Rapport BIPM–2004/11

Bureau International des Poids et Mesures

Comparison of the standards for air kerma of the NMIJ and the BIPM for ^{60}Co γ rays

by

P.J. Allisy-Roberts and D.T. Burns
BIPM

and

N. Takata, Y. Koyama, and T. Kurosawa
NMIJ

September 2004

Pavillon de Breteuil, F-92312 SEVRES Cedex

Comparison of the standards for air kerma of the NMIJ and the BIPM for ^{60}Co γ rays

by

P.J. Allisy-Roberts*, D.T. Burns*, N. Takata**, Y. Koyama**, and T. Kurosawa**

*Bureau International des Poids et Mesures, F-92312 Sèvres Cedex

** Ionizing Radiation Section, National Metrology Institute of Japan, AIST, 305-8568 Japan

Abstract
A first comparison of the standards for air kerma of the National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology (NMIJ/AIST) and of the Bureau International des Poids et Mesures (BIPM) has been carried out in ^{60}Co radiation. It shows that the NMIJ and BIPM standards differ by 0.72 % with a relative standard uncertainty of 2.4×10^{-3}.

1. Introduction

A comparison of the standards for air kerma of the National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology (NMIJ/AIST), and of the Bureau International des Poids et Mesures (BIPM), has been carried out in ^{60}Co radiation. The NMIJ standard of air kerma [1] is comprised of two cylindrical graphite cavity ionization chambers of different size constructed at the NMIJ (C-110G No. 766 and C-110G No. 764), dimensional details of which are given in section 2 of this report. The BIPM air kerma standard is described in [2]. The comparison of the standards took place at the BIPM in January 2001.

2. Determination of the air kerma rate

The air kerma rate is determined using the relation

$$\dot{K} = \frac{I}{m}\frac{W}{e}\frac{1}{1-\bar{g}}\left(\frac{\mu_{\text{en}}}{\rho}\right)_{\text{a,c}} \bar{s}_{\text{c,a}} \prod k_i \quad , \qquad (1)$$

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,
$\bar{g}$ is the fraction of electron energy lost to bremsstrahlung,
$(\mu_{\text{en}}/\rho)_{\text{a,c}}$ is the ratio of the mean mass-energy absorption coefficients of air and graphite,
$\bar{s}_{\text{c,a}}$ is the ratio of the mean stopping powers of graphite and air,
$\prod k_i$ is the product of the correction factors to be applied to the standard.

The main characteristics of the NMIJ/AIST primary standards are given in Table 1.

Table 1. Characteristics of the NMIJ/AIST standards for the measurement of air kerma

Standard Type		C-110G No. 766	C-110G No. 764
		Nominal values	
Chamber	Outer height / mm	55	24.3
	Outer diameter / mm	44	24
	Inner height / mm	50	19.3
	Inner diameter / mm	40	20
	Wall thickness / mm	2	2
	Build-up cap thickness	1	1
Electrode	Diameter / mm	2	2
	Height / mm	45	14.3
Volume	Air cavity / cm^3	62.701	6.055
	relative uncertainty	0.0003	0.0003
Wall	Material	ultrapure graphite	
	Density / $g \cdot cm^{-3}$	1.85	
	Impurity fraction	$<2 \times 10^{-5}$	
Applied tension	Voltage / V both polarities	1200	700

3. Experimental method

The air kerma is determined at the BIPM under the following conditions [3]:
- the distance from source to reference plane is 1 m,
- the field size in air at the reference plane is 10 cm × 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.

Each NMIJ/AIST chamber was placed so its centre is in the reference plane of the gamma ray field but angled at 45° to the direction of the gamma ray beam as shown in Figure 1.

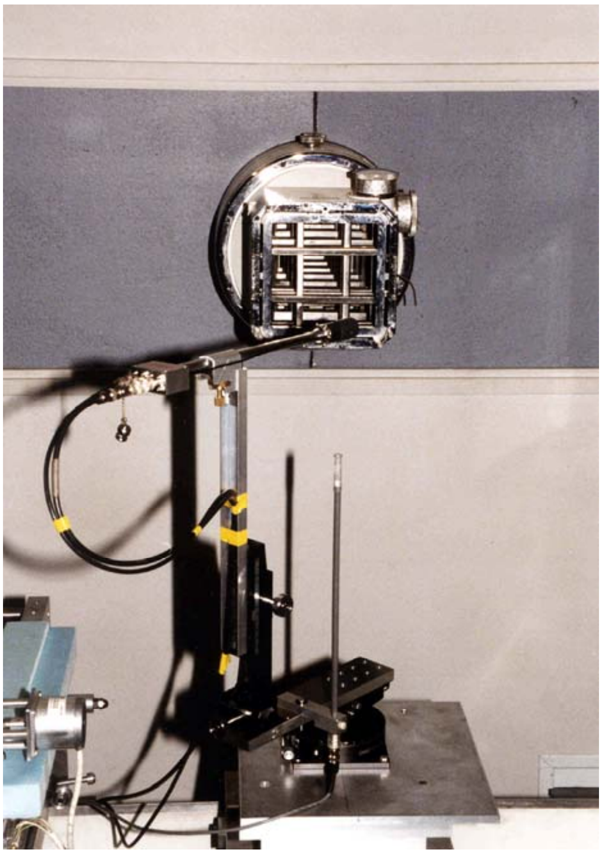


Figure 1. Photograph of the NMIJ chamber at the reference position in the ^{60}Co beam

Data concerning the various factors entering in the determination of air kerma in the ^{60}Co beam using the two standards are shown in Tables 2 and 3. They include the physical constants [4], the correction factors entering in (1), the volume of each chamber cavity and the associated uncertainties [1, 3]. Also shown are the relative uncertainties in the ratio that gives the comparison value

$$R_K = \dot{K}_{\mathrm{NMIJ}} / \dot{K}_{\mathrm{BIPM}} \ . \tag{2}$$

The correction factors for the NMIJ standard were determined at the NMIJ. Some correction factors were reassessed at the BIPM as described in the following paragraphs.

k_s : correction factor for losses due to recombination

Values of parameters for recombination loss were obtained using the method of Niatel as described in [5]. The ratio of signal currents for the usual applied voltages and half these values, i.e. n = 2, was obtained in the BIPM ^{60}Co gamma ray beam. The air kerma rate was reduced to one sixth for the No.766 chamber and to one fourth for the No.764 chamber by placing brass plates of different thickness in front of the collimator. The results are shown in Figures 2a and 2b for the two standard chambers.

k_h: correction factor for humidity

Humidity was close to 50 % for all the measurements at the BIPM. All values measured were within the range 48 % to 52 %. Although common uncertainties associated with k_h are removed in the comparison value, the uncertainty in the reference data used for the determination of k_h is assumed to be 0.03 % [6].

Figure 2a Recombination correction measurement for NMIJ chamber C-110G-0766

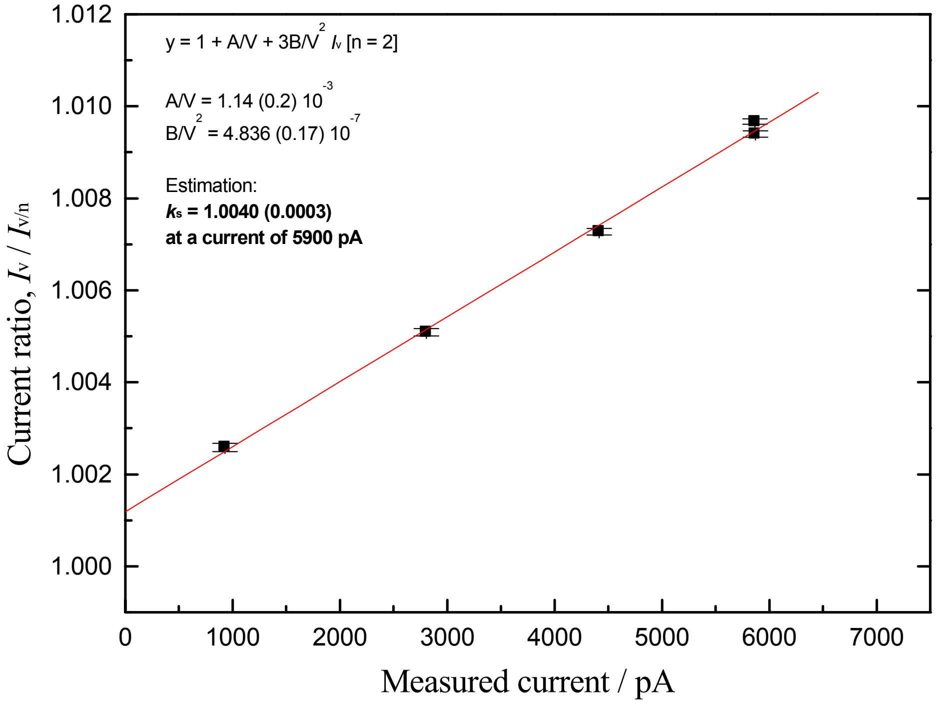


Figure 2b Recombination correction measurement for NMIJ chamber C-110G-764

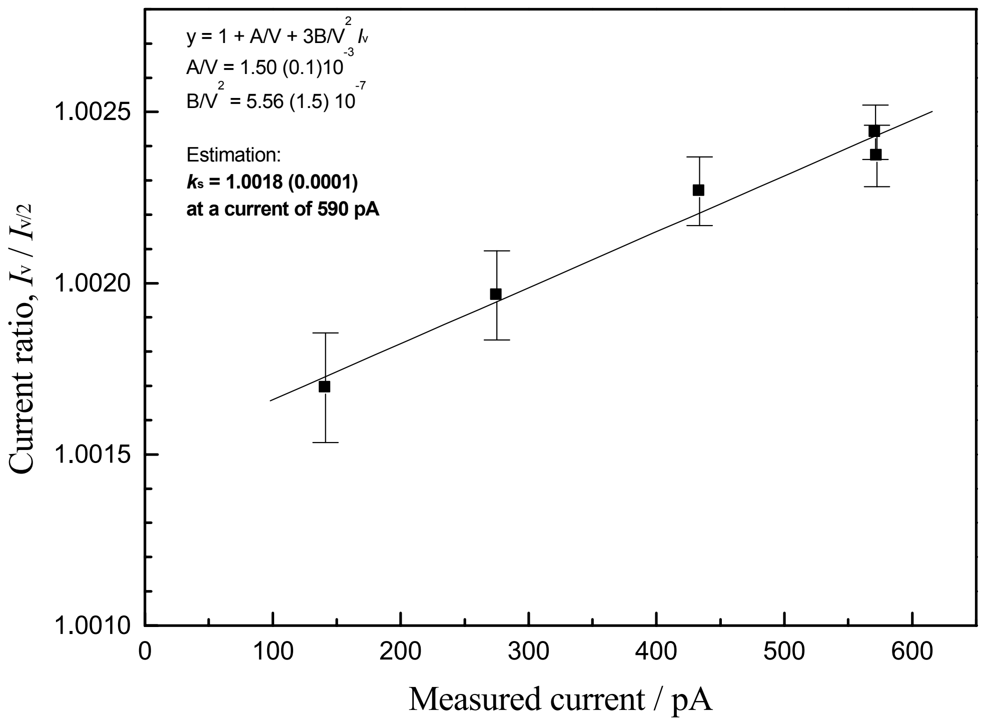


Table 2. Physical constants and correction factors entering in the determination of air kerma and their estimated relative standard uncertainties in the BIPM ^{60}Co beam for NMIJ standard C-110G-766

	BIPM values	100 × relative [(a)] uncertainty		NMIJ values	100 × relative [(a)] uncertainty		100 × relative [(a)] uncertainty of R_K	
		s_i	u_i	C-110G-766	s_i	u_i	s_i	u_i
Physical constants								
dry air density / kg·m^{-3} [(b)]	1.2930	-	0.01	1.2930	-	0.01	-	-
$(\mu_{en}/\rho)_{a,c}$	0.9985	-	0.05	0.9985	-	0.05	-	-
stopping power ratio $\bar{s}_{c,a}$	1.0010	-	0.11	1.0010	-	0.11	-	-
W/e /(J C^{-1})	33.97			33.97				
$\bar{g}$ fraction of energy lost to bremsstrahlung	0.0032	-	0.02	0.0032	-	0.02	-	-
Correction factors								
k_s recombination losses	1.0015	0.01	0.01	1.0040	0.02	0.06	0.02	0.06
k_h humidity	0.9970	-	0.03	0.9970	-	0.03	-	-
k_{st} stem scattering	1.0000	0.01	-	0.9976	0.01	0.10	0.01	0.10
k_{att} wall attenuation	1.0398	0.01	0.04	1.0209	0.06	0.10	0.06	0.13
k_{sc} wall scattering	0.9720	0.01	0.07					
k_{CEP} mean origin of electrons	0.9922	-	0.01					
k_{an} axial non-uniformity	0.9964	-	0.07	1.0008	0.08	0.05	0.08	0.09
k_{rn} radial non-uniformity	1.0016	0.01	0.02					
k_p position	1.0000	-	0.01	1.0000	-	0.06	-	0.06
Measurement of I/vρ								
v volume / cm^3	6.8028	0.01	0.03	62.701	0.01	0.03	0.01	0.04
I ionization current		0.01	0.02		0.01	0.02	0.01	0.03
Uncertainty								
quadratic summation		0.03	0.17		0.10	0.22	0.10	0.21
combined uncertainty		0.17			0.24		0.24	

[(a)] Expressed as one standard uncertainty.
s_i represents the relative standard Type A uncertainty, estimated by statistical methods;
u_i represents the relative standard Type B uncertainty, estimated by other means.

[(b)] At 101 325 Pa and 273.15 K.

k_{wall}: correction factor for wall attenuation, scattering, and CEP

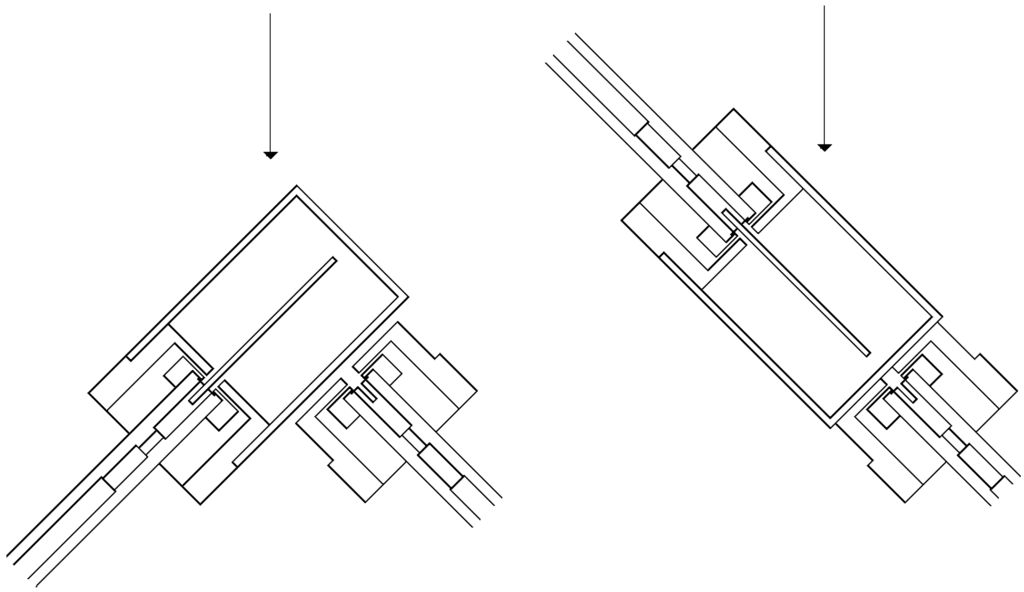
Although at the time of the comparison in January 2001, the values for k_{wall} were measured by the linear extrapolation method, this method is not recommended [7] and so the values for k_{wall} actually used were obtained by the Monte Carlo method, using the EGS4 code [8]. In the calculations, the chamber wall thickness is taken as 3 mm for ^{60}Co gamma rays. The stem of chamber was neglected in the calculation for k_{wall} because the scattering effects of the stem were obtained by measurement: k_{st}. The incident gamma ray spectrum was assumed to include no scattered gamma rays.

Table 3. Physical constants and correction factors entering in the determination of air kerma and their estimated relative standard uncertainties in the BIPM ^{60}Co beam for NMIJ standard C-110G-764

	BIPM values	100 × relative [(a)] uncertainty		NMIJ values C-110G-764	100 × relative [(a)] uncertainty		100 × relative [(a)] uncertainty of R_K	
		s_i	u_i		s_i	u_i	s_i	u_i
Physical constants								
dry air density / kg·m^{-3} [(b)]	1.2930	-	0.01	1.2930	-	0.01	-	-
$(\mu_{en}/\rho)_{a,c}$	0.9985	-	0.05	0.9985	-	0.05	-	-
stopping power ratio $\bar{s}_{c,a}$	1.0010	-	0.11	1.0010	-	0.11	-	-
W/e /(J C^{-1})	33.97			33.97				
$\bar{g}$ fraction of energy lost to bremsstrahlung	0.0032	-	0.02	0.0032	-	0.02	-	-
Correction factors								
k_s recombination losses	1.0015	0.01	0.01	1.0018	0.01	0.01	0.02	0.06
k_h humidity	0.9970	-	0.03	0.9970	-	0.03	-	-
k_{st} stem scattering	1.0000	0.01	-	0.9966	0.01	0.10	0.01	0.10
k_{att} wall attenuation	1.0398	0.01	0.04	1.0198	0.06	0.10	0.06	0.13
k_{sc} wall scattering	0.9720	0.01	0.07					
k_{CEP} mean origin of electrons	0.9922	-	0.01					
k_{an} axial non-uniformity	0.9964	-	0.07	1.0005	0.11	0.05	0.08	0.09
k_{rn} radial non-uniformity	1.0016	0.01	0.02					
k_p position				1.0000	-	0.06	-	0.06
Measurement of $I/v\rho$								
v volume / cm^3	6.8028	0.01	0.03	6.055	0.01	0.03	0.01	0.04
I ionization current		0.01	0.02		0.01	0.02	0.01	0.02
Uncertainty								
quadratic summation		0.03	0.17		0.13	0.21	0.10	0.21
combined uncertainty		0.17			0.25		0.24	

k_{st}: correction factor for stem scattering

The ratio was obtained of signal currents measured for each chamber in the BIPM beam with and without a dummy stem placed at the chamber side (Figure 3a). However, a dummy stem placed at the end of the chamber fixed in a beam (Figure 3b) seemed to represent more realistically the effects of the actual stem. Consequently, the correction factor corresponding to Figure 3b was used by measuring the ratios of signal currents with and without the dummy stem in both cases (Figures 3a and 3b) for gamma ray fields at the NMIJ. The effects of scattered gamma rays were also calculated by the Monte Carlo method for the dummy stem (Figure 3b) and for the actual stem when a chamber is placed as shown in Figure3a. The results obtained for the dummy and actual stems did not show a difference greater than the statistical uncertainty of the calculation.



(a) (b)

Figure 3 (a) and (b). Layouts of an ionization chamber and a dummy stem.

k_{nu}: correction factor for axial and radial non-uniformity

Values of k_{nu} for the NMIJ chambers are obtained by the Monte Carlo method. The correction is taken as the ratio between the deposition energies in the air of the chamber when it is placed in a uniform parallel gamma ray field and when it is placed 1 m from a gamma ray point source [9]. The gamma ray field of a point source was assumed to have the same radial non-uniformity as the profile measured by BIPM [10]. The profile was calculated from

$$F = 1 \div \left(1 + 0.00029 \times r + 0.00046 \times r^2\right) \tag{3}$$

where F is the fluence of gamma rays and r the radius (cm) from the beam axis on the plane perpendicular to the beam and passing a point 1 m from the gamma ray source. The profile for the BIPM ^{60}Co beam is shown in Figure 4. The radial profile obtained from the assumption of isotropic gamma rays from a point source is also shown (indicated by R^{-2}).

k_p: correction factor for position error

The correction factor k_p was adopted to take the position error into consideration. The value k_p was considered as 1.0000 and that of $100u_B$ was estimated as 0.06. The value was obtained for 1 m from a gamma ray source assuming that the sum of the position uncertainty in setting the chamber for measurement and that of the mark for the centre of the chamber was 0.3 mm.

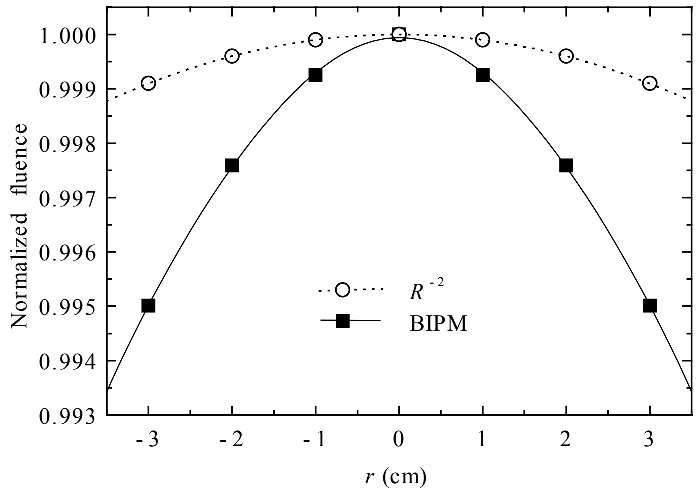


Figure 4. Radial non-uniformity for the plane passing the point on the beam axis 1 m from the ^{60}Co gamma ray source

4. Comparison results

The result of the comparison $R_K = \dot{K}_{\mathrm{NMIJ}} / \dot{K}_{\mathrm{BIPM}}$ is given in Table 4. Four independent measurements were made over ten days using the NMIJ standards. The relative combined uncertainty associated with the measurements for each standard is better than 10^{-4}. The $\dot{K}_{\mathrm{BIPM}}$ value of 2.7297 (s = 0.0003) mGy·s^{-1} is the mean of measurements that were performed over a period of several months before and after the present comparison. The ratio of the values of the air kerma rate determined by the NMIJ and the BIPM standards is 1.0072 with a combined standard uncertainty, u_c of 0.0024. Some of the uncertainties in $\dot{K}$ which appear in both the BIPM and the NMIJ determinations (such as air density, W/e, μ_{en}/ρ, $\bar{g}$, $\bar{s}_{c,a}$ and k_h) cancel when evaluating the uncertainty of R_K, as shown in Tables 2 and 3.

Table 4. Results of the NMIJ-BIPM comparison of primary standards of air kerma

Standard C-110G	I_{NMIJ} / pA	$\dot{K}_{\mathrm{NMIJ}}$ (1) / mGy·s^{-1}	R_K	u_c
766	6410.8$_7$	2.7480	1.0067	0.0024
764	622.44$_0$	2.7506	1.0077	0.0024

(1) The $\dot{K}$ values measured at the BIPM refer to an evacuated path length between source and standard and are given at the reference date of 2001-01-01, 0h UT where the half life of ^{60}Co is taken as 1925.5 days (u = 0.5 days) [11].

5. Discussion regarding k_{wall} effects

For more than 10 years there have been intensive discussions on wall correction factors for cavity ionization chambers determined with an experimental extrapolation method versus those calculated using Monte Carlo methods [12, 13, 9]. There has also been considerable debate over the corrections for non-uniformity and the point of measurement [14, 15].

Many of the national metrology institutes (NMIs) currently use wall correction factors that have been determined by the linear extrapolation method. Both experimental and theoretical results have been provided in recent years which strongly support the validity of calculated wall correction factors and these calculated values differ significantly from those obtained by linear extrapolation of experimental data to zero wall thickness. This is particularly the case for cylindrical cavity chambers that are used as primary air kerma standards. In some cases, the differences amount to 50 % of the correction itself [16].

During the 14th meeting of Section I of the Consultative Committee for Ionizing Radiation (CCRI(I)) in1999, the various approaches for determining wall and axial non-uniformity correction factors for graphite-cavity standards were discussed in detail [17]. It became apparent that several NMIs were actively re-evaluating their correction factors for ^{60}Co air kerma standards including their uncertainties at the time of the meeting. It was agreed to set up a working group (WG) to study the implications of using correction factors for ^{60}Co air kerma standards based on Monte Carlo methods. It was also decided that before publishing results in the key comparison database (KCDB), which shows the degrees of equivalence between the NMIs, the BIPM would ask the NMIs to review their uncertainty budgets for air kerma standards in ^{60}Co gamma radiation. It was further suggested that the method of determining the correction factors (e.g. Monte Carlo or experimental, particularly linear extrapolation) should be identified in the KCDB together with a statement on the implications of differences between the two methods with respect to the uncertainty [17].

The debate continued during the 15th CCRI(I) meeting in 2001 and several NMIs produced documents [16, 18-20] describing the work undertaken since the 1999 meeting. Significant contributions were made to the debate on wall correction factors for cavity chambers. As a consequence, it was agreed that the WG evaluate the information available and make recommendations on the procedure to ensure that the results to be entered in the KCDB are valid.

The present comparison with the NMIJ used two cylindrical ionization chambers with different sizes. In calculating k_{wall} and k_{nu}, the gamma ray field is assumed to have no scattered radiation and the dependence of the mass energy absorption ratio and stopping power ratio on the size of the chamber is not taken into account. The agreement in the air kerma rate determination between the two NMIJ primary standards is 10^{-3} in relative terms which is well within their combined type A uncertainties. This indicates the consistency of the calculated values for k_{wall} for the two chamber sizes. At the NMIJ/AIST, the ^{60}Co air kerma standard has been disseminated on the basis of the calculated correction factor k_{wall} rather than measured values since April 2002.

The OMH (Hungary) has also declared a new value for its air kerma standard [18], as has the PTB (Germany) [21]. The ENEA-INMRI (Italy), SZMDM (Yugoslavia) and the NCM (Bulgaria), each of which have made comparisons recently with the BIPM [22 - 24], have also changed their method of k_{wall} determination, using Monte Carlo calculations and each NMI has declared these results.

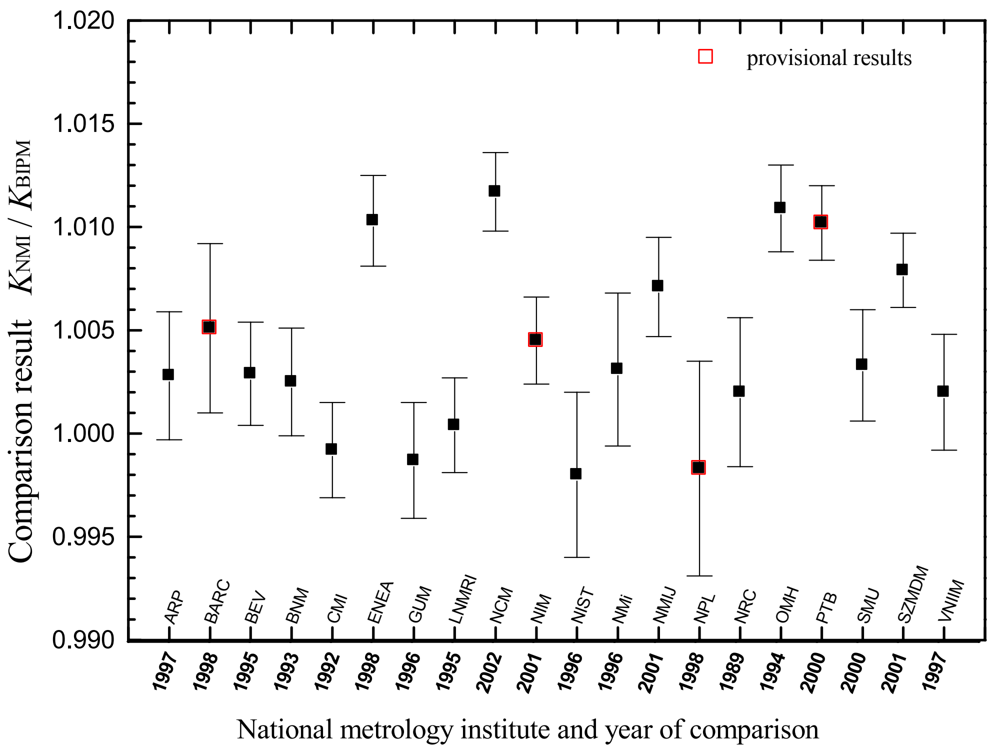
It is anticipated that it will be a further eight months before all the NMIs are ready for their results to be entered into the BIPM key comparison database (KCDB). In the meantime, the BIPM is also reviewing its experimental and calculated results for the wall corrections of its primary standard to verify the international standard of air kerma. Any future new result will need to be approved and implemented at a date to be confirmed by the Consultative Committee for Ionizing Radiation (CCRI).

7. Conclusion

The comparison result for the NMIJ standard for air kerma in ^{60}Co gamma radiation is $R_K = 1.0072$ ($u_c = 0.0024$). The results for all the NMIs are shown in Figure 5 where some differences between the NMIs can be attributed to the method of correction for the wall effect. The standard deviation of all the international comparison results is equal to 4.3×10^{-3}.

In principle, these results will be used as the basis of the entries in Appendix B of the KCDB set up under the Mutual Recognition Arrangement [25]. Many NMIs that have previously used experimental extrapolation methods to determine wall correction factors are currently checking their factors, using various Monte Carlo codes or other methods. It is anticipated that it will be a further eight months before all the NMIs will be ready for their results to be entered into the BIPM key comparison database (KCDB). In the meantime, the BIPM is also reviewing its experimental and calculated results for the wall corrections of its primary standard.

Figure 5 International air kerma comparison results



References

[1] Takata N. Kurosawa T. and Koyama Y., Establishment of standards for γ rays at AIST, *Medical Standard Dose* **7** No. 2, 2002, 11-18. (in Japanese)

[2] Boutillon M. and Niatel M.-T., A study of a graphite cavity chamber for absolute measurements of ^{60}Co gamma rays, *Metrologia*, 1973, **9**, 139-146.

[3] Boutillon M. Allisy-Roberts P.J. and Burns D.T., Measuring conditions used for the calibration of ionization chambers at the BIPM, *Rapport BIPM-01/04*, 2001, 19 pages.

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

[5] Boutillon M. Volume recombination parameter in ionization chambers *Phys. Med. Biol.* **43,** 1998**,** 2061-2072.

[6] BIPM, Correction d'humidité, in *Com. Cons. Etalons Mes. Ray. Ionisants (Section I)*, 1977, **4**, R(I)6 (Offilib, F-75240 Paris Cedex 05).

[7] BIPM, Estimations of $k_{\mathrm{att}}k_{\mathrm{sc}}k_{\mathrm{CEP}}$ and their uncertainties, in *Com.Cons.Ray.Ionisants* 2001, **17**, 172-173 (Paris: Offilib).

[8] Kurosawa T, Koyama Y; and Takata N. Ionization chamber wall correction factors for air kerma standards of gamma rays *Medical Standard Dose* **6** No. 2, 2001, 1-6.

[9] Rogers D.W.O. and Treurniet J. (1999) Monte Carlo calculated wall and axial non-uniformity corrections for primary standards of air kerma, *NRCC Report PIRS–663* and *CCRI Working document* CCRI(I)/99-26, 25 p.

[10] Boutillon M. and Perroche A.-M., Radial non-uniformity of the BIPM ^{60}Co beam, *Rapport BIPM-89/2*, 1989, 9 pages.

[11] IAEA, X- and gamma-ray standards for detector calibration, *IAEA TECDOC-619,* 1991.

[12] Rogers D.W.O., Bielajew A.F. and Nahum A.E. Ion chamber response and A_{wall} correction factors in a ^{60}Co beam by Monte Carlo simulation, *Phys. Med. Biol.*, 1985, **30**, 429–443.

[13] Bielajew A.F. and Rogers D.W.O. Implications of new correction factors on primary air kerma standards in ^{60}Co beams, *Phys. Med. Biol.*, 1992, **37**, 1283–1291.

[14] Kondo S. and Randolph M.L. Effect of finite size of ionization chambers on measurements of small photon sources, *Radiat. Res*., 1960, **13**, 37–60.

[15] Bielajew A.F. Correction factors for thick-walled ionisation chambers in point-source photon beams, *Phys. Med. Biol*., 1990, **35**, 501–516.

[16] Büermann L., Kramer H.-M. and Csete I. Results supporting calculated wall correction factors for cavity chambers, *CCRI Working document* CCRI(I)/01-18, 2001, 10 pp.

[17] BIPM, The estimation of k_{att}, k_{sc} k_{CEP} and their uncertainties in, *Com.Cons.Ray.Ionisants* 1999, **16,** 145-146 (Paris:Offilib).

[18] Csete I., New correction factors for the OMH air kerma standard for ^{137}Cs and ^{60}Co radiation, *CCRI Working document* CCRI(I)/01-03, 2001, 2 p.

[19] Kramer H.-M., Büermann L. and Csete I. Comparison of the PTB and OMH air kerma standards for ^{60}Co and ^{137}Cs gamma radiation, *CCRI Working document* CCRI(I)/01-17, 2001, 9 pp.

[20] Rogers D.W.O., Caffrey J.P., Kawrakow I. and Shortt K.R., Wall correction factors for graphite walled ion chambers, *CCRI Working document* CCRI(I)/01-25, 2001, 10 pp.

[21] Kramer H.-M., Büermann L. and Ambrosi P. Change in the realization of the gray at the PTB, *Metrologia*, 2002, **39**, 111-112.

[22] Allisy-Roberts P.J., Toni M.P. and Bovi M., Comparison of the standards for air kerma of the ENEA-INMRI and the BIPM for ^{60}Co γ rays, *Rapport BIPM-02/09*, 2002, 11 pp.

[23] Allisy-Roberts P.J., Burns D.T., Kessler C. and Spasić-Jokić V. Comparison of the standards of air kerma of the SZMDM Yugoslavia and the BIPM for ^{60}Co γ rays, *Rapport BIPM-02/01*, 2002, 9 pp.

[24] Allisy-Roberts P.J., Burns D.T., Kessler C., Ivanov R.N., Comparison of the standards of air kerma of the NCM Bulgaria and the BIPM for ^{60}Co γ rays, *Rapport BIPM-02/03*, 2002, 9 pp.

[25] MRA: *Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes*, International Committee for Weights and Measures, 14 October 1999, 45 pp. Available from the BIPM website: www.bipm.org/pdf/mra.pdf.

August 2002
Final edition September 2004