Comparison of the standards for air kerma of the ITN (Portugal) and the BIPM for ^{60}Co γ-rays

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Abstract

A first comparison of the standards for air kerma of the Instituto Tecnológico e Nuclear (ITN), Portugal and of the Bureau International des Poids et Mesures (BIPM) has been carried out in ^{60}Co radiation under the auspices of the key comparison BIPM.RI(I)-K1. The comparison result, expressed as a ratio of the ITN standard and the BIPM standard, is 1.0015 (0.0018). The degrees of equivalence between the ITN and the other participants in the key comparison have been calculated and the results are presented in the form of a matrix. A graphical presentation is also given.

1. Introduction

A new comparison of the standards for air kerma of the Instituto Tecnológico e Nuclear (ITN), Portugal and of the Bureau International des Poids et Mesures (BIPM), was carried out at the BIPM in ^{60}Co radiation in June 2005. In this comparison the ITN used their primary standard graphite-walled cavity ionization chamber constructed by the Österreichisches Forschungszentrum (ÖFS), Austria, as described in section 2 of this report. The BIPM air kerma standard is described in [1] and the results of recent evaluations of calculated correction factors and new volume estimations are presented in [2]. An indirect comparison using an ITN transfer chamber was also made.

2. Determination of the air kerma

The air kerma rate is determined by

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

where

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

The main characteristics of the ITN standard are given in Table 1.

Table 1. Characteristics of the ITN standard for air kerma

ITN cylindrical graphite cavity standard		CCO1-134
		Nominal value / mm
Chamber	Outer height	19
	Outer diameter	18.92
	Inner height	11
	Inner diameter	10.97
	Wall thickness	3.98
Electrode	Diameter	2.015
	Height	8.970
Volume	Air cavity[(1)]	1.0161 cm^3
Wall	Materials	High purity moulded graphite ATJ
	Density	1.80 $g{\cdot}cm^{-3}$
	Impurity	$< 8 \times 10^{-4}$
Insulator		PTFE Teflon
Applied voltage	Both polarities[(2)]	250 V

(1) measured by the Bundesamt für Eich-und Vermessungswesen (BEV), Austria

(2) measurements at the ITN are made using positive polarity with an applied correction $k_{\text{pol}} = 0.9990$ (1).

3. Experimental results

The air kerma is determined at the BIPM under the following conditions :
- the distance from source to reference plane is 1 m;
- the field size in air at the reference plane is 10 cm × 10 cm, the photon fluence rate at the centre of each side of the square being 50 % of the photon fluence rate at the centre.

Data concerning the various factors entering in the determination of air kerma in the ^{60}Co beam using the primary standards of the ITN and of the BIPM are shown in Table 2. They include the physical constants [3], the correction factors entering in (1), the volume of each chamber cavity and the associated uncertainties.

Table 2. Physical constants and correction factors entering in the 2006 determination of air kerma and their estimated relative uncertainties in the BIPM ^{60}Co Picker beam

	BIPM values	Relative [(a)] uncertainty		ITN values	Relative [(a)] uncertainty		R_K relative [(a)] uncertainty	
		100 s_i	100 u_i		100 s_i	100 u_i	100 s_i	100 u_i
Physical constants								
dry air density / kg·m^{-3} [(b)]	1.2930	–	0.01	1.2930	–	0.01	–	–
$(\mu_{en}/\rho)_{a,c}$	0.9985	–	0.05	0.9985	–	0.05	–	–
$\bar{s}_{c,a}$	1.0010	–	0.11[(c)]	1.0010	–	0.11[(c)]	–	–
W/e	33.97	–		33.97	–		–	–
$\bar{g}$	0.0032	–	0.02	0.0032	–	0.02	–	–
Correction factors								
k_s recombination loss	1.0015[(d)]	<0.01	0.01	1.0019[(d)]	<0.01	0.01	0.01	0.01
k_h humidity	0.9970	–	0.03	0.9970	–	0.03	–	–
k_{st} stem scattering	1.0000	0.01	–	0.9997	0.01	0.01	0.01	0.01
k_{att} wall attenuation	1.0398	0.01	0.04					
k_{sc} wall scattering	0.9720	0.01	0.07	1.0216[(e)]	0.01	0.05	0.02	0.10
k_{CEP} mean origin of electrons	0.9922	–	0.01					
k_{an} axial non-uniformity	0.9964	–	0.07	1.0000[(f)]	0.02	0.03	0.02	0.08
k_{rn} radial non-uniformity	1.0016[(g)]	0.01	0.04	1.0003[(g)]	0.01	0.02	0.01	0.04
Measurement of $I/V\rho$								
V volume / cm^3	6.8028	0.01	0.03	1.0161	–	0.10[(h)]	0.01	0.10
I ionization current / pA [(b)]		0.01	0.02		0.01	0.04	0.01	0.04
Uncertainty								
quadratic summation		0.03	0.17		0.03	0.18	0.04	0.17
combined uncertainty		**0.18**			**0.18**		**0.18**	

[(a)] 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.

[(b)] At 101.325 kPa and 273.15 K.

[(c)] Combined uncertainty for the product of stopping power ratio and W/e

[(d)] This correction is 1.0019 (1) for the BIPM standard and 1.0022 (1) for the ITN standard in the CIS Bio beam (see Table 4)

[(e)] Value for the CIS Bio beam is 1.0220 (4) taken from [4] and scaled for wall thickness (3.98 mm) and graphite density (1.80 g cm^{-3}). The lower value for the Picker beam results from the lower scatter component.

[(f)] Taken from [5].

[(g)] The radial non-uniformity correction is 1.0015 (2) for the BIPM standard and 1.0002 (1) for the ITN standard in the CIS Bio beam (see Table 5).

[(h)] as determined through dimensional measurements by the BEV

For the BIPM standard in the Picker beam, these data are taken from [6]. Also shown in Table 2 are the relative uncertainties in the ratio

$$R_K = \dot{K}_{\mathrm{ITN}} / \dot{K}_{\mathrm{BIPM}} \qquad (2)$$

Two different ^{60}Co beams were used at BIPM (the old Picker beam and the new CIS Bio beam). Table 3 gives the characteristics of the ITN ^{60}Co beam and those at the BIPM.

Table 3. Parameters of the ^{60}Co beams at the ITN and the BIPM

^{60}Co beam	Nominal source activity at 01/01/04	Source diameter and length	Scatter contribution/ energy fluence	Field size at 1 m
ITN source	50 TBq	20 mm diameter	19 % [7]	10 cm × 10 cm
BIPM Picker	23 TBq	20 mm × 5.6 mm	14 %	10 cm × 10 cm
BIPM CIS Bio	175 TBq	20 mm × 14 mm	21 %	10 cm × 10 cm

The correction factor for the ITN standard for losses due to ion recombination was determined at the BIPM during the present comparison using the method of Niatel as described in [8]. The ratio of the ionization currents with applied voltages of 250 V and 80 V (using both polarities) was measured for four different air kerma rates (using both ^{60}Co beams and brass filters, as recombination is insensitive to the spectrum). Applying the method of Niatel and the notation in [8],

$$I_V / I_{V/n} = 1 + (n-1)\, A/V + (n^2 - 1) m^2 (g/V^2) I_V \qquad (3)$$

where,

I_v is the uncorrected, measured current at the normally applied voltage, V
n is any number, not necessarily an integer
A is a constant dependent on the chamber type
m^2 is the volume recombination parameter for ionization chambers
g is the geometrical factor dependent on the chamber shape

Figure 1 illustrates the measurements made for n = 250/80 = 3.125.

The recombination correction k_s can be expressed as

$$k_s = 1 + k_{\mathrm{init}} + k_{\mathrm{vol}} I_V \qquad (4)$$

and Table 4 gives the values and uncertainties for k_{init} and k_{vol}. The current, I_V, is the measured current uncorrected for decay and not normalized for temperature and pressure. Consequently, a correction factor of 1.0019 (1) for ion recombination at 250 V was applied to the ITN standard in the BIPM Picker beam as given in Table 2. The appropriate value in the CIS Bio beam is 1.0022 (1).

The correction for the stem scatter was measured at the BIPM as 0.9997 (1). The value measured at the ITN is in agreement as 1.0000 (3).

The effect of attenuation and scatter in the graphite walls of the ITN CC01 chamber was determined by Monte Carlo calculation [4] scaled for the graphite walls of 3.98 mm thickness and 1.80 g cm^{-3} density, and adjusted from the 21 % scatter to the 14 % scatter in the BIPM Picker beam.

Figure 1. Graph of recombination measurements made at the BIPM

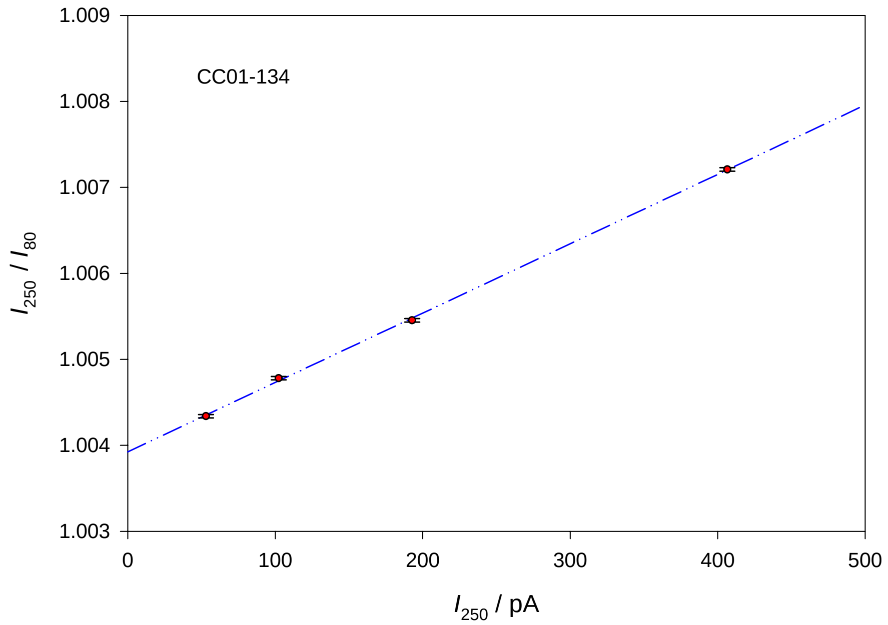

Table 4. Results of ion recombination measurements made at the BIPM for the ITN standard

ITN Standard	CC01-134	Standard uncertainty
Initial recombination and diffusion, k_{init}	18.5×10^{-4}	5×10^{-5}
Volume recombination factor, k_{vol}, per measured current / pA	9.2×10^{-7}	5×10^{-8}
k_s in the BIPM Picker beam, BIPM values	1.0019	1×10^{-4}
k_s in the BIPM CIS Bio beam, BIPM values	1.0022	1×10^{-4}

The axial non-uniformity correction for the ITN standard was taken from [5] as being very close to unity. The correction factor k_{rn} for the radial non-uniformity of the BIPM beam over the cross-section of the ITN standard is estimated to be 1.0003 (1) in the Picker beam and 1.0002 (1) in the CIS Bio beam [9].

The polarity correction determined at the ITN for the primary standard was 0.9990 (1). A similar value of 0.9994 (1) was determined at the BIPM for this chamber. However, as all measurements were made with both polarities at the BIPM, no explicit corrections for polarity were applied.

The ITN primary standard chamber was set up and measured in each of the BIPM beams on at three separate occasions. The results were reproducible to better than 10^{-4}.

The evaluation of the air kerma rate at the BIPM measured with the ITN primary standard is obtained from (1) using the data in Table 2 and the mean measured ionization current in each of the BIPM beams. The correction factors that are different for the two standards in each of the two beams are summarized in Table 5.

Table 5. Correction factors that differ in the two BIPM beams

Correction factor	Picker beam		CIS Bio beam	
	ITN standard	BIPM standard	ITN standard	BIPM standard
k_s	1.0019 (1)	1.0015 (1)	1.0022 (1)	1.0019 (1)
k_{wall}	1.0216 (5)	1.0028 (8)	1.0220 (4)	1.0028 (8)
k_{rn}	1.0003 (2)	1.0016 (4)	1.0002 (1)	1.0015 (2)

The experimental results for the comparison are given in Table 6. The $\dot{K}_{BIPM}$ value is taken from the mean of the four measurements made around the period of the comparison for the Picker beam, and the overall mean over the two years since its installation in 2003 for the CIS Bio beam. Both air kerma rates were verified immediately before the comparison measurements. The $\dot{K}_{BIPM}$ values refer to an evacuated path length between source and standard and are given at the reference date of 2005-01-01, 0 h UTC. The half-life of ^{60}Co was taken as 1925.5 days ($u = 0.5$ days) [10].

The mean ratio of the values of the air kerma rate determined by the ITN and the BIPM standards in the Picker beam taken from Table 6 is 1.0069 with a combined standard uncertainty, u_c, of 0.0019. Some of the uncertainties in $\dot{K}$ that appear in both the BIPM and the ITN determinations (such as air density, W/e, μ_{en}/ρ, $\bar{g}$, $\bar{s}_{c,a}$ and k_h) cancel when evaluating the uncertainty of R_K as given in Table 2.

An indirect comparison of the standards was also made as the ITN had brought a transfer chamber, a PTW chamber TM30001 serial number 1576. The chamber was calibrated at the ITN before and after the comparison at the BIPM using a different electrometer on each occasion. Measurements using the two electrometers differed by 3.8×10^{-3} however the calibration coefficients were in agreement when a given electrometer was used for both the ITN standard and the transfer chamber. The mean value of the calibration coefficient measured before and after the comparison at the BIPM, $N_K = 49.28$ (11) Gy μC^{-1}, is compared with that measured at the BIPM of 48.87 (9) Gy μC^{-1}, to give a ratio, R_K , of 1.0084 (19). This is in agreement with the experimental direct comparison within the calibration uncertainties, each result being prior to the later changes made to the BIPM standard as discussed in section 4. The stability of the transfer chamber at the BIPM was better than 10^{-4}. The uncertainty budget is given in Table 7. Note that at the ITN, polarity corrections and field dimension corrections are used for the primary standard and the associated combined uncertainty for these two factors is 4×10^{-4}.

Table 6. The experimental results from the ITN standard in the two BIPM beams prior to the implementation of the changes to the BIPM standard in 2007

ITN standard	Picker beam		CIS Bio beam		Ratio of the Picker to the CIS Bio result [(1)]
Date	I_{ITN} / pA	$\dot{K}_{\mathrm{ITN}}$ / mGy s^{-1}	I_{ITN} /pA	$\dot{K}_{\mathrm{ITN}}$ / mGy s^{-1}	
20/06/05	61.3988	–	–	–	–
21/06/05	–	–	468.617	–	–
22/06/05	61.3977	–	468.601	–	–
27/06/05	61.3939	–	–	–	
Mean values	61.3968	1.624 34	468.609	12.4053	13.094×10^{-2}
$\dot{K}_{\mathrm{BIPM}}$ values	–	1.613 17	–	12.3230	13.091×10^{-2}

[(1)] This difference of 3×10^{-4} has been resolved by the application of an improved method to evaluate the radial non-uniformity correction in the Picker beam for the BIPM standard [2].

Table 7. Uncertainty budget for the indirect comparison

	ITN		BIPM		ITN/BIPM	
Component	100 s_i	100 u_i	100 s_i	100 u_i	100 s_i	100 u_i
Air kerma	0.04	0.19	0.03	0.17	0.04	0.17
Current measurement	0.02	0.03	0.01	0.02	0.02	0.04
Distance	0.05	–	0.01	–	0.05	–
Radiation field	–	0.04	–	–	–	0.04
Quadratic summation	0.07	0.20	0.03	0.17	0.07	0.18
Combined uncertainty	0.21		0.17		0.19	

4. Discussion

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 Consultative Committee for Ionizing Radiation (CCRI) [11] 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. All the previous results of air kerma comparisons in ^{60}Co at the BIPM have been re-evaluated [12], taking into account the effect of changes being made in national standards following the recommendations of the CCRI and of changes to the BIPM standard itself [2]. In May 2007, the CCRI approved an overall change in the BIPM air- kerma in the Picker beam 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. Note that the values in Table 6 for the BIPM standard in the CIS Bio beam are based on the pre Monte Carlo corrections as for the Picker beam. For the CIS Bio beam, the correct evaluation of air kerma requires the application of a factor 1.0051 to the BIPM value in Table 6; this factor differs by 3 parts in 10^4 from that applied to the Picker beam for the reason outlined in the footnote to Table 6. The final results of the comparison are given in Table 8.

Table 8. Final result of the ITN/BIPM comparison for standards of ^{60}Co air kerma

BIPM beam	$\dot{K}_{\mathrm{ITN}}$ / mGy s^{-1}	$\dot{K}_{\mathrm{BIPM}}$ / mGy s^{-1}	R_K	u_c
Picker	1.624 34	1.621 88	1.0015	0.0018
CIS Bio	12.4053	12.3858	1.0016	0.0018

5. 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} (K_{B}), is taken as the key comparison reference value (KCRV), for each of the CCRI radiation qualities. 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 $D_i = (K_i - K_{\mathrm{B}i})/ K_{\mathrm{B}i})) = R_{Ki} - 1$ (5)

and the expanded uncertainty ($k = 2$) of this difference,

$$U_i = 2\ u_i. \qquad (6)$$

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

Table 9 gives the values for D_i and U_i for each NMI, i taken from [12] and this report, using (5) and (6), and forms the basis of the entries in the KCDB of the CIPM MRA. These data are presented graphically in Figure 2 where the black squares indicate results that date prior to 1998. The results of a recently published SIM comparison are also presented [13].

Comparison of any two NMIs with each other

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

$$D_{ij} = D_i - D_j = R_i - R_j \qquad (7)$$

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

$$u_{ij}^{\;2} = u_{c,i}^{\;2} + u_{c,j}^{\;2} - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_i^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_j^2 \qquad (8)$$

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. For example a number of national primary standards have a similar shape and size to the ITN standard [12] for which the wall correction factors are strongly correlated. As yet, no correlation has been assumed for the volume estimations of identically shaped standards

The results for D_i and U_i and those for D_{ij} and U_{ij} are given in Table 9 in the format in which they appear in the key comparison database. Note that the data presented in the table, while correct at the time of publication of the present report, becomes out-of-date as NMIs make new comparisons. The formal results under the CIPM MRA [14] are those available in the key comparison database.

6. Conclusion

The ITN standard for air kerma in ^{60}Co gamma radiation compared with the present BIPM air kerma standard gives a comparison result of 1.0015 (0.0018). This compares favourably with other primary standards for which the wall correction factor has been calculated using Monte Carlo methods.

All the comparison results of the national metrology institutes (NMIs) and designated laboratories are used as the basis of the entries in the KCDB set up under the CIPM MRA to which the comparison result of the ITN has now been added.

Figure 2. **Graph of degrees of equivalence with the KCRV**

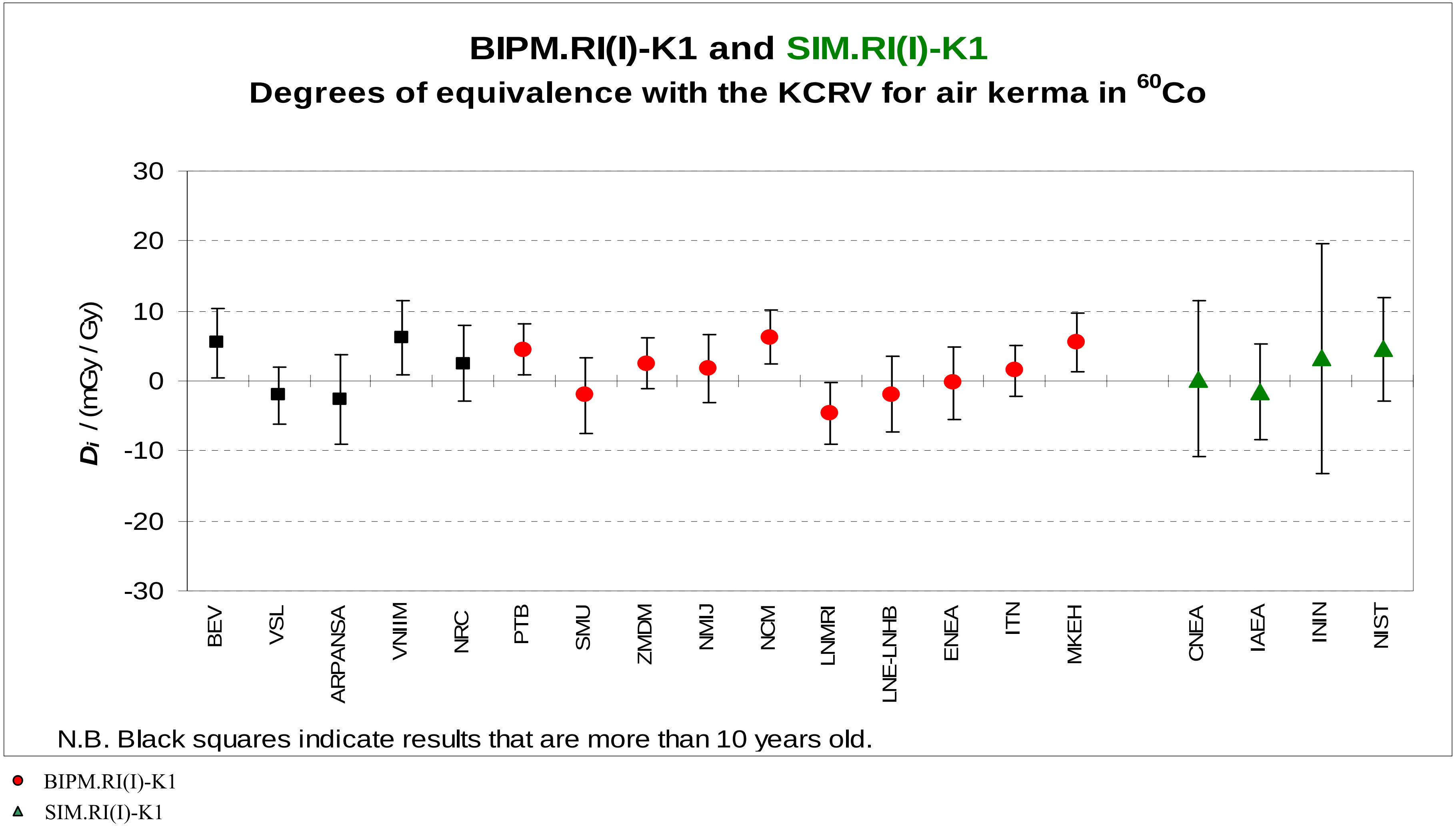

Table 9. Degrees of equivalence with the BIPM.RI(I)-K1 and SIM.RI(I)-K1 comparisons for the ITN participation

Lab i ⇩	D_i	U_i	Lab j: ITN D_{ij}	U_{ij}
	/ (mGy/Gy)		/ (mGy/Gy)	
BEV	**5.5**	5.0	**4.0**	4.9
VSL	**-2.1**	4.0	**-3.6**	3.8
ARPANSA	**-2.6**	6.4	**-4.1**	6.6
VNIIM	**6.2**	5.2	**4.7**	5.1
NRC	**2.5**	5.4	**1.0**	5.2
PTB	**4.5**	3.6	**3.0**	3.5
SMU	**-2.1**	5.4	**-3.6**	5.2
ZMDM	**2.5**	3.6	**1.0**	3.4
NMIJ	**1.8**	4.8	**0.3**	4.5
NCM	**6.3**	3.8	**4.8**	3.6
LNMRI	**-4.7**	4.4	**-6.2**	4.7
LNE-LNHB	**-1.9**	5.4	**-3.4**	4.2
ENEA	**-0.3**	5.2	**-1.8**	5.0
ITN	**1.5**	3.6		
MKEH	**5.5**	4.2	**4.0**	4.1
CNEA	**0.3**	11.2	**-1.2**	11.3
IAEA	**-1.6**	6.8	**-3.1**	7.1
ININ	**3.2**	16.4	**1.7**	16.6
NIST	**4.6**	7.4	**3.1**	7.0

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