Rapport BIPM-98/5

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

by P.J. Allisy-Roberts* and J. Shobe**

*Bureau International des Poids et Mesures, F-92312 Sèvres Cedex, France
**National Institute of Standards and Technology, Gaithersburg, MD, USA.

Abstract
A comparison of the standards of absorbed dose to water of the National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA and of the Bureau International des Poids et Mesures (BIPM) has been made in ^{60}Co radiation. The results show that the NIST and the BIPM standards for absorbed dose to water agree, the difference being well within the estimated uncertainty.

1. Introduction

An indirect comparison of the standards of absorbed dose to water of the National Institute for Standards and Technology (NIST), Gaithersburg, USA, and of the Bureau International des Poids et Mesures (BIPM), was carried out in the ^{60}Co radiation beam at the BIPM in October 1997. The primary standard of the NIST for absorbed dose is a water calorimeter and is described in [1]. The BIPM primary standard is a graphite cavity ionization chamber of pancake geometry as described in [2].

The comparison was undertaken using two NIST ionization chambers as transfer instruments. 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.

The absorbed dose to water comparison is the first such comparison made directly between the two laboratories, the previous results in 1989 being based on two bi-lateral comparisons [3]. The NIST and BIPM standards agree closely, the difference being well within the estimated uncertainty and this comparison result is also in agreement with the result of 1989.

2. Determination of the absorbed dose to water

At the BIPM, the absorbed dose rate to water is determined from

$$\dot{D}_{\mathrm{BIPM}} = (I/m)(W/e)\bar{s}_{\mathrm{c,a}}\Pi k_{\mathrm{i}}, \qquad (1)$$

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 mean ratio of the stopping powers of graphite and air,
$\Pi\, k_{\mathrm{i}}$	is the product of the correction factors to be applied to the standard.

The values of the physical constants [4] and the correction factors entering in (1) for the BIPM are given in [5] together with their estimated uncertainties, the combined relative standard uncertainty being 0.43 %.

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

$$D_{\mathrm{NIST}} = (1/2)(\Delta R/R)\left|\bar{S}^{-1}\right|c, \qquad (2)$$

where

(1/2)	is the result of using two thermistors to measure the temperature rise,
$\Delta R/R$	is the measured fractional change in the Wheatstone bridge balancing resistor,
$\left\|\bar{S}\right\|$	is the mean sensitivity of the thermistors determined from their calibration data and
c	is the specific heat capacity of water at the calorimeter operating temperature. The heat defect of water is assumed to be negligible.

The design and operation of the calorimeter is described in [1] together with the components of uncertainty, giving a combined relative standard uncertainty of 0.35 %.

The comparison of the NIST and BIPM standards was made indirectly by means of the calibration factors $N_{D_{\mathrm{w}}}$ for the transfer chambers given by

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

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

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 source to reference plane at the centre of the detector is normally 1 m,
- the field size in air at the reference plane is 10 cm x 10 cm and the NIST uses 15 cm x 15 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 $g\cdot cm^{-2}$ at the BIPM and the NIST uses 5 cm.

The value of $\dot{D}_{\mathrm{w.NIST}}$ at 5 cm is derived from the last value measured using the primary standard (1/11/90) and corrected to the date of calibration (the half life of ^{60}Co is taken as 1 925.5 d, σ = 0.5 d [6]).

The $\dot{D}_{\mathrm{w.BIPM}}$ value is the mean of measurements that were performed at 5 $g\cdot cm^{-2}$ over a period of three months before and after this comparison. By convention it is given at the reference date of 1997-01-01, 0h Universal Coordinated Time as is the value of I_{BIPM} (using the same half-life of ^{60}Co as above).

The two laboratories determine absorbed dose by methods that are quite different and are not correlated. The uncertainty of the result of the comparison is obtained by summing in quadrature, the uncertainties of $\dot{D}_{\mathrm{w.BIPM}}$ and $\dot{D}_{\mathrm{w.NIST}}$, and other contributions coming from the indirect method of comparison.

3. The NIST transfer chambers

The two NIST transfer chambers are C552 air-equivalent, conducting plastic, cavity chambers manufactured by Exradin (Type A12 serial numbers 176 and 177)[1]. Their main characteristics are listed in Table 1. These chambers were calibrated periodically at the NIST over the past year. Their calibration factors vary by less than ± 0.1 % from their mean values.

The experimental method for calibrations at the NIST is described in [7] and that for the BIPM in [5]. The NIST has made measurements to confirm that the chambers have no directional sensitivity, and at each laboratory the chambers were located with the stem perpendicular to the beam direction.

[1] Certain commercial equipment and instruments are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the NIST, nor does it imply that the materials identified are necessarily the best available for the purpose.

A collecting voltage of 300 V (negative polarity), supplied at each laboratory, was applied to each chamber at least 30 minutes before measurements were made. The polarity effect (< 0.1 %) was checked by applying each polarity in turn to each transfer chamber. Some measurements were also made at half the normal applied voltage (150 V) to confirm that the value of the recombination effect was the same in each laboratory. The volume recombination is negligible at an air kerma rate of less than 10 mGy·s^{-1} and the initial recombination loss, which is independent of the air kerma rate, is the same as measured in the two laboratories. The value of N_{D_w} at 150 V compared with N_{D_w} at 300 V is 1.001 2 (standard uncertainty s = 0.000 1) at the BIPM and at the NIST it is 1.001 1 (s = 0.000 2). For simplicity, no correction for recombination was applied at either laboratory.

Table 1. Characteristics of the NIST transfer chambers

Chamber	Exradin A12	176 and 177
		Nominal value / mm
Dimensions	Inner diameter	6.1
	Wall thickness	0.5
	Cavity length	24.65
Electrode	Diameter	1.0
Volume	Air cavity	0.65 cm^3
Wall	Materials	C552 plastic
	Density	1.781 g·cm^{-3}
Applied voltage	Negative polarity	300 V

The charge Q collected by each transfer chamber was measured using the BIPM or the NIST electrometer as relevant. Chambers were preirradiated for at least 30 minutes before measurements began.

The ionization current measured from each transfer chamber was corrected for the leakage current, the correction being less than 0.02 % at both laboratories. During a series of measurements, the water temperature was stable to better than 0.02 °C at the NIST and better than 0.01 °C at the BIPM. The ionization current was normalized to 295.15 K and 101.325 kPa.

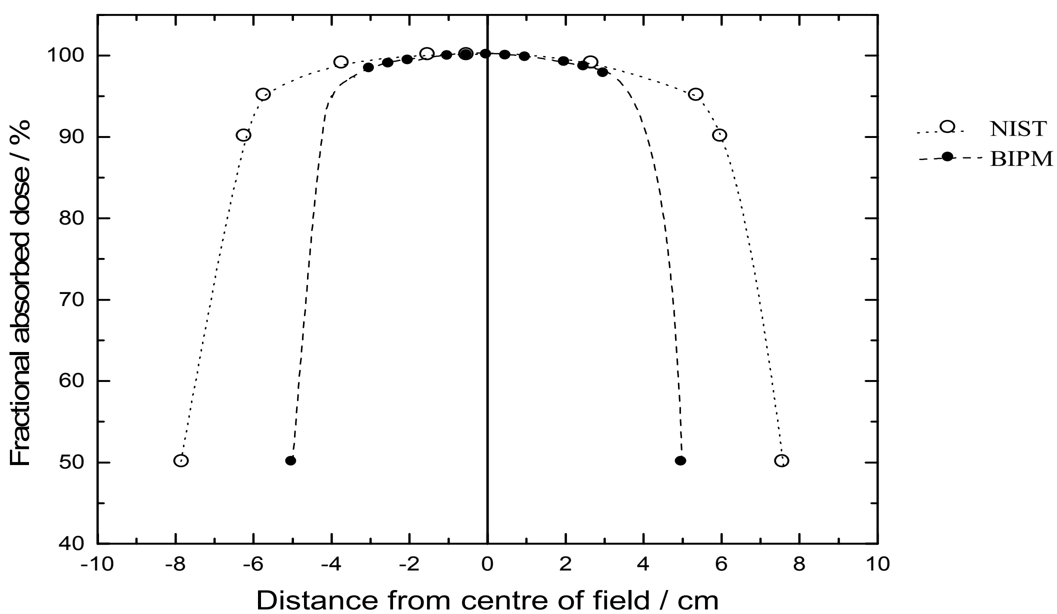
The relative standard deviation of the mean ionization current measured with each transfer chamber over the short period of calibration, was estimated to be 0.02 % (3 series of 50 measurements for each chamber) at the NIST and 0.02 % (4 series of 30 measurements for each chamber) at the BIPM.

As is usual, no correction for humidity was applied to the ionization current measured. No allowance was made for the radial non-uniformity of the beam over the section of the transfer chamber. In the BIPM beam, the correction factor for these chambers would be 1.000 2 [8] and even less at the NIST. Figure 1 shows the beam non-uniformity at the NIST and at the BIPM.

The BIPM uses a horizontal beam of radiation. Consequently a correction k_{pf} (0.04 %) which accounts for the non-equivalence of the perspex front face of the water phantom is applied to the standard and transfer chamber currents. The NIST uses a vertical beam and a correction of 0.34 % is applied to the primary standard for the presence of a lid over the water phantom.

As the calibration factor of a transfer chamber is independent of small changes in reference depth, no correction is needed for the fact that the BIPM reference depth is 5 g.cm^{-2} and that at the NIST is 5 cm; this difference is equivalent to a reference depth change of 0.1 mm of water which is not significant when $N_{D\mathrm{w}}$ is being measured.

Figure 1. Radial non-uniformity of ^{60}Co field at 5 cm in water



4. Results of the comparison

Table 2 lists the relevant values of $N_{\dot{D}_\mathrm{w}}$ together with the results of the comparison, $R_{\dot{D}_\mathrm{w}}$, expressed in the form

$$R_{\dot{D}_\mathrm{w}} = N_{\dot{D}_\mathrm{w\,NIST}} \big/ N_{\dot{D}_\mathrm{w\,BIPM}} \quad , \qquad (6)$$

Contributions to the relative standard uncertainty in $N_{\dot{D}_\mathrm{w}}$ are listed in Table 3. The uncertainty in $R_{\dot{D}_\mathrm{w}}$ is due to the uncertainties in the different methods used, in the depth positioning and the ionization currents measured by the transfer chambers at the two laboratories.

The comparison result is taken as the mean value for both transfer chambers, $R_{\dot{D}_\mathrm{w}}$ = 0.999 7, with a combined standard uncertainty equal to 0.006 0. The difference (0.13 %) between $R_{\dot{D}_\mathrm{w}}$ for the two Exradin chambers is compatible with its statistical uncertainty (0.05 %) but may include systematic effects (see Section 5).

Table 2. Results of the comparison

Chamber	$N_{\dot{D}_\mathrm{w,NIST}}$ / Gy µC^{-1}	$N_{\dot{D}_\mathrm{w,BIPM}}$ / Gy µC^{-1}	$R_{\dot{D}_\mathrm{w}}$	u_c [(1)]
Exradin 176	49.931	49.981	0.999 0	0.006 0
Exradin 177	50.122	50.107	1.000 3	0.006 0
mean values			0.9997	0.006 0

(1) standard uncertainty in R

Table 3. Estimated relative standard uncertainties* in the calibration factor, $N_{\dot{D}_\mathrm{w}}$, of the transfer chambers and on $R_{\dot{D}_\mathrm{w}}$

	NIST		BIPM	
Relative standard uncertainty in the measurement of	100 s_i	100 u_i	100 s_i	100 u_i
Absorbed dose rate to water	0.16	0.32	0.19	0.38
Co-60 decay	-	0.05	-	-
Ionization current of each transfer chamber	0.02	-	0.02	0.02
Field size and non-uniformity	0.06	0.20	-	-
Distance	0.01	-	-	0.02
Depth in water	0.01	-	-	0.10
Relative standard uncertainties in $N_{\dot{D}_\mathrm{w}}$				
quadratic summation	0.17	0.38	0.19	0.39
combined uncertainty	0.42		0.44	
Relative standard uncertainties in $R_{\dot{D}_\mathrm{w}}$		100 s	100 u	
quadratic summation		0.25	0.54	
combined uncertainty		0.60		

*s_i = relative standard uncertainty estimated by statistical methods, type A,
u_i = relative standard uncertainty estimated by other means, type B [9].

5. Discussion

The result of the present comparison of absorbed dose standards (0.999 7, u_c = 0.006 0) can be compared with that obtained in 1989. At that time, the result for the NIST, as determined through comparison of their water calorimeter standard with the NRCC (Canada) [3], gave a value relative to that of the BIPM of 1.001 9, with a combined standard uncertainty somewhat larger than 0.006 taking account of the transfer system used by the NRCC. The present result is consistent with that of 1989 but is more reliable because the comparison has been made directly between the NIST and the BIPM rather than through two bi-lateral comparisons.

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 of N_K measured at the NIST for these chambers are also known and the ratio N_K (NIST)/ N_K (BIPM) obtained for each chamber is equal to 0.997 5. This result may be compared with the latest NIST air kerma comparison result [10] of 0.998 0 in 1996. Since the statistical uncertainty associated with these ratios is 0.001 2, the agreement of these values is very good.

The measurements made in air and in water can also be used to compare the responses of the two transfer chambers. The actual difference between the two chambers when calibrated in air is 0.25 % at both the BIPM and the NIST. At the BIPM, the difference between the two chambers when calibrated in water remains 0.25 %, but is 0.38 % at the NIST. This equates to the comparison result difference of 0.13 % noted earlier in section 4.

Having obtained both N_K and N_D calibration factors for the two transfer chambers, it is interesting to compare these in the beams of the two laboratories. The ratio of N_D / N_K at the BIPM for each chamber is 1.102 0. At the NIST it is 1.103 7 for chamber 176 and 1.105 2 for chamber 177: this is compatible with the difference identified between the two chambers in the water phantom at the NIST. The BIPM result is compatible with other measurements at the BIPM for thimble-shaped transfer chambers of similar volume (e.g. NE 2571) [11].

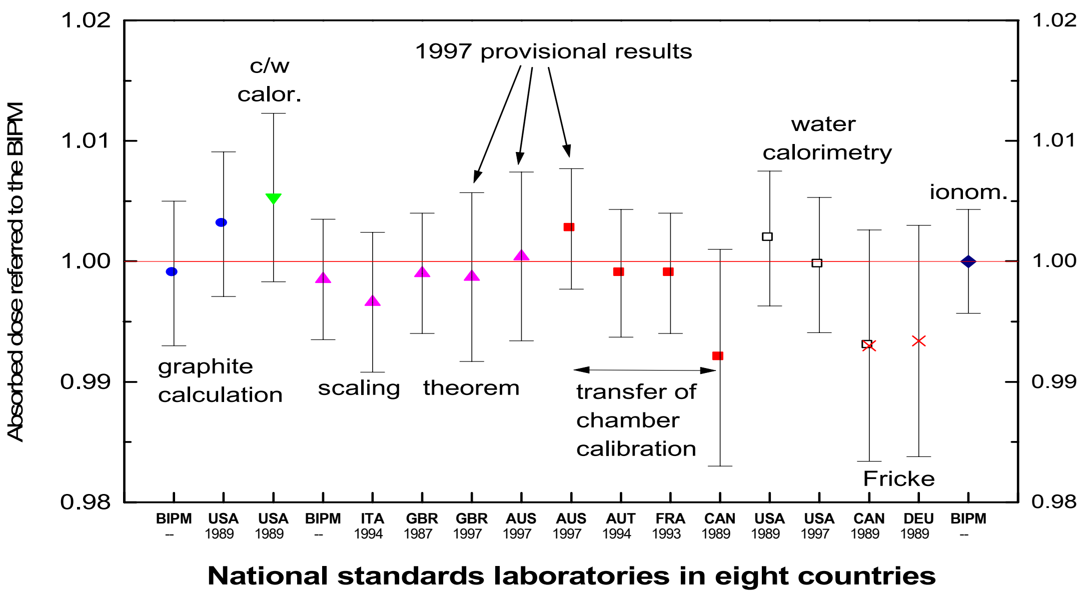
It is interesting to note that as a result of this comparison, after discussion and additional measurements at the NIST, a systematic difference in the calibration factor of more than 0.2 % was identified as being associated with a 1 mm change in the setting of the collimator jaws. This has resulted in a reassessment of the positioning procedure for absorbed dose to water measurements at the NIST, a consequent increase in the final value of $N_{\dot{D}_{\mathrm{w,NIST}}}$ and a reduction in the difference obtained in the earlier measurements for the two transfer chambers.

6. Conclusions

The standards are in very good agreement, ($R_{\dot{D}_\mathrm{w}}$ = 0.999 7, u_c = 0.006 0).

Figure 2 shows the results of all absorbed dose to water comparisons with the BIPM in ^{60}Co radiation [3, 12, 13 and 14]. The uncertainties indicated on the graph are the standard uncertainties for each of the comparison results. The agreement, much better than would be expected from the uncertainty of the individual results, can probably be attributed to partial correlations between the methods.

Figure 2 International comparison of absorbed dose to water



References

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

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

[3] BOUTILLON M., COURSEY B.M., HOHLFELD K., OWEN B. and ROGERS D.W.O. (1994), Comparison of primary water absorbed dose standards, in *Measurement Assurance in Dosimetry, IAEA-SM-330/48*, 1994, 95-111, IAEA, Vienna.

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

[5] BOUTILLON M. (1996), Measuring conditions used for the calibration of ionization chambers at the BIPM, *Rapport BIPM-96/1*, 1996, 19 pages.

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

[7] SHOBE J. and DOMEN S.R. (1998, in revision), Absorbed-dose calibration of ionization chambers in a ^{60}Co gamma-ray beam, *NIST Special Publication* 250-40, (in revision).

[8] BOUTILLON M. and PERROCHE A.-M. (1989), Radial non-uniformity of the BIPM ^{60}Co beam, *Rapport BIPM-89/2*, 1989, 9 pages.

[9] ISO (1993) *Guide to the expression of uncertainty in measurement*, International Standards Organization, Switzerland.

[10] ALLISY-ROBERTS P.J., BOUTILLON M. and LAMPERTI P.J. (1996), Comparison of the standards of air kerma of the NIST and the BIPM for ^{60}Co γ rays, *Rapport BIPM-96/9*, 1996, 8 pages.

[11] ALLISY-ROBERTS P.J. (1998), Calibration of cavity chambers in the BIPM ^{60}Co beam (in preparation).

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

[13] ALLISY-ROBERTS P. J., BOUTILLON M., BOAS J. and HUNTLEY R. (1998), (in prep) Comparison of the absorbed dose to water standards of the ARL and the BIPM for ^{60}Co γ rays, *Draft Rapport BIPM-98/E*, 1998, 11 pages.

[14] ALLISY-ROBERTS P. J., BOUTILLON M., DUANE S. and THOMAS R. (1998), (in prep) Comparison of the absorbed dose standards of the NPL and the BIPM for ^{60}Co γ rays, *Draft Rapport BIPM-98/F*, 1998, 14 pages.

(July 1998)