Rapport BIPM-03/08

Bureau International des Poids et Mesures

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September 2003

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Abstract

A comparison of the standards of absorbed dose to water of the Országos Mérésügyi Hivatal (OMH), Budapest, Hungary and of the Bureau International des Poids et Mesures (BIPM) has been made in ^{60}Co radiation. The results show that the OMH and the BIPM standards for absorbed dose to water are in close agreement, the difference being within the estimated uncertainty.

1. Introduction

An indirect comparison of the standards of absorbed dose to water of the Országos Mérésügyi Hivatal (OMH), Budapest, Hungary, and of the Bureau International des Poids et Mesures (BIPM), was carried out in the ^{60}Co radiation beam at the BIPM in April 2002. The primary standard of the OMH for absorbed dose to water is a graphite 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 OMH 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. This absorbed dose to water comparison is the first such comparison made between the two laboratories. The BIPM and OMH standards agree closely, the difference being well within the estimated uncertainty.

In this report an outline is given of the standard for absorbed dose to water of the BIPM, which is based on an ionometric technique, and that of the OMH, which is based on a measurement of absorbed dose to graphite and the application of a conversion method. Then the experimental conditions under which the transfer standards were calibrated are described. 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 results of the comparison are presented and compared with comparisons carried out between the BIPM and the 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 [2]. The dose rate is given by

$$\dot{D}_{\mathrm{w,BIPM}} = \frac{I}{m}\frac{W}{e}\bar{s}_{\mathrm{c,a}}\left(\bar{\mu}_{\mathrm{en}}/\rho\right)_{\mathrm{w,c}}\Psi_{\mathrm{w,c}}\left(1+\varepsilon\right)_{\mathrm{w,c}}\Pi k_{\mathrm{i}}, \qquad (1)$$

where I / m is the ionization current per unit mass of air 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, $(\bar{\mu}_{\mathrm{en}} / \rho)_{\mathrm{w,c}}$ is the ratio of the mean mass energy-absorption coefficients, $\Psi_{\mathrm{w,c}}$ is the ratio of the photon energy fluences, $(1 + \varepsilon)_{\mathrm{w,c}}$ is the ratio of the absorbed dose to collision component of kerma, and Πk_{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 [2] together with their uncertainties. The uncertainty budget is given in Table 1. The combined relative standard uncertainty, taking the uncertainty of the product $(W / e)^* \bar{s}_{\mathrm{c,a}}$, is 2.9×10^{-3}. The value for the rate of absorbed dose to water $\dot{D}_{\mathrm{w,BIPM}}$ is given, by convention, at the beginning of each year, at 01/01/2002 in this case.

The OMH 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 [1]. This calorimeter is of the Domen heat-loss-compensated design [3]. The photon-fluence scaling theorem [4-6] is applied to convert absorbed dose to graphite to absorbed dose to water.
Under conditions for which the theorem is valid:

- all dimensions are scaled in the inverse ratio of the electron densities of the water and graphite;
- all photon interactions take place by Compton scatter.

The ratio of the absorbed doses at corresponding points in water and graphite phantoms [5] is given by

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

where the subscripts w and c refer to water and graphite, respectively, Ψ_w and Ψ_c are the photon energy fluences at the corresponding points in the *absence* of the phantoms, $(\overline{\mu}_{en} / \rho)_w$ and $(\overline{\mu}_{en} / \rho)_c$ are the mean mass energy-absorption coefficients (averaged over the photon energy-fluence spectra at the corresponding points), and β_w and β_c are the ratios of absorbed dose and the collision components 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
$(\overline{\mu}_{en}/\rho)_{w,c}$	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 OMH has chosen to evaluate both D_w and D_c at a reference distance of 0.9 m and a reference depth of 5 g cm^{-2}. Consequently, to fulfil the requirements of the scaling theorem and eliminate the $\psi_w/\ \psi_c$ ratio in (2), additional corrections are required.

The 5 g cm^{-2} depth in water corresponds to a value for the scaled measurement depth in graphite of 5 g cm^{-2} × Z_c/Z_w = 5.5556 g cm^{-2}. The measurements of D_c by the graphite calorimeter have been made at an actual depth of 4.355g cm^{-2} at the OMH. Consequently a correction factor $k_{c,d}$ should be applied for the effect on the measured absorbed dose to graphite at these two different measurement depths. This correction factor ($k_{c,d}$ = 0.9666) was determined experimentally by the measured depth-dose profiles in the graphite phantom using the calorimeter itself, and an additional pill-box type ionization chamber was also used in the graphite phantom [7].

At the OMH, the absorbed dose to water D_w has been determined at a reference distance of 0.9 m instead of the scaled distance. The scaled distance $d = (0.9 \times n_c/n_w) = 1.4281$ m, where
$n_c = Z_c \times \rho_c = 3.0084$ E23 (e/g) × 1.76 (g/cm^3), and
$n_w = Z_w \times \rho_w = 3.34281$ E23 (e/g) × 0.997 986 (g/cm^3 at 21 °C).
Consequently, a correction $k_{w,p}$ should be made for the difference in water phantom scatter and attenuation, arising from the different radiation field and phantom sizes at these distances. The correction factor $k_{w,p}$ = 1.0394 was determined by measuring the ratio of the response of different ionization chambers to ^{60}Co gamma radiation in the water phantom to that in air at 0.9 m and 1.4281 m source-detector distances, respectively.

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 0.9 m and the reference depth 5 g cm^{-2}.

The ratio of the mean mass energy-absorption coefficients was adapted from the literature [8]. The value for $\frac{(\bar{\mu}_{en}/\rho)_w}{(\bar{\mu}_{en}/\rho)_c}$ of 1.113 is based on Hubbell's cross section data [9] and Monte Carlo simulations for the photon energy-fluence distributions in water and graphite at 5 g cm^{-2} depth. In the absence of a specific MC calculation it was assumed that the OMH beam produces similar energy-fluence distributions at the reference distance as other laboratories where the amount of scattered radiation is of a similar percentage.

The value of the ratio β_w/β_c is 1.0022 based on the calculation of the ratio of absorbed dose and the collision component of kerma using the moment method [10, 11], employing the measured depth-dose profiles and Attix' data [12] for the mean range of secondary electrons.

No corrections were applied for the deviation from the requirements of the scaling theorem, namely contributions to the total absorbed dose by photoelectric and pair-production interactions in the OMH beam, and the lack of a scaled-size water phantom in the determination of k_{wp}.

Table 2. Relative standard uncertainties for calibrations in terms of absorbed dose to water for ^{60}Co gamma rays at the OMH.

	relative standard uncertainty 100 $u_{i\mathrm{A}}$	 100 $u_{i\mathrm{B}}$
Measurement of absorbed dose rate to graphite [1]	0.28	0.20
Long-term stability of the dose rate (1991-2002) (Including the half-life of ^{60}Co)	0.09	0.03
Uncertainty of absorbed dose rate to graphite	0.29	0.20
Transfer absorbed dose from graphite to water		
Correction for scaled (5.556 g cm^{-2}) measurement depth, $k_{\mathrm{c,d}}$	–	0.01
Correction phantom scatter, $k_{\mathrm{w,p}}$	–	0.09
Ratio of mass energy-absorption coefficients	–	0.30
Ratio of dose-to-kerma ratios $\beta_{\mathrm{w}}/\ \beta_{\mathrm{c}}$	–	0.06
Deviation from scaling theorem, k_{dev}	–	0.10
Uncertainty of transfer from graphite to water	–	0.33
Measurement with ionization chambers		
Ionization current	0.07	0.02
Correction to reference distance	–	0.02
Correction to reference depth	–	0.05
Correction for air temperature and pressure	–	0.04
Correction for air humidity	–	0.01
Correction for source decay	–	0.03
Uncertainty of chamber calibration	0.07	0.08
Quadratic summation	0.30	0.40
Combined standard uncertainty of $N_{D_{\mathrm{w}},\mathrm{OMH}}$	0.50	

3. Experimental conditions for transfer chamber calibration

The environmental conditions at the two laboratories were as follows. The air and water temperature at the BIPM was controlled at around 19.5 °C (stable to better than 0.01°C during a series of measurements) and at the OMH varied between 21.0 °C and 21.6 °C. Measured transfer chamber ionization currents were normalized to the standard environmental conditions of 293.15 K and 101.325 kPa. At both laboratories the relative humidity around 50 % changed by not more than 5 %, therefore no humidity correction was applied.

Both transfer standards used in the comparison are cavity ionization chambers, one of type NE 2561 (serial number 084) and the other of type ND1006 (serial number 8502) manufactured by the OMH. Appropriate voltages (200 V positive polarity) were applied to both chambers at each laboratory. The perpendicular arm of the stem of the ND 1006 chamber was parallel with the beam in the water phantom at each laboratory and also for the measurements in air at the OMH. At the BIPM this position was not possible under the normal calibration set-up in air so the chamber arm was positioned at 45° to the axis of the beam for the air kerma calibration. A measured correction factor of 0.9994 was applied to the BIPM N_K value to equate the orientation to that of the OMH.

The ionization current of the chambers was measured using Keithley electrometers and similar methods at both laboratories. The dose rate at OMH was D_w = 79.415 mGy/min (reference date 22/05/2002) and at the BIPM D_w = 143.49 mGy/min (reference date 01/01/2002). The difference in dose-rates produces a negligible difference in the recombination effect for both transfer chambers.

The standard deviation of the measured ionization currents during one series at each laboratory was less than 4 fA, which in relative terms corresponds to less than 4×10^{-5} of the mean measured currents.

The calibration coefficient for a transfer standard in terms of absorbed dose to water is

$$N_{D_\mathrm{w},\mathrm{lab}} = \frac{\dot{D}_\mathrm{w,lab}}{I_\mathrm{w,lab}}, \qquad (4)$$

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

Both the OMH and the BIPM ^{60}Co beams are horizontal. All measurements (absorbed dose to water and air kerma) were performed at a reference distance (from source to chamber axis) of 1 m at the BIPM and 0.9 m at the OMH. The BIPM field size is 10 cm by 10 cm and at the OMH it is circular with area 100 cm^2. For measurements in water, both laboratories used a cubic water phantom of side length 30 cm and the same protective waterproof sleeve for the NE2561. The ND1006 chamber is waterproof. The calibration coefficients for absorbed dose to water were determined at a reference depth of 5 g cm^{-2}. For the air-kerma measurements each transfer chamber has its own build-up cap.

4. Comparison of air-kerma calibration coefficients

The primary standards for air kerma of the OMH and the BIPM were compared directly in 1994 [13] and, in 2001, the OMH re-evaluated its air-kerma realization [14]. Using the new k_wall and k_pn corrections, the expected K_OMH / K_BIPM = 1.0025*1.0084 = 1.0109 (0.0022).

The calibration coefficients of the two ionization chambers used in the present comparison were measured and compared as an additional consistency check on the results and confirmation of the

OMH re-evaluation. These air-kerma calibration coefficients are given for both laboratories in Table 3. The mean ratio $N_{K,\mathrm{OMH}}/ N_{K,\mathrm{BIPM}}$ for the two transfer chambers is 1.0104 (0.0022) which is in agreement with the value above of 1.0109 derived from the previous comparison. The difference between the two chambers is not incompatible with the uncertainties associated with the use of these transfer chambers in an indirect comparison, particularly as the ND1006 chamber is known to drift with time.

Table 3. Comparison of the air-kerma calibration coefficients of the OMH 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	$N_{K,\mathrm{OMH}}$ /(Gy μC^{-1})	$(N_{D_\mathrm{w}} / N_K)_\mathrm{OMH}$	$N_{K,\mathrm{BIPM}}$ /(Gy μC^{-1})	$(N_{D_\mathrm{w}} / N_K)_\mathrm{BIPM}$	$K_\mathrm{OMH} / K_\mathrm{BIPM}$	$u_\mathrm{R}(K_\mathrm{O}/K_\mathrm{B})$
NE 2561-084	94.34	1.0764	93.24_8	1.090	1.0117	0.0022
ND1006-8502	111.06	1.0756	110.05_7†	1.088	1.0091	0.0023
Mean values					1.0104*	0.0022

† corrected for the different orientation
*expected value =1.0109, see text.

The ratio $(N_{D_\mathrm{w}} / N_K)_\mathrm{BIPM}$ for the same NE 2561 chamber was 1.093 when it was measured last at the BIPM measured in 1994. The previous and present values agree within the expanded statistical uncertainties for such measurements at the BIPM using this type of chamber with a mean value for the ratio of 1.091 (0.002).

6. Results of the comparison

Calibration coefficients in terms of absorbed dose to water were determined at the OMH and at the BIPM. The measurements at the OMH were performed immediately before and after the measurements at the BIPM in April 2002, and the OMH data sets were averaged. At the BIPM, each transfer chamber was measured three times over the 5 days of the comparison and the deviations of the calibration coefficients were less than 1×10^{-4}. For both transfer chambers, 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 4. The difference of 2×10^{-3} in the results of the two transfer chambers is larger than one would normally expect in ^{60}Co. Taking the mean of the ratios given in Table 4, the result $D_{\mathrm{w,OMH}} / D_{\mathrm{w,BIPM}} = 0.9983$ (0.0049) is obtained.

The uncertainty of the ratio $D_{\mathrm{w,OMH}} / D_{\mathrm{w,BIPM}}$ is derived from the uncertainty budgets of both laboratories (see Tables 1 and 2), adding the uncertainties associated with the use of transfer chambers (see Table 5). The correlations arising from the use of mass energy-absorption coefficients and absorbed dose to kerma ratios in both methods are taken into account by applying estimated correlation coefficients f_k of 0.95 and 0.7, respectively, to the uncertainties $u_{k,\mathrm{corr}}$ from both laboratories as given in:

$$u_{R,\mathrm{NMI}}{}^2 = u_{\mathrm{c,NMI}}{}^2 + u_{\mathrm{c,\,BIPM}}{}^2 - \sum \left(f_k u_{k,\mathrm{corr}}\right)^2_{\mathrm{NMI}} - \sum \left(f_k u_{k,\mathrm{corr}}\right)^2_{\mathrm{BIPM}} . \qquad (5)$$

Table 4. **Comparison of the OMH and BIPM calibration coefficients in terms of absorbed dose to water**

Ionization Chamber	$N_{D_\mathrm{w},\mathrm{OMH}}$ /(Gy µC^{-1})	$N_{D_\mathrm{w},\mathrm{BIPM}}$ /(Gy µC^{-1})	$D_{\mathrm{w,OMH}} / D_{\mathrm{w,BIPM}}$	u_R ($D_\mathrm{OMH}/D_\mathrm{BIPM}$)
NE 2561-084	101.55	101.62	**0.9993**	0.0049
ND1006-8502	119.46	119.79	**0.9973**	0.0049
Mean value			**0.9983**	0.0049

Table 5. Uncertainties associated with calibration coefficients and the comparison value

	Uncertainty in $N_{D,\mathrm{w\ OMH}}$		**Uncertainty in $N_{D,\mathrm{w\ BIPM}}$**		**Uncertainty in $D_{\mathrm{w,OMH}} / D_{\mathrm{w,BIPM}}$**	
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	0.30	0.40	0.20	0.21	0.36	0.32*
Ionization current of transfer chamber	0.01	-	0.01	-	0.05	-
Chamber position/depth	-	0.05	0.01	0.05	0.01	0.07
Combined relative standard uncertainty						
Quadratic summation	0.30	0.40	0.20	0.21	0.36	0.33
Combined uncertainty	0.50		0.29		0.49	

* Taking into account the correlations of the uncertainties in the ($\overline{\mu}_{\mathrm{en}} / \rho$) and the β ratios.

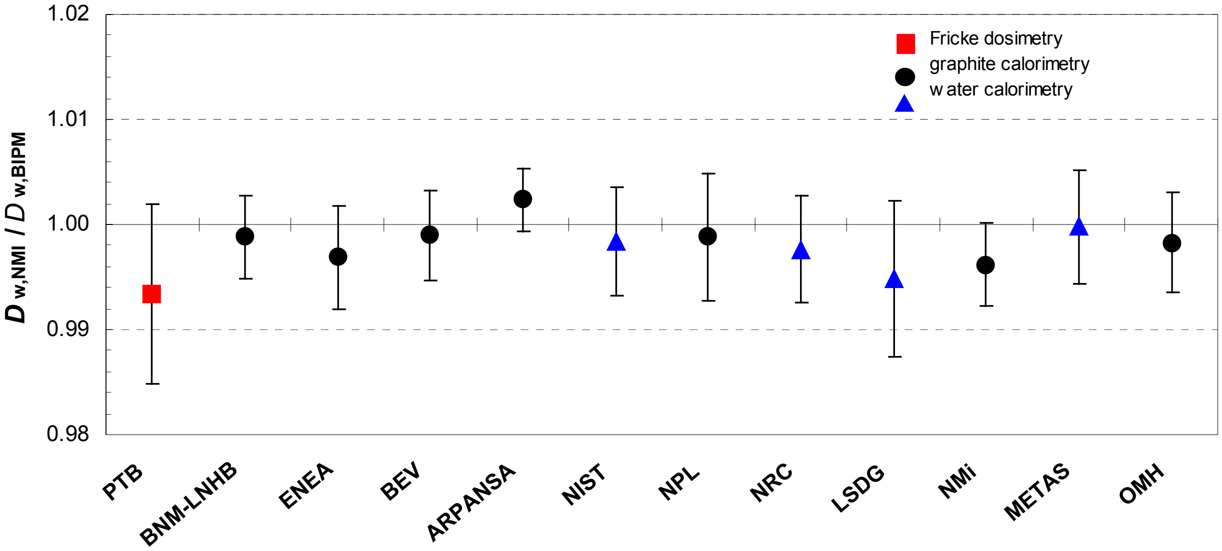
7. Comparison with other institutes

In Figure 1 the result of this comparison 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. The OMH value for $D_{\mathrm{w,OMH}} / D_{\mathrm{w,BIPM}}$ is 0.9983 (0.0049) and the mean value of the all the institutes shown in Figure 1 is 0.9979. The difference of 4×10^{-4} is well within the standard uncertainty of 24 × 10^{-4} for the distribution of the results, which demonstrates that the OMH result is in agreement with those of the other institutes.

As indicated in part in Figure 1, several different experimental methods are used to establish the standards for absorbed dose to water of the metrological institutes listed in Figure 1 [10, 15-26]. The standard of the LSDG (Belgium) is a sealed-water calorimeter as is that of the NIST (USA), the NRC (Canada) and the METAS (Switzerland). 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 remaining institutes, the ARPANSA (Australia), the ENEA (Italy), the NPL (UK) and the NMi (The Netherlands), use the same technique as the OMH, 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.

Figure 1 International comparison of absorbed dose to water

(standard uncertainties are of each comparison result)



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 level of 2 × 10^{-3} demonstrates a high degree of international consistency in the measurement of this quantity. However, further investigation of the OMH's radiation beam to determine the deviation from scaling theory, together with a recalculation of the mass energy-absorption coefficients and collision component of kerma, could decrease the uncertainty of absorbed dose to water determination at the OMH.

8. Conclusions

A key comparison was carried out between the OMH and the BIPM of standards of absorbed dose to water for ^{60}Co gamma rays, using two different ionization chambers as transfer standards. From additional air-kerma calibrations it is concluded that both transfer chambers have a very stable and predictable response. The mean comparison result derived from the two sets of calibrations shows that the OMH determination of absorbed dose to water is 1.7×10^{-3} lower than that of the BIPM. This is compatible with the combined relative standard uncertainty of the comparison (4.9×10^{-3}). When compared with the results of the other national metrological institutes that have carried out comparisons in terms of absorbed dose to water at the BIPM, the OMH standard for absorbed dose to water is in satisfactory agreement, being well within the standard uncertainty of the distribution of these results.

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September 2003.