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

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Abstract
An indirect comparison has been made between the standards of air kerma of the National Institute of Standards and Technology, Gaithersburg, USA and of the Bureau International des Poids et Mesures. The standards agree to within 0,2 %.

1. Introduction

A direct comparison between the standards of air kerma at the NIST and at the BIPM was made in 1971. In 1993, the CCEMRI(I) recommended that ionizing radiation dosimetry standards should be compared at least once in 10 years. Following this recommendation, an indirect comparison of the standards of air kerma of the National Institute of Standards and Technology (NIST), Gaithersburg, USA and the Bureau International des Poids et Mesures (BIPM), has been made in ^{60}Co radiation. Two ionization chambers belonging to the NIST were used as transfer instruments. These transfer chambers were calibrated at the NIST in November 1995 and in June 1996, and at the BIPM in January 1996. The results of the comparison are given in terms of the ratio of the calibration factors determined at the two laboratories.

The present results agree with the 1971 comparison and demonstrate the stability of the standards of the two laboratories.

2. Determination of the air kerma

The air kerma rate is determined from

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

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 by 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 values of the physical constants and the correction factors entering in (1) are shown in Table 1 for both standards together with their associated uncertainties.

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

	BIPM values	BIPM relative uncertainty[1]		NIST values	NIST 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 / kg·m^{-3}	1,293 0	-	0,01	1,293 0	-	0,01	-	-
$(\mu_{\text{en}}/\rho)_{\text{a,c}}$	0,998 5	-	0,05	0,998 5	-	0,05	-	-
$\bar{s}_{\text{c,a}}$	1,001 0	-	0,30	1,001 0	-	0,25	-	-
W/e / (J·C^{-1})	33,97	-	0,15	33,97	-	0,15	-	-
$\bar{g}$ fraction of energy lost by bremsstrahlung	0,003 2	-	0,02	0,003 2	-	0,02	-	-
Correction factors								
k_{s} recombination losses	1,001 6	0,007	0,01	1,002 6	0,01	0,10	0,01	0,10
k_{h} humidity	0,997 0	-	0,03	0,997 0	-	0,10	-	-
k_{st} stem scattering	1,000 0	0,01	-	0,999 0	-	0,10	0,01	0,10
k_{at} wall attenuation	1,040 2	0,01	0,04	1,016 8[2]	0,03	0,30	0,03	0,30
k_{sc} wall scattering	0,971 6	0,01	0,07				0,01	0,07
k_{CEP} mean origin of electrons	0,992 2	-	0,01	0,995 0	-	0,05	-	0,05
k_{an} axial non-uniformity	0,996 4	-	0,07	1,000 0	-	0,02	-	0,07
k_{rn} radial non-uniformity	1,001 6	0,01	0,02	1,000 0	-	0,01	0,01	0,02
V volume / cm^3	6,811 6	0,01	0,03	1,1[3]	0,06	0,05	0,06	0,06
I ionization current / pA		0,01	0,02		0,05	0,14	0,05	0,14
Relative standard uncertainty								
quadratic summation		0,02	0,36		0,08	0,48	0,09	0,38
combined uncertainty		0,36			0,49		0,39	

[1] Expressed as a standard deviation
s_i represents the relative standard uncertainty estimated by statistical methods, type A,
u_i represents the relative standard uncertainty estimated by other means, type B.
[2] Varies from this value to 1,0387, since the NIST standard is based on the average of 6 cavity chambers of increasing volume.
[3] Varies from this value to 50,1 cm^3 for the range of 6 cavity chambers.

The comparison of the NIST and BIPM standards is made by means of the calibration factors $N_{\dot{K}}$ for the two transfer chambers in the two ^{60}Co beams which are given by

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

where $\dot{K}_{\text{lab}}$ is the air kerma rate and I_{lab} is the ionization current of the transfer chamber, measured at the respective laboratory, the NIST or the BIPM, and corrected for the effects and influences described in this report.

The standard for the determination of air kerma at the NIST is described in [1]. The value of $\dot{\boldsymbol{K}}_{\text{NIST}}$ is the value corrected to the date of measurement of the transfer chamber (the half life of ^{60}Co is taken as (1 925,5 d, σ = 0,5 d) [2]) from 1 March 1990. The source used for the calibration was the high air kerma rate source (6 mGy s^{-1}; serial number BO36).

The standard for the determination of air kerma at the BIPM is described in [3]. The $\dot{K}_{\text{BIPM}}$ 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 1996-01-01, 0h UT (the half life of ^{60}Co is taken as the same as the NIST), as is the value of I_{lab}.

3. NIST transfer chambers used for the comparison

The two NIST transfer chambers are graphite cavity chambers manufactured by Exradin (Type A3 serial number 185) and Shonka (Type A3 serial number 2022). Their main characteristics are listed in Table 2. Details concerning the calibration, pertinent corrections and estimations of the uncertainties are described in section 4 of this report.

Table 2. Characteristics of the NIST transfer chambers

Chamber	Exradin / Shonka A3	185*	2022*
		Nominal value / mm	
Dimensions	Outer diameter	19,3	19,2
	Inner diameter	19,05	18,95
	Wall thickness	0,25	0,25
	Build up cap	2,3	3,3
Electrode	Diameter	2,00	2,00
Volume	Air cavity	3,6 cm^3	3,6 cm^3
Wall	Materials	C 552 air-equivalent plastic	C 552 air-equivalent plastic
	Density	1,76 g·cm^{-3}	1,76 g·cm^{-3}
Build-up hemispheres	Material	air-equivalent plastic	perspex
	Thickness	0,085 cm^2 g^{-1}	0,142 cm^2 g^{-1}
Applied voltage	Both polarities	500 V	500 V

* These chambers are not equivalent to recent A3 Exradin chambers.

4. Calibration procedure

The experimental method for calibrations at the NIST is described in [4] and that for the BIPM in [5].

4.1 Measuring Conditions

- *Positioning of the transfer chamber*. The axis of the transfer chamber is located in the reference plane, 1 m from the source. The field size at the reference plane is 10 cm x 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. The position of the chambers is controlled without the build-up hemispheres. The uncertainty in positioning is less than 0,01 mm at the NIST and 0,05 mm at the BIPM. The chamber 185 was positioned so that the white mark on the stem faced the radiation source and the hemispheres were oriented so that the overlap shoulder was on the front hemisphere. Chamber 2022 was placed so that its serial number on the stem faced the source and the hemispheres oriented so that the hole in the neck of the hemisphere was at the back of the chamber.

- *Humidity and temperature*. During calibration, the relative humidity was in the range of 40 % to 50 %. The air temperature was around 21 °C. During a series of measurements, the air temperature was stable to better than 0,01 °C.

- *Collecting voltage*. A collecting voltage of 500 V (both polarities), supplied by each laboratory, was applied to the chambers. Measurements with the transfer chambers were made with both polarities. The polarity effect I_+/I_-, where the symbols refer to positive and negative voltage, was measured as $3\cdot10^{-4}$ and $2\cdot10^{-4}$ for chamber 185 and $1\cdot10^{-3}$ and $7\cdot10^{-4}$ for chamber 2022, at the NIST and at the BIPM respectively. The mean ionization current obtained with the two polarities was used in (2).

- *Measurement of charge.* The charge Q collected by the chamber was measured using the BIPM or the NIST electrometer as relevant.

- *Reproducibility of measurements*. The short-term relative standard deviation of the mean ionization current, measured with the transfer chamber, is estimated to be 0,26 % for chamber 185 and 0,34 % for chamber 2022 (12 groups of measurements for each) at the NIST and 0,01 % for chamber 185 and 0,03 % for chamber 2022 (12 series of 30 measurements for each chamber) at the BIPM.

4.2 Corrections applicable to the ionization current of the NIST chambers

- *Leakage current.* The leakage current of the transfer chambers was negligible, being less than 0,001 %.

- *Temperature and pressure normalization.* The measured ionization current was normalized to 295,15 K and 101,325 kPa.

- *Recombination.* A recombination correction, k_s for incomplete ion collection (using both polarities) was derived from measurements made between 200 V and 700 V at the NIST with an extrapolation to zero of $1/I$ versus $1/V$. The BIPM used a quadratic extrapolation between 100 V and 700 V to take into account the volume recombination, which is not negligible ($5 \cdot 10^{-4}$ for I = 700 pA). The values for k_s so derived are shown in Table 3.

Table 3. Values for k_s derived from measurements made at the NIST and BIPM

Laboratory	Method : $1/I = f(1/V)$	Chamber 185	Chamber 2022
NIST	linear (700 V to 200 V)	1,002 6*	1,002 1*
BIPM	quadratic (700 V to 100 V)	1,001 5*	1,001 6*

* ***the values derived by the NIST were used in the comparison, for coherence.***

- *Build-up hemispheres.* Each chamber was supplied with build-up hemispheres for use in ^{60}Co radiation and these were in place for all measurements of ionization current. If the hemispheres are turned through 180°, the calibration factor is 0,05 % greater at the BIPM for chamber 185 and 0,05 % less for chamber 2022.

- *Other factors.* As is usual, no corrections for humidity were applied to the ionization current measured by these chambers. The stem scattering effect has not been checked at the BIPM and no allowance for the radial non-uniformity of the beam over the section of the transfer chamber has been made in the results. In the BIPM beam, k_{rn} = 1,000 5 for these chambers.

5. Uncertainties

The relative uncertainties of $\dot{K}$ are given in Table 1. Contributions to the relative standard uncertainty in $N_{\dot{K}}$ are given in Table 4.

Table 4. Estimated relative standard uncertainties* in the calibration factor, $N_{\dot{K}}$, of the transfer chambers

	NIST		BIPM	
Relative standard uncertainty in the measurement of	100 s_i	100 u_i	100 s_i	100 u_i
Air kerma rate	0,08	0,48	0,02	0,36
Ionization current of transfer chamber				
185	0,08	0,03	0,01	0,02
2022	0,08	0,03	0,03	0,02
Distance	0,01	0,01	0,01	0,02
Relative standard uncertainties in $N_{\dot{K}}$				
quadratic summation (chamber 185)	0,11	0,48	0,02	0,36
quadratic summation (chamber 2022)	0,11	0,48	0,04	0,36
combined uncertainty	0,49		0,36	

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

6. Results of the indirect comparison of BIPM and NIST standards of air kerma

The relevant $\dot{K}$ and $N_{\dot{K}}$ values obtained are shown in Table 5 and the results of the comparison, $R_{\dot{K}}$, are expressed in the form

$$R_{\dot{K}} = N_{\dot{K}\,\mathrm{lab}} \big/ N_{\dot{K}\,\mathrm{BIPM}} \quad . \qquad (2)$$

As the same physical constants were used by both laboratories, the relative uncertainty on $R_{\dot{K}}$ is due to the relative uncertainties in the correction factors , the measuring volume of the standards and the ionization currents measured by the transfer chambers at the two laboratories.

Table 5. Results of the air kerma comparison in ^{60}Co radiation using the NIST transfer chambers.

Laboratory	$\dot{K}_{\mathrm{lab}}$ (1) / mGy·s^{-1}	$N_{\dot{K}}$ / Gy·µC^{-1}	Relative standard uncertainty 100 σ	$R_{\dot{K}}$	Relative standard uncertainty 100 σ
NIST	6,087 4				
185		8,218 1	0,49		
2022		8,944 8	0,49	0,998 2	0,40
BIPM	5,269 0			0,997 9	0,40
185		8,233 3*	0,36		
2022		8,963 5*	0,36		

* using the values of k_s derived by the NIST

7. Discussion

The last air kerma comparison between the BIPM and the NIST for ^{60}Co radiation was in 1971. At that time the comparison was made directly using one of the NIST standards for measurement of air kerma in the BIPM ^{60}Co beam. The value of $\dot{K}_{\mathrm{NIST}} / \dot{K}_{\mathrm{BIPM}}$ then was 0,997 4 (σ = 0,55 %) [6] which is in agreement with the present value of 0,998 0.

In 1994, the same two NIST transfer chambers were used for a comparison between the NIST and the Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, Italy (ENEA) in ^{60}Co radiation [7]. Corrections made to the ionization current of the transfer chambers were the same as for the present comparison. Comparison of the NIST and the BIPM standards can also be made indirectly through the comparison NIST/ENEA and ENEA/BIPM. The result, as shown in Table 6 where $\dot{K}_{\mathrm{NIST}} / \dot{K}_{\mathrm{BIPM}}$ = 0,999 4 x 0,999 4 = 0,998 8, is in agreement with the present results.

Table 6. Comparison between the NIST and the BIPM indirectly through the ENEA.

Year	Lab 1	Lab 2	$\dot{K}_{\text{lab1}} / \dot{K}_{\text{lab2}}$
1983 [8]*	ENEA	BIPM	0,999 4
1994 [7]	NIST	ENEA	0,999 4
	NIST	BIPM	0,998 8

* updated according to the CCEMRI in 1985.

8. Conclusion

The present indirect comparison shows agreement, within 0,2 %, between the standards of air kerma of the NIST and the BIPM. The agreement in 1971 was within 0,3 % [6] which confirms the stability of the two standards.

Figure 1 shows the results of all air kerma comparisons with the BIPM in ^{60}Co radiation. The standard deviation of the comparisons between the 15 national primary laboratories is less than 0,2 %.

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