Summary of the BIPM.RI(I)-K1 comparison for air kerma in ^{60}Co gamma radiation

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Abstract

International comparisons of air kerma have been made at the Bureau International des Poids et Mesures (BIPM) since 1975. Twenty-one national metrology institutes have taken part, some of which have repeated the comparison over the years. The key comparison reference value (KCRV) is unity, each comparison result being the ratio of the national metrology institute (NMI) evaluation to that of the BIPM standard. The degrees of equivalence between each NMI and the KCRV, and between each pair of NMIs, are given in the form of a matrix, using the most recent published result of the past ten years for each of fifteen NMIs. A graphical presentation is also given.

The results of this comparison, identified as BIPM.RI(I)-K1, have been approved by Section I of the Consultative Committee for Ionizing Radiation (CCRI(I)) and are published in the key comparison database (KCDB).

1. Introduction

National primary standards for air kerma in ^{60}Co gamma radiation are compared at the BIPM against the BIPM primary standard in a continuous programme that started in 1975. There are now twenty-one 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, the national metrology institute must operate within the CIPM MRA, the comparison must be published and must not be older than 15 years [1]. Consequently, fifteen comparisons are eligible to be registered in the KCDB. Once the other recent comparisons have been published, their results will be added to the KCDB.

The acronyms and details of the currently eligible NMIs are given in Table 1. The results of these comparisons form the basis for degrees of equivalence [2] entered in the KCDB for BIPM.RI(I)-K1. It was agreed at the CCRI(I) meeting in 1999 that the BIPM value would be the reference value for each comparison and consequently, as each comparison result is the ratio of the NMI evaluation to the BIPM evaluation of air kerma under the reference conditions at the BIPM, the KCRV is unity. In May 2007, the CCRI agreed to change the BIPM evaluation of air kerma by a factor of 1.0054 and this change has been published [3] and implemented in the results presented here.

Table 1 Details of the participants in the key comparison BIPM.RI(I)-K1

NMI acronym	Full name	Country	Regional metrology organization	Year of most recent comparison
BEV	Bundesamt für Eich- und Vermessungswesen	Austria	EUROMET	1995
NMi	Nederlands Meetinstituut	Netherlands	EUROMET	1996
NIST	National Institute of Standards and Technology	USA	SIM	1996
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency	Australia	APMP	1997
VNIIM	D.I. Mendeleyev Institute for Metrology	Russian Federation	COOMET	1997
NRC	National Research Council Canada	Canada	SIM	1998
PTB	Physikalisch-Technische Bundesanstalt	Germany	EUROMET	2000
SMU	Slovensky Metrologicky Ustav	Slovakia	EUROMET	2000
ZMDM	Zavod Za Mere I Dragocene Metale	Serbia	EUROMET	2001
NMIJ	National Metrology Institute of Japan	Japan	APMP	2001
NCM	National Centre of Metrology	Bulgaria	EUROMET	2002
LNE-LNHB	Laboratoire National de Métrologie et d'Essais - Laboratoire National Henri Becquerel	France	EUROMET	2003
LNMRI	Laboratorio Nacional de Metrologia das Radiaçoes Ionizantes	Brazil	SIM	2003
ENEA	Ente per le Nuove Technologie, l'Energia e l'Ambiente	Italy	EUROMET	2004
MKEH*	Magyar Kereskedelmi Engedéyezési Hivatal	Hungary	EUROMET	2006

* previously known as the OMH.

2. National standards

The national primary standards for the determination of air kerma in ^{60}Co 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. This is particularly important when the same shape of primary standard is being compared. Details of the correlations are given in section 3. 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 $\dot{K}_{\mathrm{BIPM}}$ and the NMI's best estimate of the same air-kerma rate at the BIPM, $\dot{K}_{\mathrm{NMI}}$ (with combined standard uncertainty $u_{\mathrm{K,NMI}}$), is made using their national primary standard or a transfer standard calibrated at the NMI in terms of air kerma against their primary standard with a calibration coefficient, $N_{K,\mathrm{NMI}}$, in which latter case,

$$\dot{K}_{\mathrm{NMI}} = N_{K,\mathrm{NMI}} \times I_{\mathrm{BIPM}} , \qquad (1)$$

where I_{BIPM} is the ionization current measured by the NMI transfer chamber in the BIPM beam under standard calibration conditions [3, 4]. The comparison result is the ratio of the air-kerma rate measured by the NMI at the BIPM and that measured by the BIPM:

$$R_{\mathrm{NMI}} = \dot{K}_{\mathrm{NMI}} / \dot{K}_{\mathrm{BIPM}} . \qquad (2)$$

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 the correlations, 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 $\bar{\mu}_{\mathrm{en}}/\rho$, $\bar{g}$ and $\bar{s}_{\mathrm{c,a}}$), as identified in each comparison report for the common measurement equation,

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

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,
$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$	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 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 [5]. Consequently, for comparisons published before this date, the uncertainties have been modified to take this change into account. The uncertainty budget for the BIPM standard is given in the Appendix.

During the past ten 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 [6] 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 additional references given against each value describe the changes. In addition to this, all the comparison results, x_i, in Table 2 differ from the R_{NMI} because the BIPM standard changed in 2007, 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. As a consequence of this decision, the key comparison reference value (KCRV) for each comparison result is unity.

Any change in the absolute value of air kerma as determined by the BIPM standard is subject to approval by the CCRI, and in the past these have been related to changes in the physical constants used in the measurement equation by each NMI. The relative standard uncertainty of the distribution of air-kerma measurements at the BIPM is about 3×10^{-4}. Although the measurements have shown a small drift over the past fifteen years, this drift is halved on using the latest ^{60}Co half-life determination [7]. Repeat calibrations of the BIPM transfer standard type NE 2571 show a relative standard uncertainty of the distribution of the calibration coefficients of 2×10^{-4} over several years.

As a consequence of this choice of x_{R}, 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.

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 a change in the correction factor k_{wall} at the level of two standard uncertainties, there has been a more significant change in k_{an} [8]. The BIPM has also recently produced a variable-volume cavity standard to determine the air-kerma rate differentially [9]. This experiment has contributed to a new estimation for the volume of the BIPM standard and the CCRI, in May 2007, approved an overall change in the BIPM air-kerma standard by a factor of 1.0054. The combined relative standard uncertainty on the air-kerma determination is now evaluated as 1.5×10^{-3}. The small change to the BIPM uncertainty does not significantly affect the comparison result, which takes into account the

Table 2 Revised data set for published BIPM key comparisons of air kerma in ^{60}Co

NMI / *i*	**Year**	$u_{K,\mathrm{NMI}}$	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		
BEV	1995	0.0041	1.0109	[10, 11]	1.0055	0.0025	CC01 (two chambers)
NMi	1996	0.0023	1.0033	[12, 13]	0.9979	0.0020	spherical chamber[2]
NIST	1996	0.0031	1.0085	[14 to 16]	1.0031	0.0033	six spherical chambers[2]
ARPANSA	1997	0.0031	1.0028	[17]	0.9974	0.0032	BIPM type parallel plate chamber[2]
VNIIM	1997	0.0041	1.0020	[18, 19]	1.0062	0.0026	two cylindrical chambers[2]
NRC	1998	0.0028	1.0079	[20, 21]	1.0025	0.0027	"C3" cylindrical chamber[2]
PTB	2000	0.0019	1.0099	[22]	1.0045	0.0018	one parallel plate and two cylindrical chambers
SMU	2000	0.0027	1.0033	[23][3]	0.9979	0.0027	ND1005/A
ZMDM	2001	0.0019	1.0079	[24]	1.0025	0.0018	ND1005/A
NMIJ	2001	0.0024	1.0072	[25]	1.0018	0.0024	two cylindrical chambers
NCM	2002	0.0019	1.0117	[26]	1.0063	0.0019	ND1005/A
LNMRI	2003	0.0039	1.0007	[27][3]	0.9953	0.0022	CC01
LNE-LNHB	2003	0.0036	1.0035	[28]	0.9981	0.0027	cylindro-spherical chamber
ENEA	2004	0.0025	1.0051	[29]	0.9997	0.0026	cylindrical chamber
MKEH	2006	0.0021	1.0109	[30]	1.0055	0.0022	ND 1005 (two chambers)

[1] described in the reference for R_{NMI}
[2] transfer standard(s) were used for the comparison
[3] currently calculating the wall correction factors for their standard.

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 [3] and is reflected in the revised comparison results, x_i, given in Table 2 and in the degrees of equivalence presented in Table 3.

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 [2]. 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. 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 KCRV, $x_R = 1$

The degree of equivalence of a particular NMI, i, with the key comparison reference value is defined as the difference,

$$D_i = x_i - x_R\,, \qquad (4)$$

and the expanded uncertainty (coverage factor $k = 2$) of this difference, U_i, known as the equivalence uncertainty, where

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

The u_i for each NMI, i, is described in Section 3 and taken from Table 2, all correlation with the BIPM evaluation having already been taken into account. Table 3 gives the values for D_i and U_i for each NMI, using (4) and (5), and forms the basis of the entries in CIPM MRA Appendix B – Key Comparison Data Base (KCDB). These data are presented graphically in Figure 1.

Table 3 also includes the correlated uncertainties discussed in the following section when considering pair-wise degrees of equivalence.

Comparison of any pair of NMIs

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

$$D_{ij} = D_i - D_j\ , \qquad (6)$$

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

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

The various components of (7) are described in the following paragraphs.

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 uncertainties related to the BIPM measuring instrument, $u_{BIPM,instr}$, must also be removed (see Appendix).

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, $u_{k,corr}$. 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 has been used for the f_k for the Type B component of the uncertainties, as approved by the CCRI(I) in May 2007, and which are shown in the final column of Table 3. 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 complete matrix of degrees of equivalence is given in Table 4 in the form as it appears in the KCDB.

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

NMI	Year	$D_{NMI} \times 10^{-2}$	$U_{NMI} \times 10^{-2}$	$u_i(k_{wall,MC})$ Type B $\times 10^{-2}$
BEV	1995	0.55	0.50	0.06
NMi	1996	-0.21	0.40	0.08
NIST	1996	0.31	0.66	0.17
ARPANSA	1997	-0.26	0.64	–
VNIIM	1997	0.62	0.52	0.07
NRC	1998	0.25	0.54	0.10
PTB	2000	0.45	0.36	0.05
SMU	2000	-0.21	0.54	0.10
SZMDM	2001	0.25	0.36	0.08
NMIJ	2001	0.18	0.48	0.10
NCM	2002	0.63	0.38	0.08
LNMRI	2003	-0.47	0.44	–
LNE-LNHB	2003	-0.19	0.54	0.21
ENEA	2004	-0.03	0.52	0.10
MKEH	2006	0.55	0.42	0.07

6. Comments on future comparisons

The CCRI(I) has agreed that comparisons should be repeated at least every ten years, 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 includes an update of the matrix 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. For example, the NMi undertook an indirect comparison in 2005, during a comparison for absorbed dose to water at the BIPM, to update their 1996 result for air kerma and this report is in progress. New comparison reports are in hand for the NIM (China), the GUM (Poland), the ITN (Portugal) and the NPL (UK).

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).

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 ^{60}Co gamma-ray beams, BIPM.RI(I)-K1, currently comprises fifteen results. These have been analysed with respect to the KCRV and with respect to each other, 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 may be updated and new results added when NMIs make air-kerma comparisons at the BIPM.

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Table 4 Introductory text and degrees of equivalence for air kerma in ^{60}Co

Key comparison BIPM.RI(I)-K1

MEASURAND: **Air kerma relative to the BIPM evaluation**

Key comparison reference value: x_R is unity

The degree of equivalence of each laboratory with respect to the reference value is given by a pair of terms:
$D_i = (x_i - x_R)$ and U_i, its expanded uncertainty (k = 2), both expressed as ratios.
$U_i = 2u_i$.

The degree of equivalence between two laboratories is given by a pair of terms:
$D_{ij} = D_i - D_j = (x_i - x_j)$ and U_{ij}, its expanded uncertainty (k = 2), both expressed as ratios.
The approximation $U_{ij} \sim 2(u_i^2 + u_j^2 + 2u_{rep}^2 - 2u_{BIPM,instr}^2 - 0.64(u_{ki}^2 + u_{kj}^2))^{1/2}$ (see section 5 of the Final report) is used.

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Table 4 continued Degrees of equivalence for air kerma in ^{60}Co

Lab *j* ⇒

Lab *i* ⇓	D_i / 10^{-2}	U_i	BEV D_{ij} / 10^{-2}	U_{ij}	NMi D_{ij} / 10^{-2}	U_{ij}	NIST D_{ij} / 10^{-2}	U_{ij}	ARPANSA D_{ij} / 10^{-2}	U_{ij}	VNIIM D_{ij} / 10^{-2}	U_{ij}	NRC D_{ij} / 10^{-2}	U_{ij}	PTB D_{ij} / 10^{-2}	U_{ij}	SMU D_{ij} / 10^{-2}	U_{ij}
BEV	**0.55**	0.50			**0.76**	0.53	**0.24**	0.71	**0.81**	0.75	**-0.07**	0.63	**0.30**	0.64	**0.10**	0.51	**0.76**	0.64
NMi	**-0.21**	0.40	**-0.76**	0.53			**-0.52**	0.63	**0.05**	0.68	**-0.83**	0.55	**-0.46**	0.55	**-0.66**	0.41	**0.00**	0.55
NIST	**0.31**	0.66	**-0.24**	0.71	**0.52**	0.63			**0.57**	0.86	**-0.31**	0.72	**0.06**	0.72	**-0.14**	0.62	**0.52**	0.72
ARPANSA	**-0.26**	0.64	**-0.81**	0.75	**-0.05**	0.68	**-0.57**	0.86			**-0.88**	0.76	**-0.51**	0.77	**-0.71**	0.66	**-0.05**	0.77
VNIIM	**0.62**	0.52	**0.07**	0.63	**0.83**	0.55	**0.31**	0.72	**0.88**	0.76			**0.37**	0.65	**0.17**	0.53	**0.83**	0.65
NRC	**0.25**	0.54	**-0.30**	0.64	**0.46**	0.55	**-0.06**	0.72	**0.51**	0.77	**-0.37**	0.65			**-0.20**	0.54	**0.46**	0.66
PTB	**0.45**	0.36	**-0.10**	0.51	**0.66**	0.41	**0.14**	0.62	**0.71**	0.66	**-0.17**	0.53	**0.20**	0.54			**0.66**	0.54
SMU	**-0.21**	0.54	**-0.76**	0.64	**0.00**	0.55	**-0.52**	0.72	**0.05**	0.77	**-0.83**	0.65	**-0.46**	0.66	**-0.66**	0.54		
ZMDM	**0.25**	0.36	**-0.30**	0.50	**0.46**	0.39	**-0.06**	0.61	**0.51**	0.66	**-0.37**	0.52	**0.00**	0.53	**-0.20**	0.37	**0.46**	0.53
NMIJ	**0.18**	0.48	**-0.37**	0.59	**0.39**	0.50	**-0.13**	0.68	**0.44**	0.73	**-0.44**	0.60	**-0.07**	0.61	**-0.27**	0.47	**0.39**	0.61
NCM	**0.63**	0.38	**0.08**	0.52	**0.84**	0.41	**0.32**	0.62	**0.89**	0.67	**0.01**	0.53	**0.38**	0.54	**0.18**	0.39	**0.84**	0.54
LNMRI	**-0.47**	0.44	**-1.01**	0.58	**-0.26**	0.50	**-0.78**	0.73	**-0.21**	0.71	**-1.09**	0.60	**-0.72**	0.62	**-0.92**	0.47	**-0.26**	0.62
LNE-LNHB	**-0.19**	0.54	**-0.74**	0.56	**0.02**	0.47	**-0.50**	0.66	**0.07**	0.77	**-0.81**	0.58	**-0.44**	0.59	**-0.64**	0.45	**0.02**	0.59
ENEA	**-0.03**	0.52	**-0.58**	0.62	**0.18**	0.53	**-0.34**	0.71	**0.23**	0.76	**-0.65**	0.63	**-0.28**	0.64	**-0.48**	0.52	**0.18**	0.64
MKEH	**0.55**	0.42	**0.00**	0.55	**0.76**	0.45	**0.24**	0.65	**0.81**	0.70	**-0.07**	0.57	**0.30**	0.57	**0.10**	0.43	**0.76**	0.57

. . . . . . continued overleaf

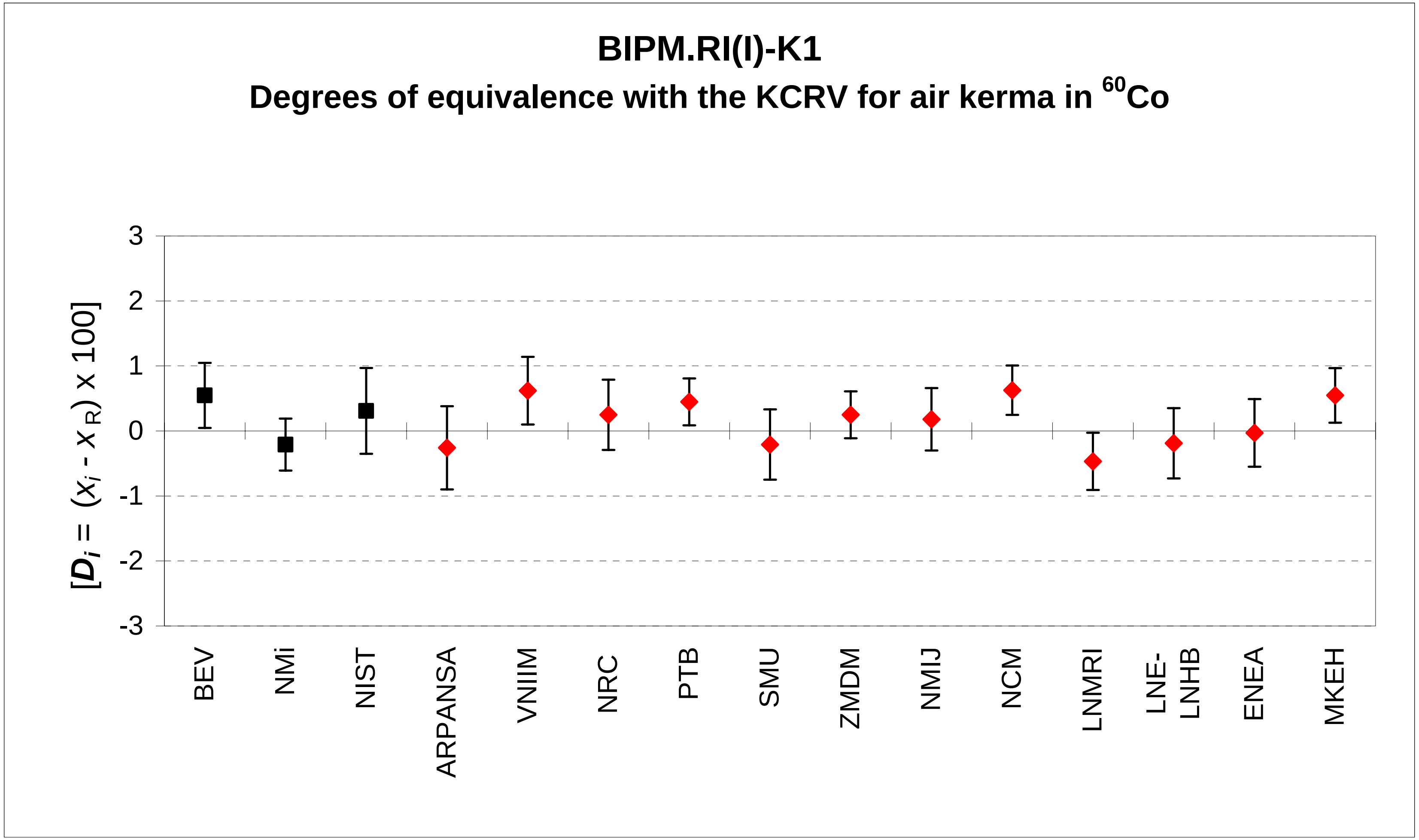
Table 4 continued   Degrees of equivalence for air kerma in ^{60}Co

Lab *j* ⟹

Lab *i* ⇓

			ZMDM		NMIJ		NCM		LNMRI		LNE-LNHB		ENEA		MKEH	
	D_i / 10^{-2}	U_i	D_{ij} / 10^{-2}	U_{ij}	D_{ij} / 10^{-2}	U_{ij}	D_{ij} / 10^{-2}	U_{ij}	D_{ij} / 10^{-2}	U_{ij}	D_{ij} / 10^{-2}	U_{ij}	D_{ij} / 10^{-2}	U_{ij}	D_{ij} / 10^{-3}	U_{ij}
BEV	**0.55**	0.50	**0.30**	0.50	**0.37**	0.59	**-0.08**	0.52	**1.01**	0.58	**0.74**	0.56	**0.58**	0.62	**0.00**	0.55
NMi	**-0.21**	0.40	**-0.46**	0.39	**-0.39**	0.50	**-0.84**	0.41	**0.26**	0.50	**-0.02**	0.47	**-0.18**	0.53	**-0.76**	0.45
NIST	**0.31**	0.66	**0.06**	0.61	**0.13**	0.68	**-0.32**	0.62	**0.78**	0.73	**0.50**	0.66	**0.34**	0.71	**-0.24**	0.65
ARPANSA	**-0.26**	0.64	**-0.51**	0.66	**-0.44**	0.73	**-0.89**	0.67	**0.21**	0.71	**-0.07**	0.77	**-0.23**	0.76	**-0.81**	0.70
VNIIM	**0.62**	0.52	**0.37**	0.52	**0.44**	0.60	**-0.01**	0.53	**1.09**	0.60	**0.81**	0.58	**0.65**	0.63	**0.07**	0.57
NRC	**0.25**	0.54	**0.00**	0.53	**0.07**	0.61	**-0.38**	0.54	**0.72**	0.62	**0.44**	0.59	**0.28**	0.64	**-0.30**	0.57
PTB	**0.45**	0.36	**0.20**	0.37	**0.27**	0.47	**-0.18**	0.39	**0.92**	0.47	**0.64**	0.45	**0.48**	0.52	**-0.10**	0.43
SMU	**-0.21**	0.54	**-0.46**	0.53	**-0.39**	0.61	**-0.84**	0.54	**0.26**	0.62	**-0.02**	0.59	**-0.18**	0.64	**-0.76**	0.57
ZMDM	**0.25**	0.36			**0.07**	0.46	**-0.38**	0.37	**0.72**	0.47	**0.44**	0.44	**0.28**	0.51	**-0.30**	0.42
NMIJ	**0.18**	0.48	**-0.07**	0.46			**-0.45**	0.48	**0.65**	0.57	**0.37**	0.53	**0.21**	0.59	**-0.37**	0.52
NCM	**0.63**	0.38	**0.38**	0.37	**0.45**	0.48			**1.09**	0.49	**0.82**	0.45	**0.66**	0.52	**0.08**	0.44
LNMRI	**-0.47**	0.44	**-0.72**	0.47	**-0.65**	0.57	**-1.09**	0.49			**-0.28**	0.62	**-0.44**	0.60	**-1.01**	0.52
LNE-LNHB	**-0.19**	0.54	**-0.44**	0.44	**-0.37**	0.53	**-0.82**	0.45	**0.28**	0.62			**-0.16**	0.57	**-0.74**	0.49
ENEA	**-0.03**	0.52	**-0.28**	0.51	**-0.21**	0.59	**-0.66**	0.52	**0.44**	0.60	**0.16**	0.57			**-0.58**	0.55
MKEH	**0.55**	0.42	**0.30**	0.42	**0.37**	0.52	**-0.08**	0.44	**1.01**	0.52	**0.74**	0.49	**0.58**	0.55		

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



The black squares indicate results that are more than ten years old.

APPENDIX

Physical constants and correction factors used in the BIPM determination of the air-kerma rate (*pre* 01/11/2007), and their estimated relative standard uncertainties [4]

Physical constant		value	Relative standard uncertainty[(1)]		
			100 s_i		100 u_i
dry air density /(kg m^{-3}) (273.15 K, 101.325 kPa)		1.2930	–		0.01
$(\bar{\mu}_{en}/\rho)_{a,c}$		0.9985	–		0.05
stopping power ratio $\bar{s}_{c,a}$		1.0010	–	}	0.11[(2)]
W/e	/(J C^{-1})	33.97	–		
g	electron kinetic energy lost in radiative processes in air	0.0032	–		0.02
Correction factor					
k_h	humidity	0.9970	–		0.03
[the following parameters are all specific to the BIPM instrument and give the combined value $u_{BIPM,instr}$ = 0.12]					
k_s	ion recombination	1.0015	0.01		0.01
k_{st}	stem scattering	1.0000	0.01		–
k_{at}	wall attenuation	1.0398	0.01		0.04
k_{CEP}	mean origin of electrons	0.9922	–		0.01
k_{sc}	wall scattering	0.9720	0.01		0.07
k_{an}	axial non-uniformity	0.9964	–		0.07
k_{rn}	radial non-uniformity	1.0016	0.01		0.02
Measurement of $I/v\rho$					
v	volume /cm^3	6.8028[(3)]	0.01		0.03
I	ionization current correction concerning ρ (temperature, pressure, air compressibility)		–		0.02
	short-term reproducibility (including positioning and current measurement)[(4)]		0.01		–

Relative standard uncertainty in $\dot{K}_{BIPM}$

quadratic sum	0.03		0.17
combined uncertainty		0.17	

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

(2) the uncertainty of the product of the stopping power ratio and W/e was agreed by the CCRI in 1999 [5]

(3) standard CH5-1

(4) over a period of 3 months. The long-term reproducibility over a period of 15 years, u_{rep} is 0.0004.