Comparisons of the radiation protection standards for air kerma of the NIST and the BIPM for ^{60}Co and ^{137}Cs gamma radiation

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Abstract

An indirect comparison of the standards for air kerma of the National Institute of Standards and Technology (NIST), USA, and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co and ^{137}Cs radiation protection-level beams of the BIPM in September 2011. The comparison results, based on the calibration coefficient for two transfer standards and expressed as a ratio of the NIST and the BIPM standards for air kerma, are 1.0023 with a combined standard uncertainty of 3.2×10^{-3} in ^{60}Co, and 0.9990 with a combined standard uncertainty of 3.5×10^{-3} in ^{137}Cs.
The result in the ^{60}Co beam for radiation protection agrees within the uncertainties with the result of the comparison carried out at the same time in the CIS Bio ^{60}Co beam for radiotherapy-level air kerma.

1. Introduction

The previous indirect comparison of the air kerma standards for radiation protection of the National Institute of Standards and Technology (NIST), USA, and the Bureau International des Poids et Mesures (BIPM) was made in 1994 for ^{137}Cs gamma radiation (Leitner *et al* 1997). The comparison result was 1.0017 (42) but when updated for the changes made to the standards at both labs, this became 1.0077 (42); the changes made to the standards (Seltzer *et al* 2003, Kessler *et al* 2009) are explained in Section 2. No comparison was made previously in the ^{60}Co radiation protection beam. A new indirect comparison between both laboratories was carried out in September 2011 in both the ^{60}Co and ^{137}Cs radiation protection-level beams at the BIPM, although only results for ^{137}Cs appear in the online BIPM key comparison database (KCDB 2014) under the reference BIPM.RI(I)-K5.

The NIST air kerma standard for ^{60}Co and ^{137}Cs is determined using a suite of six standard graphite spherical cavity ionization chambers with nominal volumes of 1 cm^3, 10 cm^3, 30 cm^3 and 50 cm^3. Three of these six standards have the same nominal volume of 50 cm^3 but different wall thickness (Loftus *et al* 1974). The main characteristics of the standards are listed in Table 1. The BIPM standards are parallel-plate graphite cavity ionization chambers with volume of about 6.8 cm^3 as described by Boutillon *et al* (1973) and Boutillon *et al* (1996) and the results of recent evaluations of calculated correction factors and new volume estimations are described by Burns *et al* (2007) and Kessler *et al* (2009).

The comparison was undertaken using two ionization chambers of the NIST as transfer standards. The results of the comparison are given in terms of the mean ratio of the calibration coefficients of the transfer standards determined at the two laboratories under the same reference conditions. Two ionization chambers of type Exradin[a] A5, serial numbers XY051604 and XY051605, were used for the present comparison.

Table 1. Characteristics of the NIST standard for air kerma

NIST standards						
Chamber						
Chamber name	Std 1	Std 10	Std 30	Std 50-1	Std 50-2	Std 50-3
Outer diameter / mm	20.65	34.28	46.07	53.40	55.80	58.00
Inner diameter / mm	12.70	26.77	38.57	46.10	45.63	45.74
Wall thickness / mm	3.980	3.76	3.75	3.65	5.09	6.13
Electrode						
Shape	cylindrical	cylindrical	cylindrical	cylindrical	cylindrical	cylindrical
Diameter / mm	1.016	1.0	1.0	3.0	3.0	3.0
Net volume(1)						
Air cavity / cm^3	1.1309	10.069	30.24	51.634	50.089	50.155
Wall						
Material	graphite	graphite	graphite	graphite	graphite	graphite
Density / g cm^{-3}	1.73	1.72	1.74	1.73	1.73	1.73
Applied voltage / V						
Both polarities	300	300	300	500	500	500

(1) Difference between cavity volume and electrode volume

2. Determination of the air kerma

The air kerma rate is determined by

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

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 by bremsstrahlung production in air,

[a] Certain commercial equipment, instruments, and materials are identified in this work in order to specify adequately the experimental procedure. Such identification does not imply recommendation nor endorsement by the NIST nor does it imply that the material or equipment identified is the best available for the purposes described in this work.

$(\mu_{en}/\rho)_{a,c}$ 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,

$\prod k_i$ is the product of the correction factors to be applied to the standard.

Physical data and correction factors

The values for the physical data used in (1) are consistent with the Consultative Committee for Ionizing Radiation recommendations (CCEMRI(I) 1985) and the correction factors needed for ^{60}Co and ^{137}Cs radiation are given in Table 2 for the BIPM standard and in Tables 3a and 3b for the NIST standards, together with their associated uncertainties.

Table 2. Physical constants and correction factors with their estimated relative uncertainties of the BIPM standards for the ^{60}Co and ^{137}Cs radiation beams at the BIPM

BIPM standard		values ^{60}Co	uncertainty (1) 100 s_i	uncertainty (1) 100 u_i	values ^{137}Cs	uncertainty (1) 100 s_i	uncertainty (1) 100 u_i
Physical Constants							
ρ_a	dry air density (2) / kg m^{-3}	1.2930		0.01	1.2930	–	0.01
$(\mu_{en}/\rho)_{a,c}$	ratio of mass energy-absorption coefficients	0.9989	0.01	0.04	0.9990		0.05
$s_{c,a}$	ratio of mass stopping powers	1.0003		0.11 (3)	1.0104	–	0.11 (3)
W/e	mean energy per charge / J C^{-1}	33.97			33.97	–	
g_a	fraction of energy lost in radiative processes	0.0031		0.02	0.0012	–	0.02
Correction factors:							
k_g	re-absorption	0.9996	–	0.01	–	–	–
k_s	recombination losses	1.0018	0.01	0.02	1.0018	0.01	0.02
k_h	humidity	0.9970	–	0.03	0.9970	–	0.03
k_{st}	stem scattering	1.0000	0.01	–	0.9998	0.01	–
k_{wall}	wall attenuation and scattering	1.0011	–	(4)	1.0002	0.01	(4)
k_{an}	axial non-uniformity	1.0020	–	(4)	1.0018	–	0.04
k_{rn}	radial non-uniformity	1.0003	–	0.02	1.0011	0.01	0.10
Measurement of I / υ							
υ	chamber volume / cm^3	6.8570 (5)	–	0.08	6.7967 (6)	–	0.08
I	ionization current / pA		0.01	0.02		0.02	0.02
Relative standard uncertainty							
quadratic summation			0.02	0.15		0.03	0.19
combined uncertainty			**0.15**			**0.19**	

(1) Expressed as one standard deviation
s_i represents the type A relative standard uncertainty estimated by statistical methods,
u_i represents the type B relative standard uncertainty estimated by other means

(2) At 101 325 Pa and 273.15 K

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

(4) Uncertainties included in the uncertainty of the chamber effective volume

(5) For standard CH2, the original measured volume 6.8116 cm^3 increased by the factor 1.0076 determined ionometrically following a chamber repair and reduced by the factor 1.0009 (Burns *et al* 2007)

(6) For standard CH5-1, the measured volume 6.8028 cm^3 reduced by the factor 1.0009 (Burns *et al* 2007).

Table 3a. Physical constants and correction factors with their estimated relative uncertainties of the NIST standards for the ^{60}Co radiation beams at the NIST

	NIST	Std 1	uncertainty		Std 10	uncertainty		Std 30	uncertainty		Std 50-1	uncertainty		Std 50-2	uncertainty		Std 50-3	uncertainty	
	Physical Constants	value	Type A	Type B	value	Type A	Type B	value	Type A	Type B	value	Type A	Type B	value	Type A	Type B	value	Type A	Type B
ρ_0	Density of dry air at T=0C and P=1atm (kg/m3)	1.2930		0.02	1.2930		0.02	1.2930		0.02	1.2930		0.02	1.2930		0.02	1.2930		0.02
$(\mu_{en}/\rho)_{a,c}$	ratio energy-absorption coefficients, air/graphite	0.9990		0.06	0.9990		0.06	0.9990		0.06	0.9990		0.06	0.9990		0.06	0.9990		0.06
$\overline{s}_{c,a}$	ratio of stopping powers, graphite/air	1.0009		0.11	1.0004		0.11	1.0002		0.11	1.0001		0.11	1.0001		0.11	1.0001		0.11
W/e	Wair/e (J/C)	33.97			33.97			33.97			33.97			33.97			33.97		
$\overline{g}$	(1-g), radiative loss correction.	0.9967		0.02	0.9967		0.02	0.9967		0.02	0.9967		0.02	0.9967		0.02	0.9967		0.02
	Correction Factors																		
k_h	humidity correction (corrects to dry air)	0.9971		0.06	0.9971		0.06	0.9971		0.06	0.9971		0.06	0.9971		0.06	0.9971		0.06
k_s	ksat, loss of ionization due to recombination	1.000	0.05	0.10	1.000	0.05	0.10	1.001	0.05	0.10	1.001	0.05	0.10	1.001	0.05	0.10	1.001	0.05	0.10
k_{st}	stem scatter	0.9982		0.05	0.9992		0.05	0.9992		0.05	0.9990		0.05	0.9990		0.05	0.9990		0.05
k_{wall}	kwall, zero wall thickness	1.0207		0.17	1.0236		0.17	1.0260		0.17	1.0263		0.17	1.0363		0.17	1.0429		0.17
k_{an}	axial nonuniformity	1.000		0.02	1.000		0.05	1.000		0.05	1.000		0.05	1.000		0.05	1.000		0.05
k_{rn}	radial nonuniformity	1.000		0.01	1.000		0.01	1.000		0.01	1.000		0.01	1.000		0.01	1.000		0.01
k_{TP}	air density			0.03			0.03			0.03			0.03			0.03			0.03
V	chamber net volume/ cm3	1.1309	0.10	0.10	10.0690	0.16	0.10	30.2400	0.06	0.05	51.6340	0.06	0.05	50.0890	0.06	0.05	50.1550	0.06	0.05
I	ionization current/ pA		0.10	0.10		0.10	0.10		0.10	0.10		0.10	0.10		0.10	0.10		0.10	0.10
t	time			0.05			0.05			0.05			0.05			0.05			0.05
d	distance (axial)			0.02			0.02			0.02			0.02			0.02			0.02
	Relative standard uncertainty																		
	quadratic summation		0.15	0.29		0.20	0.30		0.13	0.28		0.13	0.28		0.13	0.28		0.13	0.28
	combined uncertainty (for each chamber)		0.33			0.35			0.31			0.31			0.31			0.31	
	combined uncertainty of K		**0.29**																
	expanded uncertainty of K (k=2)		0.59																

Table 3b. Physical constants and correction factors with their estimated relative uncertainties of the NIST standards for the ^{137}Cs radiation beams at the NIST

	NIST	Std 1	uncertainty		Std 10	uncertainty		Std 30	uncertainty		Std 50-1	uncertainty		Std 50-2	uncertainty		Std 50-3	uncertainty	
	Physical Constants	value	Type A	Type B	value	Type A	Type B	value	Type A	Type B	value	Type A	Type B	value	Type A	Type B	value	Type A	Type B
ρ_0	Density of dry air at T=0C and P=1atm (kg/m3)	1.2930		0.02	1.2930		0.02	1.2930		0.02	1.2930		0.02	1.2930		0.02	1.2930		0.02
$(\mu_{en}/\rho)_{a,c}$	ratio energy-absorption coefficients, air/graphite	0.9993		0.06	0.9993		0.06	0.9993		0.06	0.9993		0.06	0.9993		0.06	0.9993		0.06
$\bar{s}_{c,a}$	ratio of stopping powers, graphite/air	1.0096		0.11	1.0090		0.11	1.0087		0.11	1.0086		0.11	1.0086		0.11	1.0086		0.11
W/e	Wair/e (J/C)	33.97			33.97			33.97			33.97			33.97			33.97		
$\bar{g}$	(1-g), radiative loss correction.	0.9982		0.02	0.9982		0.02	0.9982		0.02	0.9982		0.02	0.9982		0.02	0.9982		0.02
	Correction Factors																		
k_h	humidity correction (corrects to dry air)	0.9971		0.06	0.9971		0.06	0.9971		0.06	0.9971		0.06	0.9971		0.06	0.9971		0.06
k_s	ksat, loss of ionization due to recombination	1.000	0.05	0.10	1.000	0.05	0.10	1.001	0.05	0.10	1.001	0.05	0.10	1.001	0.05	0.10	1.001	0.05	0.10
k_{st}	stem scatter	0.9964		0.05	0.9979		0.05	0.9920		0.05	0.9987		0.05	0.9987		0.05	0.9987		0.05
k_{wall}	kwall, zero wall thickness	1.0285		0.17	1.0314		0.17	1.0347		0.17	1.0348		0.17	1.0468		0.17	1.0537		0.17
k_{an}	axial nonuniformity	1.000		0.02	1.000		0.05	1.000		0.05	1.000		0.05	1.000		0.05	1.000		0.05
k_{rn}	radial nonuniformity	1.000		0.01	1.000		0.01	1.000		0.01	1.000		0.01	1.000		0.01	1.000		0.01
k_{TP}	air density			0.03			0.03			0.03			0.03			0.03			0.03
V	chamber volume/ cm3	1.1309	0.10	0.10	10.0690	0.16	0.10	30.2400	0.06	0.05	51.6340	0.06	0.05	50.0890	0.06	0.05	50.1550	0.06	0.05
I	ionization current/ pA		0.10	0.10		0.10	0.10		0.10	0.10		0.10	0.10		0.10	0.10		0.10	0.10
t	time			0.05			0.05			0.05			0.05			0.05			0.05
d	distance (axial)			0.02			0.02			0.02			0.02			0.02			0.02
	Relative standard uncertainty																		
	quadratic summation		0.15	0.29		0.20	0.30		0.13	0.28		0.13	0.28		0.13	0.28		0.13	0.28
	combined uncertainty (for each chamber)		0.33			0.35			0.31			0.31			0.31			0.31	
	combined uncertainty of K		**0.29**																
	expanded uncertainty of K (k=2)		0.59																

The correction factors for the BIPM standards were re-evaluated in 2009 and the changes to the air-kerma rate determination arise from the results of Monte Carlo calculations of correction factors for the standards, a re-evaluation of the correction factor for saturation and a new evaluation of the air volume of the standards using an experimental chamber of variable volume. The combined effect of these changes is an increase in the BIPM determination of air kerma by the factor 1.0038 and 1.0030 for the ^{60}Co and ^{137}Cs radiation protection beams, respectively, and a reduction of the relative standard uncertainty of this determination to 1.5 parts in 10^3 for ^{60}Co and 1.9 parts in 10^3 for ^{137}Cs (Kessler *et al* 2009 and Burns *et al* 2007). The NIST standards were similarly re-evaluated resulting in an increase in the air kerma values by a factor of 1.0105 and 1.0090 for the ^{60}Co and ^{137}Cs radiation protection beams, respectively, as reported previously (Minniti *et al* 2011 and Seltzer *et al* 2003).

Reference conditions

Air kerma at the BIPM is determined under the following conditions (Allisy-Roberts *et al* 2011):

- the distance from source to reference plane is 1.12 m and 1 m for the ^{60}Co and ^{137}Cs beams, respectively;
- the field size in air at the reference plane is 26 cm diameter and 20 cm diameter for the ^{60}Co and ^{137}Cs beams, respectively.

The reference conditions for the measurements made at the NIST are the following:

- the distance from the source to the reference plane is 1.5 m and 1.95 m for the ^{60}Co and ^{137}Cs beams, respectively.
- the field size in air at the reference plane is 59 cm diameter and 81 cm diameter for the ^{60}Co and ^{137}Cs beams, respectively.

Reference values

The $\dot{K}_{\mathrm{BIPM}}$ value is the mean of four measurements made over a period of seven months before the comparison and is about 5 µGy s^{-1} and 15 µGy s^{-1} for the ^{60}Co and ^{137}Cs beams, respectively. By convention they are given at the reference date of 2011-01-01 T 00:00:00 UTC using the half-life value of 1925.21 d, σ = 0.29 d for ^{60}Co and 10 976 d, σ = 29 d for ^{137}Cs (Bé *et al* 2006).

The values of $\dot{K}_{\mathrm{NIST}}$ used to calibrate the transfer chambers are 0.7 µGy s^{-1} and 25 µGy s^{-1} for the ^{60}Co and ^{137}Cs beams, respectively; they are based on the air kerma rate determined with the primary standards at the reference date of 1984-12-31 (Lamperti 1988) and correcting for decay using the half-life of 1925.21 d, σ = 0.29 d for ^{60}Co and 30.05 y, σ = 0.08 y for ^{137}Cs (Bé *et al* 2006).

Beam characteristics

The characteristics of the BIPM and the NIST beams are given in Table 4.

Table 4. Parameters of the radiation protection beams at the NIST and the BIPM

Source		Nominal $\dot{K}$	Scatter contribution / energy fluence	Field size
^{137}Cs	NIST	25 µGy s^{-1} (2011-01-01)	Not available	81 cm ϕ at 1.95 m
	BIPM	15 µGy s^{-1} (2011-01-01)	30 %	20 cm ϕ at 1 m
^{60}Co	NIST	0.7 µGy s^{-1} (2011-01-01)	Not available	59 cm ϕ at 1.5 m
	BIPM	5 µGy s^{-1} (2011-01-01)	8 %	26 cm ϕ at 1.12 m

3. The transfer chambers and their calibration

The comparison of the NIST and BIPM standards was made indirectly using the calibration coefficients N_K for two transfer chambers given by

$$N_{K,\mathrm{lab}} = \dot{K}_{\mathrm{lab}} / I_{\mathrm{lab}} \,, \tag{2}$$

where $\dot{K}_{\mathrm{lab}}$ is the air kerma rate at each lab and I_{lab} is the ionization current of a transfer chamber measured at the NIST or the BIPM. The current is corrected for the effects and influences described in this section.

The ionization chambers Exradin A5 serial numbers XY051604 and XY051605, belonging to the NIST, were the transfer chambers used for this comparison. Their main characteristics are listed in Table 5.

Table 5. Characteristics of the NIST transfer chambers

Characteristic/Nominal values of the Exradin A5 (spherical chamber)		
		Nominal value
Dimensions	Outer diameter / mm	63
	Wall thickness / mm	3
Electrode	Electrode shape	cylindrical
	Electrode diameter / mm	6.5
	Electrode length / mm	37.3
Volume	Air cavity / cm^3	100
Wall	Material	Air equivalent plastic C552
	Density / g cm^{-3}	1.76
Applied voltage	Negative polarity / V [(1)]	800

[(1)] negative polarity to the outer electrode

The experimental method for calibrations at the BIPM is described by Allisy-Roberts *et al* (2011); the essential details for calibration at both laboratories are reproduced here.

Positioning

At each laboratory the chamber was positioned with the stem perpendicular to the beam direction and with the appropriate marking on the stem (white dot) facing the source.

Applied voltage and polarity

At the BIPM and at the NIST, a collecting voltage of 800 V (negative polarity) was applied to the outer electrode of the chambers at least 30 min before any measurements were made. No corrections were applied at either laboratory for polarity.

Volume recombination

Volume recombination is negligible at the dose rate of the radiation protection beams for this type of chamber, and the initial recombination loss will be the same in the two laboratories. Consequently, no correction for recombination was applied at either laboratory.

Charge and leakage measurements

The charge Q collected by each transfer chamber was measured using a Keithley electrometer, model 642 at the BIPM. The source is operational during the entire exposure series and the charge is collected for the appropriate, electronically controlled, time interval. At the NIST, the shutter that exposes the source is opened and closed for a fixed period of time that can range between 1 and 2 minutes. During this time interval, the ionization charge produced in the chamber is collected using an electrometer Keithley model 616. This process of opening and closing the shutter is repeated multiple times. The chambers were exposed to a pre-irradiation period of at least 40 min at the BIPM and at least 20 min at the NIST before any measurements were made. The ionization current measured for the transfer standards was corrected for the leakage current both at the BIPM and the NIST. This correction was less than 1×10^{-4} in relative value.

Ambient conditions

During a series of measurements, the air temperature is measured for each current measurement and it was stable to better than 0.01 °C at the BIPM. At the NIST the temperature range during the comparison was between 21.5 °C and 24.0 °C and during a series of measurements the air temperature was stable to better than 0.05 °C. The measurements are normalized to 293.15 K and 101.325 kPa at the BIPM and the NIST. Relative humidity is controlled at (50 ± 5) % at the BIPM; at the NIST, humidity varies between 22% and 50%. No correction for humidity is applied to the ionization current measured.

Radial non-uniformity

The effect of the radial non-uniformity of the BIPM ^{137}Cs and ^{60}Co beams over the section of the transfer chambers is 1.0017 and 1.0010, respectively; at the NIST, this effect is assumed to be negligible in both beams. No corrections are made at either laboratory and an uncertainty of 0.0010 is included in Tables 7 and 8 to account for this effect.

4. Result of the comparison

The result of the comparison, R_K, is expressed in the form

$$R_K = N_{K,\,\mathrm{NIST}} / N_{K,\,\mathrm{BIPM}} \quad , \tag{3}$$

in which, for each chamber, the mean value of measurements made at the NIST prior to those made at the BIPM (pre-BIPM) and those made afterwards (post-BIPM) is compared with the mean of the measurements made at the BIPM. The BIPM calibration coefficient is the mean of two calibrations with repositioning, in series of 30 measurements for each chamber. The NIST calibration coefficient is the mean of three series of ten measurements on each occasion (before and after the measurements at the BIPM).

Table 6 lists the relevant values of N_K at the stated reference conditions.

Table 6. **Results of the comparison**

Beam	Transfer Chambers Exradin A5	$N_{K,\mathrm{NIST}}$ / Gy µC^{-1} pre-BIPM	$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	$N_{K,\mathrm{NIST}}$ / Gy µC^{-1} post-BIPM	$N_{K,\mathrm{NIST}}$ / Gy µC^{-1} overall mean	R_K
^{60}Co	XY051604	0.29798	0.29718	0.29773	0.29785	1.0023
	XY051605	0.29807	0.29743	0.29815	0.29811	1.0023
					mean	1.0023
^{137}Cs	XY051604	0.30209	0.30224	0.30183	0.30196	0.9991
	XY051605	0.30227	0.30254	0.30217	0.30222	0.9989
					mean	0.9990

The comparison result is R_K = 1.0023 for ^{60}Co and R_K = 0.9990 for ^{137}Cs. The uncertainties of the comparison results are evaluated in the following section.

5. Uncertainties

Contributions to the relative standard uncertainty of $N_{K,\mathrm{lab}}$ are listed in Tables 7 and 8. The relative standard uncertainty of the mean ionization current measured with the transfer chamber over the short period of calibration was estimated to be 1×10^{-4} and 2×10^{-4} at the BIPM and at the NIST, respectively.

Table 7. Estimated relative standard uncertainties of the calibration coefficient, $\boldsymbol{N_{K,\mathrm{lab}}}$, of the transfer chambers and of the comparison result, $\boldsymbol{R_K}$ for ^{60}Co beams

Relative standard uncertainty	**NIST ^{60}Co** 100 s_i	100 u_i	**BIPM ^{60}Co** 100 s_i	100 u_i
Air kerma	0.06	0.29	0.02	0.15
Ionization current of the transfer chamber	0.02	0.10	0.01	0.02
Repeatability of measurement	0.02	–	0.01	–
Distance and orientation	–	0.02	0.01	–
Air density correction	–	0.03	–	–
Decay correction	–	0.08	–	–
Radial non-uniformity	–	–	–	0.10
Relative standard uncertainty of $\boldsymbol{N_{K,\mathrm{lab}}}$				
quadratic summation	0.07	0.32	0.03	0.18
combined uncertainty	0.32		0.18	
Relative standard uncertainties of $\boldsymbol{R_K}$ [1]				
combined uncertainty	0.32			

[1] Taking correlation into account.

Table 8. Estimated relative standard uncertainties of the calibration coefficient, $N_{K,\mathrm{lab}}$, of the transfer chambers and of the comparison result, R_K for ^{137}Cs beams

Relative standard uncertainty	NIST ^{137}Cs 100 s_i	NIST ^{137}Cs 100 s_i	BIPM ^{137}Cs 100 s_i	BIPM ^{137}Cs 100 u_i
Air kerma	0.06	0.29	0.03	0.19
Ionization current of the transfer chamber	0.02	0.10	0.01	0.02
Repeatability of measurement	0.02	–	0.01	–
Distance and orientation	–	0.02	0.01	–
Air density correction	–	0.03	–	–
Decay correction	–	0.10	–	–
Radial non-uniformity	–	–	–	0.10
Relative standard uncertainty of $N_{K,\mathrm{lab}}$				
quadratic summation	0.07	0.32	0.03	0.22
combined uncertainty	0.33		0.22	
Relative standard uncertainties of R_K [1]				
combined uncertainty	0.35			

[1] Taking correlation into account

Some of the uncertainties in $\dot{K}$ that appear in both the BIPM and the NIST determinations (namely air density, *W/e*, μ_{en}/ρ, $\bar{g}$, $\bar{s}_{\mathrm{c,a}}$ and k_{h}) are correlated and therefore cancel when evaluating the uncertainty of the comparison result R_K.

6. Degrees of equivalence

Comparison of a given NMI with the key comparison reference value

Following a decision of the CCRI, the BIPM determination of the dosimetric quantity for each of the CCRI radiation qualities is taken as the key comparison reference value (KCRV) (Allisy-Roberts *et al* 2009). It follows that for each NMI *i* having a BIPM comparison result $R_{K,i}$ (denoted x_i in the KCDB) with combined standard uncertainty, u_i, the degree of equivalence with respect to the reference value for the NMI comparison, here denoted $K_{\mathrm{R},i}$, is given by a pair of terms:

the relative difference $$D_i = (K_i - K_{\mathrm{R},i})/ K_{\mathrm{R},i} = R_{Ki} - 1 \qquad (4)$$

and the expanded uncertainty (k = 2) of this difference,

$$U_i = 2\, u_i. \qquad (5)$$

The results for D_i and U_i are expressed in mGy/Gy. Table 9 gives the values for D_i and U_i for each NMI, *i*, taken from the KCDB of the CIPM MRA (1999) and this report, using (4) and (5). These data are presented graphically in Figure 1.

Table 9. Table of degrees of equivalence and introductory text for air kerma in ^{137}Cs

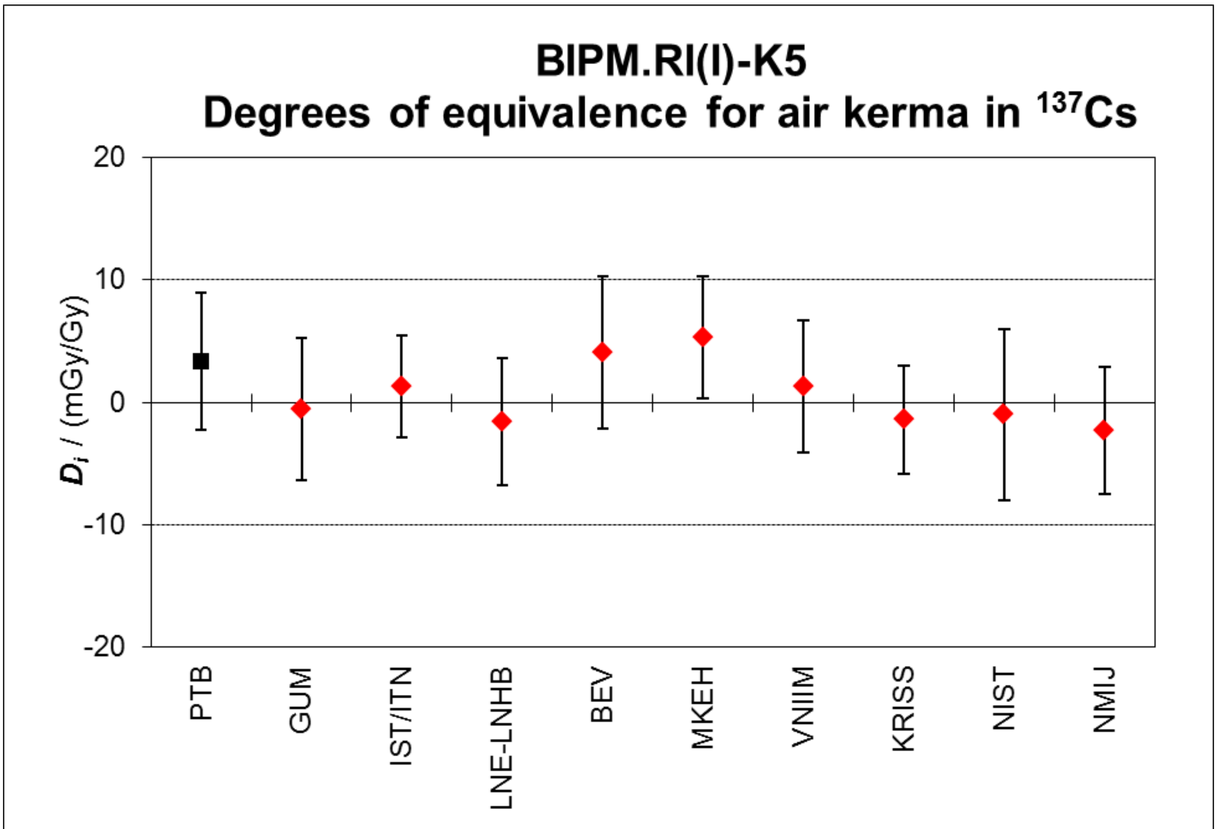
Key comparison BIPM.RI(I)-K5
MEASURAND : Air kerma
The key comparison reference value is the BIPM evaluation of air kerma

The degree of equivalence of each laboratory i with respect to the key comparison reference value is given by a pair of terms:
the relative difference D_i and $U_i = 2u_i$, its expanded uncertainty ($k = 2$), both expressed in mGy/Gy.
In evaluating u_i, account is taken of correlation between laboratory i and the BIPM.

When required, the degree of equivalence between two laboratories i and j can be evaluated by a pair of terms:
$D_{ij} = D_i - D_j$ and $U_{ij} = 2u_{ij}$, its expanded uncertainty ($k = 2$), both expressed in mGy/Gy.
In evaluating u_{ij}, account should be taken of correlation between u_i and u_j.

Lab i	D_i	U_i
	/ (mGy/Gy)	
PTB	3.4	5.6
GUM	-0.5	5.8
IST/ITN	1.3	4.2
LNE-LNHB	-1.6	5.2
BEV	4.1	6.2
MKEH	5.3	5.0
VNIIM	1.3	5.4
KRISS	-1.4	4.4
NIST	-1.0	7.0
NMIJ	-2.3	5.2

Figure 1. Graph of degrees of equivalence with the KCRV



N.B. Black squares indicate results that are more than 10 years old.

Comparison of any two NMIs with each other

The degree of equivalence between any pair of national measurement standards, when required, is expressed in terms of the difference between the two comparison results and the expanded uncertainty of this difference; consequently, it is independent of the choice of key comparison reference value.

The degree of equivalence, D_{ij}, between any pair of NMIs, i and j, is thus expressed as the difference

$$D_{ij} = D_i - D_j = R_i - R_j \tag{6}$$

and the expanded uncertainty (k = 2) of this difference, $U_{ij} = 2\, u_{ij}$, where

$$u_{ij}{}^2 = u_{c,i}{}^2 + u_{c,j}{}^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_i^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_j^2 \tag{7}$$

and the final two terms are used to take into account correlation between the primary standards, notably that arising from the physical constants and correction factors for similar types of standard.

Note that the data presented in the table, while correct at the time of publication of the present report, become out-of-date as NMIs make new comparisons. The formal results under the CIPM MRA are those available in the BIPM key comparison database KCDB.

6. Conclusion

Two comparisons have been carried out between the NIST and the BIPM for air kerma in ^{60}Co and ^{137}Cs radiation protection-level beams using two transfer chambers.
The ^{60}Co comparison result, 1.0023(32) is in agreement within the uncertainties with the result of a recent comparison carried out at the BIPM in the ^{60}Co CISBio beam for radiotherapy-level air kerma (Kessler *et al* 2013).
The NIST standard for air kerma in ^{137}Cs gamma radiation compared with the present BIPM air kerma standard gives a comparison result of 0.9990(35) and so is in agreement with the KCRV within the uncertainties.

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