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Abstract
A comparison of the standards for air kerma of the National Research Council of Canada and of the Bureau International des Poids et Mesures has been carried out in ^{60}Co gamma radiation. The results show that the NRC and the BIPM standards for air kerma are in agreement, yielding a ratio of 1.0020 for the calibration factors of the transfer chambers, the difference from unity being within the combined standard uncertainty of 0.0031.

1. Introduction

A comparison of the standards for air kerma held by the National Research Council of Canada (NRC) and the Bureau International des Poids et Mesures (BIPM), has been carried out in ^{60}Co gamma radiation. The Canadian standard C3 is a graphite-walled cylindrical cavity ionization chamber of volume about 3 cm^3 constructed at the NRC in 1958 [1]. The BIPM primary standard is a graphite-walled cavity ionization chamber of pancake geometry with a volume about 7 cm^3 designed in 1966 [2].

The comparison took place at the BIPM in November 1998 using four transfer chambers belonging to the NRC. The result of the comparison is given in terms of the ratio of the calibration factors of the transfer standards as determined at the two laboratories.

The results of the present air kerma comparison are compared with those obtained in the previous comparisons of air kerma standards with the NRC conducted in 1975 [3] and 1989 [4].

2. Determination of air kerma

Air kerma is determined under the following reference conditions:

- the distance from source to reference plane is 1 m;
- the field size in air at the reference plane is 10 cm x 10 cm;
- the photon fluence rate at the centre of each side of the square is 50 % of the photon fluence rate at the centre of the square.

The air kerma rate is determined from

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

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

The values for the physical constants [5] and the correction factors used in (1) are listed in Table 1 for both standards together with their associated uncertainties. The component uncertainties of the air kerma ratio, expressed as $R_K = K_{NRC}/K_{BIPM}$, are also listed in the table. As the values used for air density, W/e, $(\bar{\mu}_{en}/\rho)_{a,c}$, $\bar{g}$, $\bar{s}_{c,a}$ and k_h are derived from the same basic data in both laboratories, the uncertainty in R_K is due only to the uncertainties in the correction factors, the volumes of the standards, the ionization currents measured and the distance to the source.

3. Comparison of air kerma standards

The comparison of the NRC and BIPM standards was made indirectly by comparing the calibration factors N_K of the four transfer chambers as determined in the individual laboratories. The calibration factor is given by

$$N_{K\,\text{lab}} = \dot{K}_{\text{lab}} / I_{\text{lab}} \ , \qquad (2)$$

where $\dot{K}_{\text{lab}}$ is the air kerma rate measured with the standard and I_{lab} is the ionization current of the transfer chamber corrected for the effects described in section 4.

The four transfer chambers belonging to the NRC are graphite thimble cavity chambers manufactured by Nuclear Enterprises (Type NE 2571 serial numbers 1527, 2572, 2587 and 2595). Their main characteristics are listed in Table 2. Details concerning the calibrations, the corrections to the ionization current of the transfer chambers and estimations of the uncertainties of the N_K are described in section 4.

Table 1. Physical constants and correction factors entering in the determination of the air kerma rates, $\dot{K}_{\mathrm{BIPM}}$ and $\dot{K}_{\mathrm{NRC}}$, and their relative standard uncertainties

	BIPM values	BIPM relative uncertainty[(1)]		NRC values	NRC relative uncertainty[(1)]		$R_{\dot{K}}$ relative uncertainty[(1)]	
		$100\,s_i$	$100\,u_i$		$100\,s_i$	$100\,u_i$	$100\,s_i$	$100\,u_i$
Physical constants								
dry air density[(2)] / kg·m^{-3}	1.2930	-	0.01	1.2929	-	0.01	-	-
$(\mu_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$	0.9985	-	0.05	0.9987	-	0.10	-	-
$\bar{s}_{\mathrm{c,a}}$	1.0010	-	0.11[(3)]	1.0005	-	0.12[(3)]	-	-
W/e / (J·C^{-1})	33.97			33.97			-	-
$\bar{g}$ fraction of energy lost by bremsstrahlung	0.0032	-	0.02	0.0032	-	0.05	-	-
Correction factors								
k_{s} recombination loss	1.0016	0.01	0.01	1.0016	0.03	0.03	0.03	0.03
k_{h} humidity	0.9970	-	0.03	0.9970	-	0.05	-	-
k_{st} stem scattering	1.0000	0.01	-	0.9960	0.02	-	0.02	-
k_{at} wall attenuation	1.0402	0.01	0.04					
k_{sc} wall scattering	0.9716	0.01	0.07	1.0218[(4)]	0.05	0.10[(4)]	0.05	0.13[(4)]
k_{CEP} mean origin of electrons	0.9922	-	0.01					
k_{comp} compound wall	-			1.000	-	0.20	-	0.20
k_{an} axial non-uniformity	0.9964	-	0.07	0.9999[(5)]	-	0.06[(5)]	0.01	0.09[(5)]
k_{rn} radial non-uniformity	1.0016	0.01	0.02					
Measurement of $\boldsymbol{I/V\rho}$								
V volume / cm^3	6.8116	0.01	0.03	2.7552	-	0.09	0.01	0.09
I ionization current / pA		0.01	0.02		0.04	0.06	0.04	0.06
Relative standard uncertainty								
quadratic summation		0.03	0.17		0.07	0.31	0.08	0.29
combined uncertainty		0.17			0.32		0.30	

(1) s_i represents the relative standard uncertainty $u(x_i)/x_i$ estimated by statistical methods, type A, u_i represents the relative standard uncertainty $u(x_i)/x_i$ estimated by other means, type B.
(2) at 0 °C and 101.325 kPa.
(3) combined uncertainty for the product ($\bar{s}_{\mathrm{c,a}} \cdot W/e$)
(4) combined value for k_{wall}
(5) combined value for $k_{\mathrm{pn}}k_{\mathrm{an}}$

4. Experimental conditions

4.1. Conditions of Measurement

The method of calibration used at the NRC is described in [6] and that at the BIPM in [7].

- *Positioning of the transfer chamber*: The axis of each transfer chamber is located in the reference plane, 1 m from the source. At the BIPM the position is measured without the build-up cap in place. In both cases, the uncertainty in the measurement of the position is less than 0.01 mm. The chambers are positioned so that the line on the stem faces the source.

Table 2. Characteristics of the NRC transfer chambers

Characteristic		Nominal value
Dimensions	Inner diameter	6.3 mm
	Wall thickness	0.35 mm
	Cavity length	24.0 mm
	Tip to reference point	14.5 mm
Electrode (Al)	Diameter	1.0 mm
	Height	21.0 mm
Volume	Air cavity	0.69 cm^3
Wall	Material	graphite
	Density	1.7 g cm^{-3}
Build up cap	Material	Delrin
	Thickness	3.9 mm
Applied voltage	Positive polarity	300 V

- *Build-up cap*: Each transfer chamber was supplied with its own build-up cap for use in ^{60}Co radiation. These were in place for all measurements of ionization current.

- *Humidity and temperature*: During calibration at the BIPM, the relative humidity is controlled in the range 45 % to 55 %. The air temperature was around 21 °C and, during each series of measurements, it was stable to within ± 0.01 °C. At the NRC, the relative humidity is controlled in the range 30% to 70%. The air temperature was around 22 °C and during each series of measurements was stable to within ± 0.02 °C.

- *Collecting voltage*: A collecting voltage of 300 V (positive polarity), was applied to the chambers at least 30 minutes before any measurement was made at either laboratory.

- *Measurement of charge*: The charge Q collected by the chambers was measured using Keithley electrometers, model 642 at the BIPM and model 35617 at the NRC. The chambers were pre-irradiated for at least 15 minutes before measurements began.

- *Reproducibility of measurements*: The short-term relative standard deviation of the mean ionization current, measured with each transfer chamber, was estimated to be 10^{-4} at the BIPM for each chamber (1 to 5 series each of 30 measurements for each chamber). At the NRC, a single series of five repeated measurements, each lasting about 60 s, exhibited a relative standard uncertainty of less than 2×10^{-4}. The calibration of each chamber was repeated in a new set-up at least twice both before and after the measurements at the BIPM. The relative standard uncertainty of the mean normalized ionization current measured with a transfer chamber over the three months required for this comparison to be repeated at the NRC was typically 3×10^{-4}, although one chamber changed by 8×10^{-4}.

4.2. Corrections applicable to the ionization current of the transfer chambers

- *Leakage current*: The leakage current of the transfer chambers was about 0.01 % of the measured current at the BIPM, except for chamber 1527 which exhibited a leakage current of 0.03 %. The leakage currents at the NRC were less than 0.01 % as the air kerma rate is about four times greater than that at the BIPM.

- *Recombination*: No recombination correction was applied to the ionization currents. The volume recombination is negligible at an air kerma rate of less than 15 mGy s^{-1} for this chamber type and polarizing voltage, and the initial recombination loss will be the same in the two laboratories.

- *Temperature and pressure normalization*: At both laboratories, the measured ionization current of the transfer chambers was normalized to a temperature of 293.15 K for the purpose of the comparison, and a standard pressure of 101.325 kPa. (Ordinarily for its disseminated standards, NRC uses a reference temperature of 295.15 K as indicated in [6].)

- *Humidity*: Humidity is controlled at 50 % (± 5 %) at the BIPM and 50 % (± 20 %) at the NRC, consequently no correction for humidity needs to be applied to the ionization current measured.

- *Radial non-uniformity*: No correction was made for the radial non-uniformity of the beam over the section of the transfer chambers. In the BIPM beam, the correction factor for this chamber type is less than 0.02 % [8] and similarly at the NRC.

5. Results and discussion

The results of the comparison, R_K, are expressed in the form

$$R_K = N_{K_{\mathrm{NRC}}} / N_{K_{\mathrm{BIPM}}} \quad . \qquad (3)$$

The values measured for the comparison are shown in Table 3. Contributions to the relative standard uncertainty of N_K are given in Table 4. Taking the mean value for the four chambers used in the present comparison gives $R_K = 1.0020$ with a combined standard uncertainty $u_c(R_K) = 0.0031$.

The relative spread in the ratio R_K for the four chambers is 0.19 % with a statistical uncertainty, s_c of 0.05 %. The contribution to the combined standard uncertainty that arises from the use of transfer chambers is 0.09 %. Given that four chambers were calibrated at each laboratory for a total of four times (typically), the uncertainty on the mean value of R_K in this comparison should be a factor of $(15)^{-0.5}$ lower than 0.09 %, or about 0.02 %. Unfortunately, the observed statistical uncertainty of 0.05 % is about a factor of two larger than expected. Closer examination of Table 3 reveals that the NRC value of N_K for chamber

1527 is primarily responsible for this larger than expected value of statistical uncertainty. Furthermore, by comparing values of $N_{D,\mathrm{w}}$ for each chamber from the corresponding comparison of standards of absorbed dose to water in [9] to the corresponding value of N_K in this comparison, circumstantial evidence indicates that the NRC value of N_K for the chamber 1527 may be too high by about 0.09 %. Given that the value of N_K for that chamber changed by 0.08 % pre- and post- the comparison at the BIPM, perhaps it is to be expected that its response might suffer from a lack of precision.

Table 3. Results of the air kerma standards comparison

NE 2571 Chamber	$N_{K\,\mathrm{NRC}}$ / Gy µC^{-1} pre-BIPM	$N_{K\,\mathrm{BIPM}}$ / Gy µC^{-1}	$N_{K\,\mathrm{NRC}}$ / Gy µC^{-1} post-BIPM	$\overline{N_{K\,\mathrm{NRC}}}$ / Gy µC^{-1} mean	$N_{K\,\mathrm{NRC}}$ pre/post ratio	R_K	u_c
1527	41.417	41.281	41.384	41.401	1.0008	1.0029	
2572	41.165	41.095	41.160	41.163	1.0001	1.0016	
2587	40.990	40.914	40.979	40.985	1.0003	1.0017	
2595	40.905	40.834	40.892	40.899	1.0003	1.0016	
				Mean values	+0.04 %	1.0020	0.0031

The NRC values used for the comparison result are the means of measurements before and after the BIPM measurements corrected to 1998-01-01, 0h EST (the half life of ^{60}Co is taken as (1 925.02 d, σ = 0.5 d) [10]). The BIPM air kerma value is the mean of measurements which were performed over a period of three months before and after the comparison at the BIPM. It is given at the reference date of 1998-01-01, 0h UT as is each value of measured current (using the IAEA half life of ^{60}Co (1 925.5 d, σ = 0.5 d) [10]).

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

	NRC		BIPM	
Relative standard uncertainty of	100 s_i	100 u_i	100 s_i	100 u_i
Air kerma rate (Table 1)	0.07	0.31	0.03	0.17
Ionization current of each transfer chamber	0.06	0.06	0.02	0.02
Distance	0.01	–	0.01	0.02
Relative standard uncertainties of $N_{K,\mathrm{lab}}$				
quadratic summation	0.09	0.32	0.04	0.17
combined uncertainty	0.33		0.17	
Relative standard uncertainties of R_K	100 s		100 u	
quadratic summation	0.10		0.30	
combined uncertainty, u_c	0.31			

The previous comparisons of air kerma in ^{60}Co gamma radiation between the NRC and the BIPM [3, 4] are shown in Table 5 together with the estimated comparison uncertainties. In each case, the comparison was indirect using the different transfer chambers indicated. The primary standard 3C at the NRC is unchanged over this period. At the BIPM a different standard chamber has been used but each is always compared with its predecessor and comparative measurements are within 0.01 %. Each laboratory has not only changed the ^{60}Co used as is inevitable but also the ^{60}Co source container used. This has resulted in changes to correction factors for recombination.

Although the values used for physical quantities have changed over the intervening years, they have been the same at both laboratories at the time of each comparison so the air kerma ratios should be affected only if the values of the correction factors applied to the standard have been changed. In the case of the NRC standard for air kerma, the overall change, which was applied to the 1989 comparison results but not officially implemented in the disseminated standard until 1990, was a decrease of 0.45 %. This consisted of a decrease in the standard of 0.64 % due to changes in the physical quantities, offset by an increase, mostly in the wall correction factor, of 0.19 %. The absolute value of air kerma at the BIPM measured by the ionization method actually decreased by 0.8 % between 1982 and 1987 primarily because of the change to the stopping power ratio of 0.75 % implemented in 1986 by the Consultative Committee for Standards of Ionizing Radiation (since 1997 the Consultative Committee for Ionizing Radiation). Consequently, the relative difference between 1975 and 1989 appears to be mostly reconciled: relative to the BIPM's standard, the NRC's standard should have increased by 0.35 % (0.8 % - 0.45 %) resulting in a revised ratio of 1.0014 (i.e., 0.9979 x 1.0035). The 1989 comparison result agrees with the present value within the statistical uncertainties.

Table 5. Stability of comparison results between the NRC and the BIPM

Year	Transfer chambers	$R_{\underline{K}}$	u_c	s_c (1)
1975	Shonka n° 4	0.9979 1.0014 (revised)	0.0035	0.0003
1989	NE 2571-667 Capintec PR06-65838 and PR06-66564	1.0015 1.0032 1.0014	0.0035	0.0010
1998	NE2571 (Table 3)	1.0020	0.0031	0.0005

(1) statistical uncertainty associated with a repeated indirect comparison

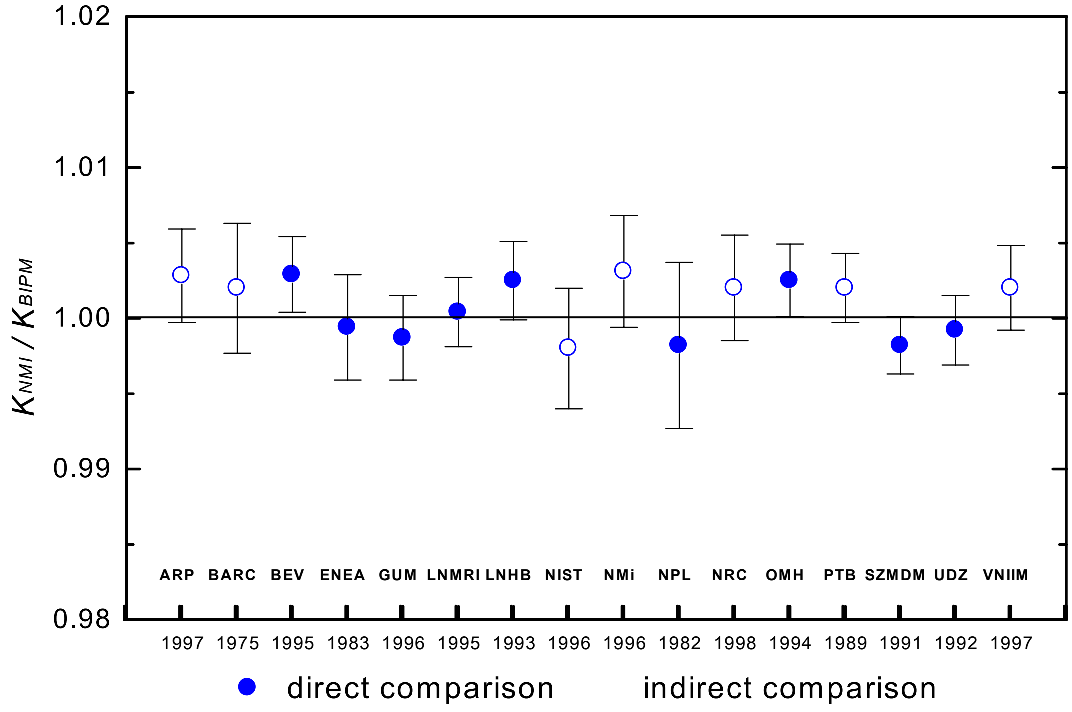
6. Conclusion

The primary standards of air kerma of the NRC (Canada) and the BIPM are in agreement, (R_{NRC} = 1.0020, u_c = 0.0031) within the comparison uncertainties. The result will be used as the basis for an entry to the BIPM key comparison database and the determination of degrees of equivalence between the sixteen national metrology institutes (NMIs) which have made such comparisons.

Figure 1 shows the most recent results of these comparisons between each NMI and the BIPM [11 - 16]. The uncertainties shown on the graph are the standard uncertainties for each comparison result. The distribution of the results of the BIPM comparisons for these sixteen NMIs has a standard uncertainty of 1.9×10^{-3}.

As the primary methods are the same for each laboratory, the correlations between the BIPM and each laboratory have been removed. There are further correlations between the NMIs depending on the similarities between their primary standard. This needs to be taken into account when comparing the results of one NMI with another.

Figure 1 International comparisons of air kerma in ^{60}Co gamma radiation



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