

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

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Abstract

A first key comparison of the standards for absorbed dose to water of the Główny Urząd Miar (GUM), Poland and the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM during June-July 2020. The comparison result, based on the calibration coefficients for two transfer standards and evaluated as a ratio of the GUM and the BIPM standards for absorbed dose to water, is 1.0030 with a combined standard uncertainty of 3.5 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

A first comparison of the standards for absorbed dose to water of the Główny Urząd Miar (GUM), Poland, and the Bureau International des Poids et Mesures (BIPM) was carried out during the period June-July 2020 in the ^{60}Co radiation beam at the BIPM. The comparison result is published in the BIPM key comparison database (KCDB 2021) under the reference BIPM.RI(I)-K4. The comparison was carried out after the implementation of the recommendations of ICRU Report 90 (ICRU 2016) at both laboratories.

The comparison was made indirectly using two thimble-type ionization chambers as transfer instruments. The final results were supplied by the GUM in February 2021.

2. Details of the standards and the transfer chambers

The primary standard of the GUM for absorbed dose is a graphite ionization chamber of cylindrical shape constructed by the GUM, referenced as GUM-Dw3. The chamber body was assembled from three graphite components: the base, the central electrode and the cylindrical cap. A high-accuracy coordinate measuring machine was used at the GUM to measure each component for the volume determination. After assembly, the ionization chamber was examined using an industrial tomograph to check the correctness of the assembly and to do an independent determination of the volume. Both methods agreed at the level of 1 part in 10^3 . A cylindrical air gap of 0.25 mm over a length of 6 mm separates the guard ring from the insulator. The chamber collecting volume, based entirely on the CMM measurements and including the air gap, is 0.5050 cm^3 with a relative standard uncertainty of 1.3 parts in 10^3 . Figure 1 shows a schematic view of the chamber and the different materials.

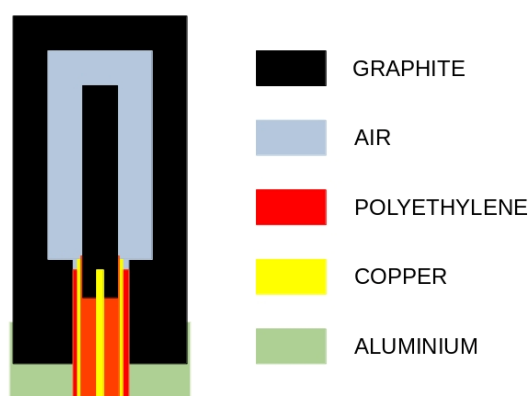


Figure 1. Schematic view of the GUM absorbed dose to water standard Dw3

The BIPM primary standard is a parallel-plate graphite cavity ionization chamber positioned at the reference depth in a water phantom (Boutillon *et al.* 1993, Burns and Kessler 2018).

The main dimensions of the GUM and the BIPM standards 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 and the GUM standards

Dimensions		CH7.1 parallel-plate	GUM-Dw3 cylindrical
Cavity	Diameter / mm	45.0	7.5
	Thickness / mm	5.147	-
	Height / mm	-	12.5
	Measuring volume / cm ³	6.7928	0.5050
Electrode	Diameter / mm	41.0	2.5
	Thickness / mm	1.027	-
	Height / mm	-	10
Wall	Thickness / mm	2.848	2.5
	Material	Graphite	Graphite
	Density / g cm ⁻³	1.85	1.81
Voltage applied to outer electrode / V		± 80	250

Table 2. Characteristics of the GUM transfer chambers

GUM chambers	Nominal values	NE 2561	PTW 30013	
Chamber	Outer diameter / mm	8.5	7.0	
	Outer length / mm	9.7	23.6	
Electrode	Diameter / mm	1.7 (hollow)	1.1	
	Length / mm	6.4	21.2	
Cavity	Measuring volume / cm ³	0.3	0.6	
Wall	Thickness / mm	0.5	0.335	0.09
	Material	graphite	PMMA	graphite
Density / g cm ⁻³		1.7	1.19	1.85
Voltage applied to outer electrode / V		200 V	400 V	

3. Determination of the absorbed dose to water

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

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

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,
- $(\mu_{en}/\rho)_{w,g}$ is the ratio water-to-graphite of mass energy-absorption coefficients,
- $\bar{s}_{g,a}$ is the ratio of the mean mass stopping powers graphite-to-air,
- $\Psi_{w,g}$ is the photon energy fluence ratio water-to-graphite
- $\beta_{w,g}$ is the absorbed-dose-to-collision-kerma ratio, and
- $\prod k_i$ is the product of the correction factors to be applied to the standard.

Physical data and correction factors

The values for the physical constants, the correction factors, the volume of the primary standards entering in equation (1) and the associated uncertainties are given in Table 3. For the BIPM standards, these values are given in Kessler and Burns 2018.

– Correction factors for the GUM standards

The step-by-step procedure (Boutillon 1983, Boutillon and Perroche, 1993, Burns and Kessler 2018) was used to calculate the perturbation correction factors for the determination of absorbed dose to water, using the Monte Carlo code FLUKA (Ferrari *et al.* 2005, Bhlen *et al.* 2014).

The simulation of the photon spectrum for the new GUM Co-60 source was performed using the Fluka 2011-3.0 together with the advanced interface Flair 3.0-1. Two photon energy lines, with equal emission probability, at 1.173 MeV and 1.332 MeV were simulated.

A phase-space file of photon energy and direction was created at 80 cm from the centre of the source. This file was used as input to do the calculation of the chamber correction factors using a comprehensive model of the chamber positioned in water at 5 g cm⁻² depth for the reference field size of 10 cm x 10 cm at 100 cm from the source centre.

– Ion recombination for the GUM standard

The ion recombination correction reported by the GUM at the time of the comparison was 1.0003 (7). This correction factor was evaluated using the two-voltage method as described in the IAEA technical protocol (IAEA 2000). Following the discussion maintained with the BIPM regarding the ion recombination correction for the air-kerma standards (Kessler *et al.* 2021), the GUM re-evaluated this factor using the Niatel method (Boutillon 1998). The new correction factor is 1.0012, resulting in an increase of 9 parts in 10⁴ of the absorbed dose determination.

Table 3. Physical constants, correction factors and relative standard uncertainties for the BIPM ionometric standard for absorbed dose to water ⁽¹⁾

Symbol	Parameter / unit	BIPM	10 ² × Relative standard uncertainty ⁽²⁾		GUM	10 ² × Relative standard uncertainty ⁽²⁾	
		Value	<i>u</i> _{iA}	<i>u</i> _{iB}	Value	<i>u</i> _{iA}	<i>u</i> _{iB}
<u>Physical constants</u>							
ρ_a	dry air density ⁽³⁾ / kg m ^{−3}	1.2930	—	0.01	1.2045	—	0.01
$(\mu_{\text{en}}/\rho)_{\text{w,g}}$	ratio of mass energy-absorption coefficients	1.1131	—	0.05	1.1129	0.02	0.04
W/e	mean energy per charge / J C ^{−1}	33.97	—	— ⁽⁴⁾	33.97	—	0.08
$D_{\text{g,air}}$ $= s_{\text{g,air}}k_{\text{cav}}$	product of the ratio of mass stopping powers and cavity perturbation correction	0.9958	0.02	0.13 ⁽⁴⁾	0.9902	0.02	0.12
$\psi_{\text{w,g}}$	energy fluence ratio	1.0037	0.01	0.07	1.0044	0.02	—
$\beta_{\text{w,g}}$	absorbed-dose-to-collision-kerma ratio	0.9998	0.01	0.01	0.9998	0.02	0.02
<u>Correction factors</u>							
k_{env}	envelope of the chamber	0.9993	0.01	0.02	1.0004	0.02	0.02
k_{win}	entrance window of the phantom	0.9997	0.01	0.01	1.0021	0.02	0.02
k_{rn}	radial non-uniformity	1.0056	0.01	0.03	1.0002	0.02	—
k_{s}	saturation	1.0021	0.01	0.02	1.0012	0.01	—
k_{h}	humidity	0.9970	—	0.03	0.9970	—	0.03
k_{stem}	stem scattering	—	—	—	0.9990	0.03	0.02
<u>Measurement of I / ν</u>							
ν	volume / cm ³	6.7928 ⁽⁵⁾	—	0.08	0.5050	0.09	0.10
I	ionization current (T , P , air compressibility)	—	—	0.02	—	0.02	0.10
	short-term reproducibility (including positioning and current measurement) ⁽⁶⁾		0.02	—		—	—
<u>Combined uncertainty of the BIPM determination of absorbed-dose rate to water</u>							
quadratic summation			0.04	0.18	0.11	0.21	
combined relative standard uncertainty			0.19		0.24		

⁽¹⁾ Details on the determination of absorbed dose to water are described by Boutillon *et al* (1993) and the re-evaluation of the standard is described by Burns and Kessler (2018).

⁽²⁾ *u*_{iA} represents the relative uncertainty estimated by statistical methods (Type A);
*u*_{iB} represents the relative uncertainty estimated by other methods (Type B).

⁽³⁾ At 101.325 kPa and 273.15 K and at 101.325 kPa and 293.15 K for the BIPM and the GUM standards, respectively

⁽⁴⁾ The uncertainty component of 0.13 represents the uncertainty of 0.08 for the product of W/e and the stopping-power ratio $s_{g,air}$, as evaluated for the BIPM and other air-kerma standards for Co-60 and the uncertainty of k_{cav} .

⁽⁵⁾ Standard CH7-1.

⁽⁶⁾ Over a period of 3 months.

Reference conditions

The reference conditions for the absorbed-dose-to-water determination at the BIPM are described by Kessler and Burns (2018):

- 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 GUM 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 2020-01-01, 0 h UTC, as is the ionization current of the transfer chambers. The half-life of ⁶⁰Co used for the decay correction was taken as 1925.21 days ($\lambda = 0.29$ days) (Bé *et al* 2006).

The value of $\dot{D}_{w,GUM}$ used for the comparison is taken as the mean of measurements made around the period of the comparison. It is given at the reference date of 2020-01-01 using the same half-life value for the decay correction as the BIPM; the ionization current for the transfer chambers is corrected to the same reference date.

Beam characteristics

The characteristics of the BIPM and GUM beams are given in Table 4.

Table 4. Characteristics of the ⁶⁰Co beams at the GUM 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		
GUM TeraBALT T-100	11.3	20	26.9	21 %	10 cm × 10 cm
BIPM Theratron 1000	6.5	20	14	21 %	10 cm × 10 cm

4. Comparison procedure

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

$$N_{D,w,lab} = \dot{D}_{w,lab} / I_{lab} \quad (2)$$

where $\dot{D}_{w,lab}$ is the absorbed dose to water rate and I_{lab} is the ionization current of a transfer chamber measured at the GUM or the BIPM. The current is corrected for the effects and influences described in this section.

The ionization chambers NE 2561, serial number 301 and PTW 30013, serial number 9967, belonging to the GUM, were used as the transfer chambers for this comparison. Their main characteristics are listed in Table 2. These chambers were calibrated at the GUM before and after the measurements at the BIPM.

The experimental method for measurements at the BIPM is described by Kessler and Burns (2018); the essential details for the determination of the calibration coefficients $N_{D,w,lab}$ 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 400 V (positive polarity) was applied to the outer electrode of the NE 2561 and the PTW 30013 transfer chambers, respectively, at least 40 min before any measurements were made.

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 is exposed during the entire measurement series and the charge is collected for the appropriate, electronically controlled, time interval. A pre-irradiation was made for at least 40 min before any measurements (~ 13 Gy). Leakage current was measured before and after each series of measurements. The relative leakage correction was less than 5 parts in 10^5 . At the GUM, the charge Q collected by the transfer chambers was measured in the same way as the BIPM using a Keithley electrometer, model 6517A. A pre-irradiation of at least 11 Gy was made for each chamber before any measurements. Leakage current was measured before and after each series of measurements. The relative leakage correction was less than 1 part in 10^4 .

Ion recombination

No correction for recombination was applied to the measured current as volume recombination is negligible for continuous beams at a dose rate of less than 10 mGy s^{-1} for these chamber types at this polarizing voltage, and the initial recombination loss will be the same in the two laboratories; a relative uncertainty component of 2 parts in 10^4 is included in Table 6.

Radial non-uniformity correction

At the BIPM, the correction to the ionization current would only be 1.0002 for the NE 2561 and 1.0008 for the PTW 30013. At the GUM, a similar correction would be applied. No radial non-uniformity correction was applied and a relative uncertainty component of 2 parts in 10^4 is included in Table 6.

Ambient conditions

At both laboratories, the water temperature is measured for each current measurement; it was stable to better than 0.02°C at the BIPM and 0.05°C at the GUM.

The ionization current is normalized to 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 GUM, relative humidity is controlled and was in the range from 41 to 51 %. No correction for humidity is applied to the measured ionization current.

PMMA phantom window and sleeve

Both laboratories use a horizontal radiation beam and, 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 in terms of interaction coefficients. Individual waterproof sleeves of PMMA were supplied by the GUM for each 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

The transfer chambers were set-up and measured in the BIPM ^{60}Co beam on two separate occasions.

The result of the comparison, $R_{D,w}$, is expressed in the form

$$R_{D,w} = N_{D,w,\text{GUM}}/N_{D,w,\text{BIPM}} \quad (3)$$

in which the average value of measurements made at the GUM 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 were reproducible to better than 1 part in 10^4 at both laboratories. The results for each chamber are presented in Table 5.

Contributions to the relative standard uncertainty of $N_{D,w,lab}$ and the combined standard uncertainty u_c for the comparison result $R_{D,w}$ are presented in Table 6. This includes a component of 1.2 parts in 10^3 for the difference in the comparison result between the two transfer chambers.

Table 5. Results of the comparison of standards for ^{60}Co absorbed dose to water

Transfer Chamber	$N_{D,w,GUM}/\text{Gy } \mu\text{C}^{-1}$			$N_{D,w,BIPM} / \text{Gy } \mu\text{C}^{-1}$	$R_{D,w}$	u_c
	pre-BIPM	post-BIPM	overall mean			
NE 2561-301	104.60	104.72	104.66	104.22	1.0043	0.0035
PTW 30013-9967	53.81	53.78	53.80	53.70	1.0018	0.0035
Mean values					1.0030	0.0035

Table 6. Uncertainties associated with the indirect comparison

	BIPM		GUM	
Relative standard uncertainty	100 u_{iA}	100 u_{iB}	100 u_{iA}	100 u_{iB}
Absorbed-dose-to-water rate	0.04	0.18	0.11	0.21
Ionization current for the transfer chambers	0.01	0.02	0.08	0.11
Distance	0.02	–	0.01	0.01
Depth in water	0.02	0.06	–	0.10
Air density correction	–	–	0.01	0.05
Reproducibility	0.01	–	0.01	–
$N_{D,w,lab}$	0.05	0.19	0.14	0.26
$N_{D,w,GUM}/N_{D,w,BIPM}^{(1)}$ Ion recombination Radial non-uniformity Different chambers	100 u_{iA}		100 u_{iB}	
	0.14		0.30	
	–		0.02	
	–		0.02	
	0.12		–	
$R_{D,w}$	$u_c = 0.0035$			

⁽¹⁾ The combined standard uncertainty of the comparison result takes into account correlation in the type B uncertainties associated with the physical constants and the humidity correction

Some uncertainties in $\dot{D}_w$ that appear in both the BIPM and the GUM determinations (namely air density, W/e , μ_{en}/ρ , $s_{g,a}$ and k_h) cancel when evaluating the uncertainty of the ratio $R_{D,w}$ of the GUM and BIPM calibration coefficients.

The comparison result is taken as the unweighted mean value for the two transfer chambers, $R_{D,w} = 1.0030$ with a combined standard uncertainty, u_c , for the comparison of 0.0035, demonstrating the agreement between the two standards for absorbed dose to water.

6. Degrees of equivalence

Comparison of a given NMI with the key comparison reference value

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-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 $D_i = (D_{wi} - D_{w,BIPM}) / D_{w,BIPM} = x_i - 1$ and its expanded uncertainty $U_i = 2 u_i$.

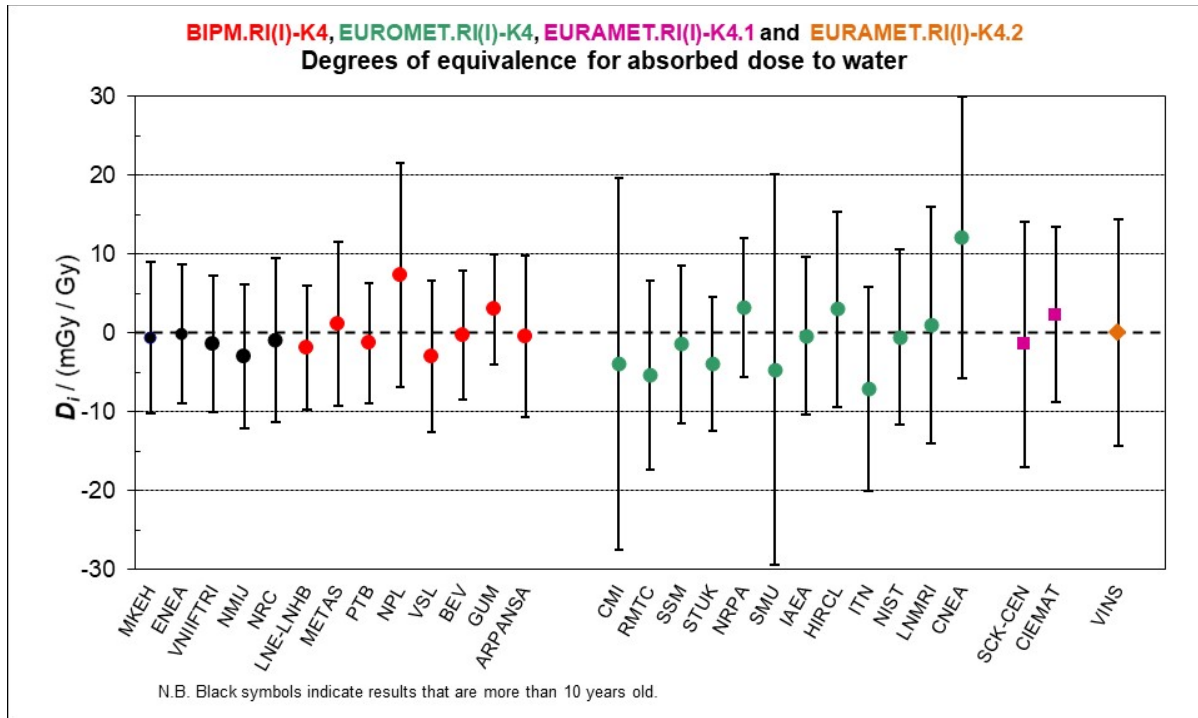
The results for D_i and U_i are usually expressed in mGy/Gy. Table 7 gives the values for D_i and U_i for each NMI, i , taken from the KCDB of the CIPM MRA (1999) and this report. These data are presented graphically in Figure 2.

Table 7. 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– EUROMET.RI(I)-K4 (2005 to 2008) – EURAMET.RI(I)-K4.1 – EURAMET.RI(I)-K4.2

Lab i	D_i	U_i
/ (mGy / Gy)		
MKEH	-0.7	9.6
ENEA	-0.1	8.8
VNII FTRI	-1.4	8.6
NMIJ	-3.0	9.2
NRC	-1.0	10.4
LNE-LNHB	-1.9	7.8
METAS	1.1	10.4
PTB	-1.3	7.6
NPL	7.3	14.2
VSL	-3.0	9.6
BEV	-0.3	8.2
GUM	3.0	7.0
ARPANSA	-0.5	10.2
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
LMMRI	1.0	15.0
CNEA	12.0	17.9
SCK-CEN	-1.5	15.5
CIEMAT	2.3	11.1
VINS	0.0	14.3

Figure 2. Graph of the degrees of equivalence with the KCRV



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.

Note that the data presented in Table 7, while correct at the time of publication of the present report, become out-of-date as NMIs make new comparisons. The formal results under the CIPM MRA are those available in the key comparison database.

7. Conclusions

The GUM 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 1.0030 (35). The GUM standard agrees within the expanded uncertainty with all the NMIs having taken part in the BIPM.RI(I)-K4 ongoing key comparison for absorbed dose to water standards in a ^{60}Co gamma-ray beam.

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