Key comparison BIPM.RI(I)-K1 of the air-kerma standards of the BFKH, Hungary and the BIPM in ^{60}Co gamma radiation

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Abstract

A new key comparison of the standards for air kerma of the Budapest Főváros Kormányhivatala (BFKH), Hungary and the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in October 2021. The comparison result, based on the calibration coefficients for a transfer chamber and expressed as a ratio of the BFKH and the BIPM standards for air kerma, is 1.0029 with a combined standard uncertainty of 2.2 parts in 10^3. The result agrees within the uncertainties with the comparison carried out in 2016. The results are analysed and presented in terms of degrees of equivalence, suitable for entry in the BIPM key comparison database.

1. Introduction

An indirect comparison of the standards for air kerma of the Budapest Főváros Kormányhivatala (BFKH), Hungary, and the Bureau International des Poids et Mesures (BIPM) was carried out in October 2021 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2016 (Kessler *et al.* 2018) published in the BIPM key comparison database (KCDB 2023) under the reference BIPM.RI(I)-K1. The comparison was carried out after the implementation of the recommendations of ICRU Report 90 (ICRU 2016) at both laboratories. The indirect comparison was made using a thimble-type ionization chamber as transfer instrument. The final results were supplied by the BFKH in March 2023.

2. Details of the standards and the transfer chamber

The BFKH ^{60}Co air-kerma standard is a set of two nominally identical cavity ionization chambers constructed at the OMH (type ND 1005, serial number 7707 and 7708) in 1977. The BIPM primary standard is described in Boutillon *et al.* 1973, Burns *et al.* 2007 and Burns and Kessler 2018. The main characteristics of the primary standards are given in Table 1. Details of the transfer chamber used for the indirect comparison are given in Table 2.

Table 1. Characteristics of the BFKH and BIPM primary standards

Dimensions		BFKH		BIPM
		ND 1005 - 7707	ND 1005 - 7708	CH6.2
Cavity	Diameter / mm	11	11	45.01
	Height / mm	11	11	–
	Thickness / mm	–	–	5.16
	Measuring volume / cm^3	1.0182	1.0227	6.8855
Electrode	Diameter / mm	2	2	41.03
	Height / mm	8.97	8.97	–
	Thickness / mm	–	–	1.005
Wall	Thickness / mm	4		2.90
	Material	Ultra-pure graphite EK51 Ringsdorf		Graphite
	Density / g cm^{-3}	1.75		1.85
Voltage applied to outer electrode / V		±250		±80

Table 2. Characteristics of the BFKH transfer chamber

Nominal values		FC65G
Chamber	Outer diameter / mm	7.0
	Outer length / mm	23.5
Electrode	Diameter / mm	1.0
	Length / mm	20.5
Cavity	Measuring volume / cm^3	0.65
Wall	Thickness / mm	0.4
	Material	graphite
	Density / g cm^{-3}	1.8
Voltage applied to outer electrode / V		+300

3. Determination of the air kerma

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

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

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 bremsstrahlung production 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 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 used for the physical constants, the correction factors, the volume of the primary standards entering in equation (1), and the associated uncertainties are given in Table 3. For the BIPM standards, these values are given in Kessler and Burns 2018.

Table 3. Physical constants, correction factors and relative standard uncertainty components of the BIPM and BFKH standards for the ^{60}Co radiation beam at the BIPM and at the BFKH

		BIPM			BFKH		
		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
$(\mu_\mathrm{en}/\rho)_\mathrm{a.c}$	ratio of mass energy-absorption coefficients	0.9989	0.01	0.04	0.9985	–	0.05
$s_\mathrm{c.a}$	ratio of mass stopping powers	0.9928	–	0.08 (3,4)	0.9925	–	0.08(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	0.0032	–	0.02
Correction factors and uncertainty components							
k_g	re-absorption of radiative loss	0.9996	–	0.01	–	–	–
k_s	recombination losses	1.0019	0.01	0.02	1.0019	0.01	0.01
k_h	humidity	0.9970	–	0.03	0.9970	–	0.03
k_st	stem scattering	1.0000	0.01	–	0.9998	0.05	–
k_wall	wall attenuation and scattering	1.0011	–	– (5)	1.0216	0.01	0.07
k_an	axial non-uniformity	1.0020	–	– (5)	0.9998	0.04	0.08
k_rn	radial non-uniformity	1.0015	–	0.02	1.0002	–	0.02
k_pol	polarity	–	–	–	1.0000	–	0.05
Measurement of *I* / *V*							
V	chamber volume / cm^3	6.8855	–	0.08 (5)	(6)	0.10	0.05
I	ionization current / pA	–	0.01	0.02	–	0.01	0.02
d	distance	–	–	–	–	–	0.02
Relative standard uncertainty							
quadratic summation			0.02	0.13		0.12	0.17
combined uncertainty			**0.13**			**0.21**	

(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 kPa and 273.15 K for the BIPM and 101.325 kPa and 293.15 K for the BFKH standards

(3) Combined uncertainty for the product of $s_\mathrm{c,a}$ and W/e adopted from ICRU Report 90 recommendations (ICRU 2016)

(4) Adopted from January 2019 (Burns and Kessler 2018)

(5) The uncertainties for k_wall and k_an are included in the determination of the effective volume (Burns *et al.* 2007)

(6) See Table 1

Reference conditions

The reference conditions for the air-kerma determination at the BIPM are described by Kessler and Burns (2018):

– the distance from source to reference plane is 1 m,

– the field size in air at the reference plane is 10 cm × 10 cm, defined by 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.

At the BFKH, the reference distance is 0.9 m and the field size is 11.3 cm × 11.3 cm, defined as it is at the BIPM.

Reference values

The BIPM reference air-kerma rate $\dot{K}_{\mathrm{BIPM}}$ is taken as the mean of the four measurements made around the period of the comparison. The $\dot{K}_{\mathrm{BIPM}}$ values refer to an evacuated path length between source and standard corrected to the reference date of 2021-01-01, 00:00 UTC. 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 0.0602 cm^2 g^{-1} for ^{60}Co. The half-life of ^{60}Co used for the decay correction was taken as 1925.21 days (u = 0.29 days) (Bé *et al.* 2006). At the BFKH, no air attenuation correction is applied and the $\dot{K}_{\mathrm{BFKH}}$ value is given at the reference date of 2021-12-29, 00:00 UTC, using the same half-life value for the decay correction.

Beam characteristics

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

Table 4. Characteristics of the ^{60}Co beams at the BFKH and the BIPM

^{60}Co beam	Nominal $\dot{K}$ / mGy s^{-1}	Source dimensions / mm		Scatter contribution in terms of energy fluence	Field size at ref distance
		diameter	length		
BFKH Gammatron I	7.2	23	36	25 %	11.3 cm ×11.3 cm (at 0.9 m)
BIPM Theratron 1000	5.6	20	14	21 %	10 cm × 10 cm (at 1 m)

4. Comparison procedure

The comparison of the BFKH and BIPM standards was made indirectly using the calibration coefficients for the transfer chamber given by

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

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

The ionization chamber FC65G, serial number 933, belonging to the BFKH, is the transfer chamber used for this comparison. Its main characteristics are listed in Table 2. The chamber was calibrated at the BFKH before and after the measurements at the BIPM. Measurements after the BIPM were completed in December 2021. Final results were supplied in March 2023.

The experimental method for measurements at the BIPM is described by Kessler and Burns (2018); the essential details for the determination of the calibration coefficients $N_{K,\mathrm{lab}}$ for the transfer chamber 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 facing away from the source.

Applied voltage and polarity

A collecting voltage of 300 V (positive polarity) was applied to the outer electrode of the transfer chamber at least 40 min before any measurements were made.

Charge and leakage measurements

The charge Q collected by the transfer chamber was measured at the BIPM using a Keithley electrometer, model 642. 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 (~13 Gy). Leakage current was measured before and after each series of measurements. The leakage correction, relative to the ionization current, was less than 1 part in 10^4. At the BFKH, the ionization current I is measured using a PAM electrometer, model 2009. A pre-irradiation of at least 30 min (~11 Gy) was made before any measurements. The relative leakage current measured at the BFKH was also less than 1 part in 10^4.

Radial non-uniformity correction

The correction for the radial non-uniformity of the beam for the transfer chamber is less than 3 parts in 10^4 at the BIPM and a similar correction is appropriate for the BFKH beam. No radial non-uniformity correction was applied and a relative uncertainty component of 2 parts in 10^4 is included in Table 7.

Ion recombination

No correction for recombination was applied to the measured current as volume recombination is negligible for continuous beams for this chamber type at this polarizing voltage, and the initial recombination loss will be the same in the two laboratories; 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 0.06 °C at the BIPM. At the BFKH, the air temperature is also measured for each current measurement and was stable to better than 0.1 °C. The ionization current is corrected to the reference conditions of 293.15 K and 101.325 kPa at both laboratories.

At the BIPM, the relative humidity is controlled in the range from 45 % to 55 %. At the BFKH, relative humidity was in the range from 20 % to 30 %; no correction for humidity is applied to the ionization current measured.

5. Results of the comparison

The transfer chamber was set-up and measured in the BIPM ^{60}Co beam on two separate occasions. The results were reproducible to better than 2 parts in 10^4.

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

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

in which the average value of measurements made at the BFKH before and after those made at the BIPM is compared with the mean of the measurements made at 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. The uncertainties associated with the calibration of the transfer chamber at each laboratory and with the indirect comparison are presented in Table 6 and Table 7, respectively.

The values $N_{K,\mathrm{BFKH}}$ measured before and after the measurements at the BIPM give rise to a relative standard deviation for the chamber, taken as a representation of the stability of the transfer instrument. The short-term stability is estimated to be 1 part in 10^4.

Table 5. Results of the indirect comparison

Transfer chamber	$N_{K,\mathrm{BFKH}}$ / Gy µC^{-1}			$N_{K,\mathrm{BIPM}}$ / Gy µC^{-1}	R_K	u_c
	pre-BIPM	post-BIPM	overall mean			
FC65G-933	43.77	43.77	43.77	43.65	1.0029	0.0022

Table 6. Uncertainties associated with the transfer chamber calibration

Transfer chamber	BIPM		BFKH	
Relative standard uncertainty	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
Air-kerma rate	0.02	0.13	0.12	0.17
Ionization current for the transfer chamber	0.01	0.02	0.03	0.05
Distance	0.01	–	–	0.02
Reproducibility	0.02	–	0.02	–
Long-term stability, leakage, orientation	–	–	–	0.03
Correction factors (P,T)	–	–	–	0.04
$N_{K,\mathrm{lab}}$	0.03	0.13	0.13	0.18

Table 7. Uncertainties associated with the indirect comparison

Relative standard uncertainty	100 $u_{i\mathrm{A}}$	100 $u_{i\mathrm{B}}$
$N_{K,\mathrm{BFKH}}$ / $N_{K,\mathrm{BIPM}}$ (1)	0.13	0.18
Ion recombination	–	0.02
Radial non-uniformity	–	0.02
Stability of the chamber	0.01	–
R_K	$u_\mathrm{c} = 0.0022$	

(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 BFKH determinations (namely air density, W/e, μ_en/ρ , $\bar{g}$, s_ca and k_h) cancel when evaluating the uncertainty of the ratio R_K of the BFKH and BIPM calibration coefficients.

The ratio of the air-kerma calibration coefficients of the transfer chamber determined by the BFKH and the BIPM taken from Table 5 is 1.0029 with a combined standard uncertainty, u_c, of 0.0022.

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, 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.

When required, the degree of equivalence between two laboratories *i* and *j* can be evaluated as the difference $D_{ij} = D_i - D_j = x_i - x_j$ and its expanded uncertainty $U_{ij} = 2\, u_{ij}$, both expressed in mGy/Gy. In evaluating u_{ij}, account should be taken of correlation between u_i and u_j. Following the advice of the CCRI(I) in 2011, results for D_{ij} and U_{ij} are no longer published in the KCDB.

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)-K1

Lab i	Di	Ui
	/ (mGy/Gy)	
VNIIM	0.8	3.6
NIST	3.9	6.8
ININ	3.5	4.2
LNE-LNHB	-0.6	3.6
PTB	3.6	3.4
ENEA-INMRI	-0.1	4.4
NIM	-0.3	5.4
IST/ITN	2.6	3.4
SCK-CEN	2.1	5.2
SMU	4.2	5.4
NPL	-0.4	6.0
VSL	-3.7	4.2
BEV	3.0	5.0
GUM	3.9	6.0
ARPANSA	-1.4	5.4
NRC	2.2	4.4
BFKH	2.9	4.4
NMIJ	1.3	4.4
KRISS	0.6	3.6

EUROMET.RI(I)-K1 (2005 to 2008) – APMP.RI(I)-K1.1 (2009 to 2012) –
EURAMET.RI(I)-K1.1 (2013-2015) – EURAMET.RI(I)-K1.2 (2017)

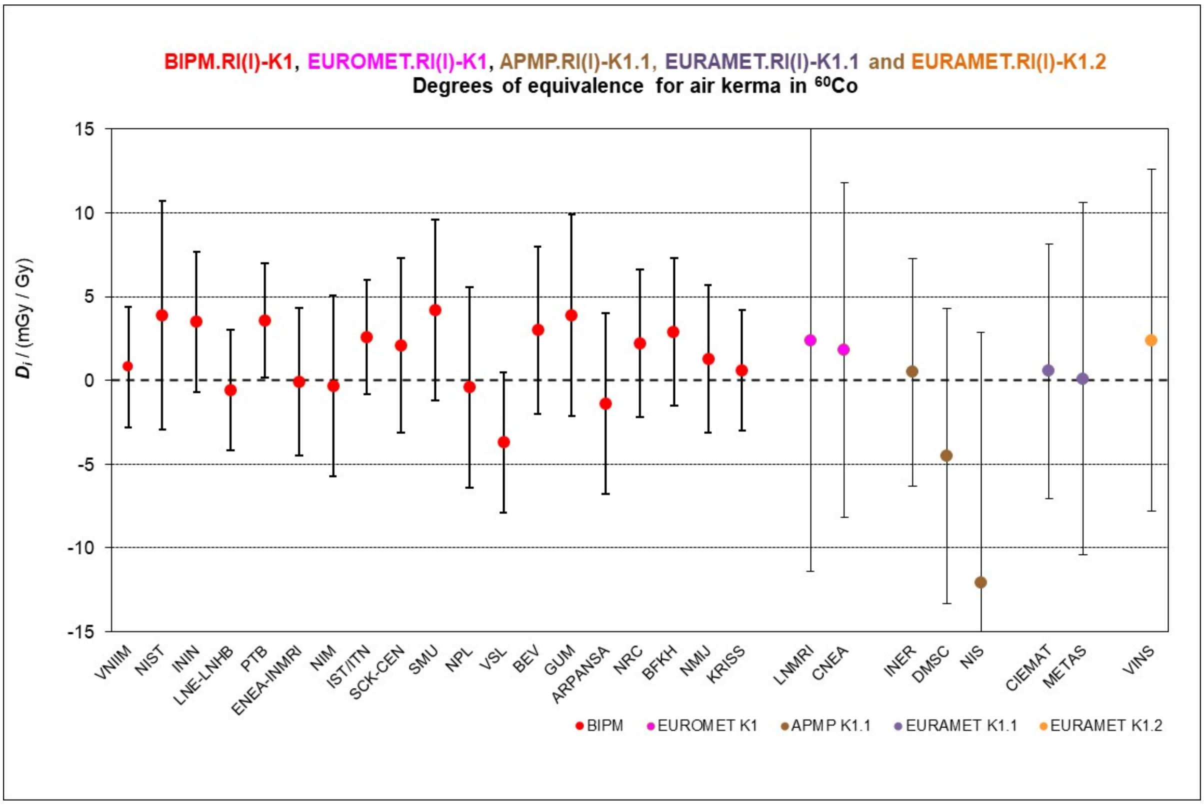
Lab i	D_i	U_i
	/ (mGy/Gy)	
LNMRI	**2.4**	13.8
CNEA	**1.8**	10.0

Lab i	*Di*	*Ui*
	/ (mGy/Gy)	
CIEMAT	**0.6**	7.6
METAS	**0.1**	10.5

Lab i	*Di*	*Ui*
	/ (mGy/Gy)	
INER	**0.5**	6.8
DMSC	**-4.5**	8.8
NIS	**-12.1**	15.0

Lab *i*	D_i	U_i
	/ (mGy/Gy)	
VINS	**2.4**	10.2

Figure 1. **Graph of degrees of equivalence with the KCRV**



7. Conclusion

The previous comparison of the air-kerma standards for ^{60}Co gamma radiation of the BFKH and the BIPM was made in 2016 using the primary standards (direct comparison) and a transfer chamber (indirect comparison). The result of the direct comparison, published in the KCDB, was 1.0047(19). The result 1.0021(20) evaluated using the calibration coefficients of the transfer chamber was in agreement within the uncertainties with the direct comparison result. As both laboratories introduced similar changes to the standards after the adoption of the ICRU 90 recommendations, the agreement between the standards remain unchanged.

For the present comparison, made indirectly using a transfer instrument, the BFKH standard for air kerma in ^{60}Co gamma radiation compared with the BIPM air-kerma standard gives a comparison result of 1.0029 (22), in agreement within the uncertainties with the previous comparison result. The BFKH standard agrees within the expanded uncertainty with all the NMIs having taken part in the BIPM.RI(I)-K1 ongoing key comparison for air-kerma standards in ^{60}Co gamma-ray beam.

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