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

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Abstract

A new key comparison of the standards for absorbed dose to water of the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), Australia and the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in November 2020. The comparison result, based on the calibration coefficients for two transfer chambers and evaluated as a ratio of the ARPANSA and the BIPM standards for absorbed dose to water, is 0.9995 with a combined standard uncertainty of 5.1 parts in 10^3. The result agrees within the uncertainties with the comparison carried out in 2010. 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 Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), Australia, and the Bureau International des Poids et Mesures (BIPM) was carried out in November 2020 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2010 (Kessler *et al.* 2012) 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 indirect comparison was made using two thimble-type ionization chambers as transfer instruments. The final results were supplied by the ARPANSA in February 2021.

2. Details of the standards and the transfer chambers

The absorbed dose to water is determined at the ARPANSA using a graphite calorimeter with a calculated dose conversion factor from graphite to water using Monte Carlo methods.

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 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 ARPANSA 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	21.2	
Cavity	Measuring 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		-250	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

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

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,

$\bar{s}_{g,a}$	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
$\Pi\ k_i$	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_{iA}	u_{iB}
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)]
$\psi_{w,g}$	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 *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) 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}

(4) Standard CH7.1.

(5) Over a period of 3 months.

The absorbed dose to water at the ARPANSA is determined by means of a graphite calorimeter operated in quasi-isothermal mode and the absorbed dose conversion from graphite to water is made by calculation using the Monte Carlo method. The absorbed dose to graphite is determined from

$$\dot{D}_{\mathrm{core}} = P/m \tag{2}$$

where:

P is the change in electrical power required to exactly compensate the radiation heating (calculated from voltages measured across the core thermistor and a known resistor in the same circuit), and

m is the mass of the core.

The absorbed dose to water is determined from

$$\dot{D}_{\mathrm{w,ARPANSA}} = \dot{D}_{\mathrm{core}}(D_{\mathrm{w}}/D_{\mathrm{core}})_{\mathrm{MC}} \tag{3}$$

where $(D_{\mathrm{w}}/D_{\mathrm{core}})_{\mathrm{MC}}$ is the ratio of absorbed dose to water to absorbed dose to the calorimeter core, calculated using the Monte Carlo method. The graphite calorimeter and water phantom are modelled precisely, obviating the need for many corrections. As such, common corrections such as those for vacuum gaps and non water-equivalence of the water phantom window are not required. The method is described by Lye *et al.* (2013).

The design and operation of the calorimeter is described in the previous comparison report (Kessler *et al.* 2012) and the references therein. A summary of the components of uncertainty is indicated in Table 4 giving a combined relative standard uncertainty of 4 parts in 10^3.

Table 4. Physical constants, correction factors and relative standard uncertainties for the ARPANSA 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_{core}				
P	electrical power	–	0.08	–
m	mass of the core / g	1.5622	–	0.01
	repeatability	–	0.12	–
k_{rn}	radial non-uniformity	1.0000	–	0.03
Determination of D_{w}				
$(D_{\mathrm{w}}/D_{\mathrm{core}})_{\mathrm{MC}}$	Monte Carlo conversion factor from graphite to water	1.0713	0.10	0.36
Combined uncertainty of the ARPANSA determination of absorbed-dose rate to water				
quadratic summation			0.18	0.36
combined relative standard uncertainty			0.40	

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 ARPANSA are as follows:

- the distance from the source to the water surface is 1 m;
- the field size in air at the water surface is 10 cm x 10 cm, the photon fluence rate at the centre of each side of the square being approximately 50 % of the photon fluence rate at the centre of the square; and
- the reference depth in the water phantom is 5 cm, leading to a source-detector distance of 1.05 m.

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 2020-01-01, 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).
At the ARPANSA, graphite calorimetry is performed annually. The value of $\dot{D}_{\mathrm{w,ARPANSA}}$ used for the comparison is taken as the mean of the last three determinations of absorbed dose to graphite, converted to absorbed dose to water using MC calculations. It is given at the reference date of 2020-01-20 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 ARPANSA beams are given in Table 5.

Table 5. Characteristics of the ^{60}Co beams at ARPANSA 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		
ARPANSA	2.2	20	20	21 %	10 cm × 10 cm
BIPM Theratron 1000	6.5	20	14	21 %	10 cm × 10 cm

4. Comparison procedure

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

$$N_{D,\mathrm{w,lab}} = \dot{D}_{\mathrm{w,lab}}/I_{\mathrm{lab}} \qquad (4)$$

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

The ionization chambers NE 2571, serial number 3075 and PTW 30013, serial number 7470, belonging to the ARPANSA, were used as the transfer chambers for this comparison. Their main characteristics are listed in Table 2. These chambers were calibrated at the ARPANSA 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 250 V (negative polarity) and 400 V (positive polarity) was applied to the outer electrode of the NE 2571 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 parts in 10^4. At the ARPANSA, the ionization current I is measured using a PTW electrometer, model T10022. A pre-irradiation of at least 30 min (~4 Gy) was made for each chamber before any measurements. Leakage current was measured 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 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 7.

Radial non-uniformity correction

The ARPANSA ^{60}Co beam profile in air has a depression in the middle, which seems to be attenuated in water, resulting in a correction for the radial non-uniformity over the section of the transfer chambers of less than 5 parts in 10^4. At the BIPM, the correction to the ionization current would only be 1.0008 for the transfer chambers. No radial non-uniformity correction was applied and a relative uncertainty component of 3 parts in 10^4 is 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 0.1 °C at the ARPANSA.
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 ARPANSA, relative humidity is uncontrolled and was in the range from 30 % to 50 %; no correction for humidity is applied to the ionization current measured.

PMMA phantom window and sleeve

Both laboratories use a horizontal radiation beam and 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.
The BIPM used its own PMMA sleeve as no waterproof sleeve was supplied by the ARPANSA. Both laboratories used similar sleeves of the same material and thickness for the NE 2571 chamber; consequently, the effect of using different sleeves is negligible and no correction was applied. No sleeve was used for the PTW 30013 chamber measurements 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, $R_{D,\mathrm{w}}$, is expressed in the form

$$R_{D,\mathrm{w}} = N_{D,\mathrm{w,ARPANSA}} / N_{D,\mathrm{w,BIPM}} \qquad (5)$$

in which the average value of measurements made at the ARPANSA 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 at the BIPM and at the ARPANSA were reproducible to better than 1 part in 10^4. The results 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. This includes a component of 1.2 parts in 10^3 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	$N_{D,\mathrm{w,ARPANSA}}$/ Gy µC^{-1}			$N_{D,\mathrm{w,BIPM}}$ / Gy µC^{-1}	$R_{D,\mathrm{w}}$	u_c
	pre-BIPM	post-BIPM	overall mean			
NE 2571-3075	45.19	45.23	45.21	45.28	0.9984	0.0050
PTW 30013-7470	53.53	53.54	53.54	53.50	1.0007	0.0051
Mean values					**0.9995**	**0.0051**

There are few correlations between the ARPANSA 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 the collision part of the kerma (β). The uncertainties are not necessarily 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 $(\bar{\mu}_\mathrm{en}/\rho)_\mathrm{w,c}$ and $\beta_\mathrm{w,c}$, respectively). Taking correlation into account, the relative standard uncertainty $u_{R,\mathrm{NMI}}$ for a comparison of a given NMI with the BIPM is given by

$$u_{R,\mathrm{NMI}}{}^2 = u_{\mathrm{c,NMI}}{}^2 + u_{\mathrm{c,BIPM}}{}^2 - \sum\left(f_k u_{k,\mathrm{corr}}\right)^2_{\mathrm{NMI}} - \sum\left(f_k u_{k,\mathrm{corr}}\right)^2_{\mathrm{BIPM}} \qquad (6)$$

where all the standard uncertainties are expressed as relative values.

Table 7. Uncertainties associated with the indirect comparison

Relative standard uncertainty	BIPM 100 u_{iA}	BIPM 100 u_{iB}	ARPANSA 100 u_{iA}	ARPANSA 100 u_{iB}
Absorbed-dose-to-water rate	0.04	0.18	0.18	0.36
Ionization current for the transfer chambers	0.01	0.02	0.05	0.11
Distance	0.02	–	–	0.10
Depth in water	0.02	0.06	–	0.11
Short-term stability	0.01	–	0.01	–
Temperature, pressure	–	–	–	0.05
Electrometer linearity	–	–	–	0.05
Phantom window	–	–	–	0.02
Decay correction				0.02
$N_{D,\mathrm{w,lab}}$	0.05	0.19	0.18	0.41

	100 u_{iA}	100 u_{iB}
$N_{D,\mathrm{w,ARPANSA}}/N_{D,\mathrm{w,BIPM}}$ (1)	0.19	0.45
Ion recombination	–	0.02
Radial non-uniformity	–	0.03
Different chambers	0.12	–
$R_{D,\mathrm{w}}$	$u_c = 0.0051$	

(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

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 $D_{\mathrm{w,BIPM}}$, 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 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.

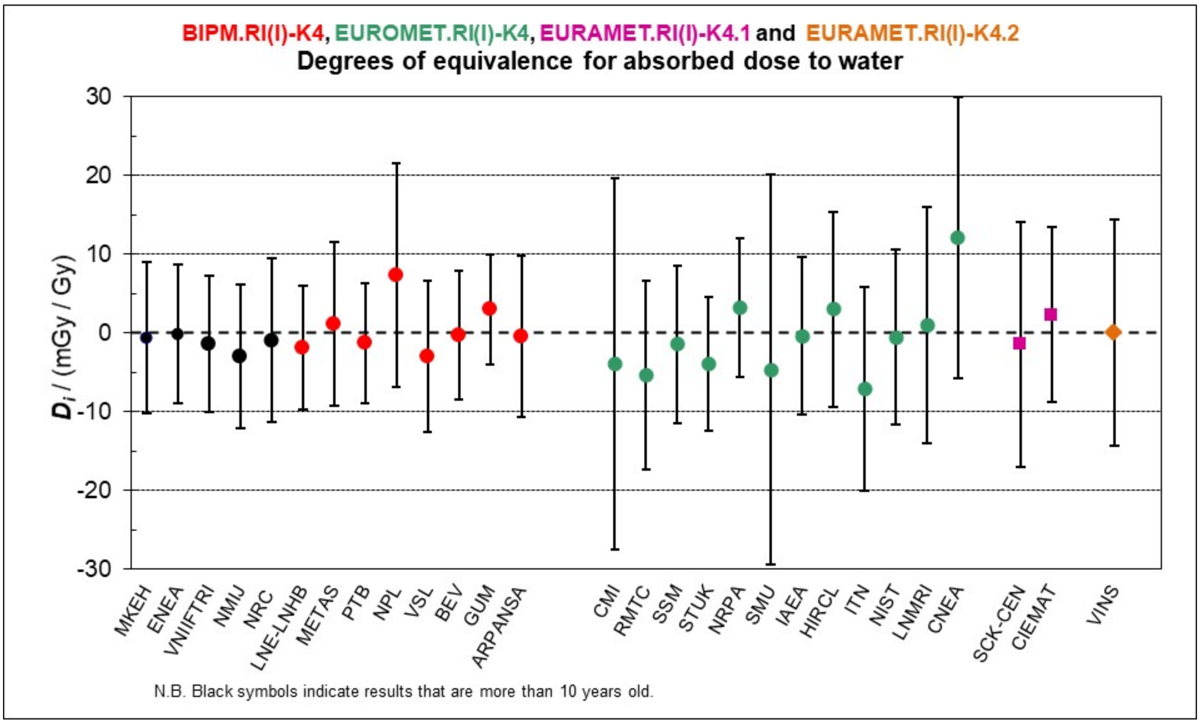
Note that the data presented in Table 8, while correct at the time of publication of the present report, become out-of-date as NMIs make new comparisons. The formal results under the CIPM MRA are those available in the key comparison database.

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

Lab *i*	D_i / (mGy/Gy)	U_i / (mGy/Gy)
MKEH	-0.7	9.6
ENEA	-0.1	8.8
VNIIFTRI	-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
LNMRI	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 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 ARPANSA and the BIPM was made indirectly in 2010. The comparison result was 0.9973 (53). Since the last comparison, the ARPANSA adopted the changes recommended by the ICRU 90 and a new absorbed dose conversion factor graphite to water, resulting in a reduction of 2.8 parts in 10^3 in the absorbed dose to water determination. Most of this reduction is due to the new absorbed dose conversion factor which has been calculated using a more recent version of the Monte Carlo EGSnrc code and an improved model (the change due to the ICRU 90 adoption is only 7 parts in 10^4). 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. Considering the implementation of the changes adopted by each laboratory, the 2010 comparison result becomes 0.9955 (51).

For the present comparison, made also indirectly using transfer instruments, the ARPANSA 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 0.9995 (51), in agreement within the uncertainties with the previous comparison result. The ARPANSA 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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