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

by Marc Pieksma and E. van Dijk
Nederlands Meetinstituut, Utrecht

D.T. Burns and P.J. Allisy-Roberts
Bureau International des Poids et Mesures, F-92312 Sèvres Cedex

Report S-TS-2001.01

Department of Temperature and Radiation
Utrecht, March 2001

NMi Van Swinden Laboratorium

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

Marc Pieksma* and E. van Dijk
NMi Van Swinden Laboratory, Department of Temperature and Radiation,
Princetonplein 1, 3584 CC Utrecht, The Netherlands

D.T. Burns and P.J. Allisy-Roberts
Bureau International des Poids et Mesures, Pavillon de Breteuil,
F-92312 Sèvres Cedex

Abstract An indirect comparison was carried out for the quantity absorbed dose to water between the Nederlands Meetinstituut (NMi) and the Bureau International des Poids et Mesures (BIPM). Calibration coefficients were determined for three NE2611A type ionization chambers under reference conditions in the ^{60}Co beams of both institutes. Measurements using a ^{90}Sr source served to check the stability of the chambers. Calibrations in terms of air kerma were also performed as an additional consistency check. The NMi calibration coefficients are 0.38 % lower than those of the BIPM. This is at the level of the relative standard uncertainty of the comparison, which is 3.8×10^{-3}.

1. Introduction

The quantity absorbed dose to water is of great importance in the field of radiotherapy, where the dose delivered to irradiated tumors during curative or palliative treatments should be known with high accuracy (1 %). Such high accuracy can only be ensured if the national standards are validated internationally. For this reason, comparisons of standards for absorbed dose to water are designated as key comparisons. This paper reports on the first such comparison between the NMi and the BIPM, which was carried out in January 2000 using three cavity ionization chambers as transfer standards.

As a consistency check, a simultaneous verification of the comparison of the standards for air kerma of the two institutes was performed, using the same transfer standards. The stability of the transfer standards was verified at the beginning and end of the comparison measurements at each institute using a portable ^{90}Sr check source of the NMi.

In this report the standard for absorbed dose to water of the BIPM, which is based on an ionometric technique, and that of the NMi, which is based on a measurement of absorbed dose to graphite and the application of a conversion method, are outlined. Then the experimental conditions under which the transfer standards were calibrated are described.

* E-mail address: mpieksma@nmi.nl

The air-kerma and check source measurements are briefly addressed. The results of the comparison are presented and compared with previous comparisons carried out between the BIPM and other national institutes. All quoted uncertainties are one standard uncertainty.

2. Determination of absorbed dose to water

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

$$\dot{D}_{\mathrm{w,BIPM}} = \frac{I}{m}\frac{W}{e}\bar{s}_{\mathrm{c,a}}\Pi k_{\mathrm{i}}\,, \tag{1}$$

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 stopping powers of graphite and air, and $\Pi\, k_{\mathrm{i}}$ 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 standard are given in [1] together with their uncertainties. The uncertainty budget is shown in Table 1. The combined relative standard uncertainty, taking the uncertainty of the product $(W/e)\,\bar{s}_{\mathrm{c,a}}$, is 0.29 %. The value for the rate of absorbed dose to water $\dot{D}_{\mathrm{w,BIPM}}$ at the reference date of 01/01/2000 is 3.111 mGy s^{-1}, u_c = 0.009 mGy s^{-1}.

The NMi standard for absorbed dose to water for ^{60}Co gamma radiation is based on the determination of absorbed dose to graphite using a graphite calorimeter. This calorimeter is of the Domen heat-loss-compensated design [2]. The photon-fluence scaling theorem [3 – 6] is applied to convert absorbed dose to graphite to absorbed dose to water. This theorem states that if Compton scattering is the dominant process, then the ratio of scattered to primary photons in two different homogeneous phantoms is equal if all dimensions are scaled in inverse proportion to the electron densities of the two media. Under conditions for which the theorem is valid, the ratio of the absorbed doses at corresponding points in water and graphite phantoms is given by [6]

$$\frac{D_{\mathrm{w}}}{D_{\mathrm{c}}} = \frac{\Psi_{(\mathrm{w})}}{\Psi_{(\mathrm{c})}}\frac{(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w}}}{(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{c}}}\frac{\beta_{\mathrm{w}}}{\beta_{\mathrm{c}}}\,, \tag{2}$$

where the subscripts w and c refer to water and graphite, respectively, $\Psi_{(\mathrm{w})}$ and $\Psi_{(\mathrm{c})}$ are the photon energy fluences at the corresponding points in the *absence* of the phantoms, $(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{w}}$ and $(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{c}}$ are the mean mass energy-absorption coefficients (averaged over the photon energy-fluence spectrum at the corresponding points), and β_{w} and β_{c} are the ratios of absorbed dose and the collision component of kerma.

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]	
		$100\ u_{iA}$	$100\ u_{iB}$
Dry air density [2] /(kg m^{-3})	1.293 0	–	0.01
W/e (J C^{-1})	33.97	–	0.11[3]
$\bar{s}_{c,a}$	1.003 0		
k_{cav} (air cavity)	0.990 0	0.03	0.04
$(\bar{\mu}_{en}/\rho)_{w,c}$	1.112 5	0.01	0.14
$\Psi_{w,c}$ (photon-fluence ratio)	1.006 5	0.04	0.06
$(1+\varepsilon)_{w,c}$ (dose-to-kerma ratio)	1.001 5	–	0.06
k_{ps} (PMMA envelope)	0.999 9	0.00_5	0.01
k_{pf} (phantom window)	0.999 6	–	0.01
k_{rn} (radial non-uniformity)	1.005 1	0.00_5	0.03
k_s (recombination losses)	1.001 6	0.00_4	0.01
k_h (humidity)	0.997 0	–	0.03
Volume of standard CH4-1 /cm^3	6.881 0	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 relative standard uncertainty $u(x_i)/\bar{x}_i$, estimated by statistical means, Type A; u_{iB} represents the relative standard uncertainty $u(x_i)/\bar{x}_i$ estimated by other means, Type B.

(2) At 0 °C and 101.325 kPa.

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

In practice, the NMi has chosen to evaluate both D_w and D_c at a reference distance of 1 m and a reference depth of 5 g cm^{-2} and therefore to fulfil the requirements of the scaling theorem, additional corrections are required. First, a measurement depth of 5 g cm^{-2} in water corresponds to a scaled measurement depth in graphite of 5.556 g cm^{-2}. Hence a

correction $k_{c,d}$ must be applied for the effect on the measured absorbed dose to graphite of the difference in the photon energy fluence spectrum in the graphite phantom at these two measurement depths. Second, D_w is determined at a reference distance of 1 m instead of the scaled distance, which is 1.670 m.[1] Consequently, a correction $k_{w,p}$ must be made for the difference in phantom scatter arising from the different radiation field sizes at these distances. Including these correction factors, the ratio of absorbed doses becomes

$$\frac{D_w}{D_c} = \frac{(\bar{\mu}_{en}/\rho)_w}{(\bar{\mu}_{en}/\rho)_c} \frac{\beta_w}{\beta_c} \frac{k_{c,d}}{k_{w,p}}, \tag{3}$$

where now the reference distance is 1 m and the reference depth 5 g cm^{-2} for both water and graphite. The correction factor for phantom scatter in water was determined experimentally by measuring the ratio of the response of an ionization chamber to ^{60}Co gamma radiation in the water phantom to that in air as a function of source-detector distance. Comparing these ratios at source-detector distances of 1 m (field size 10 cm × 10 cm) and 1.670 m (field size of 16.7 cm × 16.7 cm), yields $k_{w,p}$ = 1.041 8 ± 0.000 9. Based on the measured depth-dose profile in graphite, a correction for the measurement depth in graphite (at a fixed source-to-absorber distance of 1 m), $k_{c,d}$ = 0.983 94 ± 0.000 10, is applied. Each number following the symbol ± is the numerical value of the standard uncertainty u_c and not a confidence interval.

The ratio of the mass energy absorption coefficients was determined from values taken from the literature [7, 8] averaged over the photon energy-fluence distributions in water and graphite at 1 m distance and 5 g cm^{-2} depth. These distributions were obtained from Monte Carlo simulations. The result is

$$\frac{(\bar{\mu}_{en}/\rho)_w}{(\bar{\mu}_{en}/\rho)_c} = 1.113\,0 \pm 0.003\,0\,. \tag{4}$$

The ratio of absorbed dose and the collision component of kerma can be calculated using [1, 9]

$$\beta = 1 + \frac{\overline{\mu'}}{\rho}\rho\bar{x} + \frac{2}{z}\bar{x}, \tag{5}$$

where z is the distance from the source to the point of measurement (1 m), μ'/ρ is the effective total mass attenuation coefficient, and $\bar{x}$ is the mean distance secondary electrons carry kinetic energy downstream before depositing it as absorbed dose [9, 10]. The bars above the second and third terms on the right-hand side of (5) indicate that these quantities are averaged over the photon energy-fluence spectrum. The second term accounts for the attenuation of the photon beam over the distance $\bar{x}$, while the third term

[1] The scaled distance is obtained using a water density ρ_w = 0.996 9 g cm^{-3} (at 25 °C) [11] and a (measured) graphite density ρ_c = 1.85 g cm^{-3} [$u_c(\rho_c)/\rho_c$ = 1.4 × 10^{-2}] [12]. The corresponding electron densities are n_w = 3.332 4 × 10^{23} cm^{-3} and n_c = 5.565 4 × 10^{23} cm^{-3}.

accounts for the inverse-square dependence of the photon fluence with the distance from the source [1]. Effective mean mass attenuation coefficients are deduced from measured dose-depth curves, yielding $(\overline{\mu'/\rho})_w$ = (0.040 3 ± 0.000 9) $cm^2 g^{-1}$ and $(\overline{\mu'/\rho})_c$ = (0.028 8 ± 0.000 8) $cm^2 g^{-1}$. A small correction is made in evaluating the second term because the average value of the product is needed, not the product of average values. Numerical data for $\rho\bar{x}$ were taken from Figure 3 of Attix [9], averaged over the photon energy-fluence distributions. This yields $(\overline{\rho x})_w$ = 0.113 g cm^{-2} and $(\overline{\rho x})_c$ = 0.115 g cm^{-2}. Attix [9] gives results for two sets of calculations by Roesch [10] for the case of 6 MeV photons in aluminium. Based on these a Type B relative standard uncertainty of 0.25 is assumed for $\overline{\rho x}$. From (5), the values β_w = 1.006 6 and β_c = 1.004 5 are taken, giving

$$\frac{\beta_w}{\beta_c} = 1.002\,2 \pm 0.000\,6\ . \tag{6}$$

This value replaces the value of unity used previously and results in a relative increase in the NMi absorbed dose to water standard of 2.2×10^{-3}.

Photon interactions other than Compton scattering do not in general scale with the electron density, and weaken the validity of the scaling theorem. For example, in the low-energy tail of the photon spectrum the photoelectric effect can not *a priori* be neglected [13]. This deviation from the requirements of the scaling theorem can be accounted for by including a correction factor k_{dev} in (3), which is defined in terms of photon-energy fluences at corresponding points both inside (Ψ_w, Ψ_c) and in the absence of the phantoms $(\Psi_{(w)}, \Psi_{(c)})$ [6]:

$$\frac{\Psi_w}{\Psi_c} = \frac{\Psi_{(w)}}{\Psi_{(c)}} \frac{\exp(-\overline{\mu}d)_w}{\exp(-\overline{\mu}d)_c} \frac{S_w}{S_c} \equiv k_{dev} \frac{\Psi_{(w)}}{\Psi_{(c)}} \tag{7}$$

where d_w and d_c are the depths (again, at corresponding points in the phantoms), $\overline{\mu}_w$ and $\overline{\mu}_c$ the mean narrow beam attenuation coefficients, and S_w and S_c the scatter factors in water and graphite, respectively. The exponential terms in (7) represent attenuation factors. For the NMi setup it has been estimated that k_{dev} = 0.999 9 ± 0.000 9. Thus no significant deviation from the conditions required for the application of the photon-fluence scaling theorem is observed, and consequently no correction is made.

Table 2 gives the history of the rates of absorbed dose to graphite and absorbed dose to water determined at the NMi. A detailed uncertainty budget for the NMi absorbed dose standard is presented in the first two sections of Table 3. The average value for $\dot{D}_{w,NMi}$ of 7.476 mGy s^{-1} (statistical standard uncertainty 0.013 mGy s^{-1}) was used to calibrate the transfer chambers for the present comparison.

Table 2. History of the rates of absorbed dose to graphite and absorbed dose to water at the NMi. The dose rates are normalized to the reference date 01/01/95. The uncertainties represent one standard uncertainty.

Date	$\dot{D}_{c,NMi}$ /(mGy s^{-1})	$\dot{D}_{w,NMi}$ /(mGy s^{-1})
August 1995	7.114 ± 0.017	7.495 ± 0.031
October 1996	7.094 ± 0.017	7.474 ± 0.031
September 1997	7.087 ± 0.017	7.466 ± 0.031
October 1998	7.091 ± 0.017	7.471 ± 0.031

3. Experimental conditions

All three transfer standards used in the 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 +200 V with respect to the central electrode (at the NMi the thimble is grounded, whereas at the BIPM the central electrode is effectively at ground). The charge collected by the chambers was measured using either the BIPM or the NMi electrometer, as appropriate.

The calibration coefficient[2] for a transfer standard in terms of absorbed dose to water is defined by

$$N_{D_w,\mathrm{lab}} = \frac{\dot{D}_{w,\mathrm{lab}}}{I_{w,\mathrm{lab}}}, \tag{8}$$

where $\dot{D}_{w,\mathrm{lab}}$ is the rate of absorbed dose to water as determined by each laboratory and $I_{w,\mathrm{lab}}$ is the measured ionization current of the transfer chamber. A similar expression defines the air-kerma calibration coefficient $N_{K,\mathrm{lab}}$.

Both the NMi and the BIPM ^{60}Co beams are directed horizontally. All measurements (absorbed dose to water and air kerma) were performed at a reference distance (from source to chamber axis) of 1 m, with a field size of 10 cm by 10 cm at this distance. For measurements in water, both laboratories used a cubic water phantom of side length 30 cm, and the same protective waterproof sleeve for all chambers. The calibration coefficients were determined at a reference depth of 5 g cm^{-2}. For air-kerma measurements each transfer chamber has its own build-up cap.

[2] Recommended terminology [ISO 31-0] for what has been commonly referred to as the calibration factor.

Table 3. Relative standard uncertainties for calibrations in terms of absorbed dose to water for ^{60}Co gamma rays at the NMi.

	NMi relative standard uncertainty	
	100 u_{iA}	100 u_{iB}
1. Measurement of absorbed dose rate to graphite		
a. Long-term mean dose rate (1995-1998)	0.09	
b. Electrical calibration[(1)]		0.13
c. Mass of calorimeter core		0.03
d. Correction for calorimeter gaps		0.07
e. Correction to reference distance		0.03
f. Correction to reference depth		0.13
g. Time measurement		0.03
Uncertainty of absorbed dose rate to graphite	0.09	0.20
2. Transfer absorbed dose from graphite to water		
a. Correction scaled measurement depth, $k_{c,d}$		0.01
b. Correction phantom scatter, $k_{w,p}$		0.09
c. Ratio of mass energy-absorption coefficients	0.02	0.30
d. Ratio of dose-to-kerma ratios		0.06
e. Deviation from scaling theorem, k_{dev}		0.09
Uncertainty of transfer from graphite to water	0.02	0.33
3. Measurement of ionization current		
a. Electrometer reading	0.02	0.02
b. Correction to reference distance		0.02
c. Correction to reference depth		0.05
d. PMMA sheath		0.05
e. Correction for air temperature and pressure		0.04
f. Correction for air humidity		0.01
g. Time measurement		0.01
Uncertainty of ionization current	0.02	0.09
Quadratic summation	0.09	0.40
Combined standard uncertainty of $N_{D_w,NMi}$	0.41	

[(1)] The statistical uncertainty (u_{iA}) in the electrical calibration is accounted for in the statistical uncertainty in the long-term mean dose rate (1a).

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 0.5 °C during a series of measurements) and at the NMi varied between 22.7 °C and 23.5 °C. Measured transfer chamber ionization currents were normalized to the standard environmental conditions of 293.15 K and 101.325 kPa. At the NMi, the relative humidity varied between 30 % and 40 % and measurements were normalized to 50 % using the curve recommended by the CCEMRI [14], which yields a normalization factor of at most 1.000 15 in the quoted humidity range. At the BIPM the relative humidity was controlled at 50 % (within 5 %) and no humidity correction was applied.

4. Comparison of air-kerma calibration coefficients

The standards for air kerma of the NMi and the BIPM were compared in 1997 [15] and the calibration coefficients of the three ionization chambers used in the present comparison were measured and compared as an additional consistency check on the results.

The air-kerma calibration coefficients are given for both laboratories in Table 4. From these it can be seen that the mean ratio $N_{K,\mathrm{NMi}} / N_{K,\mathrm{BIPM}}$ is 1.002 4, determined consistently by each of the three transfer chambers. This is within 0.07 % of the result of the previous air-kerma comparison [15] and this agreement is within the expected statistical relative uncertainty (7×10^{-4}) of repeated calibrations.

Table 4. Comparison of the air-kerma calibration coefficients of the NMi and the BIPM. Also given are the ratios of the absorbed dose to water and air-kerma calibration coefficients for each chamber at each laboratory.

Ionization chamber	$N_{K,\mathrm{NMi}}$ /(Gy μC^{-1})	$(N_{D_w} / N_K)_{\mathrm{NMi}}$	$N_{K,\mathrm{BIPM}}$ /(Gy μC^{-1})	$(N_{D_w} / N_K)_{\mathrm{BIPM}}$	$K_{\mathrm{NMi}} / K_{\mathrm{BIPM}}$
NE 2611A-118	93.65	1.083 6	93.43	1.090 5	1.002 4
NE 2611A-119	93.75	1.083 5	93.53	1.090 4	1.002 3
NE 2611A-120	94.38	1.083 7	94.15	1.090 3	1.002 5

Also shown in Table 4 for each chamber and each laboratory is the ratio of the calibration coefficients for absorbed dose to water and air kerma to investigate whether the transfer chambers behaved according to chamber type.[3] All three chambers have the same ratio within the measurement uncertainty, demonstrating that their relative response in the two ^{60}Co gamma beams is reproducible and predictable and is as normally measured at each laboratory for the NE 2611A chamber type.

[3] The calibration coefficients in terms of absorbed dose to water are discussed in Section 6.

5. Check source measurements

Check source measurements were performed at the NMi and at the BIPM at the beginning and at the end of the comparison measurements to monitor the stability of the ionization chambers. This was done by placing each transfer chamber in a ^{90}Sr check source (NE 2562-061). A Keithley 6517 electrometer was operated in coulomb mode to measure the ionization current, and a laboratory timer (NE 2546-191) was used to determine the irradiation time. The air temperature was read using a Doric 450-TH digital temperature sensor and the air pressure measured using either the BIPM or the NMi barometer, as appropriate.

The measured ionization currents and their statistical standard uncertainties are given in Table 5. From the results it may be concluded that all three chambers are stable; the ionization currents determined at the beginning and at the end of the comparison differ by less than 0.07 %, while the differences between these and the long-term mean for each chamber are less than 0.11 %.

Table 5. Ionization currents (at 22 °C and 101.325 kPa) of the transfer standards in the ^{90}Sr check source of the NMi. The long-term mean values I_{mean}, determined at the NMi over a period of five years, serve as reference values, and the values s_{mean} are the relative standard uncertainties of the long-term distributions. I_{start} and I_{end} are the ionization currents measured at the start and at the end of the comparison, and s_{start} and s_{end} are the relative statistical standard uncertainties of I_{start} and I_{end}.

Ionization chamber	I_{mean} /pA	100 s_{mean}	I_{start} /pA	100 s_{start}	I_{end} /pA	100 s_{end}
NE 2611A-118	28.479	0.051	28.489	0.035	28.482	0.041
NE 2611A-119	28.318	0.071	28.347	0.041	28.330	0.044
NE 2611A-120	28.258	0.052	28.279	0.025	28.260	0.036

6. Results of the comparison

Calibration coefficients in terms of absorbed dose to water were determined at the NMi and at the BIPM. The measurements at the NMi were performed immediately before and after the measurements at BIPM in January 2000, and the two NMi data sets were averaged. At the BIPM, each transfer chamber was measured twice over the 5 days of the comparison and the difference between each pair of measurements was less than 0.04 %. For each transfer chamber, the ratio of the calibration coefficients of the two laboratories is taken to represent the ratio of the absorbed dose to water standards. The results are presented in Table 6. The uncertainty of the ratio $D_{w,NMi} / D_{w,BIPM}$ is derived from the uncertainty budgets of both laboratories (see Tables 1 and 3), removing the correlated

uncertainty arising from the common use of data relating to mass energy absorption coefficients, and adding the uncertainties associated with the use of transfer chambers (see Table 7). Taking the mean of the ratios given in Table 6, the result $D_{w,NMi} / D_{w,BIPM} = 0.996\,2$, $u_c = 0.003\,8$ is obtained.

Table 6. Comparison of the NMi and BIPM calibration coefficients in terms of absorbed dose to water.

Ionization Chamber	$N_{D_w,NMi}$ /(Gy μC^{-1})	$N_{D_w,BIPM}$ /(Gy μC^{-1})	$D_{w,NMi} / D_{w,BIPM}$
NE 2611A-118	101.48	101.88	0.9961
NE 2611A-119	101.58	101.98	0.9961
NE 2611A-120	102.28	102.65	0.9964

Table 7. Uncertainties associated with calibration coefficients and the comparison value.

	Uncertainty in $N_{D,W\ NMi}$		**Uncertainty in $N_{D,W\ BIPM}$**		**Uncertainty in $D_{w,NMi} / D_{w,BIPM}$**	
Relative standard uncertainty in the measurement of	100 s_i	100 u_i	100 s_i	100 u_i	100 s_i	100 u_i
Absorbed dose rate	0.09	0.40	0.20	0.21	0.22	0.31
Ionization current of transfer chamber	0.02	-	0.01	-	0.02	-
Chamber position/depth	-	0.05	0.01	0.02	0.01	0.05
Relative standard uncertainty						
Quadratic summation	0.09	0.40	0.20	0.21	0.22	0.31
Combined uncertainty	0.41		0.29		0.38	

7. Comparison with other institutes

In Figure 1 this comparison result is shown together with the results of similar comparisons of other national metrological institutes at the BIPM. The uncertainty bars shown represent one standard uncertainty. As can be seen, the NMi result is in agreement with those of the other institutes. The NMi value for $D_{w,NMI} / D_{w,BIPM}$ is 0.996 2 (0.003 8) and the mean value of the other institutes shown in Figure 1 is 0.997 8, a difference of

0.001 6 which is within the standard uncertainty of the distribution of the results (0.002 6).

Several different experimental methods are used to establish the standards for absorbed dose to water of the metrological institutes listed in Figure 1 [16 – 26]. The standard of the LSDG (Belgium) is a sealed-water calorimeter [27] as is that of the NIST (USA) and the NRC (Canada). The standard of the PTB (Germany) is based on Fricke dosimetry calibrated by total absorption of 6 MeV electrons. The BEV (Austria) and the BNM-LNHB (France) have graphite calorimeters, with the transfer to absorbed dose to water made using cavity theory. The other institutes, the ARPANSA (Australia), the ENEA (Italy), and the NPL (UK), use the same technique as the NMi, namely a graphite calorimeter and the photon-fluence scaling method. No obvious systematic difference in the results obtained using these different techniques can be observed.

The present comparison confirms the validity of the scaling method and although not as direct as water calorimetry this does not appear to introduce a significant reduction in accuracy. The fact that the various methods used by the different laboratories to determine absorbed dose to water agree at the 0.2 % level demonstrates a high degree of international consistency in the measurement of this quantity.

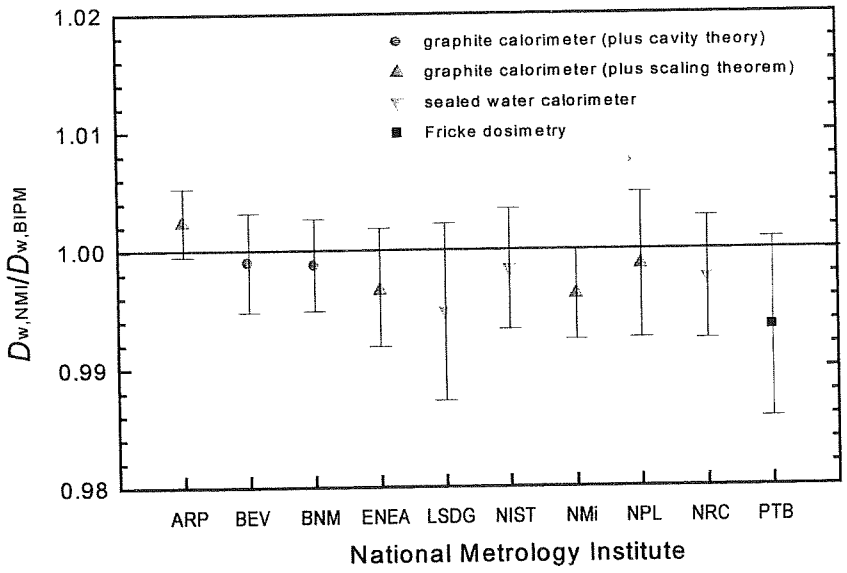

Figure 1: A comparison of the standards for absorbed dose to water for ^{60}Co gamma radiation of several national metrological institutes. All standards are normalized to the BIPM. The uncertainty bars represent the standard uncertainty of each comparison result.

8. Conclusions

A key comparison was carried out between the NMi and the BIPM of standards of absorbed dose to water for ^{60}Co gamma rays, using three NE 2611A ionization chambers as transfer standards. From additional air-kerma calibrations and ^{90}Sr check source measurements it is concluded that all three transfer chambers have a very stable and predictable response. The mean comparison result derived from the three sets of calibrations shows that the NMi determination of absorbed dose to water is 0.38 % lower than that of the BIPM. This is compatible with the total comparison relative uncertainty of 3.8×10^{-3}. When compared with the results of nine other national metrological institutes that have carried out comparisons in terms of absorbed dose to water at the BIPM, the NMi standard for absorbed dose to water is in agreement within the standard uncertainty of the distribution of these results.

References

[1] Boutillon M. and Perroche A.-M., Ionometric determination of absorbed dose to water for cobalt-60 gamma rays, *Phys. Med. Biol.* **38**, 439-54 (1993)

[2] Domen S.R. and Lamperti P.J., A heat-loss-compensated calorimeter: theory, design and performance, *J. Rec. Nat. Bur. Stand.* **78A**, 595-610 (1974)

[3] O'Connor J.E., The variation of scattered x-rays with density in an irradiated body, *Phys. Med. Biol.* **1**, 352-69 (1957)

[4] O'Connor J.E., The density scaling theorem applied to lateral electronic equilibrium, *Med. Phys.* **11**, 678-80 (1984)

[5] Pruitt J.S. and Loevinger R., The photon-fluence scaling theorem for Compton-scattered radiation, *Med. Phys.* **9**, 176-9 (1981)

[6] Burns J.E., Absorbed-dose calibrations in high-energy photon beams at the National Physical Laboratory: conversion procedure, *Phys. Med. Biol.* **39**, 1555-75 (1994)

[7] Hubbell J.H., Photon mass attenuation and energy-absorption coefficients from 1 keV to 20 MeV, *Int. J. Appl. Radiat. Isot.* **33**, 1269-1290 (1982)

[8] Hubbell J.H. and Seltzer S.M., Tables of X-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV to 20 MeV for elements Z=1 to 92 and 48 additional substances of dosimetric interest, *NIST internal report NISTIR 6532* (1995)

[9] Attix F.H., The partition of kerma to account for bremsstrahlung, *Health Phys.* **36**, 347-354 (1979)

[10] Roesch W.C., Dose for non-electronic equilibrium conditions, *Radiation Research* **9**, 399-410 (1958)

[11] Handbook of Chemistry and Physics, D.R. Lide Editor-in-Chief, 73rd edn. 1992-1993 (CRC Press: London) p. **6**-10

[12] Pieksma M., Beheer faciliteit geabsorbeerde dosis, *NMi Quality Assurance Document VSL-Beh-IO/Winstr/052* (2001)

[13] Boutillon M. and Perroche A.-M., Determination of absorbed dose to water for ^{60}Co by the scaling theorem, *Rapport BIPM-92/1* (1992)

[14] *CCEMRI R(I)* Rapport au comité international des poids et mesures, *Correction d'humidité, 6-7*, BIPM (Paris: Offilib) (1977)

[15] Allisy-Roberts P.J., Boutillon M., Grimbergen T.W.M. and van Dijk E., Comparison of the standards of air kerma of the NMi and the BIPM for ^{60}Co γ rays, *Rapport BIPM-97/4* (1997)

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

[17] Shortt K.R., Ross C. K., Schneider M., Hohlfeld K., Roos M. and Perroche A.-M., A comparison of absorbed dose standards for high-energy x-rays, *Phys. Med. Biol.* **38** 1937-1955 (1993)

[18] Perroche A.-M., Boutillon, M., Guerra A.S., Laitano R.F. and Pimpinella M., Comparison of the standards of absorbed dose of the ENEA and the BIPM for ^{60}Co γ rays, *Rapport BIPM-94/4* (1994)

[19] Perroche A.-M., Boutillon, M., Daures J., Delaunay F., Leroy E., Ostrowsky A. and Chauvenet B., Comparison of the standards of air kerma and absorbed dose of the LPRI and the BIPM for ^{60}Co γ rays, *Rapport BIPM-94/6* (1994)

[20] Perroche A.-M., Boutillon, M. and Leitner A., Comparison of the standards of air kerma and absorbed dose to water of the BEV and the BIPM for ^{60}Co γ rays, *Rapport BIPM-94/7* (1994)

[21] Allisy-Roberts P.J. and Shobe J., Comparison of the standards of absorbed dose to water of the NIST and the BIPM for ^{60}Co γ rays, *Rapport BIPM-98/5* (1998)

[22] Seltzer S. and Shobe J., Present status of the NIST standard for absorbed dose to water in ^{60}Co gamma beams *Document de travail de la 14e réunion CCRI(I)/99-8* BIPM (Paris: Offilib) (1999)

[23] Allisy-Roberts P.J., Burns D.T., Shortt K., Ross C.K. and Seuntjens J.P., Comparison of the absorbed dose to water standards of the NRC and the BIPM for ^{60}Co γ rays, *Rapport BIPM-99/13* (2000)

[24] Allisy-Roberts P.J., Burns D.T., Boas J.F., Huntley R.B. and Wise K.N. (2000) Comparison of the standards of absorbed dose to water of the ARPANSA and the BIPM for ^{60}Co gamma radiation, *Rapport BIPM-99/17* (2000).

[25] Allisy-Roberts P.J., Burns D.T. and 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)

[26] Allisy-Roberts P.J., Burns D.T., Duane S. and Thomas R., Comparison of the absorbed dose standards of the NPL and the BIPM for ^{60}Co γ rays, *Rapport BIPM-2001/-* (in preparation) (2001)

[27] Seuntjens J. and Palmans H., Correction factors and performance of a 4 °C sealed water calorimeter, *Phys. Med. Biol.* **44**, 627-646 (1999)