Comparison of the standards for absorbed dose to water of the VSL, The Netherlands, 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 VSL, Dutch Metrology Institute, Delft, The Netherlands and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in December 2017. The comparison result, based on the calibration coefficients for two transfer standards and expressed as a ratio of the VSL and the BIPM standards for absorbed dose to water, is 0.9960 with a combined standard uncertainty of 4.8×10^{-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 VSL, Dutch Metrology Institute, Delft, The Netherlands, and of the Bureau International des Poids et Mesures (BIPM) was carried out in December 2017 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2005 (Kessler *et al* 2009) published in the BIPM key comparison database (KCDB 2018) under the reference BIPM.RI(I)-K4. The comparison was undertaken using two transfer ionisation chambers type NE 2611A and NE 2571 of the VSL. 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 VSL in June 2018.

2. Details of the standards

The primary standard of the VSL for absorbed dose is a water calorimeter described by de Prez *et al* (2016).

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

Details of the transfer chambers used for the indirect comparison are given in Table 2.

Table 1. Characteristics of the BIPM standard

Dimensions		Standard 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

Table 2. Characteristics of the VSL transfer chambers

VSL chambers	Nominal values	NE 2611A	NE 2571
Chamber	Outer diameter / mm	8.5	7.0
	Outer height / mm	9.7	24 (inner length)
	Wall thickness / mm	0.5	0.36
Electrode	Diameter / mm	1.7	1.0
	Lenght / mm	6.4	20.6
Volume	Air cavity / cm^3	0.3	0.7
Wall	Materials	graphite	
	Density / g cm^{-3}	1.7	
Applied voltage	Polarity	200 V [(1)]	300 V [(1)]

(1) Positive polarity applied to the outer electrode at both laboratories

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

$\bar{s}_{\mathrm{c,a}}$ 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 3. 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 3.

Table 3. 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_a	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)	– (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) the uncertainty of μ_{en}/ρ of 0.14 is included in the uncertainty for k_p.
(3) uncertainty value for the product $s_{c,a}$ W/e.

At the VSL the absorbed-dose-to-water rate at the reference point is given by

$$\dot{D}_{w,VSL} = \frac{\Delta T_w}{t} c_{p,w} (1-h)^{-1} k_P k_C k_R k_\tau \quad (2)$$

where

t irradiation time,

$c_{p,w}$ is the specific heat capacity of water at constant pressure,

h is the chemical heat-defect caused by radiation-induced exo- or endo-thermic chemical reactions,

k_P is the perturbation correction due to the presence of non-water materials,

k_C is the correction for conductive heat flow determined using finite element methods applied to a simplified geometry,

k_R is the correction factor for deviations from the reference conditions,
k_τ correction for source timer start-stop effect.

The associated uncertainties for the VSL standard are given in Table 4.

Table 4. Relative standard uncertainties for the VSL standard for absorbed-dose-to-water rate

Symbol	Parameter / unit	Relative standard uncertainty %
ΔT_w		
R	DMM resistance calibration and resolution / Ω	< 0.01
$\Delta R/R$	repeated measurement (Type A)	0.20
T	thermistor temperature (at T = 277.15 K) / K	< 0.01
β	thermistor β-value and long-term (1 y) stability / K	0.07
k_{sh}	thermistor self-heat	0.07
$c_{p,w}$	specific heat capacity of water / J kg^{-1} K^{-1}	0.07
h	heat defect	0.20
Correction factors		
k_C	heat transfer due to conduction	0.18
Correction due to the presence of non-water materials k_P		
k_{HPC}	high-purity cell perturbation	0.05
k_{probes}	probes perturbation	0.05
$k_{phantom}$	thermostat perturbation (lid, walls, etc),	0.05
Correction for deviations from the reference conditions k_R		
k_{SDD}	reference source detector distance (100 cm)	0.02
k_{depth}	reference depth in water	0.04
k_{rn}	radial non-uniformity at position of probes	0.02
k_τ	source timer (start-stop) effect	0.01
D_w-drift	normalized long term drift	0.02
Combined uncertainty of the VSL determination of absorbed-dose-to-water rate		
combined relative standard uncertainty		0.37

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 VSL used for the dissemination of absorbed dose to water are the same as those at the BIPM.

Reference values

The BIPM reference absorbed-dose-to-water rate $\dot{D}_{w,BIPM}$ 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 1925.21 days (u = 0.29 days) (Bé *et al* 2006).
The value of $\dot{D}_{w,VSL}$ used for the comparison is based on the $\dot{D}_w$ reference value in the VSL ^{60}Co beam established in 2014. This value was based on the mean of all water calorimeter measurements made over the period 2005-2014. The ^{60}Co source was changed in 2012 and the transfer of the reference value from the old source to the new was done using secondary standards. Calorimetry measurements were carried out regularly between 2014 and 2017 (with an average frequency of 3 times per year), and compared with the 2014 reference value after correction for the output drift. The uncertainty of this drift is added as the long-term stability to the uncertainty budget of Table 4. The half-life of ^{60}Co was taken as 1925.5 days (IAEA TECDOC619).

Beam characteristics

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

Table 5. Characteristics of the ^{60}Co beams at VSL 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		
VSL source	8.0	20.3	29.9	Not evaluated	10 cm × 10 cm
BIPM source	2.5	20	14	21 %	10 cm × 10 cm

4. Comparison procedure

The comparison of the VSL and BIPM standards was made indirectly using the calibration coefficients $N_{D_w,lab}$ for the two transfer chambers given by

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

where $\dot{D}_{w,lab}$ is the water absorbed dose rate at VSL 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 number 120 and NE 2571, serial number 3235, belonging to the VSL, are the transfer chambers used for this comparison. Their main characteristics are listed in Table 2. These chambers were calibrated at the VSL before and after the measurements at the BIPM.
The experimental method for measurements at the BIPM is described by Allisy-Robert *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 and 300 V (positive polarity) was applied to the outer electrode of the VSL NE 2611 and NE 2571 transfer chambers, respectively, at least 40 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 8.

Radial non-uniformity correction

At the BIPM, the correction for the radial non-uniformity of the beam over the section of the transfer chambers is estimated to be 1.0008 and 1.0002 for the NE 2571 and NE 2611, respectively, with an uncertainty of 2×10^{-4}. At VSL, similar corrections were estimated for these transfer chambers. 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 8.

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 VSL, the current was measured using a Keithley 6517A. The chambers were pre-irradiated for at least 30 min (≈ 12 Gy) at the VSL, 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 less than 1×10^{-4} in relative value. At the VSL the ionization current measured for each transfer standard was corrected for the leakage current. This correction was less than 1×10^{-3} in relative value.

Ambient conditions

At both laboratories, the water temperature is measured for each current measurement and it 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 both laboratories. Consequently, no correction for humidity is applied to the ionization current measured.

PMMA phantom window and sleeve

The BIPM uses 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.

The VSL uses a vertical beam irradiating the water directly from above. The chamber depth was measured before and after the radiation measurements.

Both laboratories used their own PMMA water-proof sleeves for the chamber calibration; as the sleeves were of the same thickness, no correction for the influence of the sleeves was applied and a relative uncertainty component of 3×10^{-4} is included in Table 8.

5. Results of the comparison

Each transfer chamber was set-up and measured in the BIPM ^{60}Co beam on two separate occasions. The results were reproducible to better than 2×10^{-4}.

The result of the comparison, R_{D_w}, is expressed in the form

$$R_{D_\mathrm{w}} = N_{D_\mathrm{w},\mathrm{VSL}} \big/ N_{D_\mathrm{w},\mathrm{BIPM}}\,, \tag{4}$$

in which the average value of measurements made at VSL 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 6.

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

Table 6. Final result of the VSL/BIPM comparison of standards for ^{60}Co absorbed dose to water

Transfer Chamber	$N_{D_\mathrm{w},\mathrm{VSL}}$ / Gy µC^{-1}			$N_{D_\mathrm{w},\mathrm{BIPM}}$ / Gy µC^{-1}	R_{D_w}	u_c
	pre-BIPM	post-BIPM	overall mean			
NE 2611 sn 120	102.71	102.66	102.69	103.06	0.9964	0.0048
NE 2571 sn 3235	44.914	44.917	44.916	45.113	0.9956	0.0048
				Mean values	**0.9960**	**0.0048**

The comparison result is taken as the unweighted mean value for the two transfer chambers, $R_{D_\mathrm{w}} = 0.9960$ with a combined standard uncertainty for the comparison of 0.0048, demonstrating the agreement between the two standards for absorbed dose to water.

Uncertainties

Contributions to the relative standard uncertainty of $N_{D,\mathrm{w},\mathrm{lab}}$ are listed in Table 7 including the contributions arising from the use of transfer chambers.

The relative standard uncertainty of the mean ionization current measured with each transfer chamber over the short period of calibration was estimated to be 2×10^{-4} (two calibrations with repositioning, in series of 30 measurements for each chamber) at the BIPM. At the VSL, the relative standard uncertainty of the mean ionization current measured with each transfer chamber over the short period of calibration with repositioning was estimated to be within 3×10^{-4}.

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

Relative standard uncertainty	BIPM 100 s_i	BIPM 100 u_i	VSL 100 s_i	VSL 100 u_i
Absorbed-dose-to-water rate	0.20	0.21	0.20	0.31
Ionization current for the transfer chambers	0.01	0.02	0.02	0.04
Distance	0.02	–	–	0.01
Depth in water	0.02	0.06	–	0.02
Short-term stability	0.02	–	0.03	–
Relative standard uncertainties of $N_{D_\mathrm{w},\mathrm{lab}}$				
Quadratic summation	0.20	0.22	0.20	0.32
Combined uncertainty	0.30		0.37	

Table 8. Uncertainties associated with the comparison result

Relative standard uncertainty	100 s_i	100 u_i
$N_{D_\mathrm{w},\mathrm{VSL}} / N_{D_\mathrm{w},\mathrm{BIPM}}$	0.29	0.38
Recombination loss $k_{\mathrm{s,tr}}$	–	0.05
Radial non-uniformity k_{rn}	–	0.02
Different water-proof sleeves	–	0.03
Different chambers σ_{tr}	0.04	–
Relative standard uncertainties of $R_{D,\mathrm{w}}$	0.29	0.39
	u_c = 0.0048	

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 9 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.

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.

Table 9. Degrees of equivalence

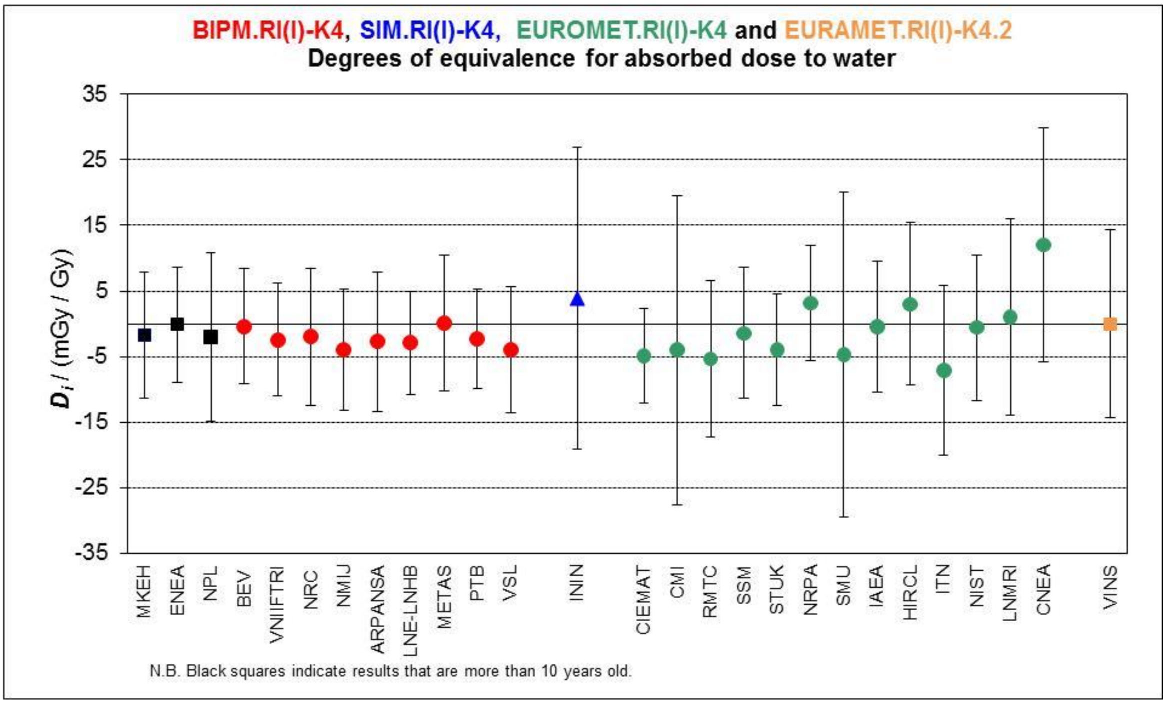
For each laboratory *i*, the degree of equivalence with respect to the key comparison reference value is the difference D_i and its expanded uncertainty U_i. Tables formatted as they appear in the BIPM key comparison database

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 / (mGy/Gy)
MKEH	-1.7	9.6
ENEA	-0.1	8.8
NPL	-2.0	12.8
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
VSL	-4.0	9.6
ININ	3.9	23.0

Lab *i*	D_i / (mGy/Gy)	U_i / (mGy/Gy)
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

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



7. Conclusions

A key comparison has been carried out between the VSL 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 VSL and the BIPM. The comparison result is 0.9960 (48) and so the VSL standard is in agreement with the KCRV within the standard uncertainty for the comparison. This result is consistent with the BIPM.RI(I)-K6 comparison results of 0.9959 and 0.9958 for 6 MV and 10 MV respectively.

The result of the comparison made in 2005 was 0.9926 (49), in agreement within the uncertainties with the present result. The latter result was based on a different water calorimeter.

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 VSL 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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