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

C. Kessler[1], D. Burns[1], Y. Morishita[2], M. Shimizu[2] and T. Kurosawa[2]

[1]Bureau International des Poids et Mesures, F-92312 Sèvres Cedex
[2] National Metrology Institute of Japan (NMIJ), Tsukuba, Japan

Abstract

A new key comparison of the standards for absorbed dose to water of the National Metrology Institute of Japan (NMIJ), Japan, and the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in February 2022. The comparison result, based on the calibration coefficients for two transfer standards and evaluated as a ratio of the NMIJ and the BIPM standards for absorbed dose to water, is 0.9952 with a combined standard uncertainty of 4.0 parts in 10^3. The result agrees within the uncertainties with the comparison carried out in 2009. 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 Metrology Institute of Japan (NMIJ), Japan, and the Bureau International des Poids et Mesures (BIPM) was carried out in February 2022 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2009 (Kessler *et al.* 2011) published in the BIPM key comparison database (KCDB 2023) under the reference BIPM.RI(I)-K4. The comparison was carried out after the implementation of the recommendations of ICRU Report 90 (ICRU 2016) only at the BIPM.

The indirect comparison was made using two thimble-type ionization chambers as transfer instruments. The final results were supplied by the NMIJ in December 2022.

2. Details of the standards and the transfer chambers

The primary standard of the NMIJ is a graphite calorimeter and a graphite walled cavity chamber (Morishita *et al.* 2013). The calorimeter determines the absorbed dose rate to graphite in the constant temperature mode of operation, and the cavity chamber determines the conversion from graphite to water absorbed dose rate. The calculations involved in the determination of the absorbed dose to water rate do not include the recommendations of ICRU Report 90.

The BIPM primary standard is a parallel-plate graphite 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.

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

Table 1. Characteristics of the BIPM standard

Dimensions		Standard CH7.1
Cavity	Diameter / mm	45.0
	Thickness / mm	5.147
	Measuring volume / cm^3	6.7928
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 NMIJ transfer chambers

Nominal values		FC65-G	PTW 30013	
Chamber	Outer diameter / mm	7.0	7.0	
	Outer length / mm	23.5	23.6	
Electrode	Diameter / mm	1.0	1.1	
	Length / mm	20.5	21.2	
Cavity	Nominal volume / cm^3	0.65	0.60	
Wall	Thickness / mm	0.4	0.335	0.09
	Material	graphite	PMMA	graphite
	Density / g cm^{-3}	1.8	1.19	1.85
Voltage applied to outer electrode / V		-400	-400	

3. Determination of the absorbed dose to water

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

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

where

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

I is the ionization current measured by the standard,

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

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

$\prod k_i$ 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 entering in equation (1) and the associated uncertainties (Kessler and Burns 2018) 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 (1)

Symbol	Parameter / unit	Value	$10^2 \times$ Relative standard uncertainty (2)	
			$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
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	1.0021	0.01	0.02
k_h	humidity	0.9970	–	0.03
Measurement of I/υ				
υ	volume / cm^3	6.7928 (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 rate to water				
quadratic summation			0.04	0.18
combined relative standard uncertainty			0.19	

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

(2) $u_{i\mathrm{A}}$ represents the relative uncertainty estimated by statistical methods (Type A);
$u_{i\mathrm{B}}$ represents the relative uncertainty estimated by other methods (Type B).

(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 Co-60, and the uncertainty of 0.10 for k_{cav}

(4) Standard CH7.1.

(5) Over a period of 3 months.

At the NMIJ, the absorbed dose to water D_w is determined using the expression

$$\dot{D}_{w,NMIJ} = \left(\frac{P}{M}\right) k_{gap}k_{imp}k_{def}k_{axl}k_{rad}I_{w,c}k_{sl}\left(\frac{\mu_{en}}{\rho}\right)_{w,c}\beta_{w,c}\Phi_{w,c} \quad (2)$$

where

P	is the absorbed power by the calorimeter core,
M	is the core mass,
k_{gap}	is the gap correction factor,

k_{imp}	is the impurity correction factor,
k_{def}	is the correction factor for the heat defect,
k_{axl} and k_{rad}	are the correction factors for the axial and radial non-uniformity of the beam,
$I_{\mathrm{w,c}}$	is the ratio of the ionization currents measured in water and graphite phantoms,
k_{sl}	is the correction factor for the waterproof sleeve,
$\left(\frac{\overline{\mu_{\mathrm{en}}}}{\rho}\right)_{\mathrm{w,c}}$	is the water-to-graphite ratio of the mean mass energy absorption coefficients,
$\beta_{\mathrm{w,c}}$	is the absorbed dose to collision kerma ratio, and
$\Phi_{\mathrm{w,c}}$	is the photon energy fluence ratio.

The values for the physical constants and the correction factors of the primary standard entering in equation (2) and the associated uncertainties (Morishita *et al.* 2013) are given in Table 4.

Table 4. Physical constants, correction factors and relative standard uncertainties for the NMIJ standard for absorbed dose to water

Symbol Parameter / unit	Value	$10^2 \times$ Relative standard uncertainty	
		$u_{i\mathrm{A}}$	$u_{i\mathrm{B}}$
Determination of D_{c}			
Power measurement P / W	1.151×10^{-5}	0.15	0.022
Core mass / kg	1.237×10^{-3}	–	0.0003
Impurity correction	0.9958	–	0.10
Air gap	0.9961	–	0.10
Heat defect	1	–	0.10
Axial non-uniformity	1.0003	–	0.02
Radial non-uniformity	1	–	0.01
Depth in the graphite calorimeter	1	–	0.06
Positioning / m	1	–	0.06
Source decay	–	–	0.04
Conversion to absorbed dose to water			
Ionization current ratio $I_{\mathrm{w}} / I_{\mathrm{c}}$	0.9722	0.09	–
Ratio of mass energy-absorption coefficients	1.1127	–	0.14
Dose to kerma ratio	1.0001	–	0.05
Fluence ratio	1.0103	–	0.15
Waterproof sleeve	1.0009	–	0.10
Graphite phantom position	–	–	0.06
Depth in graphite phantom	–	–	0.06
Water phantom position	–	–	0.06
Depth in water phantom	–	–	0.10
Combined uncertainty of the NMIJ			
quadratic summation		0.17	0.34
combined relative standard uncertainty		0.38	

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

The reference conditions at the NMIJ are 1 m distance from the source to the reference plane, 5 g cm^{-2} water equivalent depth and a circular radiation field of 11 cm in diameter.

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 2022-01-01, 0 h UTC, as is the ionization current of the transfer chambers. The half-life of ^{60}Co used for the decay correction was taken as 1925.21 days (u = 0.29 days) (Bé *et al.* 2006).
The value of $\dot{D}_{\mathrm{w,NMIJ}}$ is given at the reference date of 2019-07-20, using the half-life value of 1925.23 days (u = 0.29 days) (DDEP 2010).

Beam characteristics

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

Table 5. Characteristics of the ^{60}Co beams at the NMIJ 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		
NMIJ	10.1	20	15	35 %	11 cm in diameter
BIPM Theratron 1000	4.9	20	14	21 %	10 cm × 10 cm

4. Comparison procedure

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

$$N_{D,\mathrm{w,lab}} = \dot{D}_{\mathrm{w,lab}} / I_{\mathrm{lab}} \tag{3}$$

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

The ionization chambers FC65-G, serial number 5278, and PTW 30013, serial number 8142, belonging to the NMIJ, are the transfer chambers used for this comparison. Their main characteristics are listed in Table 2. These chambers were calibrated at the NMIJ 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 $N_{D,\mathrm{w,lab}}$ 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

At each laboratory, a collecting voltage of 400 V (negative polarity) was applied to the outer electrode of the transfer chambers 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 (~12 Gy). Leakage current was measured before and after each series of measurements. The leakage correction, relative to the ionization current, was less than 1 part in 10^4. At the NMIJ, the ionization current I is measured using a vibrating reed electrometer, model MMA-II (Kawaguchi Electric Works). A pre-irradiation of at least 5 min (~2 Gy) was made for each chamber before any measurements. The leakage current was measured; the relative leakage correction was less than 1 part in 10^4.

Ion recombination

No correction for recombination was applied to the measured current. Volume recombination is negligible in continuous beams 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 8.

Radial non-uniformity correction

No radial non-uniformity correction was applied. At the NMIJ, 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 only be 1.0008 for the transfer chambers. A relative uncertainty component of 2 parts in 10^4 is included in Table 8.

Ambient conditions

At each laboratory, the water temperature is measured for each current measurement; it was stable to better than 0.1 °C at the BIPM and 0.2 °C at the NMIJ.

For the purposes of this comparison the ionization current is normalized to 293.15 K and 101.325 kPa. The NMI provided calibration coefficients at their standard reference temperature of 295.15 K and these were renormalized to 293.15 K by the BIPM.

At the BIPM, the relative humidity is controlled in the range from 45 % to 55 %. At the NMIJ, relative humidity is controlled and was in the range from 35 % to 50 %. No correction for humidity is applied to the ionization current measured at either laboratory.

PMMA phantom window and sleeve

Each laboratory uses 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 window in terms of interaction coefficients. Two waterproof sleeves of PMMA were supplied by the NMIJ for the transfer chambers. The same sleeves were 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 transfer chambers were set-up and measured in the BIPM ^{60}Co beam on two separate occasions. The results for each chamber were reproducible to better than 1 part in 10^4. The result of the comparison, $R_{D,\mathrm{w}}$, is expressed in the form

$$R_{D,\mathrm{w}} = N_{D,\mathrm{w,NMIJ}} / N_{D,\mathrm{w,BIPM}} \quad (4)$$

in which the average value of measurements made at the NMIJ 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.

The values $N_{D,\mathrm{w,NMIJ}}$ measured before and after the measurements at the BIPM give rise to a relative standard deviation for each chamber whose rms value is taken as a representation of the stability of the transfer instruments. The short-term stability is estimated to be 1 part in 10^4. Table 8 includes a component of 3 parts in 10^4 for the difference in the comparison result between the two transfer chambers.

Table 6. Results of the comparison of standards for ^{60}Co absorbed dose to water

Transfer Chamber	$N_{D,\mathrm{w,NMIJ}}$/ Gy µC^{-1}			$N_{D,\mathrm{w,BIPM}}$ / Gy µC^{-1}	$R_{D,\mathrm{w}}$	u_c
	pre-BIPM	post-BIPM	overall mean			
FC65-G-5278	47.74	47.75	47.74	47.96	0.9954	0.0040
PTW 30013-8142	53.55	53.59	53.57	53.84	0.9950	0.0040
Mean values					**0.9952**	0.0040

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

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

	BIPM		NMIJ	
Relative standard uncertainty	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
Absorbed-dose-to-water rate	0.04	0.18	0.17	0.34
Ionization current for the transfer chambers	0.01	0.02	0.03	0.05
Distance	0.02	–	–	0.06
Depth in water	0.02	0.06	–	0.10
Short-term reproducibility	0.01	–	0.01	–
Temperature, pressure	–	–	–	0.05
$N_{D,\mathrm{w,lab}}$	0.05	0.19	0.18	0.37

There are few correlations between the NMIJ and the BIPM uncertainty budgets, using a graphite calorimeter and an ionization chamber for the determination of absorbed dose to water, respectively. Indeed the only significant correlations arise from the common use of data relating to mass energy-absorption coefficients and the ratios of absorbed dose to collision kerma (β). The uncertainties are not fully correlated and this is taken into account by applying an approximate factor, f_k (correlation coefficients $f_k = 0.95$ and $f_k = 0.7$ for $(\overline{\mu}_{en}/\rho)_{w,c}$ and $\beta_{w,c}$, respectively). Taking correlation into account, the relative standard uncertainty $u_{R,NMI}$ for a comparison of a given NMI with the BIPM is given by

$$u_{R,\mathrm{NMI}}{}^2 = u_{\mathrm{c,NMI}}{}^2 + u_{\mathrm{c,BIPM}}{}^2 - \sum \left(f_k u_{k,\mathrm{corr}} \right)^2_{\mathrm{NMI}} - \sum \left(f_k u_{k,\mathrm{corr}} \right)^2_{\mathrm{BIPM}} \qquad (5)$$

where all the standard uncertainties are expressed as relative values.

Table 8. Uncertainties associated with the indirect comparison

	100 u_{iA}	100 u_{iB}
$N_{D,w,NMIJ}/N_{D,w,BIPM}$	0.18	0.36
Ion recombination	–	0.02
Radial non-uniformity	–	0.02
Stability of the chambers	0.01	–
Different chambers	0.03	–
$R_{D,w}$	$u_c = 0.0040$	

The comparison result is taken as the unweighted mean value for the two transfer chambers, $R_{D,w} = 0.9952$ with a combined standard uncertainty for the comparison of 0.0040, demonstrating the agreement between the two standards for absorbed dose to water.

6. Degrees of equivalence

Following a decision of the CCRI, the BIPM determination of the dosimetric quantity, here $D_{w,BIPM}$, is taken as the key comparison reference value (KCRV) (Allisy *et al.* 2009). It follows that for each 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 $D_i = (D_{wi} – D_{w,BIPMi})/ D_{w,BIPMi} = x_i – 1$ 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.

Note that the data presented in Table 9, while correct at the time of publication of the present report, become out-of-date as NMIs make new comparisons. In addition, revised validity rules for comparison data have been agreed by the CCRI(I) so that any results older than 15 years are no longer considered valid and have been removed from the KCDB. The formal results under the CIPM MRA are those available in the key comparison database (KCDB 2022).

Table 9. **Degrees of equivalence**

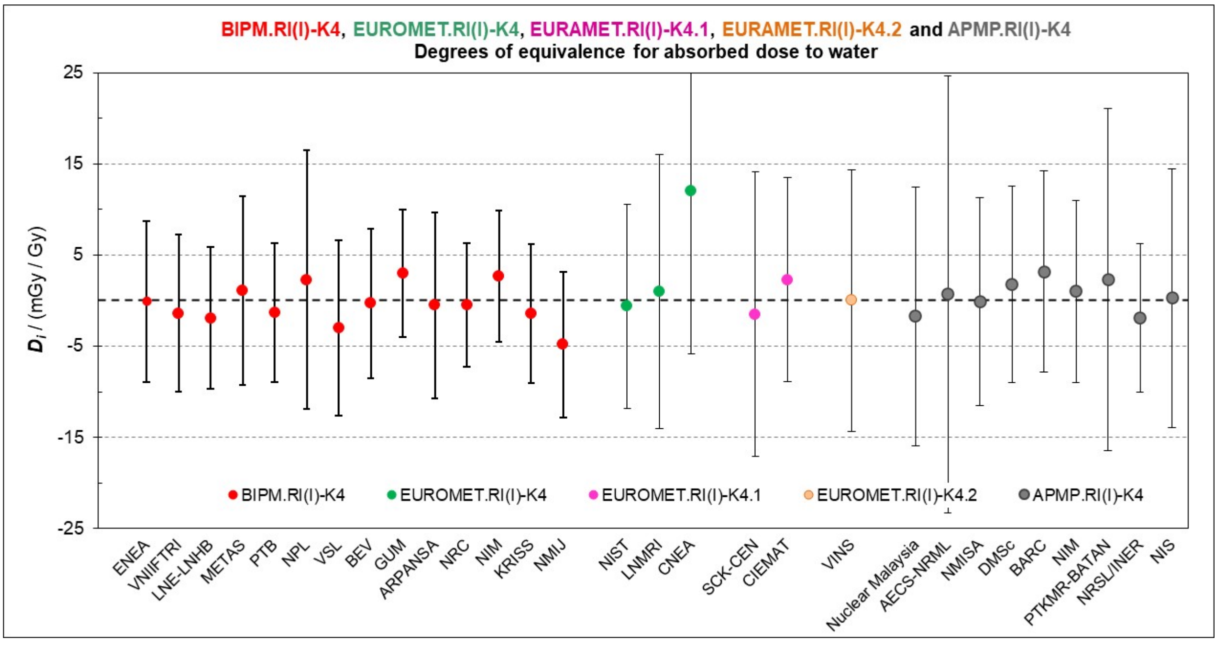
For each laboratory *i*, the degree of equivalence with respect to the key comparison reference value is the difference D_i and its expanded uncertainty U_i.

BIPM.RI(I)-K4 – EUROMET.RI(I)-K4 – EURAMET.RI(I)-K4.1 – EURAMET.RI(I)-K4.2 – APMP.RI(I)-K4

Lab *i*	D_i / (mGy / Gy)	U_i / (mGy / Gy)
ENEA	-0.1	8.8
VNIIFTRI	-1.4	8.6
LNE-LNHB	-1.9	7.8
METAS	1.1	10.4
PTB	-1.3	7.6
NPL	2.3	14.2
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
NIM	2.7	7.2
KRISS	-1.4	7.6
NMIJ	-4.8	8.0
VINS	0.0	14.3

Lab *i*	D_i / (mGy / Gy)	U_i / (mGy / Gy)
NIST	-0.6	11.1
LNMRI	1.0	15.0
CNEA	12.0	17.9
SCK-CEN	-1.5	15.5
CIEMAT	2.3	11.1
N. Malaysia	-1.7	14.2
AECS-NRML	0.7	24.0
NMISA	-0.1	11.4
DMSc	1.8	10.8
BARC	3.2	11.0
BATAN	2.3	18.8
NRSL / INER	-1.9	8.2
NIS	0.3	14.2

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



7. Conclusions

The previous comparison of the absorbed dose to water standards for ^{60}Co gamma radiation of the NMIJ and the BIPM was made indirectly in 2009. The comparison result was 0.9960 (46). The BIPM adopted the changes recommended by the ICRU 90 which results in a reduction of 1 part in 10^3 in the determination of absorbed dose to water, so that the comparison result of 2009 becomes 0.9970.

For the present comparison, made also indirectly using transfer instruments, the NMIJ 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 0.9952 (40), in agreement within the uncertainties with the previous comparison result. The NMIJ 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 ^{60}Co gamma-ray beams.

References

Allisy P J, Burns D T and Andreo P 2009 International framework of traceability for radiation dosimetry quantities *Metrologia* **46(2)** S1-S8

Bé M-M, Chisté V, Dulieu C, Browne E, Baglin C, Chechev V, Kuzmenco N, Helmer R, Kondev F, MacMahon D and Lee K B 2006 Table of Radionuclides (Vol. 3 – A = 3 to 244) *Monographie BIPM-5*

Boutillon M and Perroche A-M 1993 Ionometric determination of absorbed dose to water for cobalt-60 gamma rays *Phys Med Bio* 1993 **38** 439-454

Burns D and Kessler C 2018 Re-evaluation of the BIPM international dosimetry standards on adoption of the recommendations of ICRU Report 90 *Metrologia* **55** R21-R26

CIPM MRA: *Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes*, International Committee for Weights and Measures, 1999, 45 pp http://www.bipm.org/pdf/mra.pdf

DDEP Decay Data Evaluation Project 2010 http://www.lnhb.fr/ddep_wg/

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

KCDB 2023 BIPM Key Comparison Database ^{60}Co absorbed dose to water comparisons BIPM.RI(I)-K4

Kessler C, Allisy P J, Morishita Y, Kato M, Takata N, Kurosawa T, Tanaka T and Saito N 2011 Comparison of the standards for absorbed dose to water of the NMIJ and the BIPM for ^{60}Co γ-ray beams *Metrologia* **48** *Tech. Suppl.* 06008

Kessler C and Burns D 2018 Measuring conditions and uncertainties for the comparison and calibration of national dosimetric standards at the BIPM *Rapport* BIPM-18/06

Morishita Y, Kato M, Takata N, Kurosawa T, Tanaka T and Saito N 2013 A standard for absorbed dose rate to water in a ^{60}Co field using a graphite calorimeter at the National Metrology Institute of Japan Rad. Prot. Dosim. **154** 331-339