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Comparison of the standards of absorbed dose to water of the NRC, Canada 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 National Research Council of Canada (NRC) and of the Bureau International des Poids et Mesures (BIPM) has been made in ^{60}Co gamma radiation. The results show that the NRC and the BIPM standards for absorbed dose to water are in agreement, yielding a mean ratio of 0.9976 for the calibration factors of the transfer chambers, the difference from unity being within the combined standard uncertainty (0.0052).

1. Introduction

An indirect comparison of the standards of absorbed dose to water of the National Research Council of Canada (NRC) 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 1998. This absorbed dose to water comparison is the second such comparison made between the two laboratories, the first having been carried out in 1989 [1].

The primary standard of the NRC for absorbed dose is a Domen type [2] sealed water calorimeter as modified by Seuntjens [3] and described in [4]. The BIPM primary standard is a graphite cavity ionization chamber of pancake geometry [5].

This comparison was undertaken using four ionization chambers belonging to the NRC as transfer instruments. The result of the comparison is given in terms of the mean ratio of the calibration factors of the transfer chambers determined at the two laboratories under nearly 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 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, 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 shown in Table 1.

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

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

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 [4]. 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 NRC is maintained through the use of a series of secondary standard ionization chambers calibrated directly against the water calorimeter. Regular measurements to verify the dose are made using a Fricke dosimetry system whose G-value is determined by the water calorimeter [6].

There are five 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 0.9986 (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

Convective heat flow correction factor, k_v:
By operating the calorimeter at 4 °C, where the volume expansion coefficient is zero, convection can be avoided and k_v has the value unity. The relative uncertainty in k_v is less than 10^{-4}.

Radiation field perturbation correction factor, k_p:
The presence of the vessel and probes perturbs the radiation field. This effect was measured using a PTW-M233642 ionization chamber to be 1.0021 (0.0005) for ^{60}Co.

Dose profile non-uniformity correction factor, k_{dd}:
The dose profile in the plane perpendicular to the radiation beam axis was measured using a 0.125 cm^3 PTW ionization chamber. Since the two sensing thermistors are separated on either side of the reference point, a k_{dd} of 1.0004 is required to obtain the dose on the axis. The relative uncertainty in k_{dd} is estimated to be less than 10^{-4}.

Density of water correction factor, k_ρ:
Ionization chamber measurements are made at room temperature whereas the calorimeter is operated at 4 °C. Because the density of water increases by 0.22 % between 22 °C and 4 °C, there will be a greater mass thickness of water in front of the measurement point at 4 °C. Taking the dose gradient for ^{60}Co to be 5 % cm^{-1}, the extra attenuation at the calibration depth of 5 cm will be about 0.06 % leading to k_ρ = 1.0006. The relative uncertainty is taken to be less than 10^{-4}.

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

Source of uncertainty	NRC Value	NRC relative standard uncertainty	
		100 s_i	100 u_j
Thermistor calibration	–	0.20	–
Thermistor positioning	–	–	0.10
Specific heat of water / (J g^{-1} K^{-1})	4.2048	–	<0.01
k_c heat flow by conduction	0.9986	–	0.15
k_v heat flow by convection	1.0000	–	<0.01
k_p field perturbation	1.0021	0.05	–
k_{dd} lateral dose profile	1.0004	<0.01	–
k_ρ water density	1.0006	–	<0.01
Chemical heat defect, *h*	(3 systems)	–	0.30
Reproducibility of calorimeter response (n = 90)	–	0.06	–
Quadratic summation		0.21	0.35
Combined relative standard uncertainty in $D_{w,NRC}$		0.41	

Thermal heat defect of water correction factor, $(1-h)^{-1}$:
Various models have been used at the NRC 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. However, water saturated with hydrogen/oxygen gas has been used experimentally because it is insensitive to impurities. The latter system has a calculated heat defect, *h*, of about 0.024, and the value is slightly model-dependent. Simulations reveal similar heat

defects at 4 °C and 22 °C as are observed experimentally. 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 [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 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 NRC are similar to 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 surface distance is about 70 cm and the depth to the reference point in the tank is set to 5 g cm^{-2} including the PMMA window of 3 mm thickness. The field size at this reference point is 10 cm × 10 cm. There is an additional 5 cm of Styrofoam insulation in the beam path outside the tank, which is not included in the 5 g cm^{-2}. Ionization chambers were calibrated in the calorimeter tank and then used as the transfer to a larger tank for dissemination. In this larger calibration tank, the distance from the source to the plane at the inside front surface is nominally 1 m. At this plane, the field size in air is 10 cm × 10 cm as indicated above. The reference depth for the calibration of ionization chambers including the transfer chambers used in this comparison is 5 cm water plus a 3 mm PMMA window.

The value of $\dot{D}_{\mathrm{w,NRC}}$ used for the comparison is the mean of measurements made over a period of six months before and one month after the measurements at the BIPM. The value is normalized to the date and time of 1998-01-01 T00:00:00 Eastern Standard Time as is the ionization current of the transfer chambers (the half-life of ^{60}Co is taken as 1925.02 d, σ = 0.5 d [8]).
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 1998-01-01 T00:00:00 Universal Coordinated Time, as is the value of the ionization current (using the IAEA weighted mean half-life value of 1925.5 d, σ = 0.5 d for ^{60}Co [8]). The difference in the value of half-life used is not significant ($< 10^{-4}$) since each laboratory has made absolute measurements of absorbed dose within the preceding 2 years.

3. The transfer chambers and their calibration

The comparison of the NRC and BIPM standards was made indirectly using the calibration factors $N_{D,\mathrm{w}}$ 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 NRC or the BIPM. The current is corrected for the effects and influences described in this section.

The transfer chambers are NE2571 ionization chambers belonging to the NRC with serial numbers 1527, 2572, 2587 and 2595. Their main characteristics are listed in Table 3. These chambers were calibrated at the NRC immediately before and after the measurements at the BIPM.

Table 3 . Characteristics of the NRC NE 2571 transfer chambers

Characteristic		Nominal value
Dimensions	Inner diameter	6.3 mm
	Wall thickness	0.35 mm
	Cavity length	24.0 mm
	Tip to reference point	14.5 mm
Electrode (Al)	Length	21.0 mm
	Diameter	1.0 mm
Volume	Air cavity	0.69 cm^3
Wall	Material	graphite
	Density	1.7 g cm^{-3}
Applied voltage	Positive polarity	300 V

The experimental method for calibrations at the NRC is described in [9] and that for the BIPM in [10]. 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 300 V (positive polarity), supplied at each laboratory, was applied to each chamber at least 30 minutes before measurements were made. The mean polarity effect measured at the NRC is 1.0015 (0.0003) and this was confirmed by measurements at the BIPM. 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 this chamber type and polarizing voltage, and initial recombination loss will be the same in the two laboratories.

The charge Q collected by each transfer chamber was measured using Keithley electrometers, model 642 at the BIPM and model 35617 at the NRC. The chambers were pre-irradiated for at least 15 minutes before any measurements were made.

The ionization current measured from each transfer chamber was corrected for the leakage current, the correction being less than 0.01 % at both laboratories except for chamber 1527, which exhibited a leakage current of 0.03 % at the BIPM. During a series of measurements, the water temperature was stable to better than 0.02 °C at the NRC and better than 0.01 °C at the BIPM. The ionization current was corrected to 293.15 K and 101.325 kPa at both laboratories. (Note that for its disseminated standards, NRC uses a reference temperature of 295.15 K as indicated in [9].)

Relative humidity is controlled at (50 ± 5) % at the BIPM and at (50 ± 20) % at the NRC. Consequently, no correction for humidity is applied to the ionization current measured.

No correction was made for the radial non-uniformity of the beam over the section of the transfer chambers as there is no significant difference in uniformity between the two laboratories. In the BIPM, the correction factor for this chamber type when irradiated in the water phantom is 0.13 % [11]. Measurements in the water phantom at the NRC indicate a radial non-uniformity over the section of the transfer chambers that would result in a correction of 0.15 %.

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 cm^{-2} in the positioning of 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. A waterproof sleeve of 1 mm thick PMMA was supplied by the NRC and used at both laboratories for all the chambers. No correction for the influence of the sleeve was necessary at either laboratory as the same sleeve was used. If the same sleeve is not used in such a comparison, this should be taken into account (in terms of the sleeve material and thickness) as differences up to 0.15 % have been measured [12].

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 NRC, a single series of five repeated measurements each lasting about 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 NRC with a given transfer chamber over the three months required for this comparison was typically 3×10^{-4} and varied from 10^{-4} to 8×10^{-4} depending upon the particular chamber.

Contributions to the relative standard uncertainty of $N_{D,\mathrm{w\,lab}}$ are listed in Table 4. As the two laboratories determine absorbed dose by methods that are quite different and not correlated, the combined uncertainty of the result of the comparison is obtained by summing in quadrature the uncertainties of $\dot{D}_{\mathrm{w,BIPM}}$ and $\dot{D}_{\mathrm{w,NRC}}$, together with the contributions arising from the use of transfer chambers in terms of the ionization currents measured, in establishing the distance to the reference plane and in their depth positioning.

4. Results of the comparison

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

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

where the average value of measurements made at NRC 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 relative spread in the ratio $R_{D,\mathrm{w}}$ for the four chambers is 0.05 % with a statistical standard uncertainty, s_c of 0.02 %.

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

Relative standard uncertainty of	NRC 100 s_i	NRC 100 u_i	BIPM 100 s_i	BIPM 100 u_i
Absorbed dose rate to water (tables 1 and 2)	0.21	0.35	0.20	0.21
Ionization current of each transfer chamber	0.06	0.06	0.02	0.02
Distance	0.01	–	–	0.02
Depth in water	0.03	–	–	0.05
Relative standard uncertainties of $N_{D,\mathrm{w\ lab}}$				
quadratic summation	0.22	0.36	0.20	0.22
combined uncertainty	0.42		0.30	
Relative standard uncertainties of $R_{D,\mathrm{w}}$	100 s		100 u	
quadratic summation	0.30		0.42	
combined uncertainty, u_c	0.52			

Table 5. Results of the comparison

NE 2571 Chamber	$N_{D,\mathrm{w\ NRC}}$ / Gy µC^{-1} pre-BIPM	$N_{D,\mathrm{w\ BIPM}}$ / Gy µC^{-1}	$N_{D,\mathrm{w\ NRC}}$ / Gy µC^{-1} post-BIPM	$\overline{N_{D,\mathrm{w\ NRC}}}$ / Gy µC^{-1} mean	$N_{D,\mathrm{w\ NRC}}$ pre/post ratio	$R_{D,\mathrm{w}}$	u_c
1527	45.256	45.344	45.245	45.250	1.0003	0.9979	
2572	45.039	45.151	45.035	45.037	1.0001	0.9975	
2587	44.846	44.938	44.812	44.829	1.0008	0.9976	
2595	44.765	44.866	44.752	44.758	1.0003	0.9976	
				Mean values	+0.04 %	0.9976	0.0052

The comparison result is taken as the unweighted mean value for all four transfer chambers, $R_{D,\mathrm{w}}$ = 0.9976 with a combined standard uncertainty for the comparison of 0.0052. The statistical contribution to this uncertainty which arises from the use of transfer chambers is 0.11 %. Given that four chambers were calibrated at each laboratory a total of four times each (typically), the uncertainty on the mean value of $R_{D,\mathrm{w}}$ in this comparison should be a factor of ($1/\sqrt{15}$) lower than 0.11 % or about 0.03 %. The observed statistical uncertainty of $R_{D,\mathrm{w}}$ of 0.0002 is compatible with this expected value.

5. Discussion

The result of the present comparison of absorbed dose standards for ^{60}Co gamma radiation is 0.9976, u_c = 0.0052. The difference between the absorbed dose to water standards of the NRC and the BIPM is not significant given the combined uncertainty.

In the previous comparison in 1989, the NRC was using a stirred-water calorimeter operated in a 20 MV photon beam as the basis for its absorbed dose to water standard. The value of the chemical yield, G for the NRC Fricke dosimetry system was determined for this 20 MV beam. With the assumption that G is independent of energy and after application of a correction factor for the perturbation produced by the walls of its quartz vials, the Fricke system was used to transfer the reference dose to a point in the ^{60}Co beam. That comparison produced a result of 0.9930, u_c = 0.0096 with a statistical uncertainty in the measurements of 0.0021[1]. The reduction in the combined uncertainty for the present comparison by almost a factor of two arises from the smaller uncertainty for the NRC standard based on the sealed water calorimeter compared to the less direct method using the stirred water calorimeter and Fricke dosimetry. The improvement by a factor of ten in the statistical uncertainty in the result of the comparison (0.0002 now versus 0.0021 previously) probably comes from using four chambers of the same type rather than only three chambers of two types and a general improvement in the ability to perform comparisons with the NRC absorbed dose to water standard.

As a result of changing the basis of its standard to one using the sealed water calorimeter only, the NRC anticipated the result of the present comparison to be a factor of 1.0033 times larger than the previous value, i.e., 0.9963. (It is possible to maintain a standard of absorbed dose to water with greater precision than it is to determine the standard initially.) These two results, 0.9976 (s_c = 0.0002) in 1998 and 0.9963 (s_c = 0.0021) as modified from 1989, differ by 0.13 %, which is within the combined statistical uncertainty of the comparisons. This indicates consistency of the NRC and the BIPM standards with time.

The transfer chambers were also used for an indirect comparison in terms of air kerma in ^{60}Co. The comparison result given by the ratio $N_{K\,\mathrm{NRC}}/N_{K\,\mathrm{BIPM}}$ averaged for the four chambers is 1.0020, u_c = 0.0031 with a statistical uncertainty s_c = 0.0005 [13]. The measurements made in air and in water can also be used to compare the relative responses of the transfer chambers. The ratio of $N_{D,\mathrm{w}}/N_K$ for each chamber is 1.0985 (s_c = 0.0002) at the BIPM. This value is compatible with other measurements for NE 2571 thimble-type transfer chambers at the BIPM [14] and the low statistical uncertainty confirms the stability of the four chambers. At the NRC, the value for the same ratio is 1.0938 (s_c = 0.0006), being compatible with other measurements for NE 2571 chambers made at the NRC [15]. The higher statistical uncertainty arises mainly from chamber 1527 measurements made in air [13].

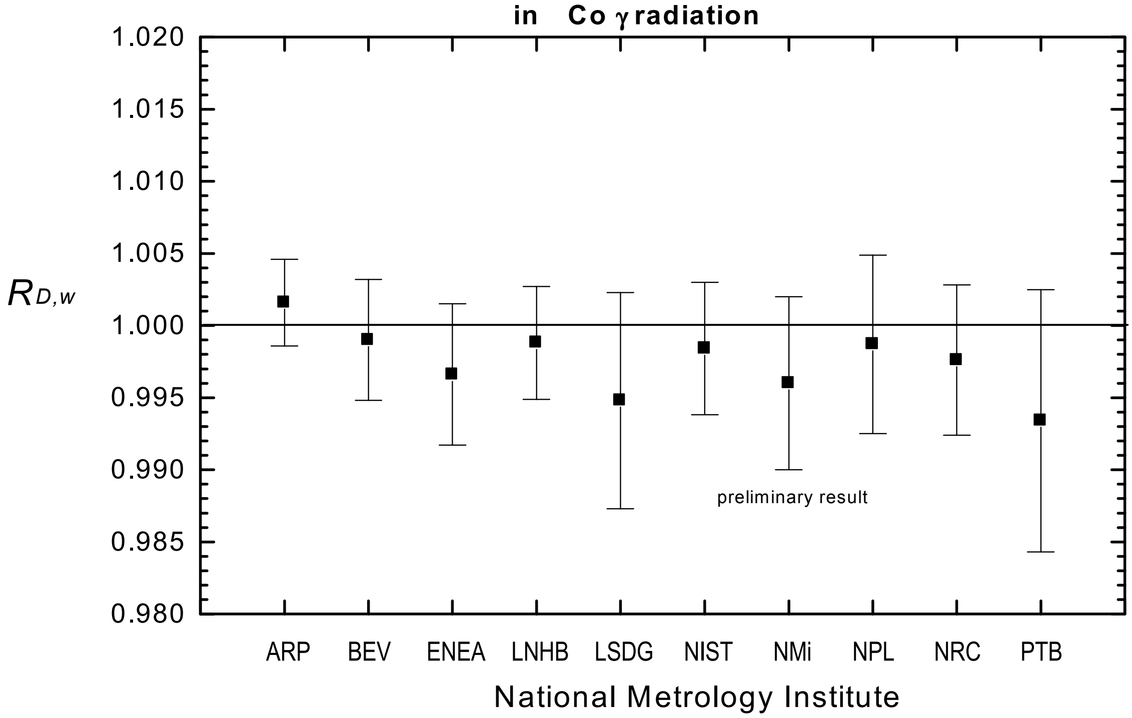
This difference between the NRC and the BIPM of 0.42 % in the ratio of $N_{D,\mathrm{w}}/N_K$ reflects the differences between the two laboratories' primary standards of air kerma (+ 0.20%) and of absorbed dose (– 0.24%). The secondary and tertiary laboratories that use standards traceable to those of the NRC or the BIPM will find similar differences if they in turn make comparisons of their reference dosimetry standards.

6. Conclusions

The primary standards of absorbed dose to water of the NRC (Canada) and the BIPM are in agreement, ($R_{D,w}$ = 0.9976, u_c = 0.0052) 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 the comparison between each NMI and the BIPM [16 - 20]. 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 which need to be taken into account when comparing one NMI with another.

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



References

[1] SHORTT K.R., ROSS C.K., SCHNEIDER M., HOHLFELD K., ROOS M., PERROCHE A.-M., A comparison of absorbed dose standards for high-energy x-rays, *Phys. Med. Biol.* 1993, **38**, 1937-1955.

[2] DOMEN S.R., A sealed water calorimeter for measuring absorbed dose, *J. Res. Nat. Bur. Stand.*, 1994, **99**, 121-141.

[3] SEUNTJENS J.P., Comparative study of ion chamber dosimetry and water calorimetry in medium energy x-ray beams, Ph.D. thesis, 1991, Gent University, Gent, Belgium.

[4] SEUNTJENS J.P., ROSS C.K., KLASSEN N.V., SHORTT K.R., A status report on the NRC sealed water calorimeter, NRC Report PIRS-0584, 1999, National Research Council, Ottawa, Canada.

[5] BOUTILLON M., PERROCHE A.-M., Ionometric determination of absorbed dose to water for cobalt-60 gamma rays, *Phys. Med. Biol.*, 1993, **38**, 439-454.

[6] KLASSEN N.V., SHORTT K.R., SEUNTJENS J., ROSS C.K., Fricke dosimetry: The difference between G(Fe^{3+}) for ^{60}Co γ-rays and high energy x-rays, *Phys. Med. Biol.*, 1999, **44**, 1609-1624.

[7] BIPM, Constantes physiques pour les étalons de mesure de rayonnement, *BIPM Com. Cons. Etalons Mes. Ray. Ionisants*, 1985, Section (I) **11**, p. R45 (Paris : Offilib).

[8] IAEA, X- and gamma-ray standards for detector calibration, *IAEA-TEC-DOC-619*, 1991.

[9] SHORTT K.R. Calibration of ionization chambers in terms of air kerma and absorbed dose to water, *Proceedings of the IAEA Interregional Training Course on Calibration Procedures and Quality Assurance in Secondary Standard Dosimetry Laboratories*, held in Havana, Cuba, September 27 – October 8, 1999, (IAEA, Vienna), 9 pages.

[10] BOUTILLON M., Measuring conditions used for the calibration of ionization chambers at the BIPM, *Rapport BIPM-96/1*, 1996.

[11] BOUTILLON M., PERROCHE A.-M., Radial non-uniformity of the BIPM ^{60}Co beam, *Rapport BIPM-89/2*, 1989.

[12] ROSS C.K., SHORTT K.R., The effect of waterproofing sleeves on ionization chamber response, *Phys. Med. Biol.*, 1992, **37**, 1403-1411.

[13] ALLISY-ROBERTS P. J., BURNS D.T., SHORTT K.R., ROSS C.K., Comparison of the air kerma standards of the NRC and the BIPM for ^{60}Co γ rays, *Rapport BIPM-99/12*, 2000.

[14] ALLISY-ROBERTS P.J., Calibration of cavity chambers in the BIPM ^{60}Co beam (in preparation).

[15] SHORTT K.R., SHOBE J., DOMEN S.R., Comparison of dosimetry calibration factors at the NRCC and the NIST, *Med. Phys*., 2000, **27**, (in press).

[16] QUINN T.J., Results of recent international comparisons of national measurement standards carried out by the BIPM, *Metrologia*, 1996, **33**, 271-287.

[17] ALLISY-ROBERTS P. J., BOUTILLON M., BOAS J., HUNTLEY R., Comparison of the absorbed dose to water standards of the ARL and the BIPM for ^{60}Co γ rays, *Rapport BIPM-99/17*, 2000.

[18] ALLISY-ROBERTS P. J., BURNS, D.T., DUANE S., THOMAS R. Comparison of the absorbed dose standards of the NPL and the BIPM for ^{60}Co γ rays, *Rapport BIPM-2000/-*, (in preparation), 2000.

[19] ALLISY-ROBERTS P. J., BURNS D.T., PALMANS H. Comparison of the standards of absorbed dose to water of the LSDG, Belgium and the BIPM for ^{60}Co γ rays *Rapport BIPM-2000/01*, 2000.

[20] PIEKSMA M., VAN DIJK E., ALLISY-ROBERTS P.J., BURNS D.T. Comparison of the standards of absorbed dose to water of the NMi and the BIPM for ^{60}Co γ rays *Report NMi* (in preparation), 2000.

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