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

C. Kessler[1], D. Burns[1], S. J. Jin [2], X. Zhang[2], Z. P. Wang[2], F. B. Liu[2], J. Huang[2], Y. P. Qi[2], X. Y. Yang[2] and K. Wang[2]

[1]Bureau International des Poids et Mesures, F-92312 Sèvres Cedex
[2] National Institute of Metrology, Beijing, China

Abstract

A key comparison of the standards for absorbed dose to water of the National Institute of Metrology (NIM), China, and the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in December 2021. The comparison result, based on the calibration coefficients for four transfer standards and evaluated as a ratio of the NIM and the BIPM standards for absorbed dose to water, is 1.0027 with a combined standard uncertainty of 3.6 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 National Institute of Metrology (NIM), China, and the Bureau International des Poids et Mesures (BIPM) was carried out in December 2021 in the ^{60}Co radiation beam at the BIPM. The comparison result is published in the BIPM key comparison database (KCDB 2022) under the reference BIPM.RI(I)-K4. The comparison was carried out after the implementation of the recommendations of ICRU Report 90 (ICRU 2016).

The comparison was made indirectly using four thimble-type ionization chambers as transfer instruments. Final results were supplied by the NIM in April 2022.

2. Details of the standards and the transfer chambers

The primary standard of the NIM for absorbed dose is a Domen-type sealed water calorimeter developed in collaboration with the National Research Council of Canada (NRC). Details of the NIM standard can be found in Picard *et al.* (2017).

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 NIM transfer chambers

Nominal values		FC65G	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 the outer electrode / V		300	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

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

where

ρ_{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,

$(\mu_{\mathrm{en}}/\rho)_{\mathrm{w,g}}$ 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
$(\mu_\mathrm{en}/\rho)_\mathrm{w,g}$	ratio of mass energy-absorption coefficients	1.1131	–	0.05
W/e	mean energy per charge / J C^{-1}	33.97	–	– (3)
$D_\mathrm{g,air} = s_\mathrm{g,air} k_\mathrm{cav}$	product of the ratio of mass stopping powers and cavity perturbation correction	0.9958	0.02	0.13 (3)
$\psi_\mathrm{w,g}$	photon energy fluence ratio	1.0037	0.01	0.07
$\beta_\mathrm{w,g}$	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 $s_\mathrm{g,air}$, 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 NIM, the absorbed dose to water D_w is determined using

$$\dot{D}_\mathrm{w,NIM} = \Delta T_\mathrm{w} c_\mathrm{w} \prod k_i \qquad (2)$$

where

ΔT_w is the measured temperature rise,

c_w is the specific heat capacity of water at the calorimeter operating temperature of 4 °C,

$\prod k_i$ is the product of the correction factors to be applied to the standard:

k_c corrects for the heat conduction due to the gradient of temperature,

k_p corrects for the perturbation of the non-water components of the vessel,
k_{HD} corrects for the heat defect of water due to chemical reactions,
k_{dd} corrects for the lateral beam non-uniformity at the depth of measurement, and
k_{en} corrects for the end of the integration time to account for the source transit.

The calorimeter was developed for high-energy photon beams with a sealed cylindrical vessel 6 cm in diameter, to be positioned in the water phantom at the reference depth of 10 g cm^{-2}. To use the calorimeter in a ^{60}Co beam, the cylindrical vessel is replaced by a parallel-plate vessel. To validate the parallel-plate configuration, calorimetric measurements using both vessel types were performed in high-energy photon beams. The agreement using the two calorimeter configurations was better than 2 parts in 10^3. Two parallel-plate vessels, of thickness 2.8 cm and 4 cm, are available and they are positioned alternately in the phantom at the reference depth of 5 g cm^{-2}. The agreement between the two parallel-plate vessels is better than 2 parts in 10^3. Absorbed dose to water is determined from the mean using both vessels and the corresponding relative uncertainty of the mean is estimated to be 1.2 parts in 10^3. The specific heat capacity for water, the correction factors for each vessel and the corresponding uncertainties are given in Table 4.

Table 4. Specific heat capacity, correction factors and relative standard uncertainties for the NIM standard for absorbed dose to water

Symbol	Parameter / unit	Value	$10^2 \times$ Relative standard uncertainty u_{iA}	u_{iB}
Determination of D_w				
$c_{w,p}$	specific heat capacity / (J g^{-1} K^{-1})	4.2048	–	<0.005
	thermistor sensitivity	–	–	0.07
k_c	heat conduction (1)	1.0148 / 0.9983	–	0.10
k_p	vessel perturbation (1)	1.0021 / 1.0016	0.01	0.05
k_{HD}	heat defect	1.0000	–	0.15
k_{rho}	change in density of water (4 °C to 22 °C)	1.0006	–	0.02
k_{en}	end of integration time/source transit	0.9955	0.01	0.02
k_{dd}	lateral beam non-uniformity	1.0005	0.01	0.01
	positioning calorimeter, probes and vessel	–	–	0.10
	reproducibility	–	0.10	–
	mean two vessels	–	0.12	–
Combined uncertainty of the D_w determination at the NIM				
quadratic summation			0.16	0.23
combined relative standard uncertainty			0.27	

(1) Values for the vessel of thickness 2.8 cm and 4 cm, respectively.

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 distance at the NIM is 0.7 m, taken from the source to the external surface of the phantom; the field size at this distance is 10 cm × 10 cm. The reference depth in the water phantom is 5 g cm^{-2}.

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 2021-01-01, 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 $\dot{D}_{\mathrm{w,NIM}}$ used for the comparison is taken as the mean value using the two parallel-plate vessels. All the measurements are corrected to the reference date 2021-10-23 using the same half-life as the BIPM.

Beam characteristics

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

Table 5. Characteristics of the ^{60}Co beams at the NIM 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 reference distance$^{(1)}$
		diameter	length		
NIM GammaBeam X-200	26.7	20	23.5	20 %	10 cm × 10 cm
BIPM Theratron 1000	5.6	20	14	21 %	10 cm × 10 cm

$^{(1)}$ The reference distance is 1 m and 0.7 m at the BIPM and the NIM, respectively.

4. Comparison procedure

The comparison of the NIM and BIPM standards was made indirectly using the calibration coefficients $N_{D,\mathrm{w,lab}}$ for the four 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 NIM or the BIPM. The current is corrected for the effects and influences described in this section.

The ionization chambers FC65G, serial numbers 1736 and 3208, and PTW 30013, serial numbers 4678 and 9166, belonging to the NIM, were used as the transfer chambers for this comparison. Their main characteristics are listed in Table 2. These chambers were calibrated at the NIM 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

A collecting voltage of 300 V and 400 V (positive polarity) was applied to the outer electrode of the FC65G and 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 1 part in 10^4. At the NIM, the ionization current I is measured using a Keithley electrometer, model 6517B. A pre-irradiation of at least 10 min (~16 Gy) was made for each chamber before any measurements. Leakage current was measured before and after each series of measurements. The relative leakage correction for each chamber 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 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 7.

Radial non-uniformity correction

The NIM applies correction for the non-uniformity of the beam over the section of the transfer chambers; the correction applied to the ionization current is 1.0016. At the BIPM, the correction to the ionization current is 1.0008. The radial non-uniformity correction was applied at both laboratories and a relative uncertainty component of 3 parts in 10^4 and 2 parts in 10^4 is included in Table 7 for the NIM and the BIPM, respectively.

Ambient conditions

At both laboratories, the water temperature is measured for each current measurement; it was stable to better than 0.1 °C at both the BIPM and the NIM.
The ionization current is normalized to 293.15 K and 101.325 kPa at both laboratories for the purposes of this calibration.
At the BIPM, the relative humidity is controlled in the range from 45 % to 55 %. At the NIM, relative humidity is controlled, but is seasonally variable, and was in the range from 30 % to 55 %. No correction for humidity is applied to the ionization current measured at either laboratory.

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 window in terms of interaction coefficients. A waterproof sleeve of PMMA was supplied by the NIM for the transfer chambers. The same sleeve was used at both laboratories and, consequently, no correction for the influence of the sleeve was necessary at either laboratory for these chambers.

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 2 parts in 10^4. The result of the comparison, $R_{D,\mathrm{w}}$, is the mean of the ratio expressed in the form

$$R_{D,\mathrm{w},i} = N_{D,\mathrm{w,NIM},i} / N_{D,\mathrm{w,BIPM},i} \tag{4}$$

calculated for each transfer chamber in which $N_{D,\mathrm{w,NIM},i}$ is the average value of measurements made at the NIM before and after those made at the BIPM and $N_{D,\mathrm{w,BIPM},i}$ is 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 $N_{D,\mathrm{w,lab}}$ and the combined standard uncertainty u_c for the comparison result $R_{D,\mathrm{w}}$ are presented in Table 7.

The values $N_{D,\mathrm{w,NIM}}$ measured before and after the measurements at the BIPM give rise to a relative standard deviation for each chamber; the r.m.s. value for the four chambers of 5 parts in 10^4 is taken as a global representation of the stability of the transfer instruments in Table 7. The short-term stability is estimated to be 1 part in 10^4. Table 7 includes a component of 2 parts in 10^4 for the difference in the comparison result between the four transfer chambers.

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

Transfer Chamber	$N_{D,\mathrm{w,NIM}}$/ Gy µC^{-1}			$N_{D,\mathrm{w,BIPM}}$ / Gy µC^{-1}	$R_{D,\mathrm{w}}$	u_c
	pre-BIPM	post-BIPM	overall mean			
FC65G -1736	47.92	47.90	47.91	47.78	1.0028	0.0036
FC65G-3208	48.04	48.09	48.07	47.95	1.0024	0.0036
PTW 30013-4678	54.11	54.13	54.12	53.96	1.0029	0.0036
PTW 30013-9166	53.82	53.85	53.84	53.70	1.0025	0.0036
Mean values					**1.0027**	**0.0036**

Table 7. Uncertainties associated with the indirect comparison

<table>
<tr><th rowspan="2">Relative standard uncertainty</th><th colspan="2">BIPM</th><th colspan="2">NIM</th></tr>
<tr><th>100 $u_{i\mathrm{A}}$</th><th>100 $u_{i\mathrm{B}}$</th><th>100 $u_{i\mathrm{A}}$</th><th>100 $u_{i\mathrm{B}}$</th></tr>
<tr><td>Absorbed-dose-to-water rate</td><td>0.04</td><td>0.18</td><td>0.16</td><td>0.23</td></tr>
<tr><td>Ionization current for the transfer chambers</td><td>0.01</td><td>0.02</td><td>0.01</td><td>0.02</td></tr>
<tr><td>Distance</td><td>0.02</td><td>–</td><td>–</td><td rowspan="2">0.05</td></tr>
<tr><td>Depth in water</td><td>0.02</td><td>0.06</td><td>–</td></tr>
<tr><td>Electrometer</td><td>–</td><td>–</td><td>–</td><td>0.01</td></tr>
<tr><td>Radial non-uniformity</td><td>–</td><td>0.02</td><td>–</td><td>0.03</td></tr>
<tr><td>Short-term reproducibility</td><td>0.01</td><td>–</td><td>0.02</td><td>–</td></tr>
<tr><td>Air density correction</td><td>–</td><td>–</td><td>–</td><td>0.05</td></tr>
<tr><td>Humidity</td><td>–</td><td>–</td><td>–</td><td>0.05</td></tr>
<tr><td>$N_{D,\mathrm{w,lab}}$</td><td>0.05</td><td>0.20</td><td>0.16</td><td>0.24</td></tr>
</table>

Table 7. Uncertainties associated with the indirect comparison (cont)

Relative standard uncertainty	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
$N_{D,\mathrm{w,NIM}}/N_{D,\mathrm{w,BIPM}}$	0.17	0.31
Ion recombination	–	0.02
Stability of the chambers	0.05	–
Different chambers	0.02	–
$R_{D,\mathrm{w}}$	u_c = 0.0036	

The comparison result is taken as the unweighted mean value for the four transfer chambers, $R_{D,\mathrm{w}}$ = 1.0027 with a combined standard uncertainty for the comparison of 0.0036, 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 $D_{\mathrm{w,BIPM}}$, is taken as the key comparison reference value (KCRV) (Allisy *et al.* 2009). It follows that for each NMI i having a BIPM comparison result x_i with 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 8 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. Note that the data presented in Table 8, 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.

Table 8. Degrees of equivalence

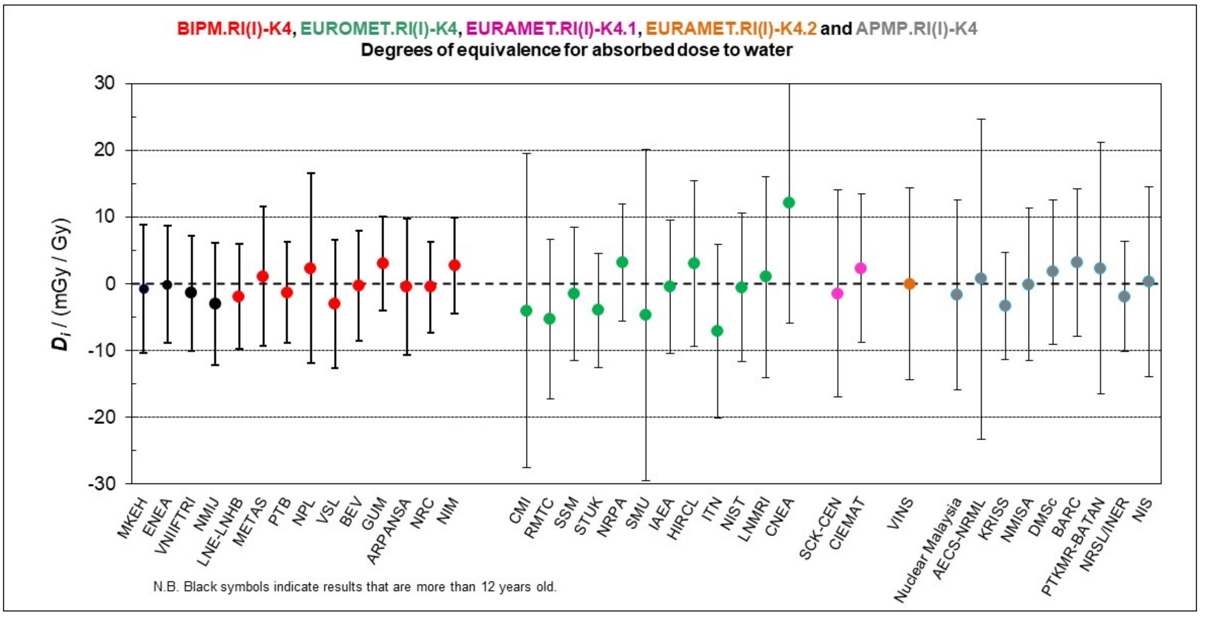
For each laboratory *i*, the degree of equivalence with respect to the key comparison reference value is the difference D_i and its expanded uncertainty U_i. Tables formatted as they appear in the BIPM key comparison database

BIPM.RI(I)-K4 – EUROMET.RI(I)-K4 (2005 to 2008) – EURAMET.RI(I)-K4.1 – EURAMET.RI(I)-K4.2 – APMP.RI(I)-K4

Lab *i*	D_i	U_i
	/ (mGy / Gy)	
MKEH	-0.7	9.6
ENEA	-0.1	8.8
VNIIFTRI	-1.4	8.6
NMIJ	-3.0	9.2
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
ARPANSA	-0.5	10.2
NRC	-0.5	6.8
NIM	2.7	7.2
SCK-CEN	-1.5	15.5
CIEMAT	2.3	11.1
VINS	0.0	14.3

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
Malaysia	-1.7	14.2
AECS-NRML	0.7	24.0
KRISS	-3.3	8.0
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 NIM 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 1.0027 (36). The NIM 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.

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

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

KCDB 2022 BIPM Key Comparison Database ^{60}Co absorbed dose to water comparisons BIPM.RI(I)-K4

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

Picard S, Kessler C, Roger P, Burns D T, Wang K, Wang Z, Fan Y, Jin S and Zhang J 2017 Key comparison BIPM.RI(I)-K6 of the standards for absorbed dose to water at 10 g cm^{-2} of the NIM, China and the BIPM in accelerator photon beams *Metrologia* **54** *Tech. Supp.* 06009