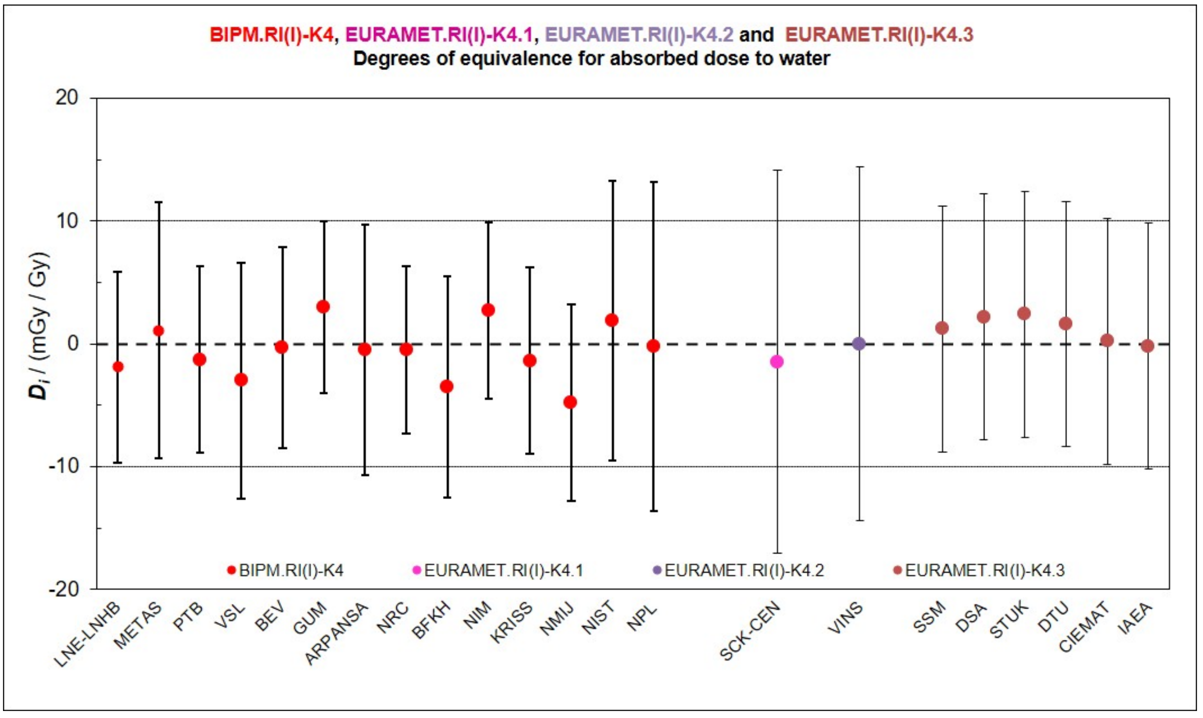
EURAMET.RI(I)-K4.2

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

The previous comparison of the NPL and BIPM standards for absorbed dose to water in a ^{60}Co beam was made in 2017 at the BIPM using two transfer chambers. The result of the indirect comparison was 1.0013 (71).

Since the previous comparison, both laboratories have implemented some changes in the standards following the recommendations of the ICRU 90 and re-evaluation of some corrections for the NPL calorimeter. For the NPL and for the BIPM, this resulted in a reduction of 3.3 parts in 10^3 and 1 part in 10^3, respectively, in the determination of absorbed dose to water, so that the previous comparison result becomes 0.9990 (68).

For the present comparison, made indirectly using transfer chambers, the NPL 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 0.9998 (67), in agreement with the previous comparison result within the uncertainties. The NPL 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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