CIPM MRA
Comparison reports

BIPM.RI(I)-K1 (LNE-LNHB 2026)

Measurement of air kerma for Cobalt 60

KEY COMPARISON

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C. Kessler *et al* 2026 *CIPM MRA Comparison reports* **06019**

https://doi.org/10.59161/KSKH7323

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

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Abstract

A new indirect key comparison of the standards for air kerma of the Laboratoire National de Métrologie et d'Essais – Laboratoire National Henri Becquerel (LNE-LNHB), France, and the Bureau International des Poids et Mesures (BIPM) was carried out in the ^{60}Co radiation beam of the BIPM in June 2026. The comparison result, based on the calibration coefficients for two transfer chambers and evaluated as a ratio of the LNE-LNHB and the BIPM standards for air kerma, is 0.9975 with a combined standard uncertainty of 2.0 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.

1. Introduction

An indirect comparison of the primary standards for air kerma of the Laboratoire National de Métrologie et d'Essais – Laboratoire National Henri Becquerel (LNE-LNHB), France, and the Bureau International des Poids et Mesures (BIPM) was carried out in June 2026 in the ^{60}Co radiation beam at the BIPM to update the previous comparison result of 2013 (Kessler *et al.* 2013) published in the BIPM key comparison database (KCDB 2026) under the reference BIPM.RI(I)-K1. The comparison was carried out after the implementation of the recommendations of the ICRU Report 90 (ICRU 2016) at both laboratories.

The indirect comparison was made using two thimble-type ionization chambers as transfer chambers, both instruments belonging to the LNE-LNHB. The final results were submitted by the LNE-LNHB in July 2026.

2. Details of the primary standards and the transfer chambers

The LNE-LNHB standard for air kerma is comprised of six graphite-walled cavity ionization chambers of different size and shape, each with a graphite inner electrode, constructed at the LNE-LNHB (Delaunay *et al*. 2010). The main characteristics of the standards are listed in Table 1a. The BIPM primary standard, identified as CH6.2, is a graphite-walled parallel-plate cavity ionization chamber described in Boutillon and Niatel (1973), Burns *et al.* (2007) and Burns and Kessler (2018). The main characteristics of the BIPM primary standard are given in Table 1b. Details of the two transfer chambers used for the indirect comparison are given in Table 2.

Table 1a. Characteristics of the LNE-LNHB standards

LNHB standards	CSp01	CSp02	CSp03	Sp01	Sp02	Sp03
Shape	Cylindro-spherical			Spherical		
Dimensions / mm						
Outer height / mm	42	39	36	-	-	-
Outer diameter / mm	30	28	26	30	28	26
Inner height / mm	36	33	30	-	-	-
Inner diameter / mm	24	22	20	24	22	20
Wall thickness / mm	3					
Graphite wall density / g cm^{-3}	1.85					
Electrode diameter / mm	3					
Electrode height / mm	25.2	23.2	21.2	13.3	12.2	11.2
Air cavity volume / cm^3	12.47	9.86	7.17	7.22	5.47	4.11
Voltage applied to outer electrode / V	+ 850					

Table 1b. Characteristics of the BIPM standard

Dimensions		BIPM standard CH6.2
Cavity	Diameter / mm	45.01
	Thickness / mm	5.16
	Measuring volume / cm^3	6.8749
Electrode	Shape	disc
	Diameter / mm	41.03
	Thickness / mm	1.005
Wall	Thickness / mm	2.90
	Material	graphite
	Density / g cm^{-3}	1.85
Voltage applied to outer electrode / V		± 80

Table 2. Characteristics of the LNE-LNHB transfer chambers

	Nominal values	NE2571
Chamber	Outer diameter / mm	7
	Outer length / mm	24.5
Electrode	Diameter / mm	1
	Length / mm	20.6
Cavity	Nominal volume / cm^3	0.7
Wall	Thickness / mm	0.36
	Material	Graphite
Build-up	Thickness / mm	3.9
	Material	Delrin CH20
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

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

where

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

I is the ionization current measured by the standard 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,

$(\mu_{\text{en}}/\rho)_{\text{a,c}}$ 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 mass stopping powers for electrons 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 entered into equation (1) and the associated uncertainties for the BIPM ^{60}Co radiation beam are given in Table 3.

Reference conditions and beam characteristics

The reference conditions for the air-kerma determination at the BIPM (Kessler and Burns 2024) and at the LNE-LNHB are the following:

- the distance from source to reference plane at the BIPM is 1 m and at the LNE-LNHB is 1.6 m,
- the field size in air at the reference plane at both laboratories 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.

The characteristics of the BIPM and LNE-LNHB beams are given in Table 4.

Reference values

The BIPM reference air-kerma rate, $\dot{K}_{\text{BIPM}}$, is taken as the mean of the four measurements made around the period of the comparison. The $\dot{K}_{\text{BIPM}}$ values refer to an evacuated path length between source and standard, corrected to the reference date of 2026-01-01, 0 h UTC. The correction for air attenuation between source and standard used the ambient air density at the time of the measurement and the linear air attenuation coefficient 0.0078 m^{-1} for ^{60}Co, which applies to the dry air density at the standard temperature and pressure used at the BIPM (see Table 3, footnote 3). The half-life of ^{60}Co used for the decay correction is taken as 1925.23 days (u = 0.29 days) (https://www.lnhb.fr/nuclides/Co-60_tables.pdf). At the LNE-LNHB, the air kerma rate is determined from measurements performed using the six primary standards and is evaluated as the unweighted mean of the resulting values. An air density correction on the path length between source and standard was applied and the reference value $\dot{K}_{\text{LNE-LNHB}}$ is given at the reference date of 2026-06-01, 0 h UTC using the same half-life value for the decay correction.

The air-kerma rate values $\dot{K}$ determined at each laboratory are given at the corresponding reference dates in Table 4.

The ionization currents measured using the transfer chambers are decay corrected to the corresponding reference dates adopted by each laboratory.

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

		BIPM CH6.2			LNE-LNHB CSp-Sp		
		values	uncertainty[1]		values[2]	uncertainty[1,2]	
			100 u_{iA}	100 u_{iB}		100 u_{iA}	100 u_{iB}
Physical Constants							
ρ_{air}	dry air density[3] / kg m^{-3}	1.2930	–	0.01	1.2048	–	0.01
$(\mu_{en}/\rho)_{a,c}$	ratio of mass energy-absorption coefficients	0.9989	0.01	0.04	0.9989	0.01	0.04
$\bar{s}_{c,a}$	ratio of mass stopping powers	0.9928	–	0.08[4,5]	0.9928	–	0.08[4]
W/e	mean energy per charge / J C^{-1}	33.97			33.97		
$\bar{g}$	fraction of energy lost in radiative processes	0.0031	–	0.02	0.0031	–	0.02
Correction factors and uncertainty components							
k_h	relative humidity	0.9970	–	0.03	0.9970	–	0.03
k_g	re-absorption of radiative loss	0.9996	–	0.01	–	–	–
k_s	recombination losses	1.0019	0.01	0.02	1.0005-1.0010	[6]	0.02
k_{pol}	polarity	–	–	–	1.0001-1.0004	<0.01	0.02
k_{st}	stem scattering	1.0000	0.01	–	0.9988-0.9993	0.03	0.02
k_{wall}	wall attenuation and scattering	1.0011	–	–[7]	1.0162-1.0197	0.01-0.02	0.10
k_{an}	axial non-uniformity	1.0020	–	–[7]	1.0000	–	0.05
k_{rn}	radial non-uniformity	1.0015	–	0.02	1.0003-1.0015	0.03-0.04	0.02
Measurement of I / V							
V	chamber volume / cm^3	6.8749	–	0.08[7]	[8]	–	0.02-0.04
I	ionization current / pA	–	0.01	0.02	–	0.01-0.03	0.07
Relative standard uncertainty[9]							
quadratic summation			0.02	0.13		0.08	0.18
combined uncertainty			**0.13**			**0.19**	

[1] Expressed as one standard deviation
u_{iA} represents the type A relative standard uncertainty estimated by statistical methods,
u_{iB} represents the type B relative standard uncertainty estimated by other means

[2] Range of values for the CSp and Sp primary standards

[3] At 101.325 kPa and 273.15 K at the BIPM (traditionally, the BIPM corrects the current measured using primary standards to these conditions of P and T); at 101.325 kPa and 293.15 K at the LNE-LNHB

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

[5] Adopted from January 2019 (Burns and Kessler 2018)

[6] Included in the uncertainty of the measured ionization current I

[7] The uncertainties for k_{wall} and k_{an} are included in the determination of the effective volume (Burns *et al.* 2007)

[8] See Table 1a. Characteristics of the LNE-LNHB standards

[9] The relative standard uncertainty for the LNE-LNHB is calculated considering the six primary standards

Table 4. Characteristics of the ^{60}Co beams at the LNE-LNHB 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 the reference distance
		diameter	length		
LNE-LNHB GammaBeam X200	2.3	20	18	21 %	10 cm × 10 cm
BIPM Theratron 1000	2.9	20	14	21 %	10 cm × 10 cm

4. Comparison procedure

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

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

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

The ionization chambers NE2571, serial numbers 3599 and 3780, belonging to the LNE-LNHB, were the transfer chambers used for this comparison. Their main characteristics are listed in Table 2. These chambers were calibrated at the LNE-LNHB before being sent to the BIPM and after measurements were made at the BIPM.

The experimental method for measurements at the BIPM is described by Kessler and Burns (2024); the essential details for the determination of the calibration coefficients $N_{K,\mathrm{lab}}$ for the transfer chambers are reproduced here.

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.

Applied voltage and polarity

At both laboratories, a collecting voltage of 300 V (positive polarity) was applied to the outer electrode of the LNE-LNHB transfer chambers, at least 40 min before any measurements were made. No corrections were applied by either laboratory for polarity.

Charge and leakage measurements

The charge Q collected by the LNE-LNHB transfer chambers was measured at the BIPM using a Keithley electrometer model 642. The source was exposed during the entire measurement series and the charge was collected for the appropriate, electronically controlled, time interval. A pre-irradiation was made for at least 40 min before any measurements (~7 Gy). The measurements were corrected by the mean leakage current measured before and after each series of measurements. The leakage correction, estimated as the ratio of the leakage current relative to the ionization current, was less than 1 part in 10^4 for the two chambers.

At the LNE-LNHB, a pre-irradiation was made for 40 min before any measurements. The ionization current I was measured using a Keithley electrometer, model 642. The relative leakage correction for each chamber was less than 1 part in 10^4.

Radial non-uniformity correction

The LNE-LNHB calibration coefficients are corrected for the radial non-uniformity of the beam; for consistency, the BIPM also applied the mentioned correction to the ionization current.

The correction factors applied are 1.0003(4) and 1.0002(2) at the LNE-LNHB and BIPM, respectively.

Ion recombination

Volume recombination is negligible for continuous beams at the present dose rates and for the applied polarizing voltage, and the initial recombination loss will be the same in the two laboratories; consequently, no correction was applied and 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 was measured for each current measurement and was stable to better than 0.05 °C at the BIPM. At the LNE-LNHB, the air temperature was also measured for each current measurement and was stable to better than 0.5 °C. The currents measured using the transfer chambers are normalized at both laboratories to the reference conditions of 293.15 K and 101.325 kPa.

At the BIPM, the relative humidity is controlled in the range from 45 % to 55 %. At the LNE-LNHB, the relative humidity is controlled in the range from 30 % to 70 %; no correction for humidity was applied to the ionization current measured.

5. Results of the comparison

The NE2571 transfer chambers were set up and measured in the BIPM ^{60}Co beam on two separate occasions. The results were reproducible to around 1 part in 10^4. The result of the comparison, R_K , is expressed as

$$R_K = N_{K,\text{LNE-LNHB}} / N_{K,\text{BIPM}} \quad (3)$$

in which the average value of measurements made at the LNE-LNHB 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 final R_K value is evaluated as the unweighted mean value for the two transfer chambers. 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 values $N_{K,\text{LNE-LNHB}}$ measured before and after the measurements at the BIPM give rise to a relative standard deviation for each chamber, whose root mean squared (rms) value is taken as a representation of the stability of the transfer instruments. The short-term stability was estimated to be less than 1 part in 10^4. Table 7 includes a component of 1 part in 10^4 for the difference in the comparison results between the two transfer chambers.

Table 5. Results of the indirect comparison

Transfer chamber	$N_{K,\text{LNE-LNHB}}$/ Gy µC^{-1}			$N_{K,\text{BIPM}}$ / Gy µC^{-1}	R_K	u_c
	pre-BIPM	post-BIPM	overall mean			
NE2571-3599	41.163	41.172	41.168	41.271	0.9975	0.0020
NE2571-3780	41.415	41.428	41.422	41.528	0.9974	0.0020
				Mean value	0.9975	0.0020

Table 6. Uncertainties associated with the transfer chamber calibration

	BIPM		LNE-LNHB	
Relative standard uncertainty	100 u_{iA}	100 u_{iB}	100 u_{iA}	100 u_{iB}
Air-kerma rate	0.02	0.13	–	0.19
Ionization current	0.01	0.02	0.02	0.04
Source to detector distance	0.01	–	–	0.01
Short-term reproducibility	0.01	–	–	–
Radial non-uniformity		0.02	0.04	0.02
Temperature, pressure	–	–	–	0.04
$N_{K,\mathrm{lab}}$	0.03	0.13	0.04	0.20

Table 7. Uncertainties associated with the indirect comparison

Relative standard uncertainty	100 u_{iA}	100 u_{iB}
$N_{K,\mathrm{LNE\text{-}LNHB}}$ / $N_{K,\mathrm{BIPM}}$ [(1)]	0.05	0.19
Ion recombination	–	0.02
Stability of the chambers	0.01	–
Different chambers	0.01	–
Combined standard uncertainty u_c of R_K	$u_c = 0.0020$	

[(1)] The combined standard uncertainty u_c of the comparison result R_K takes into account correlation in the type B uncertainties in the determination of the air kerma rate associated with the physical constants and the humidity correction

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

The comparison result, taken as the unweighted mean value for the two transfer chambers, is $R_K = 0.9975$ with a combined standard uncertainty u_c for the comparison of 0.0020, demonstrating agreement between the two standards for air kerma within the expanded uncertainty ($k = 2$).

6. Degrees of equivalence

Following a decision of the CCRI(I), 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 National Metrology Institute (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 2.

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.

BIPM.RI(I)-K1

Lab *i*	D_i / (mGy/Gy)	U_i / (mGy/Gy)
ININ	3.5	4.2
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	-3.4	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
NIST	4.4	6.8
PTB	0.4	5.0
LNE-LNHB	-2.5	4.0

APMP.RI(I)-K1.1 (2009 to 2012)

Lab *i*	D_i / (mGy/Gy)	U_i / (mGy/Gy)
DMSC	-4.5	8.8
NIS	-12.1	15.0

EURAMET.RI(I)-K1.1 (2013-2015)

Lab *i*	D_i / (mGy/Gy)	U_i / (mGy/Gy)
METAS	0.1	10.5

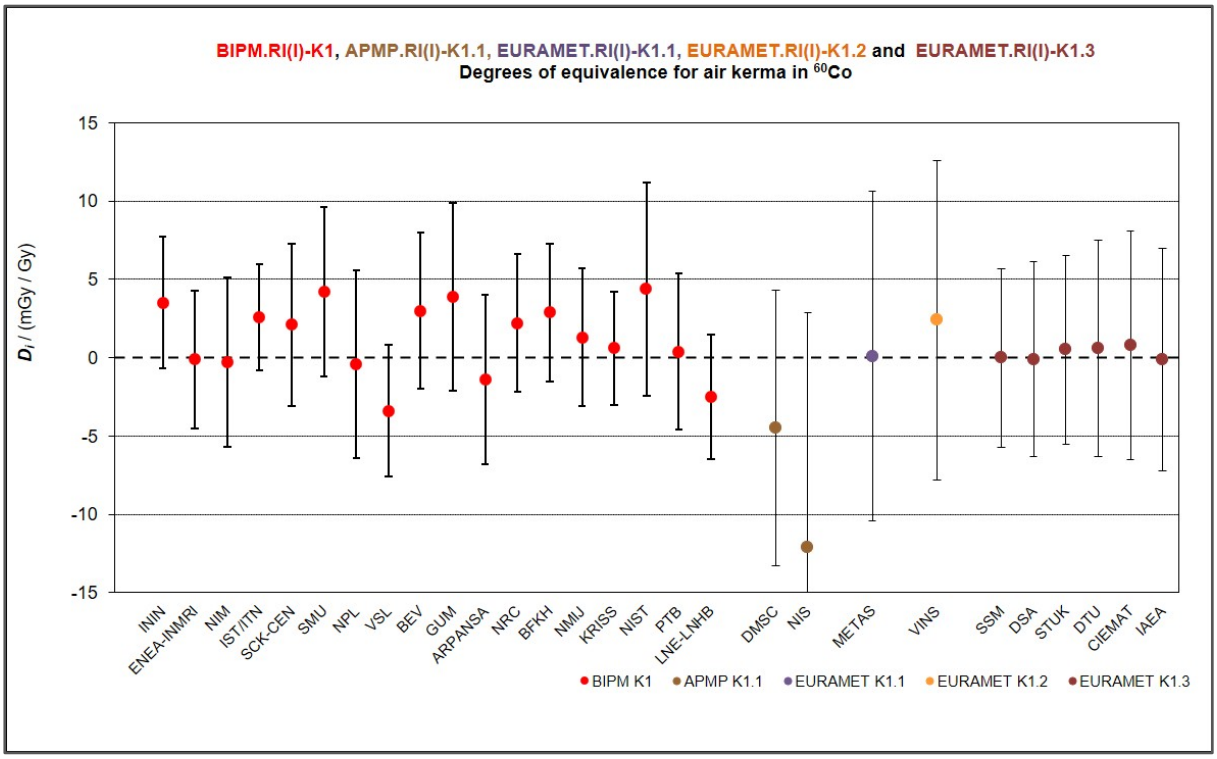
EURAMET.RI(I)-K1.2 (2017)

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

EURAMET.RI(I)-K1.3 (2022)

Lab *i*	D_i / (mGy/Gy)	U_i / (mGy/Gy)
SSM	0.0	5.7
DSA	-0.1	6.2
STUK	0.5	6.0
DTU	0.6	6.9
CIEMAT	0.8	7.3
IAEA	-0.1	7.1

Figure 2. Graph of degrees of equivalence with the KCRV



Note that the data presented in Table 8 and in Figure 2, while correct at the time of publication of the present report, becomes 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 are removed from the KCDB. The formal results under the CIPM MRA are those available in the key comparison database.

7. Conclusion

The previous comparison of the air-kerma standards for ^{60}Co gamma radiation of the LNE-LNHB and the BIPM was made indirectly in 2013. That comparison result was 0.9994 (18). Since the previous comparison, the LNE-LNHB re-evaluated the correction factor that accounts for the attenuation and scattering of the radiation beam in the wall of the standards for the new ^{60}Co source and both laboratories implemented some changes in the standards following the recommendations of the ICRU 90. For the LNE-LNHB and for the BIPM, this resulted in a reduction of 9.6 parts in 10^3 and 8.3 parts in 10^3 in the determination of air kerma, respectively. Adopting these changes, the 2013 comparison result becomes 0.9981 (20), in agreement within the uncertainties with the new comparison result of 0.9975 (20).

The LNE-LNHB 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 beams.

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