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Abstract
A comparison of the standards of absorbed dose to water of the Laboratorium voor Standaarddosimetrie Gent (LSDG), Belgium and of the Bureau International des Poids et Mesures (BIPM) has been made in ^{60}Co gamma radiation. The results show that the LSDG and the BIPM standards for absorbed dose to water are in agreement, yielding a ratio of 0.9948 for the calibration factors of the transfer chambers, the difference being within the combined standard uncertainty (0.0075).

1. Introduction

An indirect comparison of the standards of absorbed dose to water of the Laboratorium voor Standaarddosimetrie Gent (LSDG), Belgium, and of the Bureau International des Poids et Mesures (BIPM), was carried out in ^{60}Co radiation in September 1999. This absorbed dose to water comparison is the first such comparison made between the two laboratories.

The primary standard of the LSDG for absorbed dose is a Domen type sealed water calorimeter [1] as described in [2]. The BIPM primary standard is a graphite cavity ionization chamber of pancake geometry as described in [3].

The comparison was undertaken using two ionization chambers belonging to the LSDG as transfer instruments. The chambers were calibrated at the LSDG before and after the measurements made at the BIPM. The result of the comparison is given in terms of the ratio of the calibration factors of the transfer chambers determined at the two laboratories.

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/m is the mass ionization current measured by the standard,

W is the average energy spent by an electron of charge e to produce an ion pair in dry air,

$\bar{s}_{\mathrm{c,a}}$ is the ratio of the mean mass stopping powers of graphite and air,

$\Pi\, k_i$ 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) for the BIPM are given in [3] together with their uncertainties, the combined relative standard uncertainty being 2.9×10^{-3}. The uncertainty budget is shown in Table 1.

At the LSDG, the absorbed dose to water D is determined from

$$D_{\mathrm{w,\,LSDG}} = c_{\mathrm{w}} \cdot \Delta T_{\mathrm{w}} \cdot k_{\mathrm{c}} \cdot k_{\mathrm{sc}} \cdot k_{\mathrm{dd}} \cdot \frac{1}{1-h}\,, \qquad (2)$$

where

c_{w} is the specific heat capacity of water at the calorimeter operating temperature of 4 °C

ΔT_{w} is the temperature rise measured using two calibrated thermistors and a balancing resistor in a one-armed AC bridge

k_{c} is the correction factor for conductive heat flow

k_{sc} is the correction factor for changes in absorbed dose to water due to the perturbation of the radiation field by non-water materials (scatter correction)

k_{dd} is the correction factor for the non-homogeneity of the lateral dose distribution

h is the correction for the chemical heat defect of water.

The design and operation of the calorimeter are described in [2]. The components of uncertainty, giving a combined relative standard uncertainty of 6.6×10^{-3}, are given in Table 2.

The standard of absorbed dose to water at the LSDG is maintained through the use of a secondary standard consisting of three NE2571-type ionization chambers calibrated directly against the water calorimeter. The uncertainty of this determination is shown in Table 3.

Table 1. Physical constants, correction factors and relative standard uncertainties for the BIPM ionometric standard of 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)]
$\bar{s}_{c,a}$	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
$(1+\varepsilon)_{w,c}$ (dose to kerma ratio)	1.0015	–	0.06
k_{ps} (PMMA[(4)] envelope)	0.9999	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 relative standard uncertainty of $D_{w,BIPM}$		0.29	

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

Absorbed dose is determined at the BIPM under conditions defined by the Consultative Committee for Ionizing Radiation (CCRI), previously known as the CCEMRI [4]:

- 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 x 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,
- the reference depth in water is 5 g cm^{-2}.

Table 2. Relative standard uncertainties for the LSDG calorimetric standard of absorbed dose to water

Source of uncertainty	LSDG Value	LSDG relative standard uncertainty	
		100 s_i	100 u_i
Bridge calibration	–	0.20	–
Reproducibility of calorimeter response	–	0.20	–
Thermistor calibration	–	–	0.15
Thermistor positioning	–	–	0.13
k_c heat flow correction factor(*)	1.0016 to 1.0038	–	0.25
k_{sc} scatter correction factor(*)	0.9999 to 1.0010	–	0.04
k_{dd} lateral dose distribution correction factor	1.0003	–	0.01
h chemical heat defect	1.0000	–	0.50
Quadratic summation		0.28	0.59
Combined relative standard uncertainty of $D_{w,LSDG}$		0.66	

(*) Values for different sealed-water vessels in the water calorimeter

Table 3. Relative standard uncertainties for the maintenance of the secondary standards of absorbed dose to water at the LSDG

Source of uncertainty	LSDG Value	LSDG relative standard uncertainty	
		100 s_i	100 u_i
D_w determination	–	0.28	0.59
Transfer standard measurements	–	0.05	–
Transfer standard position	–	–	0.13
k_{dd} lateral dose distribution correction factor	1.0005	–	0.02
k_{PT} temperature and pressure normalization	–	–	0.04
k_{ion} ion recombination correction factor	1.0012	–	0.05
k_{pol} polarity correction factor	1.0006	–	0.02
Quadratic summation		0.28	0.61
Combined relative standard uncertainty in transfer of $D_{w,LSDG}$		0.68	

The reference conditions at the LSDG differ from those of the BIPM, in that the source to reference plane distance is 75 cm and the field size at the reference plane is 12 cm × 12 cm. The effect of these differences on the comparison result should be small and is neglected.

3. The transfer chambers and their calibration

The comparison of the LSDG and BIPM standards was made indirectly using the calibration factors N_{D_w} for the two transfer chambers given by

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

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

The value of $\dot{D}_{\mathrm{w,LSDG}}$ used for the comparison is the mean of measurements made over a period of 28 months using the secondary standard calibrated directly against the primary standard. The value is corrected to the date and time of 1999-09-01 0 h local time as is the current I_{LSDG} of the transfer chambers. The value for the half life of ^{60}Co of 1925.5 d, σ = 0.5 d as recommended by the IAEA [5] is used at both laboratories.

The $\dot{D}_{\mathrm{w,BIPM}}$ value is the mean of measurements made over a period of three months before and after the comparison. By convention it is given at the reference date of 1999-01-01, 0h Universal Coordinated Time, as is the value of I_{BIPM} .

The two transfer chambers from the LSDG are NE2571 ionization chambers with serial numbers 2588 and 2923. Their main characteristics are listed in Table 4. These chambers were calibrated at the LSDG during the month of September 1999, immediately before and after the measurements at the BIPM. The statistical uncertainty of the mean LSDG calibration factor for each chamber is about 3×10^{-4}.

The experimental method for calibrations at the LSDG is described in [6] and that for the BIPM in [7]. At each laboratory the chambers were positioned with the stem perpendicular to the beam direction and with the appropriate markings on both chamber and envelope (engraved lines) facing the source.

A collecting voltage of 240 V (negative polarity), supplied at each laboratory, was applied to each chamber at least 30 minutes before measurements were made. No polarity correction was applied at either laboratory. Neither was a correction for recombination applied at either laboratory. The volume recombination is negligible at an air kerma rate of less than 10 mGy s^{-1} and the loss due to initial recombination will be the same in the two laboratories.

Table 4. Characteristics of the transfer chambers type NE 2571

Characteristic		Serial No. 2588, 2923
		Nominal value / mm
Dimensions	Inner diameter	6.4
	Wall thickness	0.38
	Cavity length	24.0
	Tip to reference point	14.5
Electrode	Diameter	1.0
Volume	Air cavity	0.69 cm^3
Wall	Material	graphite
	Density	1.8 g cm^{-3}
Applied voltage	Negative polarity	240 V

The charge Q collected by each transfer chamber was measured using electrometers, a Keithley 642 at the BIPM and a PTW DCI8500 electrometer at the LSDG. The chambers were irradiated for at least 30 minutes before any measurements were made.

The ionization current measured by each transfer chamber was corrected for the leakage current, the correction being less than 0.01 % in all cases. During a series of measurements, the water temperature was stable to better than 0.02 °C at the LSDG and better than 0.01 °C at the BIPM. The ionization current was corrected to 293.15 K and 101.325 kPa.

The relative standard uncertainty of the mean ionization current, measured with each transfer chamber over the period of the comparison, was typically 3×10^{-4} at the LSDG (four series of 20 measurements for each chamber) and 10^{-4} at the BIPM (three series of 30 measurements for each chamber).

As humidity is controlled at (50 ± 5) % at both the BIPM and the LSDG, no correction for humidity needs to be applied to the ionization current measured. No correction was made at the BIPM for the radial non-uniformity of the beam over the section of the transfer chambers. In the BIPM beam, the correction factor for this chamber type is less than 0.01 % [8]. At the LSDG a correction of 0.03 % was applied.

Both laboratories use a horizontal beam of radiation and the thickness of the PMMA front window has been accounted for as a water-equivalent thickness in g cm^{-2} in the positioning of the chamber. In addition, the BIPM applies a correction factor k_{pf} (0.9996) which accounts for the non-equivalence to water of the PMMA in terms of interaction coefficients.

4. Results of the comparison

Table 5 lists the relevant values for $N_{D,\mathrm{w}}$ together with the results of the comparison, $R_{D,\mathrm{w}}$, expressed in the form

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

The comparison result is taken as the mean value for both transfer chambers, $R_{D,\mathrm{w}}$ = 0.9948, with a combined standard uncertainty of 0.0075. Contributions to the relative standard uncertainty of $N_{D,\mathrm{w\ lab}}$ are listed in Table 6. The two laboratories determine absorbed dose by methods that are quite different and not correlated. The uncertainty of the result of the comparison is obtained by summing the uncertainties of $\dot{D}_{\mathrm{w,BIPM}}$ and $\dot{D}_{\mathrm{w,LSDG}}$ in quadrature, together with other contributions arising from the use of transfer standards. Thus the uncertainty of $R_{D,\mathrm{w}}$ arises from the uncertainties in the different methods used, in the chamber positioning and in the ionization currents measured by the transfer chambers at the two laboratories. The difference (3×10^{-4}) between $R_{D,\mathrm{w}}$ for the two chambers is compatible with its statistical uncertainty (3×10^{-4}).

Table 5. Results of the comparison

NE 2571 Chamber	$N_{D,\mathrm{w\ LSDG}}$ / Gy µC^{-1}	$N_{D,\mathrm{w\ BIPM}}$ / Gy µC^{-1}	$R_{D,\mathrm{w}}$	u_c (1)
2588	45.124	45.357	0.9949	0.0075
2923	44.949	45.191	0.9946	0.0075
Mean values			0.9948	0.0075

(1) combined standard uncertainty of $R_{D,\mathrm{w}}$

5. Discussion

While the transfer chambers were at the BIPM, the opportunity was taken to calibrate them in terms of air kerma in the ^{60}Co beam. The values for the calibration factor N_K measured at the LSDG for these chambers are also known and the ratio $N_{K,\mathrm{LSD}} / N_{K,\mathrm{BIPM}}$ obtained for each chamber is 1.0055. As this result is significantly higher than all other NMI comparisons of air kerma it could indicate that a direct comparison with the LSDG of air kerma standards may be prudent. Indeed it is interesting to note that as a result of this comparison 0.3 % of the difference in the air kerma calibration factors at the LSDG and the BIPM was traced to a pre-existing transcription error in the LSDG chamber wall correction factor.

Table 6. Estimated relative standard uncertainties of the calibration factor, $N_{D,\mathrm{w\,lab}}$, of the transfer chambers and of $R_{D,\mathrm{w}}$

	LSDG		BIPM	
Relative standard uncertainty of	100 s_i	100 u_i	100 s_i	100 u_i
Absorbed dose rate to water	0.28	0.59	0.20	0.21
Use of laboratory standard	0.05	0.15	–	–
Ionization current of each transfer chamber	0.03	0.04	0.01	0.02
Distance	–	0.01	–	0.02
Depth in water	–	0.13	–	0.10
Relative standard uncertainties of $N_{D,\mathrm{w\,lab}}$				
Quadratic summation	0.29	0.62	0.20	0.23
Combined uncertainty	0.69		0.31	
Relative standard uncertainties of $R_{D,\mathrm{w}}$	100 s		100 u	
Quadratic summation	0.35		0.66	
Combined uncertainty	0.75			

The measurements made in air and in water can also be used to check the stability of the two transfer chambers. The relative difference in calibration factors between the two chambers when calibrated in air is 40×10^{-4} in relative value at the BIPM and at the LSDG. This difference between the two chambers remains when calibrated in water (37×10^{-4} and 39×10^{-4} respectively). These results confirm the stability of the transfer chambers and the standards.

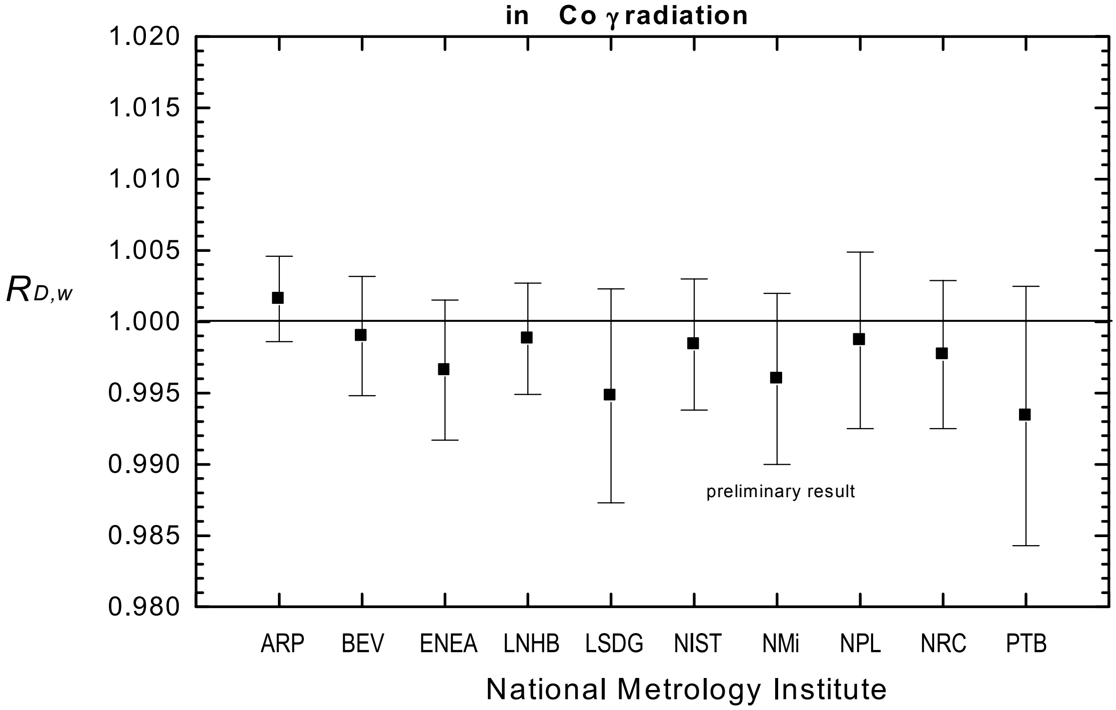
The ratio of $N_{D,\mathrm{w}}/N_K$ at the BIPM for each chamber is 1.098, which is compatible with other measurements at the BIPM for NE2571 thimble-type transfer chambers [9].

6. Conclusions

The primary standards of absorbed dose to water of the LSDG (Belgium) and the BIPM are in agreement, (R_{LSD} = 0.9948, u_c = 0.0075) within the comparison uncertainties. The result will be used as the basis for an entry to the BIPM key comparison database and the determination of degrees of equivalence between the ten national metrology institutes (NMIs) which have made such comparisons. The distribution of the results of the BIPM comparisons for these ten NMIs has a standard uncertainty of 2.4×10^{-3}.

Figure 1 shows the results of these comparison between each NMI and the BIPM [10 - 14]. The uncertainties shown on the graph are the standard uncertainties for each comparison result. When the same methods are used there are correlations between the results which need to be taken into account when comparing one NMI with another. It is interesting to note that the NIST, the NRC and the LSDG each has a water calorimeter as its primary standard. The largest correlated uncertainty between these results is that due to the chemical heat defect of water. Removing the correlations due to the heat defect (3×10^{-3} to 5×10^{-3}) and to the BIPM standard (2.9×10^{-3}) in each comparison and taking the other uncertainties into account, the combined standard uncertainty of the difference between each pair of the laboratories reduces to between 3.5×10^{-3} and 5.6×10^{-3}. The agreement between each pair of the three laboratories is within the appropriate combined uncertainty.

Figure 1. International comparison of absorbed dose to water standards in ^{60}Co γ radiation



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