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Comparison of the standards for absorbed dose to water of the PTB, Germany and the BIPM for ^{60}Co γ rays

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Abstract

A comparison of the standards for absorbed dose to water of the Physikalisch-Technische Bundesanstalt (PTB), Germany and of the Bureau International des Poids et Mesures (BIPM) has been made in ^{60}Co gamma radiation under the auspices of the key comparison BIPM.RI(I)-K4. The comparison result, based on the calibration coefficients for three transfer standards and expressed as a ratio of the PTB and the BIPM standards for absorbed dose to water, is 0.9961 (0.0037). This result replaces the earlier PTB value in this key comparison. The degrees of equivalence between the PTB and the other participants in this comparison have been calculated and the results are given in the form of a matrix for the twelve national metrology institutes (NMIs) that have taken part in the ongoing comparison for absorbed dose to water. A graphical presentation is also given.

1. Introduction

An indirect comparison of the standards of absorbed dose to water of the Physikalisch-Technische Bundesanstalt (PTB) 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 October 2005. This absorbed dose to water comparison replaces the indirect comparison made between the two laboratories in 1990 [1] that was previously registered in the BIPM.RI(I)-K4 key comparison [2].

The primary standard of the PTB for absorbed dose to water is a water calorimeter based on the design by Domen [3] and described in full in [4]. The BIPM primary standard is a parallel-plate graphite cavity ionization chamber [5].

The comparison was undertaken using three ionization chambers of the PTB 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 PTB 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.

At the PTB, the absorbed dose to water D_{w} is determined from

$$D_{\mathrm{w,\,PTB}} = \Delta T_{\mathrm{w}}\, c_{\mathrm{w}}\, \Pi k_i\, (1 - h)^{-1}\ , \qquad (2)$$

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,

Πk_i is the product of the correction factors to be applied to the standard, and

$(1-h)^{-1}$ is a correction factor for the heat defect of water.

The design and operation of the calorimeter is described in [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 2.0×10^{-3}.

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

Quantity	BIPM value	BIPM relative standard uncertainty[1]	
		100 s_i	100 u_i
Dry air density [2] / (kg m^{-3})	1.2930	–	0.01
W/e / (J C^{-1})	33.97	–	0.11[3]
$\bar{s}_{\mathrm{c,a}}$	1.0030	–	
k_{cav} (air cavity)	0.9900	0.03	0.04
$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w,c}}$	1.1125	0.01	0.14
$\Psi_{\mathrm{w,c}}$ (photon fluence ratio)	1.0065	0.04	0.06
$(1+\varepsilon)_{\mathrm{w,c}}$ (dose to kerma ratio)	1.0015	–	0.06
k_{ps} (polyethylene envelope)	0.9994	0.01	0.01
k_{pf} (phantom window)	0.9996	–	0.01
k_{rn} (radial non-uniformity)	1.0051	0.01	0.03
k_{s} (recombination losses)	1.0015	0.01	0.01
k_{h} (humidity)	0.9970	–	0.03
Volume of standard CH4-1 / cm^3	6.8810	0.19	0.03
I (ionization current)	–	0.01	0.02
Quadratic summation		0.20	0.21
Combined relative standard uncertainty of $D_{\mathrm{w,BIPM}}$		0.29	

(1) In each Table, s_i represents the Type A relative standard uncertainty $u_{\mathrm{A}}(x_i)/\bar{x}_i$, estimated by statistical means; u_i represents the Type B relative standard uncertainty $u_{\mathrm{B}}(x_i)/\bar{x}_i$ estimated by other means.

(2) At 0 °C and 101.325 kPa.

(3) Combined uncertainty for the product of $(W/e)\bar{s}_{\mathrm{c,a}}$.

The PTB water calorimeter consists of a water-filled cubic phantom of side 30 cm, made of 1 cm thick PMMA[1]. The entrance window for the horizontal beam is 3 mm thick. To avoid convection inside the water phantom, the calorimeter is operated at 4 °C. The phantom is surrounded by a thick layer of polystyrene (8 cm) and is placed inside a container of side length about 100 cm in which active temperature stabilization is realized.

The radiation-induced temperature rise at the point of measurement inside the water is measured using two thermistors of 0.25 mm diameter. Each thermistor is fused in glass at the

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[1] PMMA is the acronym for polymethylmethacrylate

cone-shaped tip of a thin glass pipette of 110 mm length and 0.5 mm diameter. The pipettes are mounted inside a thin-walled plane-parallel glass cylinder of outside diameter 95 mm, perpendicular to the cylinder and opposite to each other, such that the opposing tips are about 8 mm apart. This detector is filled with high-purity water saturated either with hydrogen or nitrogen gas to control the heat defect. During irradiation, the resistance change of the thermistors is determined by measuring the out-of-balance voltage of a DC-powered resistance bridge calibrated in terms of voltage change with resistance.

The absorbed dose to water at the PTB is maintained through the use of a series of secondary standard ionization chambers calibrated directly against the water calorimeter, three of which have been used in this comparison. The water calorimeter is used every 3 months to confirm its stability and provide long-term monitoring.

Table 2. Relative standard uncertainties for the PTB water calorimeter for absorbed dose to water

Source of uncertainty	PTB Value	PTB relative standard uncertainty	
		100 s_i	100 u_j
Relative resistance change*	–	0.02	–
Thermistor calibration	–	–	0.07
Specific heat capacity of water / (J g^{-1} K^{-1})	4.2068	–	0.03
Positioning			
- source to surface distance		–	0.01
- detector position		–	0.03
Heat conduction effects**			
- detector cylinder	1.0004	–	0.04
- pipettes	0.9982	–	0.05
- depth-dose distribution	0.9999	–	0.01
- lateral dose distribution	0.9997	–	0.02
Chemical heat defect, *h*	0	–	0.14
Lateral dose distribution	1.0003	–	0.01
Perturbation effect	1.0013	–	0.05
Transfer to reference field***	1.1276	–	0.08
Quadratic summation		0.02	0.20
Combined relative standard uncertainty in $D_{\mathrm{w,PTB}}$		0.20	

* The given standard uncertainty is the standard deviation of the mean value of 20 experiments performed with 8 different detectors (prepared as H_2- or N_2-system). The total number of single measurements for the 20 experiments is about 4500.

** The given correction factors for the different heat conduction effects are the mean correction of eight successive irradiations of 120 s with drift periods of 125 s between the irradiations.

*** Ratio of ionization chamber measurements performed in the water phantom of the calorimeter and in the normal water phantom, respectively.

Heat conduction effects

Finite-element heat conduction calculations have been made that take into account the depth-dose distribution as well as the lateral dose distribution of the radiation beam. This is in addition to previous investigations concerning the irradiation of the non-water elements of the detector [6]. Typically, series of eight successive irradiations of 120 s with drift periods of 125 s between the irradiations are recorded. The calculated evolution of the water temperature during these irradiations, taking into account the different sources of heat conduction, is in agreement with the calorimetric signal over a time period of more than 45 min [4]. In addition, the calculated differences between the measurements using thermistor pipettes with different diameters are in agreement with the experimental results. It is concluded that the corresponding heat conduction is adequately described by the calculations. The standard uncertainties in Table 2 for the different heat conduction effects are estimated on the basis of small variations within the finite-element calculations, including geometry, material parameters and heat generation rates.

Radiation field perturbation

The presence of the vessel and probes perturbs the radiation field. With the aid of a dummy glass cylinder with a small opening in the cylinder wall to place a thimble ionization chamber inside, the correction for the perturbation effect can be determined as the ratio of the ionization chamber reading without and with the glass cylinder present. In this way the correction factor, k_P, was measured to be 1.0013 (5). By simulating the photon transport through the water phantom of the calorimeter by Monte Carlo calculation, the experimental result was confirmed, by the calculated result of 1.0010 (3), as 1.0013 (5) for ^{60}Co.

Thermal heat defect of water

Water saturated with H_2 or N_2 gas is used in the detectors of the calorimeter and it is assumed that these solutions offer a heat defect h equal to zero after a small accumulated dose. By measuring the response of such detectors as a function of accumulated dose, it is shown that they remain stable within less than 0.1 % up to doses of several kGy. This is supported by the results of corresponding model calculations for the radiolysis of water. In addition, measurements using the H_2/O_2 system show that the measured ratio of 1.022 between the response of this and the mean value of the H_2 and N_2 systems is in agreement with the predicted value based on the model calculation, taking into account the actual measurement conditions, including irradiation time, drift periods and dose rate [4]. The relative uncertainty for the assumed zero heat defect for the mean result of the H_2- and N_2-detectors is taken as 1.4×10^{-3}, which has been estimated from the maximum variation of the results for these detectors. The response of newly prepared detectors is now verified against the expected results to be within the stated uncertainty.

Reference conditions

Absorbed dose is determined at the BIPM 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 is 5 g cm^{-2}.

The reference conditions at the PTB are the same as those at the BIPM. However, the experimental arrangement used to establish the absorbed dose via water calorimetry does not comply exactly with the reference conditions. For water calorimetry the source to reference distance is 105 cm with the depth to the reference point in the tank set to 5 g cm^{-2} including the PMMA window of 3 mm thickness as a water-equivalent thickness in g cm^{-2}. The field size at this reference point is slightly larger than 10 cm × 10 cm. In total, there is 12 cm of polystyrene insulation in the beam path outside the tank that is not included in the 5 g cm^{-2}. The correction factor for the transfer to reference conditions has been determined as the ratio of ionization chamber measurements performed in the water phantom of the calorimeter and in the normal water phantom, respectively.

The value of $\dot{D}_{\text{w,PTB}}$ used for the comparison is the mean of five measurements made over a period of five months before, and two measurements made over a period of one month after, the measurements at the BIPM. The value, of order 21 mGy s^{-1}, is normalized to the date and time of 2004-07-30 T 00:00:00 Coordinated Universal Time (UTC) as is the ionization current of each transfer standard (using the IAEA weighted mean half-life value of 1925.5 d, $\sigma = 0.5$ d for ^{60}Co [8]).

The $\dot{D}_{\text{w,BIPM}}$ value is the mean of four measurements made over a period of six months before and one after the comparison and is of order 1.6 mGy s^{-1}. By convention it is given at the reference date of 2005-01-01 T 00:00:00 UTC as is the value of the ionization current of each transfer standard, using the same half-life as above.

3. The transfer chambers and their calibration

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

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

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

The transfer chambers are: one NE2571 ionization chamber serial number 2906, one NE2561 serial number 244 and one Wellhöfer FC65-G serial number 771, all belonging to the PTB. Their main characteristics are listed in Table 3. These chambers were calibrated over several months at the PTB before and after the measurements at the BIPM.

The experimental method for calibrations at the PTB is described in [9] and that for the BIPM in [10] and the essential details are reproduced here. At each laboratory the chambers were positioned with the stem perpendicular to the beam direction and with the appropriate markings on both chamber and, for the NE chambers, envelope (engraved lines or serial numbers and dots) facing the source, the Wellhöfer chamber being waterproof.

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. At the PTB, both polarities are normally used although calibration coefficients are available for each polarity. No corrections were applied at either laboratory for polarity as the PTB results for the single polarity used at the BIPM were applied directly. 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.

The charge Q collected by each transfer chamber was measured using a Keithley electrometer, model 642 at the BIPM. The source is operational during the entire exposure series and the charge is collected for the appropriate, electronically controlled, time interval. At the PTB, the current was measured using a Keithley 616 electrometer whose analogue voltage output (proportional to the input current) was digitized by an IOtech ADC488/16A digitizer and averaged numerically. The PTB source is also operational during the entire exposure series so that shutter timer errors do not influence the measurement. The chambers were pre-irradiated for at least 10 min (≈ 10 Gy) at the PTB, and for at least 30 min (≈ 3 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. The PTB does not correct for leakage as long as this is less than 0.01 % of the ionization current. During a series of measurements, the water temperature is measured for each current measurement and was stable to better than 0.02 °C at the PTB and better than 0.01 °C at the BIPM. The ionization current is corrected to 293.15 K and 101.325 kPa at both laboratories.

Table 3. Characteristics of the PTB transfer chambers

Characteristic/Nominal values		NE2571-2906	NE2561-244	FC65-G-771
Dimensions	Inner diameter	6.3 mm	7.5 mm	6.2 mm
	Wall thickness	0.35 mm	0.5 mm	0.4 mm
	Cavity length	24.0 mm	9.22 mm	23.1 mm
	Tip to reference point	13 mm	5 mm	13 mm
Electrode	Length	21.0 mm	6.4 mm	20.0 mm
	Diameter	1.0 mm	1.7 mm (hollow)	1.0 mm
Volume	Air cavity	0.69 cm^3	0.325 cm^3	0.65 cm^3
Wall	Material	graphite	graphite	graphite (plastic coated)
	Density	1.7 g cm^{-3}	1.7 g cm^{-3}	1.82 g cm^{-3}
Voltage applied to outer electrode	Negative polarity	250 V	200 V	
	Positive polarity			250 V

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

At the PTB, 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 % over the central 4 cm. At the BIPM, the corrections applied to the ionization current would only be 1.0003 for the NE2561 and 1.0006 for the NE2571, each with an uncertainty of 2×10^{-4} [11]. No non-uniformity correction is made.

Both laboratories use a horizontal beam of radiation and, at the BIPM, the thickness of the PMMA front window 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 PTB, the reference depth is 5 cm from the outside of the phantom window. This reference depth is the same for both the standard and the transfer chambers. Individual waterproof sleeves of 1 mm thick PMMA were supplied by the PTB 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.

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 and not correlated. 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 $\dot{D}_{\mathrm{w,PTB}}$, together with 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.

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

	PTB		**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), $u_{D\mathrm{w}}$	0.02	0.20	0.20	0.21
Ionization current of the transfer chambers	0.02	0.04	0.02	0.02
Distance	–	0.02	–	0.02
Depth in water	–	0.06	–	0.05
Relative standard uncertainties of $N_{D,\mathrm{w,\,lab}}$				
quadratic summation	0.03	0.21	0.20	0.22
combined uncertainty	0.22		0.30	
Relative standard uncertainties of $R_{D,\mathrm{w}}$		100 s	100 u	
quadratic summation		0.20	0.30	
combined uncertainty, u_R	0.37			

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 to three calibrations with repositioning, in series of 30 measurements for each chamber) at the BIPM. At the PTB, a single series of 25 repeated measurements each lasting 60 s exhibited a relative standard uncertainty of less than 2×10^{-4}. The calibration of each chamber was repeated with repositioning at least five times before the measurements at the BIPM. The relative standard uncertainty of the mean normalized ionization current measured at the PTB with a given transfer chamber over the several months required for this comparison was typically better than 2×10^{-4}. The calibrations were repeated at the PTB once after the comparison at the BIPM and the results are consistent as shown in Table 5.

4. Results of the comparison

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

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

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

The comparison result is taken as the unweighted mean value for all three transfer chambers, $R_{D,\mathrm{w}} = 0.9961$ with a combined standard uncertainty for the comparison of 0.0037. The difference between the absorbed dose to water standards of the PTB and the BIPM is not significant given the combined uncertainty.

Two of the transfer chambers were also calibrated in terms of air kerma in ^{60}Co at the BIPM. The measurements made in air and in water can be used to compare the relative responses of the transfer chambers. The ratio of $N_{D,\mathrm{w}}/N_K$ at the BIPM for the NE2571 chamber is 1.0972 and for the NE2561 chamber is 1.0898, each with a statistical uncertainty of 10^{-4}. These values, for which no beam profile corrections have been made, are within the expected values for similar thimble-type transfer chambers [1.098 (1) and 1.092 (1) respectively] measured at the BIPM. The coherence with these figures for each type of chamber confirms the response of the chambers while at the BIPM.

Table 5. Results of the comparison

Transfer Chamber	$N_{D,\mathrm{w,PTB}}$ / Gy µC^{-1} pre-BIPM	$N_{D,\mathrm{w,\,BIPM}}$ / Gy µC^{-1}	$N_{D,\mathrm{w,\,PTB}}$ / Gy µC^{-1} post-BIPM	$N_{D,\mathrm{w,PTB}}$ / Gy µC^{-1} overall mean*	$R_{D,\mathrm{w}}$	u_c
NE 2561-244	102.285	102.633	102.303	102.287	0.9966	0.0037
NE 2571-2906	45.473	45.658	45.472	45.473	0.9959	0.0037
FC65-G-771	47.589	47.784	47.585	47.589	0.9959	0.0037
				Mean values	**0.9961**	**0.0037**

* for at least six calibrations at the PTB.

5. Comparison with other metrology institutes

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 PTB, is given in [2], and the results are available in the key comparison database (KCDB) of the CIPM MRA [12].

The relative combined standard uncertainty associated with a determination of absorbed dose to water at an NMI is designated $u_{D\mathrm{w,NMI}}$. The relative combined standard uncertainty $u_{R,\mathrm{NMI}}$ of each comparison result R_{NMI} takes into account the combined standard uncertainty $u_{\mathrm{c,NMI}}$ of $N_{D\mathrm{w,NMI}}$ derived from the uncertainty budget and the combined standard uncertainty $u_{\mathrm{c,BIPM}}$ of $N_{D\mathrm{w,BIPM}}$ (see Table 4). For comparisons between the metrology institutes, the correlations between the measurement methods need to be taken into account; this procedure is outlined below.

As the BIPM absorbed dose to water is measured ionometrically, there are few correlations between the NMI and the BIPM uncertainty budgets. 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), for those NMIs using graphite calorimetry. The uncertainties are not necessarily fully correlated and this is taken into account by applying an approximate factor, f_k, as indicated in [2].

The numerical values of $u_{R,\mathrm{NMI}}$ for the PTB are given in Table 6 and are those used for the KCDB entries.

Table 6. Results for the PTB key comparisons of absorbed dose to water

Year	$u_{D\mathrm{w,NMI}}$	R_{NMI}	$u_{R,\mathrm{NMI}}$	Primary standard	Ref.
	in relative value				
1990	0.0076	0.9934	0.0081	Fricke solution	[1]
2005	0.0020	0.9961	0.0037	water calorimeter	–

The degree of equivalence of a given measurement standard, D_{NMI}, is the degree to which this standard is consistent with the key comparison reference value (KCRV) [12]. The degree of equivalence is expressed quantitatively in terms of the deviation of the comparison result from the key comparison reference value, R_{ref}, and the expanded uncertainty of this deviation ($k = 2$).

The degree of equivalence between any pair of national measurement standards is expressed in terms of the difference in the two comparison results and the expanded uncertainty of this difference; consequently, it is independent of the choice of key comparison reference value.

Comparison of a given NMI with $R_{\mathrm{ref}} = 1$

The degree of equivalence of a particular NMI, *i*, with the key comparison reference value is expressed as the difference

$$D_{\mathrm{NMI}} = R_{\mathrm{NMI}} - 1 \qquad (5)$$

and the expanded uncertainty ($k = 2$) of this difference, U_{NMI}, known as the equivalence uncertainty. It follows that

$$U_{\mathrm{NMI}} = 2u_{R,\mathrm{NMI}} \, . \qquad (6)$$

Table 7 gives the values for D_{NMI} and U_{NMI} for each NMI taken from [2] and [13] and this report, using (5) and (6), and forms the basis of the entries in the KCDB of the MRA Appendix B. These data are presented graphically in Figure 1 where the black squares indicate results that date prior to 1995. However, as the LSDG has not yet been officially designated as the dosimetry NMI for Belgium, their results do not appear in the KCDB.

Table 7. Degrees of equivalence of each NMI's measurement standard

Country	**NMI**	**Year**	$u_{D\mathrm{w,NMI}} \times 10^{-3}$	$D_{\mathrm{NMI}} \times 10^{-3}$	$U_{\mathrm{NMI}} \times 10^{-3}$
Germany	PTB	1990	7.6	-6.6	16.2
Italy	ENEA	1994	4.4	-3.1	9.8
Austria	BEV	1994	3.7	-1.0	8.6
Australia	ARPANSA	1997	2.0	2.4	6.0
U.S.A.	NIST	1997	3.5	-1.6	10.2
Canada	NRC	1998	4.1	-2.4	10.2
Belgium	LSDG	1999	6.6	-5.2	14.8
Netherlands	NMi	2000	4.0	-3.8	7.8
Switzerland	METAS	2000	4.1	-0.1	10.8
Russian Federation	VNIIFTRI	2000	4.0	-3.3	8.6
Hungary	OMH	2001	4.8	-1.7	9.6
France	LNE-LNHB[2]	2003	4.8	-3.0	10.6
Germany	PTB	2005	2.0	-3.9	7.4

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[2] Previously known as the BNM-LNHB.

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 the difference

$$D_{ij} = D_i - D_j = R_i - R_j \tag{7}$$

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

$$u_{ij}{}^2 = u_{c,i}{}^2 + u_{c,j}{}^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_i^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_j^2 \tag{8}$$

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

The common components of the uncertainty budgets for the PTB and the other NMIs with water calorimeters are given in Table 8. In Table 8, $u_{D\mathrm{w,NMI}}$ 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. The uncertainty in the heat defect is taken to have some correlated component as shown. The value of 0.7 for the correlation coefficient was approved by the CCRI in 2005 [14], until better evidence for another value is available.

In Table 8, k_{c} is the heat flow correction factor, k_{sc} (also referred to as k_{p}) is the scatter correction factor or field perturbation, k_{dd} is the lateral dose distribution and h is the chemical heat defect; the uncertainty components and uncertainties are given in relative value. The numerical values of k_{c} and k_{p} for the METAS in Table 8 are the same as for the NRC [2], so a correlation coefficient of 1.0 has been taken for these uncertainties.

Table 8. Common components in the uncertainty budgets for water calorimetry primary standards, standard uncertainties per 10^3

NMI	k_{c}	k_{sc} **or** k_{p}	k_{dd}	h	$u_{D\mathrm{w,NMI}}$	u_{transfer}	$u_{\mathrm{c,NMI}}$	$\sqrt{\left(\sum_k \left(f_k u_{k,\mathrm{corr}}\right)_i^2\right)}$
NIST	1.0			3.0	3.5	2.2	4.2	2.1
NRC	1.5	0.5	0.1	3.0	4.1	2.1	4.2	2.1
LSDG	2.5	0.4	0.1	5.0	6.6	3.5	6.8	3.5
METAS	1.5	0.5	0.2	3.0	4.1	2.1	4.5	2.1
PTB	0.7	0.5	0.1	1.4	2.0	0.8	2.2	1.0
$f_{k,\mathrm{NMI}}$	-	-	-	0.7				

The matrix of degrees of equivalence takes into account the correlations between each pair of NMIs and is given in Table 9 in the form that appears in the KCDB.

Figure 1 Graph of the degrees of equivalence with the KCRV

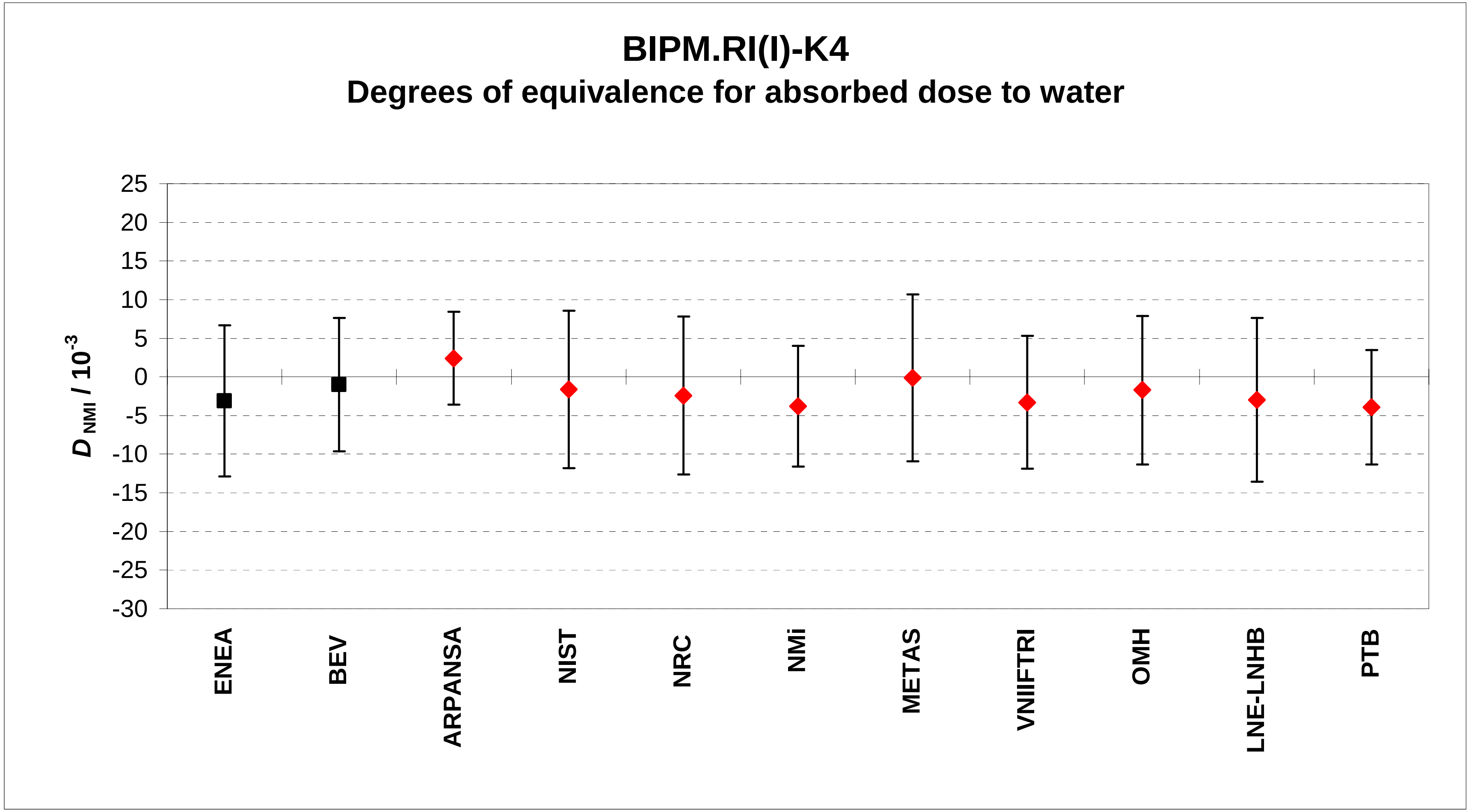

Table 9. Introductory text and table of degrees of equivalence for absorbed dose to water

Key comparison BIPM.RI(I)-K4

MEASURAND : **Absorbed dose to water relative to the BIPM evaluation**

Key comparison reference value: x_R is taken as unity

The degree of equivalence of each laboratory *i* with respect to the reference value is given by a pair of terms: $D_i = (x_i - 1)$ and U_i, its expanded uncertainty ($k = 2$), expressed in relative units, where $U_i = 2u_i$.

The degree of equivalence between two laboratories is given by a pair of terms: $D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij}, its expanded uncertainty ($k = 2$), bexpressed in relative units. In evaluating $U_{ij} = 2u_{ij}$ for the table below account is taken of correlations between u_i and u_j (see Section 5 of the Final report).

Lab *j* ⇨

Lab *i* ⇩

			ENEA		BEV		ARPANSA		NIST		NRC		NMi	
	D_i / 10^{-3}	U_i	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}
ENEA	**-3.1**	9.8			**-2.1**	10.7	**-5.5**	8.9	**-1.5**	12.5	**-0.7**	12.5	**0.7**	10.1
BEV	**-1.0**	8.6	**2.1**	10.7			**-3.4**	7.6	**0.6**	11.2	**1.4**	11.2	**2.8**	9.0
ARPANSA	**2.4**	6.0	**5.5**	8.9	**3.4**	7.6			**4.0**	9.4	**4.8**	9.4	**6.2**	6.6
NIST	**-1.6**	10.2	**1.5**	12.5	**-0.6**	11.2	**-4.0**	9.4			**0.8**	10.3	**2.2**	11.7
NRC	**-2.4**	10.2	**0.7**	12.5	**-1.4**	11.2	**-4.8**	9.4	**-0.8**	10.3			**1.4**	11.7
NMi	**-3.8**	7.8	**-0.7**	10.1	**-2.8**	9.0	**-6.2**	6.6	**-2.2**	11.7	**-1.4**	11.7		
METAS	**-0.1**	10.8	**3.0**	12.9	**0.9**	11.7	**-2.5**	9.9	**1.5**	10.8	**2.3**	9.8	**3.7**	12.2
VNIIFTRI	**-3.3**	8.6	**-0.2**	10.8	**-2.3**	9.8	**-5.7**	7.7	**-1.7**	12.3	**-0.9**	12.3	**0.5**	9.1
OMH	**-1.7**	9.6	**1.4**	11.6	**-0.7**	10.6	**-4.1**	8.7	**-0.1**	13.1	**0.7**	13.1	**2.1**	10.0
LNE-LNHB	**-3.0**	10.6	**0.1**	12.1	**-2.0**	11.2	**-5.4**	9.4	**-1.4**	12.6	**-0.6**	12.6	**0.8**	10.5
PTB	**-3.9**	7.4	**-0.8**	10.2	**-2.9**	8.6	**-6.3**	6.1	**-2.3**	8.3	**-1.5**	8.3	**-0.1**	9.3

Lab *j* ⇨

Lab *i* ⇩

			METAS		VNIIFTRI		OMH		LNE-LNHB		PTB	
	D_i / 10^{-3}	U_i	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}
ENEA	**-3.1**	9.8	**-3.0**	12.9	**0.2**	10.8	**-1.4**	11.6	**-0.1**	12.1	**0.8**	10.2
BEV	**-1.0**	8.6	**-0.9**	11.7	**2.3**	9.8	**0.7**	10.6	**2.0**	11.2	**2.9**	8.6
ARPANSA	**2.4**	6.0	**2.5**	9.9	**5.7**	7.7	**4.1**	8.7	**5.4**	9.4	**6.3**	6.1
NIST	**-1.6**	10.2	**-1.5**	10.8	**1.7**	12.3	**0.1**	13.1	**1.4**	12.6	**2.3**	8.3
NRC	**-2.4**	10.2	**-2.3**	9.8	**0.9**	12.3	**-0.7**	13.1	**0.6**	12.6	**1.5**	8.3
NMi	**-3.8**	7.8	**-3.7**	12.2	**-0.5**	9.1	**-2.1**	10.0	**-0.8**	10.5	**0.1**	9.3
METAS	**-0.1**	10.8			**3.2**	12.7	**1.6**	13.5	**2.9**	13.0	**3.8**	8.9
VNIIFTRI	**-3.3**	8.6	**-3.2**	12.7			**-1.6**	10.7	**-0.3**	11.3	**0.6**	10.0
OMH	**-1.7**	9.6	**-1.6**	13.5	**1.6**	10.7			**1.3**	12.0	**2.2**	10.9
LNE-LNHB	**-3.0**	10.6	**-2.9**	13.0	**0.3**	11.3	**-1.3**	12.0			**0.9**	10.4
PTB	**-3.9**	7.4	**-3.8**	8.9	**-0.6**	10.0	**-2.2**	10.9	**-0.9**	10.4		

6. Comments on future comparisons

The CCRI(I) has agreed that comparisons should be repeated at least every ten years and new comparison results added to the database as soon as they are approved. Each NMI's results are published in a report of the comparison, which includes an update of the matrix of degrees of equivalence and the corresponding graphical presentation as they will appear in the KCDB. This report is sent to the CCRI(I) for approval once the results have been agreed by the participants.

An updated summary of the results is presented to each CCRI(I) meeting. Scientific decisions to remove results from the KCDB are made only by the CCRI(I).

If an NMI makes a bilateral comparison for this quantity, the results can be included in the database with the approval of the Key Comparison Working Group. Such approval requires that the comparison is declared in advance and that at least one of the NMIs already has a BIPM comparison result.

The BIPM is currently reassessing its primary standard for absorbed dose to water using Monte Carlo calculations to determine the various correction factors. The results of this reassessment will be presented to the CCRI(I). Although this may result in a change to the BIPM determination of absorbed dose to water, it will not change the degrees of equivalence between the participants in this comparison.

7. Conclusions

A key comparison has been carried out between the PTB (Germany) and the BIPM of standards for absorbed dose to water in ^{60}Co gamma rays, using three ionization chambers as transfer standards. From air kerma calibrations made at the same time it is concluded that the transfer chambers have a stable and predictable response. The mean comparison result shows that the PTB determination of absorbed dose to water is 3.9×10^{-3} lower, in relative terms, than that of the BIPM. This is compatible with the combined relative standard uncertainty of the comparison (3.7×10^{-3}) and is consistent with the changes made to the PTB standard since the previous result of 1989. When compared with the results of the other national metrological institutes that have carried out comparisons in terms of absorbed dose to water at the BIPM, the PTB standard for absorbed dose to water is in satisfactory agreement, being within the standard uncertainty 1.9×10^{-3} of the distribution of these results.

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