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Comparison of the standards for absorbed dose to water of the BEV, Austria and the BIPM for ^{60}Co gamma radiation

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Abstract
A comparison of the standards for absorbed dose to water of the Bundesamt für Eich- und Vermessungswesen (BEV), Austria, and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in March 2009 under the auspices of the key comparison BIPM.RI(I)-K4. The comparison result, based on the calibration coefficients measured for two transfer standards and expressed as a ratio of the BEV and the BIPM standards for absorbed dose to water, is 0.9996 (37). This result replaces the 1994 BEV value of 0.9990 (43) in this key comparison. The degrees of equivalence between the BEV and the other participants in this comparison have been calculated and the results are given in the form of a matrix for the ten national metrology institutes (NMIs) that have published results in this ongoing comparison for absorbed dose to water. A graphical presentation is also given.

1. Introduction

An indirect comparison of the standards for absorbed dose to water of the Bundesamt für Eich- und Vermessungswesen (BEV), Austria and of the Bureau International des Poids et Mesures (BIPM) has been carried out in ^{60}Co radiation. The measurements at the BIPM took place in March 2009. This absorbed dose to water comparison replaces the indirect comparison made between the two laboratories in 1994 [1] that was previously registered in the BIPM.RI(I)-K4 key comparison [2].

[*] Co-worker in the framework of a Ph.D. thesis which was supported by the BEV.

The absorbed dose to water is determined at the BEV using a graphite calorimeter and a graphite cavity ionization chamber type CC01 calibrated directly against the calorimeter [3], [4]. The BIPM primary standard is a parallel-plate graphite cavity ionization chamber [5].

The comparison was undertaken using two ionization chambers of the BEV as transfer standards. The result of the comparison is given in terms of the mean ratio of the calibration coefficients of the transfer chambers determined at the two laboratories under the same reference conditions.

The comparison result has been approved by the Consultative Committee for Ionizing Radiation (CCRI) and the degrees of equivalence between the BEV and the other participants in this ongoing comparison for absorbed dose to water have been evaluated and are presented in the form of a matrix in Section 5. A graphical presentation is also given.

2. Determination of the absorbed dose to water

At the BIPM, the absorbed dose rate to water is determined from

$$\dot{D}_{\mathrm{w,\,BIPM}} = (I/m)(W/e)\bar{s}_{\mathrm{c,a}}\Pi k_i\,, \qquad (1)$$

where

I	is the ionization current measured by the standard,
m	is the mass of air in the ionization chamber,
W	is the mean energy expended in dry air per ion pair formed,
e	is the electronic charge,
$\bar{s}_{\mathrm{c,a}}$	is the ratio of the mean mass stopping powers of graphite and air, and
$\Pi\, k_i$	is the product of the correction factors to be applied to the standard.

The values of the physical constants and the correction factors entering in (1) are given in [5] together with their uncertainties, the combined relative standard uncertainty being 2.9×10^{-3}. The uncertainty budget is reproduced in Table 1.

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

Symbol	Parameter / unit	Value	Relative standard uncertainty [(1)] s_i	u_i
Physical constants				
ρ_a	dry air density (0°C, 101.325 kPa) / kg m^{-3}	1.2930	–	0.01
$(\mu_{en}/\rho)_{w,c}$	ratio of mass energy-absorption coefficients	1.1125 [(2)]	0.01 [(2)]	0.14 [(2)]
$s_{c,a}$	ratio of mass stopping powers	1.0030	}	0.11 [(3)]
W/e	mean energy per charge / J C^{-1}	33.97		
Correction factors				
k_p	fluence perturbation	1.1107	0.05	0.17
k_{ps}	polythene envelope of the chamber	0.9994	0.01	0.01
k_{pf}	front face of the phantom	0.9996	–	0.01
k_{rn}	radial non-uniformity [(4)]	1.0056	0.01	0.03
k_s	saturation [(4)]	1.0017	0.01	0.01
k_h	humidity	0.9970	–	0.03
Measurement of I/υ				
υ	effective volume / cm^3	6.8810 [(5)]	0.19	0.03
I	ionization current (T, P, air compressibility)	–	–	0.02
	short-term reproducibility (including positioning and current measurement) [(6)]		0.02	–
Combined uncertainty of the BIPM determination of absorbed dose to water rate				
quadratic summation			0.20	0.21
combined relative standard uncertainty			0.29	

[(1)] expressed as one standard deviation.
s_i represents the relative uncertainty estimated by statistical methods, type A
u_i represents the relative uncertainty estimated by other methods, type B.
[(2)] included in the uncertainties for k_p.
[(3)] uncertainty value for the product $s_{c,a}\ W/e$.
[(4)] values for the CISBio beam adopted in November 2007.
[(5)] standard CH4-1.
[(6)] over a period of 3 months. The long-term reproducibility over a period of 15 years, u_R is 0.0006.

At the BEV, the absorbed dose rate to water is determined by means of a graphite calorimeter. The design and operation of the calorimeter is described in [3], [4] and some pertinent details are given in the following paragraphs. A summary of the components of uncertainty is indicated in Table 2, giving a combined relative standard uncertainty of 3.7×10^{-3}.

The BEV graphite calorimeter is a Domen-type calorimeter [6], intended for quasi-adiabatic and quasi-isothermal [3] mode of operation. The calibration of the instrument can be made quasi-adiabatically or heat-loss compensated. The graphite calorimeter was designed and implemented by Witzani et al. at the Austrian Research Center, Seibersdorf, and is in operation since 1983. The realization of the unit absorbed dose to water is based upon absorbed dose to graphite measurements according to (2) and (3):

$$D_{\mathrm{g,adiabat.}} = \frac{1}{m_c} \cdot \left(\frac{\Delta R}{R} + k_2 \cdot \Delta U \right) \cdot k_1 \cdot k_{\mathrm{gap}} \cdot k_{\mathrm{gc}} \cdot k_{T1/2} \cdot k_{\mathrm{stab}}, \qquad (2)$$

$$D_{\mathrm{g,isotherm}} = \frac{1}{m_{\mathrm{c}}} \cdot \left[\left(\frac{\Delta R}{R} + k_2 \cdot \Delta U \right) \cdot k_1 + P_0 \cdot t \right] \cdot k_{\mathrm{gap}} \cdot k_{\mathrm{gc}} \cdot k_{T1/2} \cdot k_{\mathrm{stab}} , \tag{3}$$

where

D_{g}	is the absorbed dose to graphite,
m_{c}	is the mass of the core,
$\Delta R/R$	is the change in resistance,
k_2	is the chart calibration factor,
ΔU	is the difference in voltage,
k_1	is the quasi-adiabatic calibration factor,
k_{gap}	is the correction for the effect of the vacuum gaps,
k_{gc}	is the correction for the effective measurement depth in graphite,
$k_{\mathrm{T1/2}}$	is the normalization factor for the reference date and time,
k_{stab}	is the correction for the long term stability of the dose rate and
P_0	is the normalization factor for the reference date and time.

The resulting absorbed dose rate to graphite $\dot{D}_{\mathrm{g}}$ is the quotient of the absorbed dose to graphite D_{g} and the irradiation time t.

The conversion from absorbed dose rate to graphite to absorbed dose rate to water is made using two methods based on the photon fluence scaling theorem.
The conversion by the calculation method uses the inverse square law, according to (4) and the experimental method uses an ionization chamber as a transfer instrument, expressed by (5):

$$\dot{D}_{\mathrm{w}} = \dot{D}_{\mathrm{g}} \cdot \left(\frac{R_{\mathrm{g}}}{R_{\mathrm{w}}} \right)^2 \cdot \left(\frac{\overline{\mu_{\mathrm{en}}}}{\rho} \right)_{\mathrm{w,g}} \cdot \beta_{\mathrm{w,g}} \cdot k_{\Delta\mathrm{air}} \cdot k_{\mathrm{gs}} \cdot k_{\mathrm{depth}} \cdot k_{\mathrm{front}} , \tag{4}$$

$$\dot{D}_{\mathrm{w}} = \dot{D}_{\mathrm{g}} \cdot \frac{I_{\mathrm{w}}}{I_{\mathrm{g}}} \cdot \left(\frac{\overline{\mu_{\mathrm{en}}}}{\rho} \right)_{\mathrm{w,g}} \cdot \frac{1}{k_{\mathrm{gi}}} \beta_{\mathrm{w,g}} \cdot p_{\mathrm{w,g}} \cdot k_{ps} \cdot k_{\mathrm{depth}} \cdot k_{\mathrm{front}} \tag{5}$$

where

$\dot{D}_{\mathrm{w}}$	is the absorbed dose rate to water,
$R_{\mathrm{g}}/R_{\mathrm{w}}$	is the ratio of the source to reference point distances in graphite and water,
$(\overline{\mu_{en}}/\rho)_{w,g}$	is the ratio of the average mass energy-absorption coefficients,
$\beta_{\mathrm{w,g}}$	is the ratio of the absorbed dose to collision kerma of water and graphite,
$k_{\Delta\mathrm{air}}$	is the correction for the difference in air attenuation,
k_{gs}	is the correction for the deviation of the size and shape of the graphite phantom from the scaling requirements,
k_{depth}	considers the depths in graphite and in water and respectively the chamber position in graphite and in water in case of ionization chamber measurements,
k_{front}	is the correction for the front wall of the water phantom,
I_w	is the ionization current in water (*T, P*, air compressibility),
I_{g}	is the ionization current in graphite (*T, P*, air compressibility)
k_{gi}	is the correction for the effective measurement depth in graphite,
$p_{\mathrm{w,g}}$	is the replacement factor, and
k_{ps}	is the correction for the envelope of the CC01-105 chamber.

The correction factors k_{gap}, $k_{\Delta air}$ and k_{gs} were determined by Monte Carlo simulations with the PENELOPE-2006 code, see [4]. The simulations make use of the Monte Carlo calculated energy spectrum of the BEV teletherapy unit.

For the determination of absorbed dose rate to water both methods for the measurement of absorbed dose rate to graphite are used. The conversion is also made by both methods and the mean value of the four results is used to assign the BEV absorbed dose rate to water reference value.

Table 2. Physical constants and correction factors entering in the BEV determination of the absorbed dose rate to water at 5 g cm^{-2}, and estimated relative standard uncertainties

Source of uncertainty		Value	Rrelative standard uncertainty 100 s_i	 100 u_j
Determination of $(\dot{D}_g)_{BEV}$				
	calorimetric measurement of absorbed dose rate in graphite at 5.56 g cm^{-2} (see [4])	–	–	0.25
	irradiation time	–		0.03
	interpolation on BEV depth dose curve: calorimeter	0.9886	–	0.03
Conversion to absorbed dose rate to water by calculation (method 1)				
	distance from the source to the phantom	–	–	0.20
	depths in graphite and in water	–	–	0.10
	front wall of water phantom	–	–	0.05
	air attenuation correction	0.9971		0.03
	scaling correction	0.9998		0.02
Conversion to absorbed dose rate to water with ionization chamber CC1(method 2)				
	measurement of ionization current ratio	–	0.05	0.05
	chamber position in graphite and in water	–	–	0.07
	envelope of the chamber	1.006	–	0.05
	front wall of the water phantom	–	–	0.05
	replacement factor	1.0150	–	0.20
	interpolation on BEV depth dose curve: CC01	0.9913	–	0.03
Physical constants				
$(\mu_{en}/\rho)_{w,g}$	ratio of mass energy-absorption coefficients	1.1123	–	0.10
$\beta_{w,g}$	ratio of the absorbed dose to collision kerma of water and graphite	1.0003	–	0.10
Uncertainty in $(\dot{D}_w)_{BEV}$ *(method 1 or method 2)*				
	quadratic summation		0.05	0.37
	combined relative standard uncertainty in $D_{w,BEV}$		0.37	

Reference conditions

Absorbed dose to water is determined at the BIPM and the BEV under reference conditions defined by the CCRI, previously known as the CCEMRI [7]:

- the distance from the source to the reference plane (centre of the detector) is 1 m;
- the field 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}.

For the BEV graphite calorimeter measurements and the ionization chamber measurements in the graphite phantom, the required source to reference point distances, measuring depths and field size are obtained by application of the photon fluence scaling theorem [8].

Reference values

The $\dot{D}_{\mathrm{w,BIPM}}$ value is taken from the mean of the four measurements made around the period of the comparison. The value is given at the reference date of 2009-01-01, 0 h UTC as is the ionization current of the transfer chambers. The half-life of ^{60}Co was taken as 1925.21 days (u = 0.29 days) [9].

The value of $\dot{D}_{\mathrm{w,BEV}}$ used for the comparison is the mean of several measurements made over a longer period in 2007 and 2008 using both methods to measure D_{g} and both conversion methods. The BEV reference value of 6.064 mGy/s [4] is normalized to the laboratory reference date 2004-12-31 using the same half-life [9].

3. The transfer chambers and their calibration

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

$$N_{D,\mathrm{w,\,lab}} = \dot{D}_{\mathrm{w,\,lab}} \big/ I_{\mathrm{lab}} \;, \qquad (6)$$

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

The ionization chambers NE 2571 serial number 1050 and NE 2561 serial number 276, both belonging to the BEV, were the transfer chambers used for this comparison. Their main characteristics are listed in Table 3. These chambers were calibrated over several months at the BEV before and after the measurements at the BIPM.

The experimental method for calibrations at the BEV is described in [10] and that for the BIPM in [11] and the essential details are reproduced here.

Table 3. Characteristics of the BEV transfer chambers

Characteristic/Nominal values		NE 2571-1050	NE 2561-276
Dimensions	Inner diameter	6.3 mm	7.5 mm
	Wall thickness	0.35 mm	0.5 mm
	Cavity length	24.0 mm	9.22 mm
	Tip to reference point	13 mm	5 mm
Electrode	Length	21.0 mm	6.4 mm
	Diameter	1.0 mm	1.7 mm (hollow)
Volume	Air cavity	0.60 cm^3	0.30 cm^3
Wall	Material	graphite	graphite
	Density	1.7 g cm^{-3}	1.7 g cm^{-3}
Voltage applied to outer electrode	Negative polarity	200 V	200 V

Positioning

At each laboratory the chambers were positioned with the stem perpendicular to the beam direction and with the same orientation (text or line on the stem of the chambers facing the source and marking on the sleeves facing away the source).

Applied voltage and polarity

A collecting voltage as indicated in Table 3 was applied to the outer electrode of each chamber at least 30 min before measurements were made. No polarity correction was applied as both laboratories apply the same polarity.

Volume recombination

Volume recombination is negligible at a dose rate of less than 15 mGy s^{-1} for these chambers at these polarizing voltages, and the initial recombination loss will be the same in the two laboratories. Consequently, no correction for recombination was applied.

Charge and leakage measurements

The charge Q collected by each transfer chamber was measured using a Keithley electrometer, model 642 at the BIPM. At the BEV, the current was also measured using a Keithley electrometer. The chambers were pre-irradiated for at least 20 min (≈ 10 Gy) at the BEV and for at least 30 min (≈ 10 Gy) at the BIPM before any measurements were made.
The ionization current measured from each transfer chamber was corrected for the leakage current at the BIPM as well as at the BEV. This correction was less than 2×10^{-4} in relative value.

Ambient conditions

During a series of measurements, the water temperature is measured for each current measurement and was stable to better than 0.01 °C at the BIPM and 0.05 °C at the BEV. The ionization current is normalized to 293.15 K and 101.325 kPa at both laboratories.

Relative humidity is controlled at (50 ± 5) % at both the BIPM and (50 ± 10) % at the BEV. Consequently, no correction for humidity is applied to the ionization current measured.

Radial non-uniformity correction

At the BEV, no correction is applied to the ionization current for the radial non-uniformity of the beam over the section of the transfer chambers as the beam non-uniformity is better than 0.1 %. At the BIPM, the corrections applied to the ionization current would only be 1.0002 for the NE 2561 and 1.0008 for the NE 2571, each with an uncertainty of 2×10^{-4}. Consequently, no non-uniformity correction is made.

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. At the BEV, the reference depth is 5 g cm^{-2}. This reference depth is the same for both the standard and the transfer chambers. Individual waterproof sleeves of PMMA were supplied by the BEV for each NE chamber. The same sleeves were used at both laboratories and, consequently, no correction for the influence of each sleeve was necessary at either laboratory.

Uncertainties

Contributions to the relative standard uncertainty of $N_{D,\mathrm{w,lab}}$ are listed in Table 4. The two laboratories determine absorbed dose by methods that are quite different. Nevertheless, some correlation exists in the values used for $(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,c}}$ and $\beta_{\mathrm{w,c}}$. In accordance with the analysis used for the existing data in the BIPM.RI(I)-K4 comparison [2], these are taken to have correlation coefficients $f_k = 0.95$ and $f_k = 0.7$, respectively. Consequently, the combined uncertainty of the result of the comparison is obtained by summing in quadrature the uncertainties of $\dot{D}_{\mathrm{w,BIPM}}$ and $\dot{D}_{\mathrm{w,BEV}}$, taking correlation into account and including the contributions arising from the use of transfer chambers. These latter terms include the uncertainties of the ionization currents measured, the distance to the reference plane and the depth positioning.

The relative standard uncertainty of the mean ionization current measured with each transfer chamber over the short period of calibration was estimated to be 10^{-4} (two calibrations with repositioning, in series of 30 measurements for each chamber) at the BIPM. At the BEV the calibration of each chamber was repeated twice with repositioning before and after the measurements at the BIPM. The relative standard uncertainty of the mean normalized ionization current measured at the BEV with a given transfer chamber over the several months required for this comparison was typically better than 2×10^{-4}.

Table 4. Estimated relative standard uncertainties of the calibration coefficient, $N_{D,\mathrm{w,\,lab}}$, of the transfer chambers and of the comparison result, $R_{D,\mathrm{w}}$

	BEV		BIPM	
Relative standard uncertainty of	$100\,s_i$	$100\,u_i$	$100\,s_i$	$100\,u_i$
Absorbed dose rate to water (tables 1 and 2), $u_{D\mathrm{w}}$	0.05	0.37	0.20	0.21
Ionization current of the transfer chambers	0.02	0.05	0.01	0.02
Distance	–	–	0.02	–
Depth in water	–	0.02	0.02	0.06
Normalization T, P	–	0.01	–	–
Relative standard uncertainties of $N_{D,\mathrm{w,\,lab}}$				
quadratic summation	0.05	0.37	0.20	0.22
combined uncertainty	0.38		0.30	
Relative standard uncertainties of $R_{D,\mathrm{w}}$	$100\,s_i$		$100\,u_i$	
quadratic summation*	0.21		0.39	
combined uncertainty, u_R	**0.44**			

* taking correlation into account

4. Results of the comparison

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

$$R_{D,\mathrm{w}} = N_{D,\mathrm{w,\,BEV}} / N_{D,\mathrm{w,\,BIPM}}\,, \tag{7}$$

in which the average value of measurements made at the BEV prior to those made at the BIPM (pre-BIPM) and those made afterwards (post-BIPM) for each chamber is compared with the mean of the measurements made at the BIPM. Table 5 lists the relevant values of $N_{D,\mathrm{w}}$ for each chamber at the stated reference conditions.

Table 5. Results of the comparison

Transfer Chamber	$N_{D,\mathrm{w,BEV}}$* / Gy μC^{-1} pre-BIPM	$N_{D,\mathrm{w,\,BIPM}}$ / Gy μC^{-1}	$N_{D,\mathrm{w,\,BEV}}$* / Gy μC^{-1} post-BIPM	$N_{D,\mathrm{w,\,BEV}}$ / Gy μC^{-1} overall mean	$R_{D,\mathrm{w}}$	$u_{R,\mathrm{NMI}}$
NE 2561-276	103.656	103.568	103.594	103.625	1.0005	0.0044
NE 2571-1050	45.376	45.433	45.362	45.369	0.9986	0.0044
				Mean values	**0.9996**	**0.0044**

* Correction for ion recombination normally applied at the BEV was not included here, as the correction is the same at both laboratories.

The comparison result is taken as the unweighted mean value for both transfer chambers, $R_{D,\mathrm{w}} = 0.9996$ with a combined standard uncertainty for the comparison of 0.0044, demonstrating the agreement between the two absorbed dose to water standards.

5. Comparison with other National Metrology Institutes

Comparison of a given NMI with the key comparison reference value

Comparisons of absorbed dose to water at the BIPM have been undertaken since 1988. A summary report of the most recent comparisons, including the previous comparison with the BEV, is given in [2]. Subsequent comparisons with the LNE-LNHB, PTB, VSL, ENEA, VNIIFTRI and the NRC have been published [12], [13], [14], [15], [16] and [17]and the results are available in the key comparison database (KCDB) of the CIPM MRA [17].

The degree of equivalence of a given measurement standard, D_i, is the degree to which this standard is consistent with the key comparison reference value (KCRV) [17]. The degree of equivalence is expressed quantitatively in terms of the deviation of the comparison result from the key comparison reference value and the expanded uncertainty of this deviation ($k = 2$).

Following a decision of the CCRI, the BIPM determination of the dosimetric quantity is taken as the key comparison reference value (KCRV), for each of the CCRI radiation qualities. It follows that for each NMI i having a BIPM comparison result $R_{D,\mathrm{w},i}$ (denoted x_i in the KCDB) with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is given by a pair of terms:

the relative difference $D_i = (D_{\mathrm{w}i} - D_{\mathrm{w,BIPM}i})/\, D_{\mathrm{w,BIPM}i})) = R_{D,\mathrm{w},i} - 1$ (8)

and the expanded uncertainty ($k = 2$) of this difference,

$$U_i = 2\, u_i. \tag{9}$$

The results for D_i and U_i, are usually expressed in mGy/Gy.

Table 6 gives the values for the NMI absorbed dose uncertainty $u_{D\mathrm{w},i}$, the D_i and U_i for each NMI, i taken from [2], [12], [13], [14], [15], [16] and [17] and this report, using (8) and (9), and forms the basis of the entries in the KCDB of the CIPM MRA. These data are presented graphically in Figure 1 where the black squares indicate results that date prior to 1999; note that the NPL has undertaken a comparison more recently and the result is awaiting publication. The results of a published SIM comparison and a EUROMET comparison are also presented [19] in the graph. Note that the data presented in the tables and graph, while correct at the time of publication of the present report, will become out-of-date as NMIs make new comparisons. The formal results under the CIPM MRA are those given in the KCDB where the NMI acronyms are also given.

Table 6. Degrees of equivalence of each NMI's measurement standard

NMI, *i*	**Year**	$u_{D\mathrm{w},i} \times 10^{-3}$	$D_i \times 10^{-3}$	$U_i \times 10^{-3}$
ARPANSA	1997	2.0	2.4	6.0
LSDG[1]	1999	6.6	-5.2	14.8
METAS	2000	4.1	-0.1	10.8
MKEH[2]	2001	4.8	-1.7	9.6
LNE-LNHB[3]	2003	4.6	-3.0	10.6
PTB	2005	2.0	-3.9	7.4
VSL[4]	2005	3.9	-7.4	9.8
ENEA	2009	3.6	-0.1	8.8
VNIIFTRI	2009	4.0	-2.4	8.6
NRC	2009	4.1	-2.0	10.4
BEV	1990	7.6	-6.6	16.2
BEV	1994	3.7	-1.0	8.6
BEV	**2009**	**3.7**	**-0.4**	**8.8**

Comparison of any two NMIs with each other

The degree of equivalence, D_{ij}, between any pair of NMIs, i and j, is expressed as two terms, the difference

$$D_{ij} = D_i - D_j = R_i - R_j \tag{10}$$

and the expanded uncertainty (k = 2) of this difference, $U_{ij} = 2\,u_{ij}$, where

$$u_{ij}^{\ 2} = u_{c,i}^{\ 2} + u_{c,j}^{\ 2} - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_i^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_j^2 \tag{11}$$

of which the final two terms take into account the correlations between the primary standard methods.

The matrix of degrees of equivalence takes into account the correlations between each pair of NMIs as indicated in (11). The common components of the uncertainty budgets for the BEV and the other NMIs with graphite calorimeters are given in Table 7. In this table, $u_{D\mathrm{w,NMI}}$ is the combined standard uncertainty of the NMI primary standard (all components being included), u_{transfer} is the combined standard uncertainty associated with the transfer standard and $u_{\mathrm{c,NMI}}$ is the combined standard uncertainty for an absorbed dose to water calibration by the NMI; all uncertainties being in relative value.

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[1] This Belgium laboratory is not a designated institute
[2] Previously known as the OMH
[3] Previously known as the BNM-LNHB
[4] Previously known as the NMi

Table 7. Correlated components in the uncertainty budgets for absorbed dose to water from graphite calorimetry primary standards, standard uncertainties per 10^3

NMI	k_{gap}	$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,c}}$	$(\beta)_{\mathrm{w,c}}$	$u_{D\mathrm{w,NMI}}$	u_{transfer}	$u_{\mathrm{c,NMI}}$	$\sqrt{\sum\left(f_k u_{k,\mathrm{corr}}\right)^2_{\mathrm{NMI}}}$
ARPANSA	0.4	1.4	0.1	2.0	0.6	2.1	1.3
VSL	0.7	3.0	0.6	3.9	0.9	4.1	2.9
VNIIFTRI	1.0	2.9	0.5	4.0	1.8	4.5	2.8
MKEH	0.8	3.0	0.6	4.8	1.1	5.0	2.9
LNE-LNHB	1.5	1.5	0.5	4.6	1.1	4.8	1.6
ENEA	0.6	1.4	1.0	3.6	1.0	3.8	1.5
BEV	1.5	1.0	1.0	3.7	0.6	3.8	1.4
$f_{k,\mathrm{BIPM}}$	–	0.95	0.7				
$f_{k,\mathrm{NMI}}$	0.5	0.95	0.7				

The matrix of degrees of equivalence takes into account the correlations between each pair of NMIs and is given in Table 8 in the form that appears in the KCDB.

Figure 1 Graph of the degrees of equivalence with the KCRV

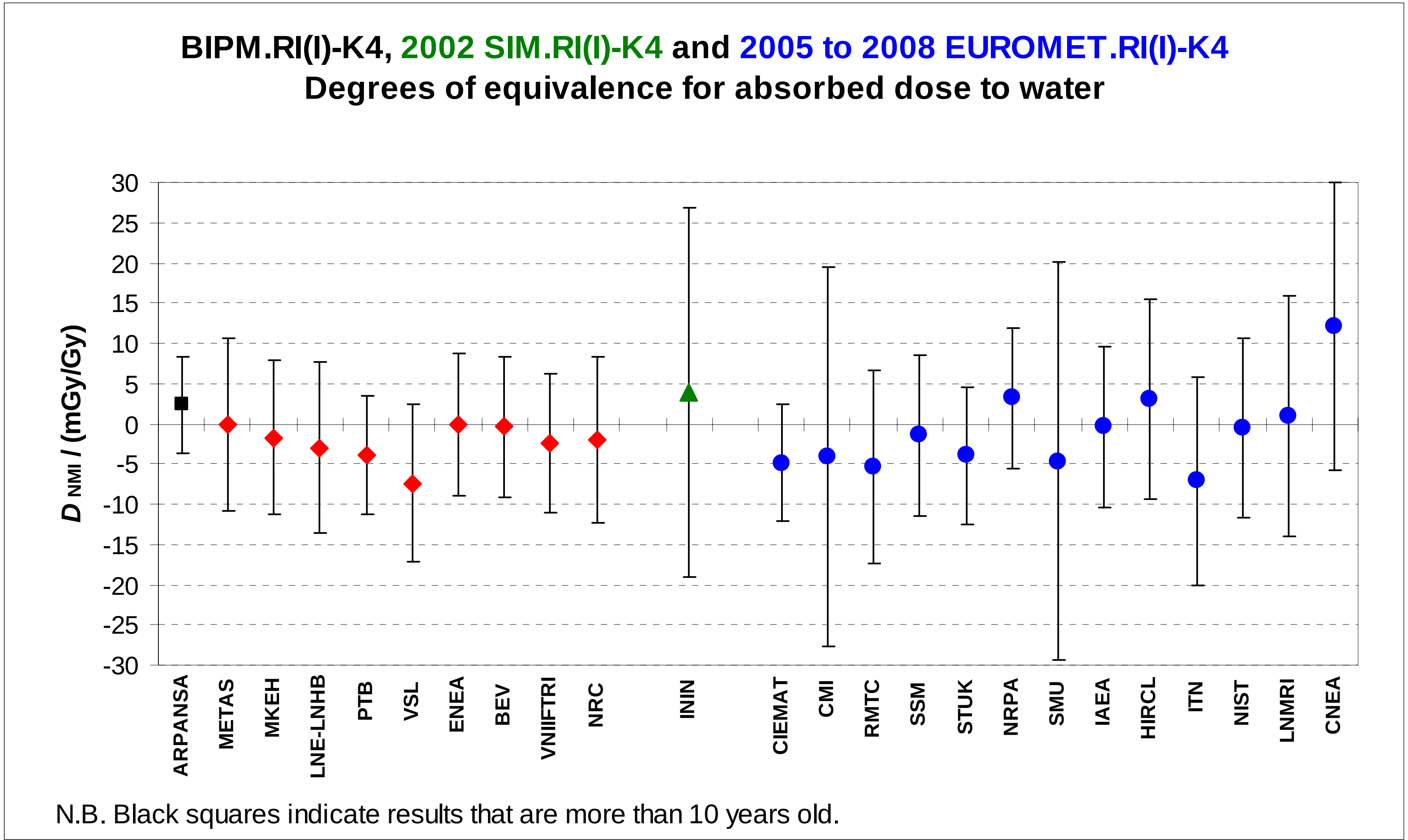

Table 8. Evaluation of degrees of equivalence as presented in the KCDB

The key comparison reference value is the BIPM evaluation of absorbed dose to water.

The degree of equivalence of each laboratory *i* with respect to the reference value is given by a pair of terms both expressed in mGy/Gy:

$\boldsymbol{D_i}$ and $\boldsymbol{U_i}$, its expanded uncertainty (k = 2), with $\boldsymbol{U_i = 2u_i}$.

The degree of equivalence between two laboratories is given by a pair of terms both expressed in mGy/Gy:

$\boldsymbol{D_{ij} = D_i - D_j}$ and $\boldsymbol{U_{ij}}$, its expanded uncertainty (k = 2). In evaluating $\boldsymbol{U_{ij} = 2\ u_{ij}}$ for the Matrix of equivalence account is taken of correlations between $\boldsymbol{u_i}$ and $\boldsymbol{u_j}$.

- **Linking SIM.RI(I)-K4 or EUROMET.RI(I)-K4 to BIPM.RI(I)-K4**

The value $\boldsymbol{x_i}$ is the comparison result for laboratory *i* participant in SIM.RI(I)-K4 having been normalized to the value of the NRC as the linking laboratory (see SIM.RI(I)-K4 Final Report [19]), or in the EUROMET.RI(I)-K4 having been linked as described in the Final Report [20].

The degree of equivalence of each laboratory *i* participant in SIM.RI(I)-K4 or EUROMET.RI(I)-K4 with respect to the reference value is given by a pair of terms both expressed in mGy/Gy:

$\boldsymbol{D_i}$ and $\boldsymbol{U_i}$, its expanded uncertainty (k = 2).

See the relevant Final Report for the computation of $\boldsymbol{D_i}$ and the approximation used for $\boldsymbol{U_i}$ in the matrix of equivalence.

The degree of equivalence between two laboratories *i* and *j*, one participant in BIPM.RI(I)-K4 and one in the RMO comparison, or both participant in an RMO comparison, is given by a pair of terms both expressed in mGy/Gy:

$\boldsymbol{D_{ij} = D_i - D_j}$ and $\boldsymbol{U_{ij}}$, its expanded uncertainty (k = 2).

The approximation for $\boldsymbol{U_{ij}}$ is given in the relevant Final Report [19, 20].

See Table overleaf.

Table 8 continued. Evaluation of degrees of equivalence as presented in the KCDB

Lab *i* ⇓	D_i / (mGy/Gy)	U_i	Lab *j* BEV D_{ij} / (mGy/Gy)	U_{ij}
ARPANSA	2.4	6.0	2.8	6.5
METAS	-0.1	10.8	0.3	11.7
MKEH	-1.7	9.6	-1.3	9.9
LNE-LNHB	-3.0	10.6	-2.6	10.4
PTB	-3.9	7.4	-3.5	8.6
VSL	-7.4	9.8	-7.0	11.0
ENEA	-0.1	8.8	0.3	8.9
BEV	-0.4	8.8	0.0	0.0
VNIIFTRI	-2.4	8.6	-2.0	8.8
NRC	-2.0	10.4	-1.6	11.2
ININ	3.9	23.0	4.3	24.9
CIEMAT	-4.9	7.3	-4.5	10.5
CMI	-4.0	23.6	-3.6	24.8
RMTC	-5.3	12.0	-4.9	14.1
SSM	-1.4	10.0	-1.0	12.5
STUK	-3.9	8.5	-3.5	11.4
NRPA	3.2	8.8	3.6	11.5
SMU	-4.7	24.7	-4.3	25.1
IAEA	-0.4	10.0	0.0	12.5
HIRCL	3.0	12.4	3.4	14.5
ITN	-7.1	13.0	-6.7	15.0
NIST	-0.6	11.1	-0.2	12.0
LNMRI	1.0	15.0	1.4	16.8
CNEA	12.0	17.9	12.4	17.8

See the KCDB for the NMI acronyms

6. Conclusions

A key comparison has been carried out between the BEV (Austria) and the BIPM of standards for absorbed dose to water in ^{60}Co gamma rays, using two ionization chambers as transfer standards. The comparison result, expressed as a ratio of the calibration coefficients measured by the BEV against their primary standard for absorbed dose to water using a graphite calorimeter to that of the BIPM is 0.9996 (44), which is consistent with the results of the previous comparison in 1994.

When compared with the results of the other national metrology institutes that have carried out comparisons in terms of absorbed dose to water at the BIPM, the BEV standard for absorbed dose to water is in satisfactory agreement.

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