Key comparison BIPM.RI(I)-K5 of the air-kerma standards of the GUM, Poland and the BIPM in ^{137}Cs gamma radiation

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Abstract

A new indirect comparison of the standards for air kerma of the Główny Urząd Miar (GUM), Poland, and of the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{137}Cs radiation beam using the radiation protection facility of the International Atomic Energy Agency (IAEA) in Seibersdorf, Austria, in June 2024[a]. The comparison result, based on the calibration coefficients for two transfer chambers and expressed as a ratio of the GUM and the BIPM standards for air kerma, is 1.0005 with a combined standard uncertainty of 2.8 parts in 10^3. The results are analysed and presented in terms of degrees of equivalence, suitable for entry in the BIPM key comparison database, to update the 2006 comparison result.

1. Introduction

A new comparison of the standards for air kerma of the Główny Urząd Miar (GUM), Poland, and of the Bureau International des Poids et Mesures (BIPM) was carried out in June 2024 in the ^{137}Cs radiation beam at the International Atomic Energy Agency (IAEA) in Seibersdorf, Austria, to update the previous comparison result of 2006 (Allisy Roberts *et al.* 2011).

The comparison result is published in the BIPM key comparison database (KCDB 2024) under the reference BIPM.RI(I)-K5. The comparison was carried out after the implementation of the recommendations of ICRU Report 90 (ICRU 2016) at both laboratories.

The comparison was undertaken using two ionization chambers of different type as transfer instruments, one of spherical shape and the other of cylindrical shape, belonging to the GUM.

2. Details of the standards and the transfer chambers

The air-kerma standard of the GUM for ^{137}Cs is based on a spherical graphite-walled cavity ionization chamber referenced as PS-50, serial number 000011, constructed at the PTW Freiburg, Germany (type TN32007) and fully characterized by the GUM.

The BIPM standard is a parallel-plate graphite-walled cavity ionization chamber with a volume of about 6.8 cm^3 (Boutillon and Niatel 1973, Burns *et al.* 2007, Kessler *et al.* 2009, Burns and Kessler 2018).

Details of the GUM transfer chambers used for the indirect comparison are given in Table 2.

[a] Since 2018, the BIPM no longer maintains reference radiation protection beams for ^{137}Cs and ^{60}Co. To continue the services of calibration and comparison (BIPM.RI(I)-K5) in ^{137}Cs beams, in 2022 the BIPM has installed the primary standard together with a BIPM measurement and data acquisition system at the IAEA laboratories in Seibersdorf, Austria.

Table 1. **Characteristics of the BIPM and the GUM standards**

Dimensions		BIPM CH6.3 (paralell-plate)	GUM PS-50 (spherical)
Cavity	Diameter / mm	45.00	52.76
	Thickness / mm	5.10	3.5
	Measuring volume / cm^3	6.8313	49.992
Electrode	Diameter / mm	41.00	3.0
	Thickness / mm	0.96	–
	Height / mm	–	25.58
Wall	Thickness / mm	2.98	3.526
	Material	Graphite	Graphite
	Density / g cm^{-3}	1.85	1.85
Voltage applied to outer electrode / V		± 80	+800

Table 2. **Characteristics of the GUM transfer chambers**

Dimensions		PTW TN23361 - sn 0514 cylindrical	PTW TN32005 - sn 000229 spherical
Chamber	Outer diameter / mm	39.0	44.44
	Outer length / mm	68.0	–
Electrode	Diameter / mm	14	4.24
	Length / mm	43.5	29.66
Cavity	Nominal volume / cm^3	30.0	27.9
Wall	Thickness / mm	1.0	3.0
	Material	PMMA graphited	POM (polyoxymethylene)
Voltage applied to outer electrode / V		+300	+400

3. Determination of the air kerma

For a cavity chamber with measuring volume V, the air-kerma rate is determined by the relation

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

where

ρ_{air} is the density of air under reference conditions,

I is the ionization current under the same conditions,

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 radiative processes in air,

$(\mu_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$ is the ratio of the mean mass energy-absorption coefficients of air and graphite,

$\bar{s}_{\mathrm{c,a}}$ is the ratio of the mean mass electronic stopping powers for electrons in 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 used for the physical constants, the correction factors, the volume of the primary standards entering in equation (1), and the associated uncertainties for the ^{137}Cs radiation beams at the IAEA and at the GUM are given in Table 3.

Table 3. Physical constants and correction factors with their relative standard uncertainties of the BIPM and GUM standards for the ^{137}Cs radiation beams

		BIPM	CH 6.3		GUM	PS-50	
		values	uncertainty (1)		values	uncertainty (1)	
			100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$		100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
Physical Constants							
ρ_{air}	dry air density (2) / kg m^{-3}	1.2930	–	0.01	1.2048	–	0.01
$s_{\mathrm{c,a}}$	ratio of mass stopping powers	1.0023	–	0.12(3)	1.0019	–	0.14(3)
W/e	mean energy per charge / J C^{-1}	33.97	–		33.97		
$(\mu_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$	ratio of mass energy-absorption coefficients	0.9990	0.01	0.04	0.9995	0.11(4)	–
g_{a}	fraction of energy lost in radiative processes	0.0012	–	0.02	0.0015		–
Correction factors							
k_{s}	recombination losses	1.0013	0.01	0.02	1.0016	0.02	0.01
k_{h}	humidity	0.9970	–	0.03	0.9970	–	0.03
k_{st}	stem scattering	0.9998	0.01	–	0.9982	0.04	–
k_{wall}	wall attenuation and scattering	1.0002	0.01	– (5)	1.0397	0.01	0.04
k_{an}	axial non-uniformity	1.0018	–	0.04	0.9997	0.01	0.05
k_{rn}	radial non-uniformity	1.0009	–	0.05	1.0008	0.01	–
k_{or}	orientation	0.9997	0.01	0.01	–	–	–
Measurement of I / V							
V	chamber volume / cm^3	6.8313	–	0.08	49.992	–	0.10
k_{vol}	volume correction	1.0004	–			–	–
I	ionization current / pA	–	0.02	0.02	–	0.03	0.01
	reproducibility		0.03	–		0.09	–
Relative standard uncertainty							
quadratic summation			0.04	0.17		0.15	0.19
combined uncertainty			**0.17**			**0.24**	
Removing correlations			0.04	0.11		0.11	0.12

(1) Expressed as one standard deviation
$u_{i\mathrm{A}}$ represents the type A relative standard uncertainty estimated by statistical methods
$u_{i\mathrm{B}}$ represents the type B relative standard uncertainty estimated by other means

(2) At 101 325 Pa and 273.15 K for the BIPM; at 101 325 Pa and 293.15 K for the GUM

(3) Combined uncertainty for the product of $s_{\mathrm{c,a}}$ and W/e (for the BIPM standard, see Burns and Kessler 2018)

(4) Uncertainty for the product $(\mu_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$ / $(1-g_{\mathrm{a}})$

(5) The uncertainty for k_{wall} is included in the determination of the effective volume (Burns *et al* 2007)

The corrections for the GUM standard are described in the following paragraphs.

Attenuation and scattering in the chamber wall (k_{wall}) and axial non-uniformity (k_{an})

The effect of attenuation and scatter in the wall of the GUM PS-50 chamber and the axial non-uniformity correction were determined by the GUM using Monte Carlo EGSnrc user cavity codes (Rogers *et al*. 2000, Rogers *et al*. 2003).

Scatter from the stem (k_{st})

The correction factor for the stem scatter was measured at the GUM as 0.9982 (4), determined from measurements using a dummy stem placed next to the standard.

Radial non-uniformity of the beam (k_{rn})

The correction factor for the radial non-uniformity of the GUM beam over the cross-section of the standard is estimated to be 1.0008 (1), calculated using measured beam profiles.

Recombination loss (k_s)

The correction factor for the GUM standard for losses due to ion recombination was determined using the method of Niatel as described in Allisy-Roberts *et al*. (2011). The recombination correction can be expressed as

$$k_s = 1 + k_{\mathrm{init}} + k_{\mathrm{vol}} I_V \qquad (2)$$

where k_{init} and k_{vol} are the initial (0.0013) and volume (2.93 x 10^{-6} / pA) recombination components, respectively. Consequently, a correction factor of 1.0016(2) for ion recombination at 800 V was applied to the standard in the GUM ^{137}Cs beam.

Volume determination

The volume of the PS-50 was determined from measurements made at the Institute of Coordinate Metrology at the Metrology and Biomedical Engineering Institute of the Faculty of Mechatronics, Warsaw University of Technology (WUT) using the Zeiss METROTOM 800 industrial tomograph. A second estimation of the volume was made using the data shown in PTW's technical drawings; the agreement between both determinations is 3 parts in 10^3.

The air-kerma rate determination and measurement conditions at each laboratory are explained in the following paragraphs.

Reference values

The BIPM reference air-kerma rate $\dot{K}_{\mathrm{BIPM}}$ is taken as the mean of four measurements made during September 2023 and June 2024. The $\dot{K}_{\mathrm{BIPM}}$ value refers to an evacuated path length between source and standard corrected to the reference date of 2024-01-01, 0 h UTC. The half-life of ^{137}Cs was taken as 10 976 days (u = 30 days) (Bé *et al.* 2006). The correction for air attenuation between source and standard uses the ambient air density at the time of the measurement and the air attenuation coefficient 0.010 cm^2 g^{-1} for ^{137}Cs.

At the GUM, the $\dot{K}_{\mathrm{GUM}}$ value was determined using the PS-50 primary standard and is the mean of the measurements made during the period of the comparison (May-June 2024 before BIPM measurements and June-July 2024 after BIPM measurements). No correction for air attenuation between source and standard is applied. The long-term stability of the reference value is estimated to be better than 9 parts in 10^4. By convention it is given at the reference date of 2024-01-01, 0 h UTC using the same half-life value for the decay correction as the BIPM.

Reference conditions and beam characteristics

The characteristics of the IAEA and GUM beams are given in Table 4. The distance from source to reference plane is 1 m at both laboratories.

Table 4. Characteristics of the ^{137}Cs beams at the GUM and the IAEA

^{137}Cs beam	Source dimensions / mm		Nominal $\dot{K}$/ µGy s^{-1}	Field diameter / mm
	diameter	length		
GUM source	17.6	13.0	66.1	280
IAEA source	14.3	19.9	17.0	230

4. Comparison procedure

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

$$N_{K,\mathrm{lab}} = \dot{K}_{\mathrm{lab}} / I_{\mathrm{lab}} \tag{3}$$

where $\dot{K}_{\mathrm{lab}}$ is the air-kerma rate and I_{lab} is the corrected ionization current of a transfer chamber measured by each laboratory.

The PTW TN32005, serial number 000229, and PTW 23361, serial number 0514, belonging to the GUM, are the transfer chambers used for this comparison. Their main characteristics are listed in Table 2. These chambers were calibrated at the GUM before and after the measurements at the BIPM.

The BIPM and the GUM experimental method for measurements and the correction factors applied to the current I_{lab} are described in the following paragraphs.

Positioning

At each laboratory the transfer chambers were positioned with the stem perpendicular to the beam direction and with the appropriate marking on the stem facing the source. At the IAEA, the transfer chambers PTW TN32005 and PTW 23361 were set-up and measured by the BIPM on four and three separate occasions, respectively, after being repositioned each time.

Applied voltage and polarity

The collecting voltages indicated in Table 2 were applied to the outer electrode of the GUM transfer chambers at least 40 min before any measurements were made.

Charge and leakage measurements

The charge Q collected by the GUM chambers was measured by the BIPM at the IAEA using a Keithley electrometer, model 6517B. The source is exposed during the entire measurement series and the charge is collected for the appropriate, electronically controlled, time interval. A pre-irradiation was made for at least 40 min before any measurements. Leakage current was measured before and after each series of measurements. The measured leakage values for both chambers were around 1 fA, 1 part in 10^4 in relative terms, of the ionization current.

At the GUM, the charge Q collected by the transfer chambers was measured in the same way as the BIPM using a Keithley electrometer, model 6517A. A pre-irradiation of at least 30 min was made for each chamber before any measurements. Leakage current was measured after each series of measurements. The measured leakage values for both chambers were around 10 fA, 2 parts in 10^4 in relative terms, of the ionization current.

Radial non-uniformity correction

The correction for the radial non-uniformity of the beam for the transfer chambers is less than 3 parts in 10^4 at the GUM; at the IAEA, the radial non-uniformity correction is 1.0005 for the PTW TN32005 and 1.0015 for the PTW 23361. As the difference of the PTW 23361 corrections for each beam is not negligible, the radial non-uniformity correction factors were applied for each chamber at both laboratories and a relative uncertainty component of 5 parts in 10^4 is included in Table 7.

Ion recombination

Ion recombination was determined for the present comparison, resulting in a negligible value for volume recombination at the present ^{137}Cs dose rates at this polarizing voltage. As the initial recombination loss is the same in the two laboratories, no correction for recombination was applied to the measured current for the present comparison; a relative uncertainty component of 2 parts in 10^4 is included in Table 7.

Ambient conditions

During a series of measurements, the air temperature is measured for each current measurement and was stable to better than 0.2 °C at the IAEA. At the GUM, the air temperature was stable to better than 0.2 °C during each series of measurements. At both laboratories, the current measured using the transfer chambers is normalized to the reference conditions of 293.15 K and 101.325 kPa.

Relative humidity is controlled and it was between 45 % and 55 % at the IAEA and between 46 % and 59 % at the GUM.

5. Results of the comparison

The result of the comparison R_K is expressed in the form

$$R_K = N_{K,\mathrm{GUM}} / N_{K,\mathrm{BIPM}} \tag{4}$$

in which the average value of measurements made at the GUM before and after those made at the IAEA by the BIPM is compared with the mean of the measurements made by the BIPM.

Table 5 lists the relevant values of N_K at the stated reference conditions (293.15 K and 101.325 kPa) and the final results of the indirect comparison.

Table 5. Final result of the GUM/BIPM comparison of standards for ^{137}Cs air kerma

Transfer chamber	$N_{K,\mathrm{GUM}}$/ Gy µC^{-1}			$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	R_K	u_c
	pre-BIPM	post-BIPM	overall mean			
PTW TN320005	1.1061	1.1059	1.1060	1.1041	1.0017	0.0028
PTW 23361	0.9398	0.9398	0.9398	0.9405	0.9993	0.0028
				Mean value	1.0005	0.0028

The uncertainties associated with the calibration of the transfer chambers at each laboratory and with the indirect comparison are presented in Table 6 and Table 7, respectively. The reproducibility at the IAEA is estimated to be 3 parts in 10^4 and 9 parts in 10^4 at the GUM, included in Table 6.

The values $N_{K,\mathrm{GUM}}$ measured before and after the measurements at the BIPM give rise to a relative standard deviation for each chamber, whose rms value is taken as a representation of the stability of the transfer instruments. Table 7 includes a component of 1.2 parts in 10^3 for the difference in the comparison result between the two transfer chambers.

Table 6. Uncertainties associated with the transfer chamber calibration

Relative standard uncertainty	BIPM		GUM	
	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
Air-kerma rate	0.04	0.17	0.15	0.19
Ionization current for the transfer chambers	0.01	0.02	0.10	0.01
Distance	0.01	–	0.01	–
Reproducibility	0.03	–	0.09	–
Correction factors (P,T)	–	–	–	0.02
$N_{K,\mathrm{lab}}$	0.05	0.17	0.20	0.19

Table 7. Uncertainties associated with the indirect comparison

Relative standard uncertainty	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
$N_{K,\mathrm{GUM}}$ / $N_{K,\mathrm{BIPM}}$	0.18	0.16(1)
Ion recombination	–	0.02
Radial non-uniformity	–	0.05
Stability of the chambers	0.02	–
Different chambers	0.12	–
$R_{K,\mathrm{GUM}}$	u_c = 0.0028	

(1) The combined standard uncertainty of the comparison result takes into account correlation in the type B uncertainties associated with the physical constants and the humidity correction

Some uncertainties in $\dot{K}_\mathrm{air}$ that appear in both the BIPM and the GUM determinations (namely air density, W/e, $(\mu_\mathrm{en}/\rho)_\mathrm{a,c}$, $\bar{g}$, $s_\mathrm{c,a}$ and k_h) cancel when evaluating the uncertainty of the ratio R_K of the GUM and BIPM calibration coefficients.

The mean ratio of the air-kerma calibration coefficients of the transfer chambers determined by the GUM and the BIPM taken from Table 5 is 1.0005 with a combined standard uncertainty, u_c, of 0.0028.

6. Degrees of equivalence

Following a decision of the CCRI, the BIPM determination of the dosimetric quantity, here K_BIPM, is taken as the key comparison reference value (KCRV) (Allisy *et al.* 2009). It follows that for each NMI i having a BIPM comparison result x_i with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is the relative difference $D_i = (K_i - K_{\mathrm{BIPM},i}) / K_{\mathrm{BIPM},i} = x_i - 1$ and its expanded uncertainty $U_i = 2\,u_i$.

The results for D_i and U_i are usually expressed in mGy/Gy. Table 8 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. These data are presented graphically in Figure 1.

Note that the data presented in Table 8, while correct at the time of publication of the present report, become out-of-date as NMIs make new comparisons. In addition, revised validity rules for comparison data have been agreed by the CCRI(I) so that any results older than 15 years are no longer considered valid and have been removed from the KCDB. The formal results under the CIPM MRA are those available in the key comparison database.

Table 8. Degrees of equivalence

For each laboratory i, the degree of equivalence with respect to the key comparison reference value is the difference D_i and its expanded uncertainty U_i. Tables formatted as they appear in the BIPM key comparison database

BIPM.RI(I)-K5

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
IST / ITN	1.3	4.2
LNE-LNHB	-1.6	5.2
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
PTB	2.4	5.4
NIM	-3.3	4.2
ININ	4.8	4.0
VSL	-4.8	7.6
SMU	5.1	5.4
BEV	4.3	5.4
CIEMAT	-0.8	4.4
GUM	0.5	5.6

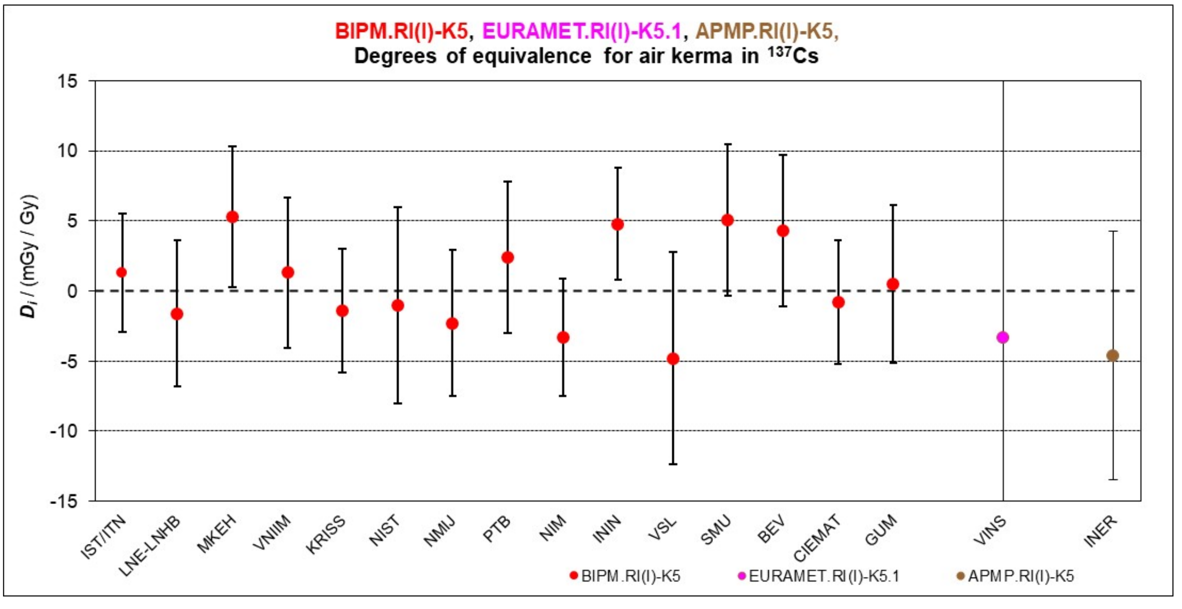
EURAMET.RI(I)-K5.1

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
VINS	-3.3	20.2

APMP.RI(I)-K5

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
INER	-4.6	8.9

Figure 1. Graph of degrees of equivalence with the KCRV



7. Conclusion

The previous comparison of the GUM and BIPM standards for air kerma in ^{137}Cs beam was made in 2006 using the primary standards at the BIPM. The result of the direct comparison was 0.9995 (29). The present comparison made indirectly using two transfer standards gives a result of 1.0005 (28), in agreement within the uncertainties with the 2006 result.

The GUM is in agreement within the expanded uncertainty with all the NMIs having taken part in the BIPM.RI(I)-K5 ongoing key comparison for air-kerma standards in ^{137}Cs gamma-ray beams.

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