Summary of the BIPM.RI(I)-K5 comparison for air kerma in ^{137}Cs gamma radiation

P. J. Allisy-Roberts, C. Kessler, D.T.Burns
Bureau International des Poids et Mesures,
Pavillon de Breteuil, 92312 Sèvres Cedex

Abstract

International comparisons of air kerma in ^{137}Cs gamma radiation beams have been made at the Bureau International des Poids et Mesures (BIPM) since 1994. Twelve national metrology institutes have taken part, seven of which have repeated the comparison over the intervening years. The key comparison reference value (KCRV) is taken as the BIPM evaluation, each comparison result being the ratio of the national metrology institute (NMI) evaluation to that of the BIPM standard under the same reference conditions. The degrees of equivalence between each NMI and the KCRV and a graphical presentation are given using the most recent published result for eleven NMIs.

1.   Introduction

National primary standards for air kerma in ^{137}Cs gamma radiation are compared at the BIPM against the BIPM primary standard as part of a continuous programme of ongoing comparisons that started in 1994, following the advice of the Consultative Committee for Ionizing Radiation (CCRI). There are now twelve national institutes that have made such comparisons. However, for the results to appear in the key comparison database (KCDB) under the auspices of the CIPM MRA [1], the national metrology institute must operate within the CIPM MRA, the comparison must be published and must not be older than 15 years [2] unless the CCRI(I) permits an exception. Consequently, eleven comparisons are eligible to have their results in the KCDB, although the NIST only provisionally while awaiting publication of a more recent comparison held in 2011.

The acronyms and details of the eligible NMIs are given in Table 1. The results of these comparisons form the basis for degrees of equivalence [3] entered in the KCDB for BIPM.RI(I)-K5. In May 2009, the CCRI agreed to change the BIPM evaluation of air kerma in ^{137}Cs gamma radiation by a factor of 1.0030 and this change has been published [4] and implemented in the results presented here.

Table 1   Details of the participants in the key comparison BIPM.RI(I)-K5

NMI acronym	Full name	Country	Regional metrology organization	Year of most recent comparison
NIST	National Institute of Standards and Technology	USA	SIM	1994 (2011)
ENEA	Ente per le Nuove Technologie, l'Energia e l'Ambiente	Italy	EURAMET	1998
PTB	Physikalisch-Technische Bundesanstalt	Germany	EURAMET	2000
NMIJ	National Metrology Institute of Japan	Japan	APMP	2001 (2012)
GUM	Główny Urząd Miar	Poland	EURAMET	2006
ITN	Instituto Tecnológico e Nuclear	Portugal	EURAMET	2008
LNE-LNHB	Laboratoire National de Métrologie et d'Essais - Laboratoire National Henri Becquerel	France	EURAMET	2008
BEV	Bundesamt für Eich- und Vermessungswesen	Austria	EURAMET	2009
MKEH*	Magyar Kereskedelmi Engedéyezési Hivatal	Hungary	EURAMET	2009
VNIIM	D.I. Mendeleyev Institute for Metrology	Russian Federation	COOMET	2009
KRISS	Korea Research Institute of Standards and Science	Korea	APMP	2010

* previously known as the OMH.

2. National standards

The national primary standards for the determination of air kerma in ^{137}Cs gamma radiation beams are exclusively graphite-walled ionization chambers. As the standards are based on the same method, the resulting correlations in the uncertainties need to be taken into account when determining the degrees of equivalence. In addition to the correlation due to the method, the correction factors for the effects of the graphite walls for similar shapes of primary standard have significant correlation. Details of the correlations are given in section 5. Occasionally, transfer standards have been used to compare the primary realizations and this is indicated in Table 2 when applicable.

3.   Data from each national metrology institute

When a comparison is undertaken at the BIPM, the NMI and the BIPM each measure the air-kerma rate using their own standard. The BIPM value using the primary standard is $\dot{K}_{\text{BIPM}}$ and the NMI's best estimate of the same air-kerma rate at the BIPM, $\dot{K}_{\text{NMI}}$ (with combined standard uncertainty $u_{\text{K,NMI}}$), is made using their national primary standard, or using a transfer standard calibrated at the NMI in terms of air kerma against their primary standard with a calibration coefficient, $N_{K,\text{NMI}}$, in which latter case,

$$\dot{K}_{\text{NMI}} = N_{K,\text{NMI}} \times I_{\text{BIPM}}, \tag{1}$$

where I_{BIPM} is the ionization current measured by the NMI transfer chamber in the BIPM beam under standard calibration conditions [5]. The comparison result is the ratio of the air-kerma rate measured by the NMI at the BIPM and that measured by the BIPM:

$$R_{\text{NMI}} = \dot{K}_{\text{NMI}} / \dot{K}_{\text{BIPM}}. \tag{2}$$

The most recent comparison result for each laboratory is listed in Table 2, together with the reported comparison uncertainty, $u_{i,}$ for each NMI, i.

The comparison uncertainty takes into account correlation, particularly for the use of the same constants (such as air density, W/e and k_{h}) and for factors based on the same physical data (such as $\bar{\mu}_{\text{en}}/\rho$, $\bar{g}$ and $\bar{s}_{\text{c,a}}$), as identified in each comparison report for the common measurement equation,

$$\dot{K} = \frac{I}{m} \frac{W}{e} \left(\frac{1}{1-\bar{g}} \right) \left(\frac{\bar{\mu}_{\text{en}}}{\rho} \right)_{\text{a,c}} \bar{s}_{\text{c,a}} \, \prod k_i \ , \tag{3}$$

where

I/m is the ionization current measured by the standard per mass of air,
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 kinetic energy lost in radiative processes in air,
$(\bar{\mu}_{\text{en}}/\rho)_{\text{a,c}}$ 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 electron stopping powers of graphite and air, and
$\prod k_i$ is the product of the correction factors to be applied to the standard.

The relative uncertainty of the product of the stopping-power ratio and W/e was accepted as 1.1×10^{-3} by the CCRI in 1999 [6]. Consequently, for comparisons published before this date, the uncertainties have been modified to take this change into account. The present uncertainty budget for the BIPM standard is given in [5].

During the past fifteen years, significant progress has been made in applying Monte Carlo techniques to make better estimates of the various correction factors that are applied in the measurement equation for cavity chamber standards, particularly for the effects of attenuation and scattering in the graphite walls. Since 2003, each NMI has been encouraged by the CCRI [7] to verify its correction factors and to publish any changes to its national standards that it feels are appropriate so that the results may be included in the KCDB. Consequently, a

comparison result, R_{NMI} listed in Table 2 might be different from the original published comparison result if the NMI has changed its method of estimating the correction factors and/or uncertainties since publication of the result. When this is the case, the references given against each value describe the changes. In addition to this, all the comparison results, x_i, in Table 2 that were published prior to 2009 differ from the original R_{NMI} because the BIPM standard changed in 2009, as described below in section 4.

4.   The key comparison reference value

As agreed at the CCRI(I) meeting in 1999, the BIPM value is the reference value for each ongoing comparison [8]. Consequently, any change in the absolute value of air kerma as determined by the BIPM standard is subject to approval by the CCRI. In the past these have mostly been related to changes in the physical constants used in the measurement equation by every NMI as well as the BIPM.

However, in addition to the NMIs re-evaluating their wall correction factors using Monte Carlo (MC) methods, the BIPM has also undertaken this work for the BIPM standard. Although the MC calculations show no change in the correction factor k_{wall} at the level of two standard uncertainties, there has been a more significant change in k_{an} [9]. The BIPM has also recently produced a variable-volume cavity standard to determine the air-kerma rate differentially [10]. This experiment has contributed to a new estimation for the volume of the BIPM standard and the CCRI, in May 2009, approved an overall change in the BIPM air-kerma standard by a factor of 1.0030. The combined relative standard uncertainty on the air-kerma determination is now evaluated as 1.9×10^{-3}. The small change to the BIPM uncertainty does not significantly affect each comparison result, which takes into account the correlation in uncertainties for the physical constants and some other parameters as described in each comparison report.

This change to the BIPM standard has been published [4] and is reflected in the revised comparison results, x_i, u_i, given in Table 2 and in the degrees of equivalence presented in Table 3.

The relative standard uncertainty of the distribution of air-kerma measurements at the BIPM is about 4×10^{-4}. Although the measurements have shown a small drift over the past nine years, this drift is reduced significantly on using the latest ^{137}Cs half-life determination [11].

As a consequence of the choice of reference value, the degree of equivalence between a given NMI and the key comparison reference value remains constant between comparisons with that NMI. New comparison results have no impact on the reference value and can be added to the database as soon as they are approved and published. Furthermore, the degree of equivalence between any two NMIs is not affected by the KCRV.

Table 2   **Revised data set for published BIPM key comparisons of air kerma in ^{137}Cs**

NMI / i	Year	$u_{K,\text{NMI}}$	R_{NMI}	Ref. for R_{NMI}	x_i	u_i[1]	**Primary standard type**[1]
		standard uncertainty of the K_{NMI}	published comparison result		revised comparison result	uncertainty of x_i	
		in relative value			in relative value		
NIST	1994	0.0031	1.0017	[12, 13, 4]	1.0077	0.0042	spherical chambers[2]
ENEA	1998	0.0059	0.9927	[14]	0.9927	0.0067	extrapolation method using ^{60}Co and 250 kV standards
PTB	2000	0.0040	1.0064	[15, 4]	1.0034	0.0028	one parallel plate and two cylindrical chamber
NMIJ	2001	0.0025	1.0005	[16, 4]	0.9975	0.0028	two different volume cylindrical chambers
GUM	2006	0.0028	0.9995	[17]	0.9995	0.0029	ND1005/A
ITN	2008	0.0021	1.0013	[18]	1.0013	0.0021	CC01 chamber
LNE-LNHB	2008	0.0036	0.9984	[19]	0.9984	0.0026	cylindrical chamber with hemispherical ends
BEV	2009	0.0031	1.0041	[20]	1.0041	0.0031	CC01 chamber
MKEH	2009	0.0040	1.0053	[21]	1.0053	0.0025	ND1005
VNIIM	2009	0.0021	1.0013	[22]	1.0013	0.0027	two different volume cylindrical chambers[2]
KRISS	2010	0.0022	0.9986	[23]	0.9986	0.0022	cylindrical chamber

[1] taken from each reference for R_{NMI}
[2] transfer standard(s) were used for the comparison

5. Expression of the degree of equivalence

The degree of equivalence of a given measurement standard is the degree to which this standard is consistent with the key comparison reference value [1]. The degree of equivalence is expressed quantitatively in terms of the deviation of the comparison result from the key comparison reference value and the expanded uncertainty of this deviation (coverage factor $k = 2$). The degree of equivalence between any pair of national measurement standards is the degree to which the two standards are consistent. When required, it is expressed in terms of the difference in the two comparison results and the expanded uncertainty of this difference.

Comparison of a given NMI with the key comparison reference value

Following the decision of the CCRI, the BIPM determination of the dosimetric quantity, here K_B, is taken as the key comparison reference value (KCRV), for each of the CCRI radiation qualities [12]. It follows that for each NMI i having a BIPM comparison result $R_{,i}$ (denoted x_i in the KCDB) with combined standard uncertainty u_i, the degree of equivalence with respect to the reference value is given by a pair of terms:

the relative difference $D_i = (K_i - K_{Bi})/ K_{Bi} = R_{Ki} - 1$ (4)

and the expanded uncertainty ($k = 2$) of this difference,
$$U_i = 2\, u_i. \tag{5}$$

The results for D_i and U_i, are expressed in mGy/Gy.

The u_i for each NMI, i, is shown in Table 2, all correlation with the BIPM evaluation having already been taken into account. Table 3 gives the values for the degrees of equivalence with the KCRV, D_i and U_i for each NMI, using (4) and (5), and forms the basis of the entries in the KCDB. These data are presented graphically in Figure 1.

Comparison of any two NMIs with each other

When required, the degree of equivalence between any pair of national measurement standards 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

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

$$U_{ij} = 2\left[u_i^{\;2} + u_j^{\;2} + 2u_{\mathrm{rep}}^{\;2} - 2u_{\mathrm{BIPM,instr}}^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_i^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_j^2 \right]^{1/2} \tag{7}$$

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.

The various components of (7) are described in the following paragraphs to enable these calculations to be made.

The long-term reproducibility of the BIPM air kerma determination, u_{rep}, is 0.0004 in relative value and arises from the statistical uncertainty of the BIPM realizations of air kerma over more than 15 years. When comparing NMIs i and j, for which comparisons may have been made many years apart, this uncertainty needs to be taken into account as this is not included in each comparison uncertainty u_i and u_j.

Each comparison result is a ratio with respect to the BIPM, and the uncertainties related to the physical constants and the correction for humidity have already been removed in evaluating the comparison uncertainties u_i and u_j. However, the relative uncertainties related to the BIPM measuring instrument, $u_{\text{BIPM,instr}} = 0.0012$ must also be removed.

In general there will be correlation between the results of each pair of NMIs and this is taken into account by removing uncertainty components, k, that are correlated, $u_{k,\text{corr}}$. However, as the uncertainties are not necessarily fully correlated, an approximate factor, f_k, is applied, usually chosen by the CCRI. The only significant remaining correlation between NMIs i and j relates to the wall correction. For those pairs of NMIs that have calculated the wall correction factors for their standards using MC methods, a value of 0.8 can be used for the f_k for the Type B component of the uncertainties, as approved by the CCRI(I) in May 2007. Although the correction for axial non-uniformity is also calculated using MC methods, the values for cylindrical and for spherical chambers are not significantly different from unity and the uncertainties are sufficiently small to ignore in the correlation. Similarly, other possible correlations are ignored as the associated uncertainties are small.

The table of degrees of equivalence with the KCRV is given in Table 3 in the form as it appears in the KCDB.

Table 3   The degrees of equivalence of each NMI's measurement standard

	D_i	U_i
	mGy/Gy	
NIST	7.7	8.4
ENEA	-7.3	13.4
PTB	3.4	5.7
NMIJ	-2.5	5.7
GUM	-0.5	5.9
ITN	1.3	4.3
LNE-LNHB	-1.6	5.3
BEV	4.1	6.3
MKEH	5.3	5.1
VNIIM	1.3	5.5
KRISS	-1.4	4.5

6.   Comments on future comparisons

The CCRI(I) has agreed that comparisons should be repeated approximately every ten years, or sooner if there has been any significant change at the NMI, and new comparison results added to the database as soon as they are approved. Each NMI's results are published in a report of the comparison, which will now include an update of the table of degrees of equivalence and the corresponding graphical presentation as they will appear in the KCDB. This report is sent to the CCRI(I) for approval once the participant and the CCRI(I) Key Comparison Working Group (KCWG) have agreed on the result. An updated summary of the results is presented to each CCRI(I) meeting. Decisions to remove results from the KCDB are made only by the CCRI(I). The CCRI has agreed that results may remain in the KCDB after 10 years as long as a new comparison has been scheduled within the next 5 years [2].

If an NMI makes a bilateral comparison of their primary standard with another NMI for this quantity, the results can be included in the database with the approval of the KCWG. Such approval requires that the comparison is declared in advance, that it follows an approved protocol and that at least one of the NMIs already has a BIPM comparison result.

7.   Conclusion

The BIPM ongoing key comparison for air kerma in ^{137}Cs gamma-ray beams, BIPM.RI(I)-K5, currently comprises eleven results. These have been analysed with respect to the KCRV and the results are compatible within the expanded uncertainties. The matrix of degrees of equivalence has been approved by the CCRI(I) and is published in the CIPM MRA key comparison database. Results will be updated and new results added as they are published, whenever NMIs make air-kerma comparisons at the BIPM.

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Figure 1   **Graph of the degrees of equivalence with the KCRV**
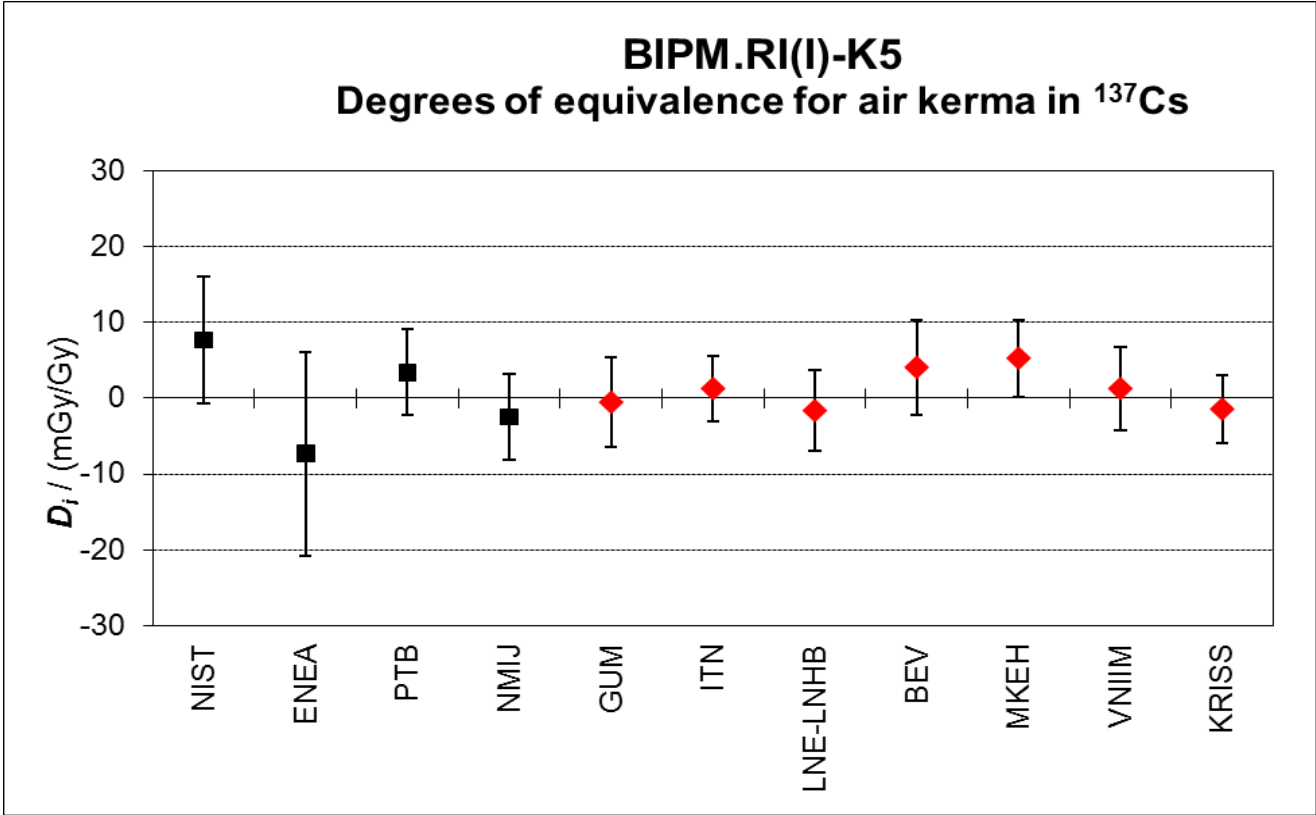
The black squares indicate results that are more than ten years old.