Key comparison BIPM.RI(I)-K4 of the absorbed dose to water standards of the KRISS, Republic of Korea 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 Korea Research Institute of Standards and Science (KRISS), Republic of Korea, and the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in March 2022. The comparison result, based on the calibration coefficients for two transfer standards and evaluated as a ratio of the KRISS and the BIPM standards for absorbed dose to water, is 0.9986 with a combined standard uncertainty of 3.8 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 Korea Research Institute of Standards and Science (KRISS), Republic of Korea, and the Bureau International des Poids et Mesures (BIPM) was carried out in March 2022 in the ^{60}Co radiation beam. 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 two thimble-type ionization chambers as transfer instruments. Final results were supplied by the KRISS in July 2022.

2. Details of the standards and the transfer chambers

The primary standard of the KRISS for absorbed dose is an NRC type sealed water calorimeter (Seuntjens *et al* 1999). The water calorimeter was constructed at the National Research Council (NRC) of Canada and has been operating at the KRISS since 2018.

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		± 80

Table 2. Characteristics of the KRISS transfer chambers

Nominal values		NE 2571	PTW 30013	
Chamber	Outer diameter / mm	7.0	7.0	
	Outer length / mm	24.5	23.6	
Electrode	Diameter / mm	1.0	1.1	
	Length / mm	20.6	21.0	
Cavity	Nominal volume / cm^3	0.7	0.6	
Wall	Thickness / mm	0.36	0.335	0.09
	Material	graphite	PMMA	graphite
	Density / g cm^{-3}	1.7	1.19	1.85
Voltage applied to outer electrode / V		-300	-300	

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

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

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

$\Pi\, k_i$ 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)]
$D_{g,air} = s_{g,air} k_{cav}$	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_{afari}, as evaluated for the BIPM and other air-kerma standards for Co-60 and the uncertainty of k_{cav}

(4) Standard CH7.1.

(5) Over a period of 3 months.

At the KRISS, the absorbed dose to water rate $\dot{D}_w$ is determined using

$$\dot{D}_{w,KRISS} = \frac{\Delta T_w c_w}{t_{irr}} \frac{1}{1-k_{HD}} \prod k_i \quad (2)$$

where

ΔT_w is the measured temperature rise,
c_w is the specific heat capacity of water at 4 °C,
t_{irr} is the irradiation time,
k_{HD} is the heat defect of the water,
$\prod k_i$ is the product of the correction factors to be applied to the standard.

The absorbed dose to water at the KRISS is determined using the primary standard water calorimeter. A secondary standard ionization chamber is calibrated directly against the water calorimeter, and becomes the reference chamber used to calibrate transfer chambers.

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

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

Symbol	Parameter / unit	Value	$10^2 \times$ Relative standard uncertainty u_{iA}	u_{iB}
Determination of $\dot{D}_w$				
$c_{w,p}$	specific heat capacity of water at 4 °C/ (J g^{-1} K^{-1})	4.2048	–	< 0.01
ΔT_w	temperature rise	–	0.10	0.08
t_{irr}	irradiation time	–	–	0.03
k_{HD}	heat defect	1	–	0.15 (1)
k_c	heat conduction	0.9961	–	0.10 (1)
k_p	vessel perturbation	1.0025	–	0.05 (1)
k_{rho}	change in density of water (4 ºC to 20 ºC)	1.0004	–	0.02 (1)
k_β	thermistor sensitivity	1	–	0.08
k_{dd}	lateral profile non-uniformity	1.0002	–	0.06
k_{decay}	source decay	–	–	<0.01
	distance and positioning	–	–	0.07
Calibration of reference chamber				
I	ionization current of the chamber	–	0.007	-
P_{elec}	calibration of the electrometer	1	–	0.02
P_{dd}	correction for lateral profile non-uniformity	1.0011	–	0.04
P_{decay}	correction for decay of the ^{60}Co source	–	–	<0.01
P_{ion}	ion recombination (2)	–	–	0.04
P_{pol}	polarity (2)	–	–	0.01
P_{TP}	air density correction	–	–	0.04
	positioning of chamber	–	–	0.06
	humidity (range 20 % - 70 %)	–	–	0.05
	long term stability of reference chamber	–	–	0.12
Combined uncertainty of the KRISS calibration of the reference chamber $N_{D,w,ref}$				
quadratic summation			0.10	0.29
combined relative standard uncertainty			0.31	

(1) Refer to C. Kessler *et al* 2021, B.R. Muir *et al* 2017 and Seuntjens *et al* 1999

(2) For this comparison, corrections for ion recombination and polarity were not applied but are included in Table 4 for completeness. For the KRISS reference chamber, the P_{ion}, P_{pol} measured values are 1.0008(4) and 0.9994(1), 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 conditions at the KRISS are the same as those at the BIPM.

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 KRISS reference absorbed-dose-to-water rate $\dot{D}_{\mathrm{w,KRISS}}$ used for this comparison is taken as the mean of two series of 40 measurements each, made using the reference chamber during the comparison period. The same half-life of ^{60}Co given above for the BIPM decay correction is used at the KRISS.

Beam characteristics

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

Table 5. Characteristics of the ^{60}Co beams at the KRISS and the BIPM

^{60}Co beam	Nominal $\dot{D}_w$ / mGy s^{-1}	Source dimensions / mm diameter	Source dimensions / mm length	Scatter contribution in terms of energy fluence	Field size at 1 m
KRISS Eldorado 8	7.2	23	23	19 %	10 cm × 10 cm
BIPM Theratron 1000	4.9	20	14	21 %	10 cm × 10 cm

4. Comparison procedure

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

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

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

The ionization chambers NE 2571, serial number 3776, and PTW 30013, serial number 8979, belonging to the KRISS, are the transfer chambers used for this comparison. Their main characteristics are listed in Table 2. These chambers were calibrated at the KRISS 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 facing the source.

Applied voltage and polarity

At both laboratories, a collecting voltage of 300 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 (~13 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 KRISS, the ionization current I is measured using a Keithley electrometer, model 6517B. A pre-irradiation of at least 30 min (~13 Gy) was made for each chamber before any measurements. Leakage current was measured for each chamber. 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 8.

Radial non-uniformity correction

At the KRISS, a correction of 1.0011 was applied to the measured current to account for the radial non-uniformity of the beam over the section of the transfer chambers, with a relative standard uncertainty of 4 parts in 10^4. For consistency, a corresponding correction of 1.0008 was also applied at the BIPM, with a relative standard uncertainty of 2 parts in 10^4. The uncertainties are included in Table 7.

Ambient conditions

At both laboratories, 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 KRISS.
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 KRISS, relative humidity is controlled and was in the range from 40 % to 55 %; no correction for humidity is applied to the ionization current measured.

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. Each laboratory used its own waterproof sleeve, of thickness 1 mm. No correction for the influence of using different sleeves was applied and a relative uncertainty component of 2 parts in 10^4 is included in Table 8.

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

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

in which the average value of measurements made at the KRISS 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 uncertainties associated with the calibration of the transfer chambers at each laboratory and the combined standard uncertainty u_c for the comparison result $R_{D,\mathrm{w}}$ are presented in Table 7 and Table 8, respectively.

The values $N_{D,\mathrm{w,KRISS}}$ 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 less than 1 part in 10^4. Table 8 includes a component of 6 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	$N_{D,\mathrm{w,KRISS}}$/ Gy µC^{-1}			$N_{D,\mathrm{w,BIPM}}$ / Gy µC^{-1}	$R_{D,\mathrm{w}}$	u_c
	pre-BIPM	post-BIPM	overall mean			
NE 2571-3776	44.95	44.97	44.96	45.05	0.9980	0.0038
PTW 30013-8979	53.41	53.41	53.41	53.45	0.9993	0.0038
Mean values					**0.9986**	**0.0038**

Table 7. Uncertainties associated with the transfer chamber calibration

<table>
<tr><td rowspan="2">Relative standard uncertainty</td><td colspan="2">BIPM</td><td colspan="2">KRISS</td></tr>
<tr><td>100 $u_{i\mathrm{A}}$</td><td>100 $u_{i\mathrm{B}}$</td><td>100 $u_{i\mathrm{A}}$</td><td>100 $u_{i\mathrm{B}}$</td></tr>
<tr><td>Absorbed-dose-to-water rate</td><td>0.04</td><td>0.18</td><td>0.10</td><td>0.29</td></tr>
<tr><td>Ionization current for the transfer chambers</td><td>0.01</td><td>0.02</td><td>0.01</td><td>0.04</td></tr>
<tr><td>Distance</td><td>0.02</td><td>–</td><td>–</td><td rowspan="2">0.06</td></tr>
<tr><td>Depth in water</td><td>0.02</td><td>0.06</td><td>–</td></tr>
<tr><td>Radial non-uniformity</td><td>–</td><td>0.02</td><td>–</td><td>0.04</td></tr>
<tr><td>Short-term reproducibility</td><td>0.01</td><td>–</td><td>0.01</td><td>–</td></tr>
<tr><td>$N_{D,\mathrm{w,lab}}$</td><td>0.05</td><td>0.20</td><td>0.10</td><td>0.30</td></tr>
</table>

Table 8. Uncertainties associated with the indirect comparison

	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
$N_{D,\mathrm{w,KRISS}}/N_{D,\mathrm{w,BIPM}}$	0.11	0.36
Ion recombination	–	0.02
Different sleeves	–	0.02
Stability of the chambers	0.01	–
Different chambers	0.06	–
$R_{D,\mathrm{w}}$	u_c = 0.0038	

The comparison result is taken as the unweighted mean value for the two transfer chambers, $R_{D,\mathrm{w}}$ = 0.9986 with a combined standard uncertainty for the comparison of 0.0038, 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 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**

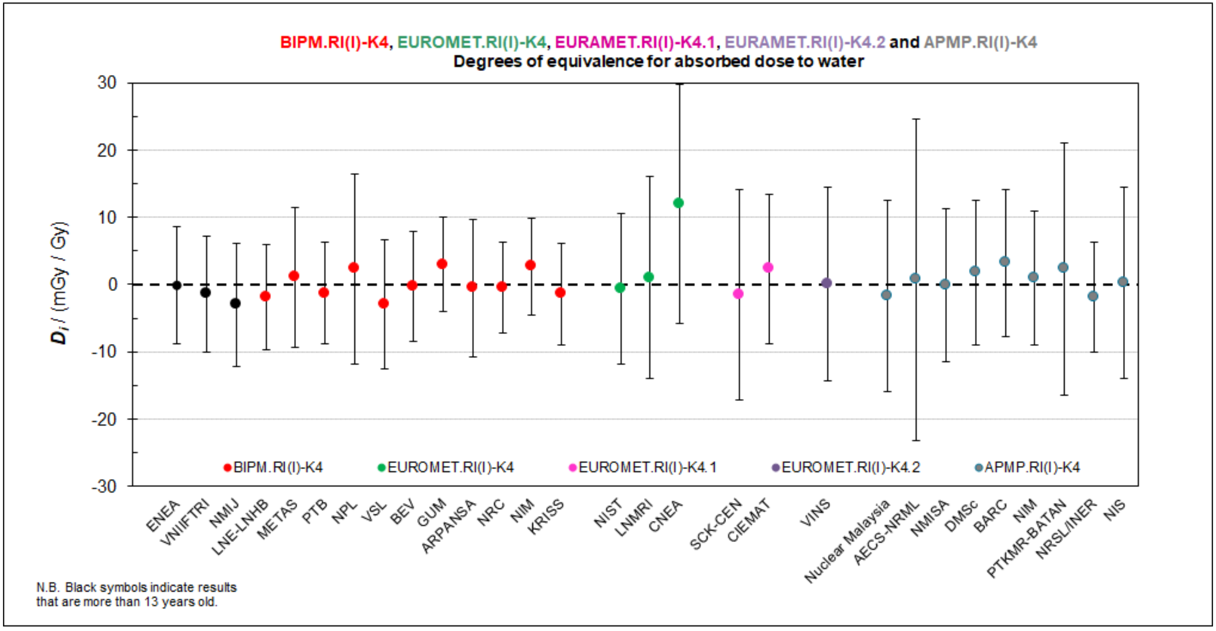
For each laboratory *i*, the degree of equivalence with respect to the key comparison reference value is the difference D_i and its expanded uncertainty U_i.

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
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	7.0
ARPANSA	-0.5	10.2
NRC	-0.5	6.8
NIM	2.7	7.2
KRISS	-1.4	7.6
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 KRISS 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 0.9986 (38). The KRISS 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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