

Comparison of the standards for absorbed dose to water of the VSL and the BIPM for ^{60}Co gamma rays

C. Kessler¹, P.J. Allisy-Roberts¹, D.T. Burns¹, P. Roger¹,
L.A. de Prez², J.A. de Pooter², P.M.G. Damen²

¹Bureau International des Poids et Mesures, Pavillon de Breteuil,
Sèvres

² Van Swinden Laboratorium, Delft, The Netherlands

Abstract

An indirect comparison of the standards for the quantity absorbed dose to water was carried out between the Van Swinden Laboratorium (VSL) and the Bureau International des Poids et Mesures (BIPM) in September 2005. The comparison was based on the calibration coefficients determined for three NE2611A type ionization chambers under reference conditions in the ^{60}Co beams of both institutes. The comparison result, reported as a ratio of the VSL and the BIPM evaluations, is 0.9926 with a relative standard uncertainty of 4.9×10^{-3} . This result replaces the previous indirect comparison result obtained in 2000 for the ongoing BIPM.RI(I)-K4 comparison. The degrees of equivalence for the VSL standard and the nine other national metrology institutes in this comparison are presented in the form of a matrix, together with those of a linked regional comparison. The opportunity was also taken to undertake a pilot study using the VSL water calorimeter at the BIPM.

1. Introduction

Comparisons of standards for absorbed dose to water are designated as key comparisons by the Consultative Committee for Ionizing Radiation (CCRI). This paper describes the second such comparison between the VSL* and the BIPM, which was carried out in September 2005 using three cavity ionization chambers as transfer standards in the BIPM Picker ^{60}Co beam.

In this report, the standard for absorbed dose to water of the BIPM, which is based on an ionometric technique, and that of the VSL, which is now based on a water calorimeter, are outlined. The experimental conditions under which the transfer standards were calibrated are also described. The results of the indirect comparison are presented and compared with previous comparisons carried out between the BIPM and other national institutes. All quoted uncertainties are one standard uncertainty, except for the final degrees of equivalence that are expressed with expanded uncertainties.

The water calorimeter of the VSL was also used to measure the absorbed dose in the BIPM CIS-Bio ^{60}Co beam as a pilot study. Subsequent to the measurements at the

* Previously known as the NMi-VSL, the Nederlands Meetinstituut -Van Swinden Laboratorium

BIPM, the VSL conducted additional measurements at the VSL to confirm the calibration coefficients of the transfer chambers in water, to re-evaluate the excess heat correction in the water calorimeter and the correction for self-heating of the thermistor probes. In addition, as the geometry of the beams is different in the two institutes, the VSL made further measurements using the calorimeter in a radiotherapy department where the same cobalt beam could be orientated both vertically and horizontally to simulate the beams at the VSL and the BIPM, respectively. All the additional measurements needed to complete this work took place between the end of 2005 and the end of 2007.

2. Determination of absorbed dose to water

2.1 Description of the primary standards

At the BIPM, the rate of absorbed dose to water is determined using an ionometric method [1]. The dose rate is given by

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

where I/m is the ionization current per mass of air measured by the standard, W is the average energy spent by an electron of charge e to produce an ion pair in dry air, $\bar{s}_{c,a}$ is the ratio of the mean stopping powers of graphite and air, and Πk_i is the product of the correction factors applied to the standard.

The values of the physical constants and the correction factors entering in (1) for the BIPM standard are given in [1, 2] together with their uncertainties. The uncertainty budget is shown in Table 1. The combined relative standard uncertainty, taking the accepted uncertainty of the product $(W/e) \bar{s}_{c,a}$, is 0.29 %. The value for the rate of absorbed dose to water $\dot{D}_{w,BIPM}$ in the Picker ^{60}Co beam at the reference date of 2005-01-01 was $1.6119 \text{ mGy s}^{-1}$ with a combined standard uncertainty u_c of $0.0047 \text{ mGy s}^{-1}$.

The VSL standard for absorbed dose to water for ^{60}Co gamma radiation is based on the design by Domen [3]. The water calorimeter consists of a computer-controlled water-cooled thermostat surrounding a 30 cm sided cubic phantom. The calorimeter is operated at 4 °C in order to eliminate undesired temperature effects as a result of convection. Two thermistor probes are positioned at the reference depth inside a thin-walled glass vessel. The temperature rise of the water due to irradiation by ^{60}Co photons is measured at the position of the thermistors. The quality of the water inside the glass vessel is controlled by preparing the water before filling the glass vessel. This is achieved by purifying the water and then saturating it with argon gas at about 200 mL min^{-1} for one hour to establish a known heat defect. A schematic drawing of the VSL water calorimeter is given in Figure 1.

Table 1. Physical constants, correction factors and relative standard uncertainties for the BIPM ionometric standard for absorbed dose to water in the Picker ^{60}Co beam.

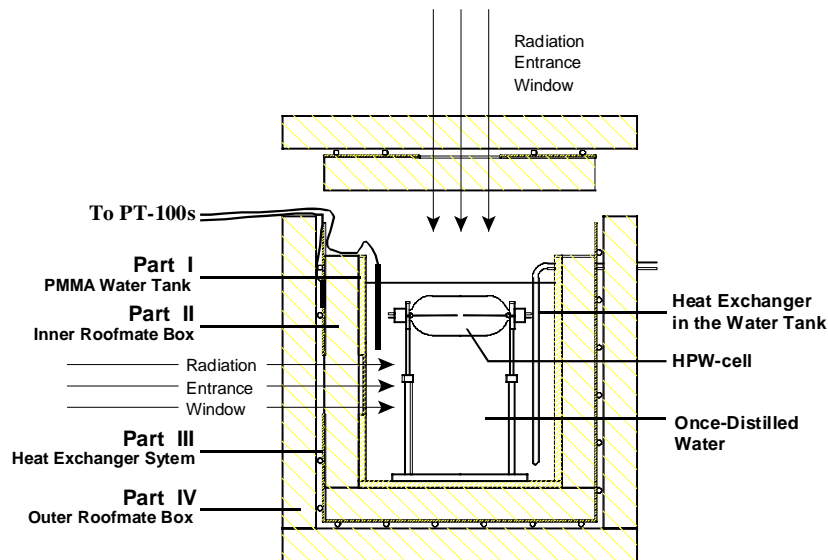
Quantity	BIPM value	BIPM relative standard uncertainty ⁽¹⁾	
		100 u_{iA}	100 u_{iB}
Dry air density ⁽²⁾ (kg m^{-3})	1.2930	–	0.01
W/e (J C^{-1})	33.97	–	0.11 ⁽³⁾
$\bar{s}_{c,a}$	1.0030		
k_{cav} (air cavity)	0.9900	0.03	0.04
$(\bar{\mu}_{en}/\rho)_{w,c}$	1.1125	0.01	0.14
$\Psi_{w,c}$ (photon-fluence ratio)	1.0065	0.04	0.06
$(1+\epsilon)_{w,c}$ (dose-to-kerma ratio)	1.0015	–	0.06
k_{ps} (PMMA envelope)	0.9994	0.00 ₅	0.01
k_{pf} (phantom window)	0.9996	–	0.01
k_{rn} (radial non-uniformity)	1.0051	0.00 ₅	0.03
k_s (recombination losses)	1.0016	0.00 ₄	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 standard uncertainty of $\dot{D}_{w,BIPM}$		0.29	

(1) u_{iA} represents the Type A relative standard uncertainty $u(x_i)/\bar{x}_i$, estimated by statistical means; u_{iB} represents the Type B relative standard uncertainty $u(x_i)/\bar{x}_i$, estimated by other means.

(2) At 0 °C and 101.325 kPa.

(3) Combined uncertainty of the product $(W/e)\bar{s}_{c,a}$ [4]

Figure 1. Schematic diagram of the VSL water calorimeter with the cell positioned for a vertical beam (the BIPM beam is horizontal).



At the VSL, the absorbed dose to water $D_{w,VSL}$ is inferred from the change in water temperature T_w by

$$D_{w,VSL} = c_w \Delta T_w k_{hd} k_c k_{nw} k_f, \quad (2)$$

where

- c_w is the specific heat capacity of water at 4°C, the calorimeter operating temperature
- k_{hd} is the correction for the heat defect of water
- k_c is the excess heat correction for conductive heat effects
- k_{nw} is the composite correction factor for perturbations due to the presence of non-water materials (detection vessel, thermistor probes, cooling jacket etc) and
- k_f is the product of all other correction factors.

The values and associated uncertainties are discussed in Section 3.

2.2 Operation of the VSL water calorimeter

The VSL water calorimeter is compact and transportable, weighing 40 kg when empty, and having outer dimensions of only $60 \times 60 \times 70 \text{ cm}^3$. The dimensions of the water phantom are a standard 30 cm sided cube. A small spacing between the inner and outer polystyrene foam insulation boxes encloses a copper heat exchange system. The six copper walls are connected in a parallel manner, which helps to reduce temperature gradients inside the water phantom. Cooling is performed by a computer-controlled water-cooling thermostat, which uses two PT100 thermometers (one

mounted on one of the copper walls and the other mounted inside the water phantom) to control and monitor the calorimeter temperature. A built-in magnetic stirrer enables a reduction of temperature drifts due to conduction between irradiation runs. The phantom is filled with water that is already at around 4 °C to reduce the time needed to cool down after closing the calorimeter. A cold-finger heat exchanger placed inside the water phantom can be switched into the cooling circuit to speed up this process.

Resistance changes in the thermistor probes are measured with a digital multi-meter. The calorimeter has been tested extensively in the ^{60}Co gamma beam of the VSL and has been used to determine k_Q -factors in clinical beams of many Dutch and Belgian hospitals [5].

Various correction factors for the water calorimeter as a function of photon energy have been determined experimentally and by the use of a computer program to simulate heat transport [6]. Although the VSL water calorimeter can be used in both horizontal and vertical beams, it is normally used in a vertical beam. However, the beam at the BIPM is horizontal and some additional correction factors to account for this were measured at the BIPM (see Section 3).

The VSL water calorimeter was compared with the VSL graphite calorimeter for ^{60}Co absorbed dose based on long term averages between 1995 and 2004 for the graphite calorimeter and between 2002 and 2006 for the water calorimeter. To convert the dose to graphite measured with the graphite calorimeter to dose to water, the fluence scaling theorem is used, as was described in the previous comparison with the BIPM [7]. The result of the comparison at the VSL between the two VSL primary standards expressed as the ratio of absorbed dose to water determined with the water calorimeter to that with the graphite calorimeter is 0.9969 (54).

Table 2 gives the history of the rates of absorbed dose to water determined at the VSL that provides input to Table 3 long-term stability. The average value for $\dot{D}_{w,\text{VSL}}$ of 9.329 mGy s^{-1} (statistical standard uncertainty 0.017 mGy s^{-1}) at the reference date of 2005-01-01 was used to calibrate the transfer chambers for the indirect comparison as discussed in Section 4.

Table 2. History of the rates of absorbed dose to water at the VSL. These dose rates are mean values over different periods and have been normalized to the reference date 2005-01-01.

Date	$\dot{D}_{w,\text{VSL}}(u_c) / (\text{mGy s}^{-1})$
2002	9.318 (31)
2004	9.343 (33)
2005	9.320 (33)

3. Indirect comparison of the BIPM and VSL standards

All three transfer standards used in the indirect comparison are cavity ionization chambers of the type NE 2611A, with serial numbers 118, 119 and 120. A polarizing voltage of 200 V was applied to each chamber, in the sense that the thimble was at a positive potential of 200 V with respect to the central electrode (at the VSL the thimble is grounded, whereas at the BIPM the central electrode is effectively at ground). The polarity correction for each chamber has been measured to be less than 0.04 % by the VSL and no correction was applied at either laboratory. The charge collected by the chambers was measured using the BIPM electrometer at the BIPM.

The calibration coefficient for a transfer standard in terms of absorbed dose to water is defined by

$$N_{D_w, \text{lab}} = \frac{\dot{D}_{w, \text{lab}}}{I_{w, \text{lab}}}, \quad (3)$$

where $\dot{D}_{w, \text{lab}}$ is the rate of absorbed dose to water as determined by each laboratory and $I_{w, \text{lab}}$ is the measured ionization current of the transfer chamber.

The VSL ^{60}Co beam is vertical while those of the BIPM are horizontal. All measurements were performed at a reference distance (from source to chamber axis) of 1 m, with a field size of 10 cm \times 10 cm at this distance. For measurements in water, both laboratories use a cubic water phantom of side length 30 cm, and the same protective waterproof sleeve for each chamber. The calibration coefficients were determined at a reference depth of 5 g cm⁻². The VSL quality assurance procedure for calibration of an ionization chamber in ^{60}Co beams, recently updated, was followed [8].

The environmental conditions at the two laboratories were as follows. The air temperature at the BIPM was controlled around 20 °C (stable to better than 0.1°C during a series of measurements) with the water temperature stable to within 10 mK during a calibration. At the VSL the air temperature was controlled around 20 °C (stable to better than 0.1°C during a series of measurements) with the water temperature stable to within 20 mK during a calibration. Measured transfer chamber ionization currents were normalized to the standard environmental conditions of 293.15 K and 101.325 kPa. At both laboratories, the relative humidity was controlled at 50 % (within 5 %) and no humidity correction was applied. No corrections were made at either laboratory for ion recombination as the volume recombination is known to be negligible in the respective ^{60}Co beams.

At the VSL, the stability of the transfer chambers is checked using a check source of ^{90}Sr . The long-term check source measurements are normally consistent within 0.1 %. Measurements of the ionization currents measured in water at the VSL are normally consistent within 0.25 %

4. Pilot study using the VSL water calorimeter at the BIPM

The VSL water calorimeter was positioned in the horizontal beam of the BIPM CIS-Bio ^{60}Co source. A special support had been made by the VSL to hold the sealed water vessel at the correct depth in water and at the centre of the phantom window for a horizontal beam. Initial measurements at the BIPM identified that the positioning wires were at a depth inside the water phantom of 47.1 mm. These measurements were later confirmed by calibration at the length department of the VSL as 47.1 (1) mm. The beam entrance window of the phantom is 3 mm thick. The calorimeter was positioned so that the reference distance of 1 m from the source coincided with the depth position of 50.1 mm. A correction was applied for the measurement depth to 5 g cm^{-2} . The VSL laser was aligned to coincide with the BIPM laser at the reference plane and then used to verify the height and horizontal position of the thermistor probes inside the water phantom. These had previously been adjusted to be perpendicular to the beam axis and aligned with each other at the reference depth.

The phantom was filled with the prepared and cooled ($4 \text{ }^\circ\text{C}$) de-mineralized water and the calorimeter was left to stabilize for several hours with the cooling system in operation while being pre-irradiated with 70 Gy.

The water calorimeter signal was corrected for the horizontal beam profile of the BIPM beam (since the two probes are positioned 10 mm apart), for attenuation by the glass detection vessel, and for deviations from the reference distance (1 m) and depth (5 g cm^{-2}). The additional corrections for attenuation and scatter from the calorimeter thermostat enclosure and PMMA supports were measured at the BIPM using a VSL transfer chamber to give relative ionization currents under various experimental conditions, with and without the PMMA supports, and with and without different amounts of the surrounding thermostat enclosure. The measured absorbed dose rates are also corrected for the heat defect (due to chemical reactions) and for excess heat effects (due to undesired heat flow as a result of the temperature gradients in different materials as a result of the irradiation in glass and water).

All these and the other corrections associated with the VSL water calorimeter [6] are given in Table 3 together with their uncertainties.

5. Results of the indirect comparison

The absorbed dose to water values at the VSL are long-term averages measured using the water calorimeter together with their associated uncertainties. The calibration coefficients measured at the VSL are the mean of the measurements made at the VSL between July 2005 before the comparison and May 2006 and again in November 2007 after the comparison. At the BIPM, each transfer chamber was measured twice over the four days of the indirect comparison, in each of the two BIPM ^{60}Co beams, and the difference between each pair of measurements was less than 0.04 %. The BIPM values for absorbed dose to water are taken as the mean values over 4 months around the comparison measurements, the statistical standard uncertainty of this mean being less than 0.005 %.

Table 3. Uncertainty budget for the VSL water calorimeter in the horizontal BIPM beam and in the vertical VSL beam.

Measurement of absorbed dose rate to water referred to 01/01/2005	VSL value at the BIPM	VSL relative standard uncertainty		VSL value at the VSL	VSL relative standard uncertainty	
		100 u_{iA}	100 u_{iB}		100 u_{iA}	100 u_{iB}
						–
D_w (mGy s ⁻¹)	12.153	0.16	–	9.329	0.25	–
ΔR , resistance change (Ω)	-0.2008	–	0.05	-0.1544	–	0.06
R_{midrun} , mid-run resistance (Ω)	100 60	–	0.00	100 62	–	0.00
S , thermistor sensitivity at 4 °C (% K ⁻¹)	-4.3050	–	0.03	-4.3050	–	0.03
c_w (J kg ⁻¹ K ⁻¹)	4207.5	–	0.05	4207.5	–	0.05
t , time measurement (s)	180.00	–	0.03	180.00	–	0.03
k_{hd} (heat defect)	0.9995	–	0.20	0.9995	–	0.20
k_{nw} (non-water materials)	1.0184	–	0.11	1.0188	–	0.15
k_c (excess heat)	0.9984	–	0.10	0.9984	–	0.10
K_{dd} (depth and distance)	1.0031	–	0.06	0.9982	–	0.06
k_{att} (air attenuation)	1.0058	–	0.02	1.0059	–	0.02
k_{decay} (decay correction)	1.0938	–	0.00	1.0938	–	0.00
k_τ (source timing)	1.0073	–	0.07	0.9952	–	0.07
k_{rn} (radial non-uniformity)	1.0000	–	0.01	1.0000	–	0.01
Quadratic summation	–	0.16	0.28	–	0.25	0.30
Combined standard uncertainty of \dot{D}_w	–	0.33		–	0.39	

For each transfer chamber, the ratio of the calibration coefficients for the two laboratories obtained under the same conditions is taken to represent the ratio of the absorbed dose to water standards. The results are presented in Table 4. The uncertainty of the ratio $R = D_{w,\text{VSL}} / D_{w,\text{BIPM}}$ is derived from the uncertainty budgets of both laboratories (see Tables 1 and 3), and adding the uncertainties associated with the use of transfer chambers (Table 5). Taking the mean of the ratios given in Table 4, the indirect result, $D_{w,\text{VSL}} / D_{w,\text{BIPM}} = 0.9926$, $u_c = 0.0049$, is obtained.

The three chambers were also calibrated in terms of air kerma at the BIPM to confirm the consistency of their behaviour and the ratios of the results in terms of calibration coefficients indicate that the chambers were each self-consistent at the 10^{-4} level

although changes of between 2×10^{-3} and 3×10^{-3} in relative terms were noted since they were previously measured at the BIPM in 2000 [9].

Table 4. Comparison of the VSL and BIPM calibration coefficients in terms of absorbed dose to water.

Ionization Chamber	$N_{D_w, VSL}$ (Gy μC^{-1})	$N_{D_w, BIPM}$ (Gy μC^{-1})	$D_{w, VSL} / D_{w, BIPM}$	u_R
NE 2611A-118	101.428	102.155	0.9929	0.0049
NE 2611A-119	101.390	102.201	0.9921	0.0049
NE 2611A-120	102.178	102.920	0.9928	0.0049
Mean values			0.9926	0.0049

Table 5. Relative uncertainties associated with calibration coefficients and the indirect comparison result.

	Uncertainty in $N_{D_w, VSL}$		Uncertainty in $N_{D_w, BIPM}$		Uncertainty in R	
Relative standard uncertainty in the measurement of	100	100	100	100	100	100
Absorbed dose rate	u_{iA} 0.25	u_{iB} 0.30	u_{iA} 0.20	u_{iB} 0.21	u_{iA} 0.32	u_{iB} 0.35
Ionization current of transfer chamber	0.02	0.01	0.01	–	0.02	–
Chamber position/depth	0.03	0.05	0.01	0.02	0.03	0.06
Chamber response	0.04	–	0.03	–	0.05	–
Relative standard uncertainties						
Quadratic summation	0.26	0.31	0.20	0.21	0.33	0.36
Combined uncertainty	0.41		0.29		0.49	

6. Results of the pilot study

The VSL water calorimeter and its use are well described in [5, 6 and 10].

Using the measurement equation (2), the values in Table 3 together with the calorimeter measurements at the BIPM gave a provisional VSL evaluation of absorbed dose in the BIPM CIS-Bio beam. The pilot study result is then given in Table 6.

Table 6. Absorbed dose values measured at the BIPM in the CIS-Bio beam.

VSL D_w	u_c (VSL)	BIPM D_w	u_c (BIPM)	R	$u_c(R)$
mGy s ⁻¹		mGy s ⁻¹		mGy mGy ⁻¹	mGy mGy ⁻¹
12.153	0.040	12.310	0.036	0.9873	0.0044

In view of the difficulty in setting up the calorimeter in the horizontal CIS-Bio beam at the BIPM, the VSL subsequently carried out some experiments to confirm the consistency of horizontal and vertical beam results by taking the calorimeter to a radiotherapy department (AZ Sint-Maarten, Duffel, Belgium) that could offer the two configurations using the same ⁶⁰Co source. The results showed that there is no reason to assume a systematic difference between the horizontally and vertically oriented set-ups. However, as the uncertainty of this conclusion is of the order of 6 parts in 10³ (for details of this uncertainty see Table 7), the measurements at the BIPM using the VSL calorimeter are considered part of a pilot study rather than a direct comparison.

A further study and direct comparison is planned between the VSL and the BIPM.

Table 7. Uncertainties in the absorbed dose to water measurements at AZ Sint-Maarten, Duffel, Belgium.

Uncertainty contribution	Vertical beam		Horizontal beam		Ratio horizontal / vertical	
	100 u_{iA}	100 u_{iB}	100 u_{iA}	100 u_{iB}	100 u_{iA}	100 u_{iB}
Statistical uncertainty	0.34		0.34		0.48	
Linearity DMM		0.04		0.04		0.06
SDD		0.06		0.06		0.09
SDD deformation				0.01		0.01
Depth in water		0.08		0.08		0.12
Depth deformation				0.05		0.05
Position in field		0.05		0.05		0.07
PMMA window				0.09		0.09
Presence of phantom		0.10		0.02		0.12
Quadratic sum	0.34	0.16	0.34	0.16	0.48	0.25
Combined uncertainty	0.38		0.38		0.54	

7. Comparison outcome

The indirect comparison has produced a result of 0.9926 (49). The previous comparison with the VSL of standards for absorbed dose to water was made at the BIPM in 2000 [7] and the new result is in agreement with the previous result of 0.9962 (39). At that time the standard of the VSL was based on the determination of absorbed dose to graphite using a graphite calorimeter and the application of a conversion method. The agreement at the VSL between the graphite calorimeter and the water calorimeter is 0.9969 (54). On the basis of this difference and the previous

comparison, the result expected now would be 0.9931 (60) which is close agreement with that obtained indirectly.

The result of the pilot study is 0.9873 (44). Bearing in mind that the VSL calorimeter has been demonstrated, in off-site measurements, to be independent of beam direction at a level of 6 parts in 10^3 , this result agrees with the indirect comparison within the uncertainties.

8. 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 VSL, is given in [11] 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, i , is designated $u_{D_{w,i}}$. Almost all the comparisons are made indirectly using transfer standards and the relative combined standard uncertainty u_{R_i} of each comparison result R_i takes this into account together for the combined standard uncertainty $u_{c,i}$ of $D_{w,i}$ and the combined standard uncertainty $u_{c,BIPM}$ of $D_{w,BIPM}$ (see Tables 1 and 3, and Table 5 for the combined uncertainty budgets for the calibration of the transfer standards for the VSL and the BIPM). For comparisons between the metrology institutes, the correlations between the primary measurement methods need to be taken into account.

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 [11].

The numerical values of u_{R_i} for the VSL are given in Table 8 and are those used for the KCDB entries.

Table 8. Results for the VSL key comparisons of absorbed dose to water.

Year	$u_{D_{w,i}}$	R_i	u_{R_i}	Primary standard	Ref.
	in relative value				
2000	0.0040	0.9962	0.0039	graphite calorimeter	[7]
2005	0.0033	0.9926	0.0049	water calorimeter	–

The common components of the uncertainty budgets for the VSL and the other NMIs with water calorimeters are given in Table 9 [11]. In this table, $u_{D_{w,i}}$ 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 $u_{c,i}$ is the combined standard uncertainty for an absorbed dose to water calibration by the NMI, i ; all uncertainties being in relative value. The uncertainty in the heat defect is taken to have some correlated component as shown.

In Table 9, 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 9 are the same as for the NRC so a correlation coefficient of 1.0 has been taken for these uncertainties [11].

Table 9. Common components in the uncertainty budgets for water calorimetry primary standards, standard uncertainties per 10^3 .

NMI, i	k_c	k_{sc} or k_p	k_{dd}	h	$u_{Dw,i}$	u_{transfer}	$u_{c,i}$	$\sqrt{(\sum_k (f_k u_{k,\text{corr}})_i^2)}$
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
VSL	1.0	1.5	0.1	2.0	3.8	1.4	4.1	1.4
PTB	0.7	0.5	0.1	1.4	2.0	0.8	2.2	1.0
$f_{k,\text{NMI}}$	-	-	-	0.7				

Values for other National Metrology Institutes are taken from [11, 13] where the acronyms are also explained.

Comparison of a given NMI with the key comparison reference value

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) [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 ($k = 2$).

Following a decision of the CCRI, the BIPM determination of the dosimetric quantity, here $D_{w,R}$, 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_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:

$$\text{the relative difference } D_i = (D_{wi} - D_{w,Ri}) / D_{w,Ri} = R_i - 1 \quad (5)$$

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

$$U_i = 2 u_i. \quad (6)$$

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

Table 10 gives the values for D_i and U_i for each NMI, i taken from [11, 13 and 14] and this report, using (5) and (6), and forms the basis of the entries in the KCDB of the CIPM MRA. These data are presented graphically in Figure 2 where the black squares indicate results that date prior to 1998. The results of a recently published SIM comparison are also presented [15].

Comparison of any two NMIs with each other

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.

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

$$D_{ij} = D_i - D_j = R_i - R_j \quad (7)$$

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

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

and 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 (8) using the values for water calorimetry in Table 9. The matrix is given in Table 10 in the form that appears in the KCDB.

9. Conclusions

A key comparison has been carried out between the VSL and the BIPM standards of absorbed dose to water for ^{60}Co gamma rays, using three NE 2611A ionization chambers of the VSL as transfer standards. The comparison result, expressed as a ratio of the calibration coefficients measured by the VSL against their primary standard water calorimeter to that of the BIPM is 0.9926 (49), which is close to that expected from the results of the previous comparison in 2000. At the same time a pilot study was made of the primary measurement in the BIPM CIS-Bio ^{60}Co beam using the VSL water calorimeter.

The VSL comparison for absorbed dose to water is in agreement within the expanded uncertainties with the results of the other NMIs with primary standards for absorbed dose to water.

Table 10 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:

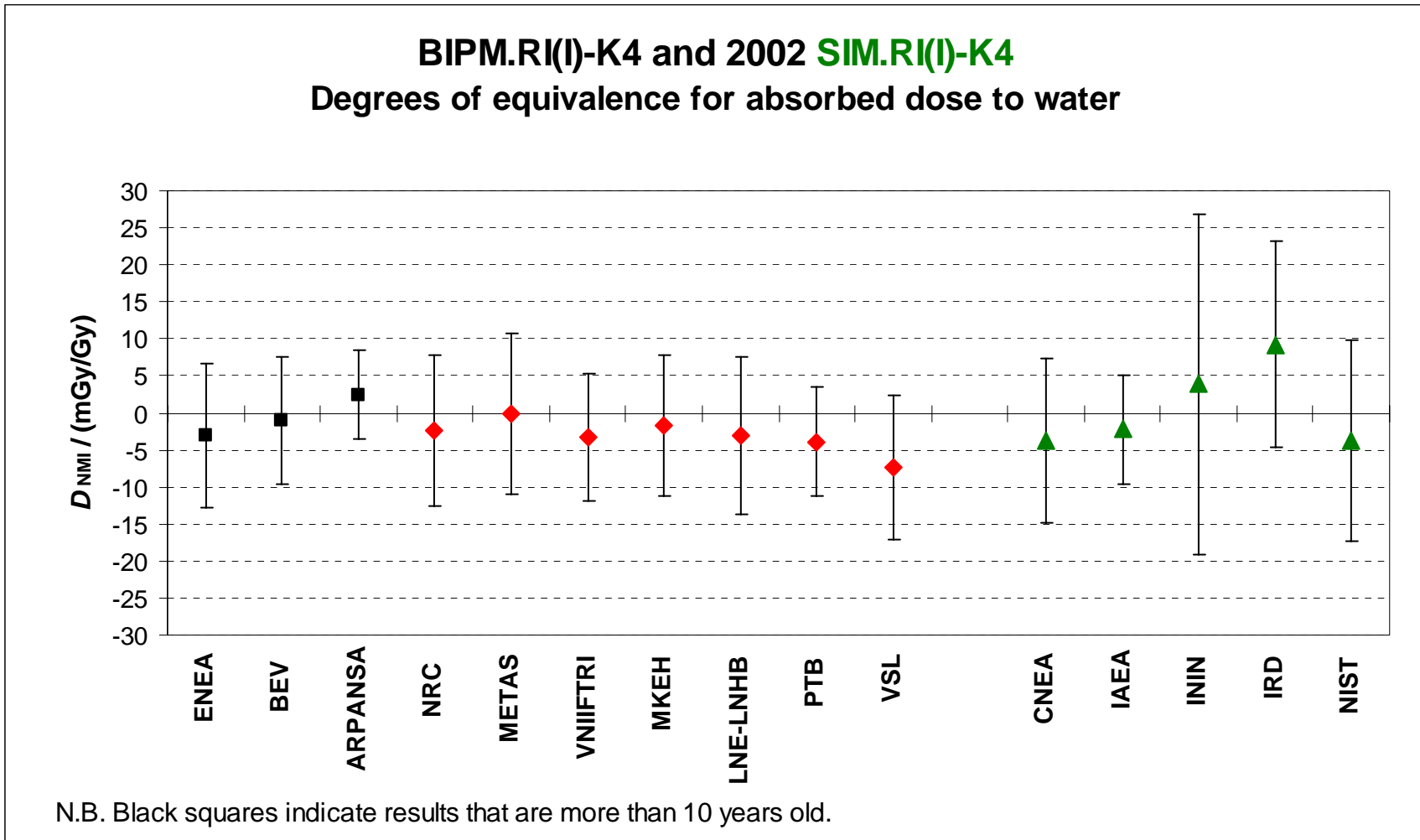
D_i and U_i , its expanded uncertainty ($k = 2$), with $U_i = 2u_i$.

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

$D_{ij} = D_j - D_i$ and U_{ij} , its expanded uncertainty ($k = 2$). In evaluating $U_{ij} = 2u_{ij}$ for the matrix of equivalence account is taken of correlations between u_i and u_j , see section 8 of the Report.

Lab <i>i</i> ↓			Lab <i>j</i>	
	D_i	U_i	VSL	
	/ (mGy/Gy)		D_{ij}	U_{ij}
			/ (mGy/Gy)	
ENEA	-3.1	9.8	4.3	12.3
BEV	-1.0	8.6	6.4	11.0
ARPANSA	2.4	6.0	9.8	9.2
NRC	-2.4	10.2	5.0	10.6
METAS	-0.1	10.8	7.3	11.1
VNIIFTRI	-3.3	8.6	4.1	12.2
MKEH	-1.7	9.6	5.7	12.9
LNE-LNHB	-3.0	10.6	4.4	12.5
PTB	-3.9	7.4	3.5	8.7
VSL	-7.4	9.8		
CNEA	-3.7	11.1	3.7	15.1
IAEA	-2.2	7.4	5.2	12.6
ININ	3.9	23.0	11.3	25.1
IRD	9.2	14.0	16.6	17.3
NIST	-3.7	13.6	3.7	13.8

Figure 2. Graph of the degrees of equivalence with the KCRV.



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