Comparison of the standards for absorbed dose to water of the NPL, United Kingdom and the BIPM for ^{60}Co γ rays

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Abstract

A 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 November 2017. The comparison result, based on the calibration coefficients for two transfer standards and expressed as a ratio of the NPL and the BIPM standards for absorbed dose to water, is 1.0013 with a combined standard uncertainty of 7.1×10^{-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 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 November 2017 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2007 (Kessler *et al* 2012) published in the BIPM key comparison database (KCDB 2019) under the reference BIPM.RI(I)-K4. The comparison was undertaken using two transfer ionisation chambers of type NE 2611A belonging to the NPL. The result of the comparison is given in terms of the mean ratio of the calibration coefficients of these transfer instruments determined at the two laboratories. The final results were supplied by the NPL in May 2018.

2. Details of the standards

The primary standard of the NPL for absorbed dose is a Domen-type 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).

The BIPM primary standard is a parallel-plate graphite cavity ionization chamber described by Boutillon *et al* (1993) positioned at the reference depth in a water phantom. The main dimensions are given in Table 1.

Table 1. Characteristics of the BIPM standard

Dimensions		CH4-1
Cavity	Diameter / mm	45.0
	Thickness / mm	5.147
	Volume / cm^3	6.8810
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 polarity	80

3. Determination of the absorbed dose to water

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

$$\dot{D}_{\mathrm{w,\,BIPM}} = \frac{I}{\rho_{\mathrm{air}} V} \frac{W}{e} \bar{s}_{\mathrm{c,a}} \Pi k_i \,, \tag{1}$$

where

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

I is the ionization current measured by the standard,

W is the mean energy expended in dry air per ion pair formed,

e is the electronic charge,

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

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

The values for the physical constants and the correction factors entering in equation (1) are given in Table 2. The correction factors entering in equation (1), the volume of the primary standard and the associated uncertainties for the BIPM standard (Allisy-Roberts *et al* 2011) are also included in Table 2. Note that, as the comparison was carried out during 2017, changes to the standards made in 2019 as the result of the implementation of the recommendations of ICRU Report 90 (ICRU 2016) are not included.

Table 2. Physical constants, correction factors and relative standard uncertainties for the BIPM ionometric standard for absorbed dose to water

Symbol	Parameter / unit	Value	Relative standard uncertainty [1]	
			100 s_i	100 u_i
Physical constants				
ρ_{air}	dry air density (0°C, 101.325 kPa) / kg m^{-3}	1.2930	–	0.01
$(\mu_{en}/\rho)_{w,c}$	ratio of mass energy-absorption coefficients	1.1125 [2]	0.01 [2]	0.14 [2]
$s_{c,a}$	ratio of mass stopping powers	1.0030	–	0.11 [3]
W/e	mean energy per charge / J C^{-1}	33.97		
Correction factors				
k_p	fluence perturbation	1.1107	0.05	0.17
k_{ps}	polythene envelope of the chamber	0.9994	0.01	0.01
k_{pf}	front face of the phantom	0.9996	–	0.01
k_{rn}	radial non-uniformity	1.0056	0.01	0.03
k_s	saturation	1.0017	0.01	0.01
k_h	humidity	0.9970	–	0.03
Measurement of I /υ				
υ	effective volume of CH4-1/ cm^3	6.8810	0.19	0.03
I	ionization current (T, P, air compressibility)	–	–	0.02
	short-term reproducibility (including positioning and current measurement)		0.02	–
Combined uncertainty of the BIPM determination of absorbed dose to water rate				
quadratic summation			0.20	0.21
combined relative standard uncertainty			0.29	

[1] expressed as one standard deviation.
s_i represents the relative uncertainty estimated by statistical methods, type A
u_i represents the relative uncertainty estimated by other methods, type B.
[2] included in the uncertainties for k_p.
[3] uncertainty value for the product $s_{c,a}$ W/e.

At the NPL the absorbed dose to water is determined from measurements of absorbed dose to graphite with a graphite calorimeter and a conversion from graphite to water with a set of reference standard ionization chambers. The reference chambers of type NE2611 are calibrated in terms of absorbed dose to graphite and the calibration coefficients are converted into absorbed dose to water using factors determined by Nutbrown *et al* (2002).

Absorbed dose to graphite

The NPL standard of absorbed dose is a Domen-type graphite calorimeter constructed by the NPL with the physical dimensions presented in Tables 3 and 4. A summary of the correction factors and their uncertainties are listed in Table 5. 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 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

$$D_{g,ref} = \left(E^{rad}/m_{core,eff}\right) k_{imp} k_{gap} k_{z,cal} k_{d,cal} k_{rn,cal} k_{an,cal} k_{lead\ res,th} \qquad (2)$$

where

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

$m_{\text{core, eff}}$ 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 $D_{\text{core,gaps}} / D_{\text{core,all}}$ where $D_{\text{core,gaps}}$ 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 $D_{\text{core,all}}$ is the dose to the core in the real calorimeter,

k_{gap} is the MC calculated vacuum gap correction factor, calculated as the dose ratio $D_{\text{core,nogaps}} / D_{\text{core,gaps}}$, with all non-graphite parts in the calorimeter substituted with pure graphite (no impurities) with mass density of the core graphite and scaled in terms of electron density,

$k_{\text{z,cal}}$ is the correction factor for the reference distance from the ^{60}Co source.

$k_{\text{d,cal}}$ is the correction factor for the reference depth in graphite.

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

$k_{\text{an,cal}}$ 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 5.6 g cm^{-2} in graphite 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.

$k_{\text{lead res,th}}$ is the correction factor for the change in thermistor lead resistance between calibration and final assembly.

Table 3. Main dimensions of the NPL standard

Vertical dimensions / mm		Horizontal dimensions / mm	
Core diameter	19.984	Core thickness	5.005
Inner jacket inner diameter	21.484	Core/Inner jacket gap (front)	0.768
Inner jacket outer diameter	29.467	Inner jacket thickness (front)	0.762
Outer jacket inner diameter	30.950	Inner jacket/Outer jacket gap (front)	0.769
Outer jacket outer diameter	38.969	Outer jacket thickness (front)	0.750
Mantle inner diameter	40.527	Outer jacket/Mantle gap (front)	0.822
Mantle outer diameter	149.963	Mantle thickness (front)	3.005
Vacuum housing inner diameter	151.5	Vacuum housing thickness (front)	3.033
Vacuum housing outer diameter	210	Build-up plate thickness	20.788
Phantom outer diameter	320	Core/Inner jacket gap (back)	0.768
		Inner jacket thickness (back)	0.772
		Inner jacket/Outer jacket gap (back)	0.769
		Outer jacket thickness (back)	0.782
		Outer jacket/Mantle gap (back)	0.822
		Mantle thickness (back)	2.799
		Vacuum housing thickness (back)	2.940

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 to inner front jacket / mm	0.768
	Gap between inner to 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 core components were constructed from a single block of graphite. The build-up plates were constructed from a different block with the density stated in the table.

Table 5. Correction factors and their uncertainties in the NPL calorimetric determination of the absorbed dose to graphite

Correction factors	Numerical value	Relative uncertainty (1)	
		100 s_i	100 u_i
Product of $k_{gap} \times k_{geom} \times k_{imp}$ (2)	1.0064	0.10	0.10
$k_{z,\,cal}$ distance	1.0000	–	0.10
$k_{d,\,cal}$ depth	1.0000	–	<0.01
$k_{rn,\,cal}$ radial non-uniformity	1.0008	–	0.03
$k_{an,\,cal}$ axial non-uniformity	1.0000	–	0.01
$k_{lead\ res,th}$ thermistor lead resistance	0.9991	–	0.01

(1) expressed as one standard deviation.

s_i represents the relative uncertainty estimated by statistical methods, type A

u_i represents the relative uncertainty estimated by other methods, type B.

(2) k_{geom} is defined in equation 3

The NPL reference standards

The NPL uses a set of three reference standard ionisation chambers, two manufactured by Nuclear Enterprises of type NE 2611 and one manufactured by NPL of type NPL 2611, respectively, to maintain and transfer absorbed dose to graphite (Pearce *et al* 2011). The main characteristics of these standards are listed in Table 6. The reference chambers are set up in a cuboidal graphite phantom and calibrated against the calorimeter.

Table 6. Characteristics of the reference and transfer chambers type NE 2611 and NPL 2611

Characteristic		Nominal values
Dimensions	Inner diameter / mm	7.35
	Wall thickness / mm	0.5
	Cavity length / mm	9.22
	Cavity centre from tip / mm	5.00
Electrode	External diameter / mm	1.00
Volume	Air cavity / cm^3	0.325
Wall	Material	graphite < 0.01% impurity
	Density / (g cm^{-3})	1.80
Applied voltage	Negative polarity* / V	200

* Electric potential of the chamber wall with respect to the central electrode.

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

$$D_g = D_{g,ref}\, k_{geom} \tag{3}$$

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 secondary standard thimble 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}).

The reference standard 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

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

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 chamber in the graphite phantom,

k_{elec} is the electrometer correction factor,

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

$k_{z,\ cham}$ is the correction factor for the different distance of the graphite phantom from the ^{60}Co source,

$k_{rn,\ cham}$ is the correction factor for the radial non-uniformity of the ^{60}Co beam over the reference ionisation 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

The correction factors for ion recombination k_{ion}, distance $k_{z,\ cham}$ and radial non-uniformity $k_{rn,\ cham}$ are listed in Table 7 together with their uncertainties.

Table 7. Correction factors and their uncertainties in the calibration coefficient in terms of absorbed dose to graphite for the NPL reference standards

Correction factors		Numerical value	Relative uncertainty (1)	
			100 s_i	100 u_i
k_{ion}	ion recombination	1.0014	–	0.03
$k_{z,cham}$	distance	1.0000	–	0.10
$k_{rn,cham}$	radial non-uniformity	1.0001	–	0.01

Conversion to absorbed dose to water from absorbed dose to graphite

At the NPL the reference 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 chamber calibration coefficient, $N_{Dg,NPLref\ cham}$, 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):

$$N_{Dw,\ NPL\ ref\ cham} = N_{Dg,\ NPL\ ref\ cham}(N_w/N_c) \tag{5}$$

where

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

Nutbrown *et al* 2002 give the numerical value of the graphite to water conversion factor for the ^{60}Co beam quality as 1.1270, with a standard uncertainty of 3.2×10^{-3}.

Table 8 summarises the relative standard uncertainties associated with the primary standard correction factors, the primary standard measurement of absorbed dose to graphite, the conversion from dose to graphite to dose to water and the calibration of the NPL reference chambers in terms of absorbed dose to water.

Table 8. Relative standard uncertainties for the NPL absorbed dose to water calibration

	NPL relative standard uncertainty	
	100 s_i	100 u_i
Calorimetry		
Effective core mass, $m_{core,\ eff}$	–	0.01
Total build-up material in front of the centre of the calorimeter core	<0.01	<0.01
Inverse square correction for source-to-core distance, $k_{z,\ cal}$	–	0.10
Reference depth in graphite, $k_{d,\ cal}$	–	<0.01
Radial non-uniformity correction for the calorimeter, $k_{rn,\ cal}$	–	0.03
Axial non-uniformity correction for the calorimeter, $k_{an,\ cal}$	–	0.01
Core alignment on beam axis	–	<0.01
Monte Carlo considerations		
Product of factors: $k_{gap} \times k_{imp} \times k_{geom}$	0.10	0.10
Source modelling	–	0.10
MC self-consistency, transport parameters	–	0.10
Electrical calibrations		
Electronics and thermistor calibrations	0.2	0.08
Specific heat capacity of core graphite		
Measurement of effective specific heat capacity	0.28	0.21

Table 8. (cont)

	NPL relative standard uncertainty	
Calorimeter measurements		
Calorimeter data analysis	–	0.16
Repeatability of calorimetry results	0.03	–
Dose to graphite at the reference point, D_g (combined uncertainty)	0.50	
Ion chamber measurements		
Ion chamber repeatability	0.04	-
Electrometer calibration, k_{elec}	–	0.1
Ion recombination, k_{ion}	–	0.03
Inverse square correction for source-to-chamber distance, $k_{z,\,cham}$	–	0.10
Radial beam non-uniformity correction for the ion chamber, $k_{rn,\,cham}$	–	0.01
Air temperature	–	0.06
Air pressure	–	0.05
Relative humidity	–	0.1
Reference chamber calibration coefficient, $N_{D_g,\mathrm{NPL\ ref\ cham}}$	0.36	0.39
Conversion of absorbed dose from graphite to water	0.16	0.28
Reference chamber calibration coefficient, $N_{D_w,\,\mathrm{NPL\ ref\ cham}}$	0.62	

Reference conditions

Absorbed dose is determined at the BIPM under reference conditions defined by the CCRI, previously known as the CCEMRI (1985):

- 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 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; and
- the reference depth in the water phantom is 5 g cm^{-2}.

The reference conditions at the NPL used for the dissemination of absorbed dose to water are as given above.

Reference values

The BIPM reference absorbed dose to water rate $\dot{D}_{w,\mathrm{BIPM}}$ is taken as the mean of the four measurements made around the period of the comparison, corrected to the reference date of 2017-01-01, 0 h UTC, as is the ionization current of the transfer chambers. The half-life of ^{60}Co was taken as 1925.19 days (u = 0.29 days) (Bé *et al* 2006).

A conventional value of absorbed dose rate is not maintained at NPL. Rather, the absorbed dose rate to water is measured at the time of transfer standard calibration using the reference standard ionization chambers. In this calibration, reference and transfer standards are ionization chambers of the same type, the same instruments are used to measure and correct their ionization currents, and the only significant contributions to the uncertainty arise from any long term drift in reference standard sensitivity, short term repeatability of reference and transfer chamber measurements and any difference in leakage currents.

Beam characteristics

The characteristics of the BIPM and NPL beams are given in Table 9.

Table 9. Characteristics of the ^{60}Co beams at the NPL and the BIPM

^{60}Co beam	Nominal $\dot{D}_w$ / mGy s^{-1} (2017-01-01)	Source dimensions / mm		Scatter contribution in terms of energy fluence	Field size at 1 m
		diameter	length		
NPL source	18.3	20	20	17 %	10 cm × 10 cm
BIPM source	2.5	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 $N_{D_w,\mathrm{lab}}$ for the two transfer chambers given by

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

where $\dot{D}_{\mathrm{w,\,lab}}$ is the water absorbed dose rate at the NPL or the BIPM and I_{lab} is the corresponding ionization current for a transfer chamber measured at each laboratory.

The ionization chambers NE 2611, serial numbers 163 and 134, belonging to the NPL, are the transfer chambers used for this comparison. Their main characteristics are listed in Table 6. These chambers were calibrated at the NPL before and after the measurements at the BIPM.

The experimental method for measurements at the BIPM is described by Allisy-Roberts *et al* (2011); the essential details for the determination of the calibration coefficients N_{D_w} 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 and waterproof sleeve facing the source.

Applied voltage and polarity

A collecting voltage of 200 V (negative polarity) was applied to the outer electrode of each chamber at least 30 min before any measurements were made. No corrections were applied at either laboratory for polarity.

Volume recombination

Volume recombination is negligible at a dose rate of less than 15 mGy s^{-1} for these chambers at these polarizing voltages, and the initial recombination loss will be the same in the two laboratories. Consequently, no correction for recombination was applied and a relative uncertainty component of 5×10^{-4} is included in Table 12.

Radial non-uniformity correction

At the NPL, the correction for the radial non-uniformity of the beam over the section of the transfer chambers is estimated to be 1.0001 with an uncertainty of 1×10^{-4}. At the BIPM, the corresponding correction would be less than 1.0002, with an uncertainty of 2×10^{-4}. No

correction for the radial non-uniformity of the beam is applied and a relative uncertainty component of 2×10^{-4} is included in Table 12.

Charge and leakage measurements

The charge Q collected by each transfer chamber was measured using a Keithley electrometer, model 642 at the BIPM. The source is operational during the entire exposure series and the charge is collected for the appropriate, electronically controlled, time interval. At the NPL, the current was measured directly using a Keithley electrometer, model 6514. The chambers were pre-irradiated for at least 4 min (≈ 4 Gy) at the NPL, and for at least 30 min (≈ 4 Gy) at the BIPM before any measurements were made.

The ionization current measured from each transfer standard was corrected for the leakage current at the BIPM. This correction was around than 3×10^{-4} in relative value. At the NPL the leakage current was measured before and after each series of measurements. The relative leakage correction was less than 1×10^{-3}.

Ambient conditions

At the BIPM and at the NPL, the water temperature was measured for each measurement and was stable to better than 0.02 °C.

The ionization current is normalized to 293.15 K and 101.325 kPa at both laboratories.

Relative humidity is controlled at (50 ± 5) % at the BIPM. At the NPL, relative humidity is controlled, and calibrations were made in the range 20 to 70 % RH. Consequently, no correction for humidity is applied to the ionization current measured.

PMMA phantom window and sleeve

Both laboratories use a horizontal radiation beam and the thickness of the PMMA front window of the water 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 in terms of interaction coefficients.

Individual waterproof sleeves of 1.8 mm thick PMMA were supplied by the NPL for each NE chamber. The same sleeves were used at both laboratories and, consequently, no correction for the influence of each sleeve was necessary at either laboratory.

5. Results of the comparison

Each NE 2611 transfer chamber was set-up and measured in the BIPM ^{60}Co beam on two separate occasions. The results were reproducible to better than 3×10^{-4}.

The result of the comparison, $R_{D_{\mathrm{w}}}$, is expressed in the form

$$R_{D_{\mathrm{w}}} = N_{D_{\mathrm{w}},\mathrm{NPL}} \big/ N_{D_{\mathrm{w}},\mathrm{BIPM}} \,, \qquad (7)$$

in which the average value of measurements made at the NPL before and after those made at the BIPM is compared with the mean of the measurements made at the BIPM. The results for each chamber are presented in Table 10.

Contributions to the relative standard uncertainty of $N_{D_{\mathrm{w}},\mathrm{lab}}$ are listed in Table 11 and the combined standard uncertainty u_c for the comparison result $R_{D_{\mathrm{w}}}$ is presented in Table 12.

Table 10. Final result of the NPL/BIPM comparison of standards for ^{60}Co absorbed dose to water

Transfer Chamber	$N_{D_w,\mathrm{NPL}}$ / Gy μC^{-1} pre-BIPM	$N_{D_w,\mathrm{NPL}}$ / Gy μC^{-1} post-BIPM	$N_{D_w,\mathrm{NPL}}$ / Gy μC^{-1} overall mean	$N_{D_w,\mathrm{BIPM}}$ / Gy μC^{-1}	R_{D_w}	u_c
NE 2611-134	104.25	104.25	104.25	104.08	1.0016	0.0071
NE 2561-163	102.54	102.44	102.49	102.38	1.0011	0.0071
				Mean values	**1.0013**	**0.0071**

The $N_{D_w,\mathrm{NPL}}$ values provided by the NPL included an ion recombination correction that has been removed in accordance with Section 4.

The comparison result is taken as the unweighted mean value for the two transfer chambers, $R_{D_w} = 1.0013$ with a combined standard uncertainty for the comparison of 0.0071, demonstrating the agreement between the two standards for absorbed dose to water.

Uncertainties

Contributions to the relative standard uncertainty of $N_{D,\mathrm{w,lab}}$ are listed in Table 11 including the contributions arising from the use of transfer chambers.

The two laboratories determine absorbed dose by methods that are quite different. Some correlation exists in the use of Monte Carlo calculations in the dose conversion, but this will have a negligible effect on the comparison uncertainty and is not taken into account.

The relative standard uncertainty of the mean ionization current measured with each transfer chamber over the short period of calibration was estimated to be 3×10^{-4} (two calibrations with repositioning, in series of 30 measurements for each chamber) at the BIPM.
At the NPL, the relative standard repeatability of the mean calibration coefficient measured with a given transfer chamber over the several months required for this comparison was 3×10^{-4}.
An uncertainty of 3×10^{-4} is included in Table 11 to represent the short-term stability of the transfer chambers at both laboratories.

Table 11. Uncertainties associated with the calibration of the transfer chambers

	BIPM		NPL	
Relative standard uncertainty	100 s_i	100 u_i	100 s_i	100 u_i
Absorbed dose to water rate	0.20	0.21	–	–
Reference chamber calibration coefficient in graphite	–	–	0.36	0.39
Conversion of absorbed dose from graphite to water	–	–	0.16	0.28
Ionization current for the reference chambers	–	–	0.04	0.12
Ionization current for the transfer chambers	0.01	0.02	0.04	0.12
Distance	0.02	–	0.01	–
Depth in water	0.02	0.06	–	–
Short-term stability	0.03	–	0.03	–
Relative standard uncertainties of $N_{D_w,\mathrm{lab}}$				
Quadratic summation	0.20	0.22	0.40	0.51
Combined uncertainty	0.30		0.65	

Table 12. Uncertainties associated with the comparison result

Relative standard uncertainty	100 s_i	100 u_i
$N_{D_w,\mathrm{NPL}} / N_{D_w,\mathrm{BIPM}}$	0.45	0.55
Recombination loss $k_{\mathrm{s,tr}}$	–	0.05
Radial non-uniformity k_{rn}	–	0.02
Different chambers σ_{tr}	0.02	–
Relative standard uncertainties of $R_{D,\mathrm{w}}$	0.45	0.56
	$u_c = 0.71$	

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-Roberts *et al* 2009). It follows that for each NMI i having a BIPM comparison result x_i with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is the relative difference $D_i = (D_{\mathrm{w}i} - D_{\mathrm{w,BIPM}i})/ D_{\mathrm{w,BIPM}i} = x_i - 1$ and its expanded uncertainty $U_i = 2\,u_i$.

The results for D_i and U_i are usually expressed in mGy/Gy. Table 13 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.

Table 13. **Degrees of equivalence**

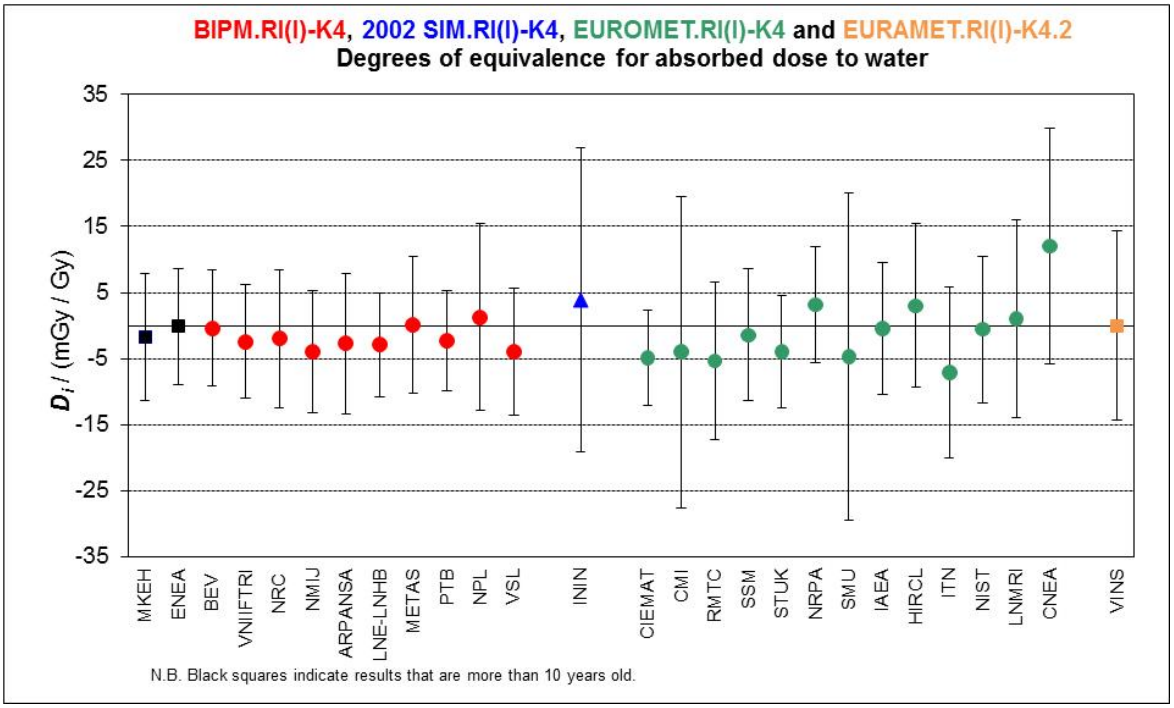
For each laboratory *i*, the degree of equivalence with respect to the key comparison reference value is the difference D_i and its expanded uncertainty U_i. Tables formatted as they appear in the BIPM key comparison database

BIPM.RI(I)-K4 – SIM.RI(I)-K4 (2002) – EUROMET.RI(I)-K4 (2005 to 2008) – EURAMET.RI(I)-K4.2

Lab *i*	D_i / (mGy / Gy)	U_i
MKEH	-1.7	9.6
ENEA	-0.1	8.8
BEV	-0.4	8.8
VNIIFTRI	-2.4	8.6
NRC	-2.0	10.4
NMIJ	-4.0	9.2
ARPANSA	-2.7	10.6
LNE-LNHB	-2.9	7.8
METAS	0.1	10.4
PTB	-2.3	7.6
NPL	1.3	14.2
VSL	-4.0	9.6
ININ	3.9	23.0
CIEMAT	-4.9	7.3
CMI	-4.0	23.6
RMTC	-5.3	12.0
SSM	-1.4	10.0
STUK	-3.9	8.5
NRPA	3.2	8.8
SMU	-4.7	24.7
IAEA	-0.4	10.0
HIRCL	3.0	12.4
ITN	-7.1	13.0
NIST	-0.6	11.1
LNMRI	1.0	15.0
CNEA	12.0	17.9
VINS	0.0	14.3

When required, the degree of equivalence between two laboratories *i* and *j* can be evaluated as the difference $D_{ij} = D_i - D_j = x_i - x_j$ and its expanded uncertainty $U_{ij} = 2\,u_{ij}$, both expressed in mGy/Gy. In evaluating u_{ij}, account should be taken of correlation between u_i and u_j. Following the advice of the CCRI(I) in 2011, results for D_{ij} and U_{ij} are no longer published in the KCDB.

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



7. Conclusions

A key comparison has been carried out between the NPL and the BIPM standards for absorbed dose to water in ^{60}Co gamma rays, using two ionization chambers as transfer instruments. The comparison result is evaluated as the ratio of the calibration coefficients measured by the NPL and the BIPM. The comparison result is 1.0013 (71) and so the NPL standard is in agreement with the KCRV within the standard uncertainty for the comparison. The result of the comparison made in 2007 was 0.9980 (64), in agreement within the uncertainties with the present result.

When compared with the results for the other laboratories that have carried out comparisons in terms of absorbed dose to water at the BIPM, the NPL standard for absorbed dose to water is in good agreement.

Note that the data presented in the tables, while correct at the time of publication of the present report, become out of date as laboratories make new comparisons with the BIPM. The formal results under the CIPM MRA are those available in the BIPM key comparison database.

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