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

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Abstract
A comparison of the standards of absorbed dose to water of the Swiss Federal Office of Metrology and Accreditation (METAS), Switzerland and of the Bureau International des Poids et Mesures (BIPM) has been made in ^{60}Co gamma radiation. The results show that the METAS and the BIPM standards for absorbed dose to water are in agreement, yielding a comparison result of 1.0001 for the mean ratio of the calibration coefficients for the transfer chambers, the difference from unity being within the combined standard uncertainty (0.0054).

1. Introduction

An indirect comparison of the standards of absorbed dose to water of the Office (METAS) 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 November 2000. This absorbed dose to water comparison is the first such comparison made between the two laboratories.

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

This comparison was undertaken using four ionization chambers belonging to the METAS as transfer instruments. 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.

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 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 [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 METAS, the absorbed dose to water D_{w} is determined from

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

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 [2]. The correction factors applied to the standard are described below and the components of uncertainty are indicated in Table 2, giving a combined relative standard uncertainty of 4.1×10^{-3}.

The absorbed dose to water at the METAS is maintained through the use of a series of secondary standard ionization chambers calibrated directly against the water calorimeter.

There are four correction factors, k_i, to be applied in (2) as follows:

Conductive heat flow correction factor, k_{c}.
There are two possible sources of conductive heat flow in the sealed water calorimeter. The specific heat capacity of glass is only about one fifth that of water. Consequently, radiation energy deposited in the glass walls of the vessel and of the thermistor probes will be transferred as heat to the water. There is a decrease in temperature immediately after the cessation of irradiation caused by excess heat conducted away from the thermistor probes into the water. Some minutes later there is an increase in temperature due to excess heat from the vessel arriving at the probes. These effects result in a relative correction of about 10^{-3}. The second source of conductive heat loss is that driven by temperature differentials because of dose gradients. The conductive heat flow correction factor has a calculated value k_{c} of 0.9982 (0.0015).

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 for the product of $(W/e)\bar{s}_{c,a}$.
(4) PMMA is the acronym for polymethylmethacrylate

Radiation field perturbation correction factor, k_p:
The presence of the vessel and probes perturbs the radiation field. This effect was measured using a SCX Si-diode to be 1.0021 (0.0005) for ^{60}Co.

Beam profile non-uniformity correction factor, k_{bp}:
The beam profile in the plane perpendicular to the radiation beam axis was measured using a SCX Si-diode. Since the two sensing thermistors are separated on either side of the reference point, a k_{bp} of 0.9996 is required to obtain the dose on the axis. The relative uncertainty in k_{dd} is estimated to be less than 2×10^{-4}.

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

Source of uncertainty	METAS Value	METAS relative standard uncertainty	
		100 s_i	100 u_j
Thermistor calibration	–	0.20	–
Thermistor positioning (depth in water)	–	–	0.10
Specific heat of water / (J g^{-1} K^{-1})	4.2048	–	0.01
k_c heat flow by conduction	0.9982	–	0.15
k_p field perturbation	1.0021	0.05	–
k_{bp} beam profile	0.9996	–	0.02
Chemical heat defect, h	0	–	0.30
Source to surface distance	–	–	0.03
Measurement of ΔT (n = 160)	–	0.06	–
Quadratic summation		0.21	0.35
Combined relative standard uncertainty in $D_{w,METAS}$		0.41	

Thermal heat defect of water correction factor, $(1-h)^{-1}$:
Various models have been used to simulate the chemistry occurring in aqueous solutions. Water saturated with N_2 or H_2 gas is used in the calorimeter because these solutions are calculated to have h equal to zero after a small accumulated dose, regardless of the model used. The relative uncertainty in the heat defect correction is taken as 3×10^{-3}.

Reference conditions

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

The reference conditions at the METAS are the same as those at the BIPM. However, the experimental arrangement used to establish the absorbed dose via water calorimetry and that used to disseminate the dose are not identical. Water calorimetry is performed in a small cubic tank of side length 30 cm. The source to reference distance is 100 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 10 cm × 10 cm. There is 11.2 cm of Styrofoam insulation in the beam path outside the tank that is not included in the 5 g·cm^{-2} but is the same for reference and transfer measurements.

The value of $\dot{D}_{\mathrm{w,METAS}}$ used for the comparison is the mean of measurements made over a period of four months before and two months after the measurements at the BIPM. The value is normalized to the date and time of 1999-07-01 T 00:00:00 Coordinated Universal Time (UTC) as is the ionization current of the transfer chambers (using the IAEA weighted mean half-life value of 1925.5 d, σ = 0.5 d for ^{60}Co [5]).

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 2000-01-01 T 00:00:00, UTC as is the value of the ionization current, using the same half-life as above.

3. The transfer chambers and their calibration

The comparison of the METAS and BIPM standards was made indirectly using the calibration coefficients $N_{D,\mathrm{w}}$ for the four 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 water absorbed dose rate and I_{lab} is the ionization current of a transfer chamber measured at the METAS or the BIPM. The current is corrected for the effects and influences described in this section.

The transfer chambers are two NE2571 ionization chambers belonging to the METAS with serial numbers 2806 and 2807, and two NE2611A ionization chambers with serial numbers 129 and 147. Their main characteristics are listed in Table 3. These chambers were calibrated at the METAS before and after the measurements at the BIPM.

The experimental method for calibrations at the METAS 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 or serial numbers) facing the source.

A collecting voltage of 250 V (negative polarity), supplied at each laboratory, was applied to each chamber at least 30 min before measurements were made. No corrections were applied at either laboratory for polarity or recombination. Volume recombination is negligible at an air kerma rate of less than 15 mGy s^{-1} for these chambers at this polarizing voltage, and the initial recombination loss will be the same in the two laboratories.

Table 3. Characteristics of the METAS NE transfer chambers

Characteristic/Nominal values		NE2571	NE2611A
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	14.5 mm	5 mm
Electrode (Al)	Length	21.0 mm	6.4 mm
	Diameter	1.0 mm	1.7 mm (hollow)
Volume	Air cavity	0.69 cm^3	0.325 cm^3
Wall	Material	graphite	graphite
	Density	1.7 g cm^{-3}	1.7 g cm^{-3}
Applied voltage	Negative polarity	250 V	250 V

The charge Q collected by each transfer chamber was measured using Keithley electrometers, model 642 at the BIPM and model 6517 at the METAS. The chambers were pre-irradiated for at least 10 min (≈ 10 Gy) at the METAS 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 METAS 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 was stable to better than 0.02 °C at the METAS 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.

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

At the METAS a correction was applied to the ionization current for the radial non-uniformity of the beam over the section of the transfer chambers. The correction factor for the NE2611A is 0.9998 and for the NE2571A 0.9999. A possible explanation for the values being less than unity is an inhomogeneity in the Styrofoam in front of the METAS standard. At the BIPM the corrections applied to the ionization current are 1.0003 for the NE 2611A and 1.0006 for the NE2571, each with an uncertainty of 2×10^{-4} [8].

Both laboratories use a horizontal beam of radiation and the thickness of the PMMA front window is included at the BIPM as a water-equivalent thickness in $g \cdot cm^{-2}$ 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. Individual waterproof sleeves of PMMA were supplied by the METAS for each chamber, 1.5 mm thick for the NE 2611A chambers and 1 mm thick for the NE 2571 chambers. The same sleeves were used at both laboratories and consequently no correction for the influence of each sleeve was necessary at either laboratory.

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

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 $\dot{D}_{\mathrm{w,METAS}}$, 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.

4. Results of the comparison

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

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

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

The comparison result is taken as the unweighted mean value for all four transfer chambers, $R_{D,\mathrm{w}} = 1.0001$ with a combined standard uncertainty for the comparison of 0.0054.

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

	METAS		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)	0.22	0.35	0.20	0.21
Ionization current of the transfer chambers	0.06	0.15	0.02	0.02
Distance	–	0.03	–	0.02
Depth in water	–	0.09	–	0.05
Relative standard uncertainties of $N_{D,\mathrm{w\,lab}}$				
quadratic summation	0.23	0.39	0.20	0.22
combined uncertainty	0.45		0.30	
Relative standard uncertainties of $R_{D,\mathrm{w}}$	100 s	100 u		
quadratic summation	0.30	0.45		
combined uncertainty, u_c	0.54			

Table 5. Results of the comparison

NE Chamber	$N_{D,\mathrm{wMETAS}}$ / Gy μC^{-1} pre-BIPM	$N_{D,\mathrm{w\,BIPM}}$ / Gy μC^{-1}	$N_{D,\mathrm{w\,METAS}}$ / Gy μC^{-1} post-BIPM	$N_{D,\mathrm{wMETAS}}$ / Gy μC^{-1} mean	$R_{D,\mathrm{w}}$	u_c
2806	45.36_8	**45.36_0**	45.34_1	**45.35_4**	**0.9999**	
2807	45.21_9	**45.24_1**	45.25_5	**45.23_7**	**0.9999**	
129	102.7_4	**102.6_3**	102.6_5	**102.6_9**	**1.0006**	
147	103.6_3	**103.6_6**	103.6_4	**103.6_4**	**0.9998**	
				Mean values	**1.0001**	**0.0054**

5. Discussion

The result of the present comparison of absorbed dose standards for ^{60}Co gamma radiation is $R_{D,\mathrm{w}}$ = 1.0001, u_c = 0.0054. The difference between the absorbed dose to water standards of the METAS and the BIPM is not significant given the combined uncertainty.

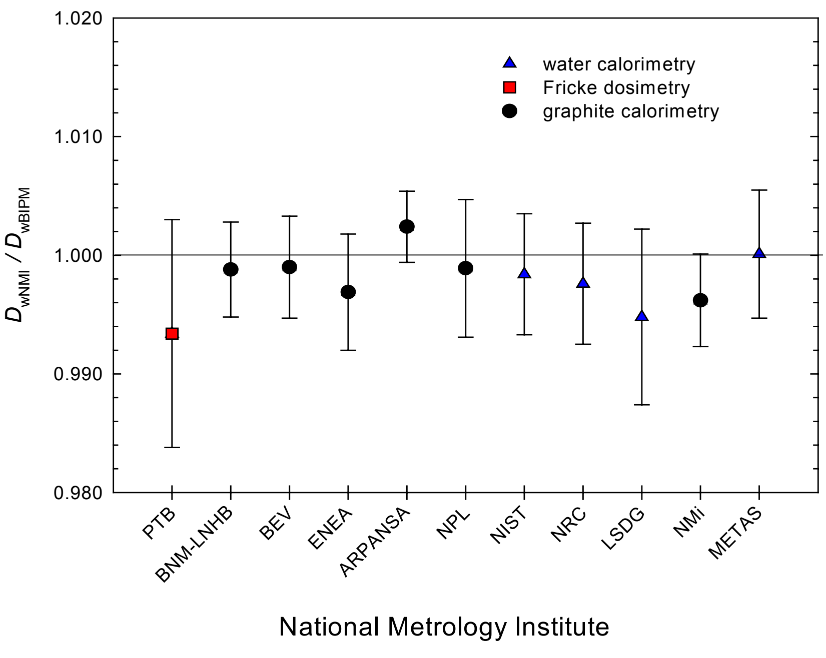
The transfer chambers were also calibrated in terms of air kerma in ^{60}Co at the BIPM. The measurements made in air and in water can be used to compare the relative responses of the transfer chambers. The ratio of $N_{D,\mathrm{w}}/N_K$ at the BIPM for the NE2571 chambers is 1.0981 and for the NE2611A chambers is 1.0901, 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 measured at the BIPM [9]. The coherence within each type of chamber confirms the stability of the chambers while at the BIPM.

6. Conclusions

The primary standards of absorbed dose to water of the METAS (Switzerland) and the BIPM are in agreement, ($R_{D,\mathrm{w}}$ = 1.0001, u_c = 0.0054) 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 for the eleven national metrology institutes (NMI) that have made such comparisons. The distribution of the results of the BIPM comparisons for these eleven NMIs has a standard uncertainty of 2.5×10^{-3}.

Figure 1 shows the results of the comparisons between each NMI and the BIPM [10 to 15] in chronological order since 1987. The uncertainties shown on the graph are the standard uncertainties for each comparison result. When similar methods are used, there are correlations between the results that need to be taken into account when comparing one NMI with another.

Figure 1 International comparison of absorbed dose to water



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