Comparison of the standards for air kerma of the ITN (Portugal) and the BIPM for ^{137}Cs γ-rays

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

J. Cardoso and C. Oliveira
Instituto Tecnológico e Nuclear
Unidade de Protecção e Segurança Radiológica
Laboratório de Metrologia das Radiações Ionizantes
Estrada Nacional 10, Apartado 21, 2686-953 Sacavém
Portugal

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 ^{137}Cs gamma radiation. The comparison result, expressed as a ratio of the ITN standard and the recently re-evaluated BIPM standard, is 1.0013 (0.0021).

1. Introduction

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), was carried out at the BIPM in the ^{137}Cs gamma radiation beam in July 2008.

In this comparison the ITN used their primary standard graphite-cavity ionization chamber constructed by the Österreichisches Forschungszentrum (ÖFS), Austria. Some details regarding the ITN primary standard are given in Table 1. It was also used in a ^{60}Co air kerma comparison at the BIPM [1].

The BIPM air kerma standard is described in [2, 3] and the results of recent evaluations of calculated correction factors and new volume estimations are presented in [4].

Table 1. Characteristics of the ITN cavity standard for air kerma

ITN 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_{pol} = 0.9994 (2).

2. Experimental conditions

The ITN primary standard was positioned at 1 m from the source in the BIPM ^{137}Cs radiation beam. The reference conditions of measurement used at the BIPM [5] and at the ITN are given in Table 2.

At the BIPM, a thermally insulating cabin was used to minimize temperature fluctuations, and during a series of measurements in the ^{137}Cs beam the air temperature was stable to better than 0.06 °C.

Table 2. Measurement conditions for ^{137}Cs at the BIPM during the comparison and the usual conditions at the ITN

Parameter	BIPM	ITN
Position of the centre of the standard chamber	1 m from the source	1 m from the source
Beam cross-section	11 cm ϕ (small collimator) 20 cm ϕ (large collimator)	17 cm ϕ
Nominal $\dot{K}$	16 µGy s^{-1}	95 µGy s^{-1} (14 July 2008)
Incident scatter in terms of energy fluence	30 %	31 %
Humidity range /%	50 ± 5	50 ± 10
Temperature / °C	20.2 to 20.5	20.4 to 20.8
Pressure / kPa	98.9 to 102.1	101.2 to 102.6
Measurement of charge	Keithley electrometer	PTW UNIDOS electrometer

3. Determination of the air kerma

The air kerma rate is determined by

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

where

I/m	is the ionization current per 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,
$(\mu_{\text{en}}/\rho)_{\text{a,c}}$	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 values for the physical data used in (1) are consistent with the CCEMRI(I) 1985 recommendations [6] and the values for the correction factors needed for ^{137}Cs radiation are shown in Table 3 for the BIPM and the ITN standards at the BIPM, together with their associated uncertainties.

For the BIPM standard, these data are taken from [4]. The correction factors for the ITN standard at the BIPM are described in section 4.

The comparison result is given by

$$R_{\dot{K}} = \dot{K}_{\text{ITN}} / \dot{K}_{\text{BIPM}}, \tag{2}$$

where $\dot{K}$ is the value of the air kerma rate at the BIPM measured by the ITN and BIPM standards, respectively. The relative uncertainties in the ratio R_K are also shown in Table 3.

4. Correction factors for the ITN standard

Some of the correction factors applied to the air kerma rate measurement made with the ITN standard at the BIPM, were determined previously at the ITN under the reference conditions listed in Table 2.

Attenuation and scattering in the chamber wall (k_{wall}) and axial non-uniformity (k_{an})

The effect of attenuation and scatter in the graphite walls of the ITN CC01 chamber and the axial non-uniformity correction were determined by Monte Carlo calculation, taken from [7] and [8], respectively. The Type B uncertainty includes a contribution considering the different graphite density.

Scatter from the stem (k_{st})

The correction for the stem scatter was measured at the BIPM as 0.9998 (2). The value measured at the ITN is in agreement as 0.9999 (4).

Radial non-uniformity of the beam (k_{rn})

The correction factor k_{rn} for the radial non-uniformity of the BIPM beam over the cross-section of the ITN standard is estimated from the measured beam profile in the radial direction [3]; its numerical value is 1.0004 (1) and 1.0002 (1) for the small and the large field, respectively.

Table 3. Physical constants and correction factors entering in the determination of air kerma and their estimated relative uncertainties in the BIPM ^{137}Cs beam

	BIPM			ITN			R_K	
	values	uncertainty [(a)]		values	uncertainty [(a)]		uncertainty [(a)]	
		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	–	–
$(\mu_{en}/\rho)_{a,c}$	0.9990	–	0.05	0.9990	–	0.05	–	–
$\bar{s}_{c,a}$	1.0104	–	0.11$^{(c)}$	1.0101	–	0.11$^{(c)}$	–	–
W/e	33.97	–		33.97	–		–	–
$\bar{g}$	0.0012	–	0.02	0.0012	–	0.02	–	–
Correction factors								
k_s recombination loss (d)	1.0018	0.01	0.02	1.0018	0.01	0.02	0.01	–
k_h humidity	0.9970	–	0.03	0.9970	–	0.03	–	–
k_{st} stem scattering	0.9998	0.01	–	0.9998	0.02	0.01	0.02	0.01
k_{wall} wall attenuation and scattering	1.0002	0.01	(e)	1.0291	–	0.06		0.06
k_{an} axial non-uniformity	1.0018	–	0.04	1.000	–	0.10		0.11
k_{rn} radial non-uniformity (f)	1.0070	0.01	0.10	1.0004	0.01	0.02	0.01	0.10
Measurement of $I/V\rho$								
V volume / cm^3	6.8283	–	0.08	1.0161	–	0.10		0.13
I ionization current (b)		0.02	0.02		0.02	0.02	0.03	
I_{leak} leakage current						0.03		0.03
Uncertainty								
quadratic summation		0.03	0.19		0.03	0.20	0.04	0.21
combined uncertainty		**0.19**			**0.21**		**0.21**	

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

(b) At 101 325 Pa and 273.15 K

(c) Combined uncertainty for the product of $\bar{s}_{c,a}$ and W/e

(d) BIPM determination for the ITN standard

(e) Major uncertainty component is included in the uncertainty of the volume estimation of the standard

(f) k_{rn} for the small field; values for the large field are 1.0011 and 1.0002 for the BIPM and ITN standards, respectively with the same uncertainties as for the small field

Polarity correction (k_{pol})

The polarity correction determined at the ITN for the primary standard was 0.9994 (1). A value of 0.9985 (2) was determined at the BIPM for this chamber. However, as all measurements were made with both polarities at the BIPM, no corrections for this effect were applied.

Recombination loss (k_s)

The correction factor for the ITN standard for losses due to ion recombination was determined at the BIPM during the ^{60}Co comparison made in 2005 [1] using the method of Niatel as described in [9]. As the ion recombination does not depend on the photon energy, the same values for k_{init} and k_{vol} from [1] were used in the present comparison. Table 4 gives these values and their uncertainties. Thus, using the measured current uncorrected for decay and not normalized for temperature and pressure, a correction factor of 1.0018 (1) for ion recombination at 250 V was applied to the ITN standard in the BIPM ^{137}Cs beam.

Table 4. Results of ion recombination measurements made at the BIPM for the ITN standard during the ^{60}Co comparison in 2005

ITN Standard	CC01-134	Standard uncertainty
Initial recombination and diffusion, k_{init}	$18.4_6 \times 10^{-4}$	5×10^{-5}
Volume recombination factor, k_{vol}, per measured current / pA^{-1}	9.2×10^{-7}	5×10^{-8}
k_s in the BIPM ^{137}Cs, BIPM values	1.0018	1×10^{-4}

Leakage correction

The usual practice at the BIPM is to correct the ionization current for any leakage current. However, for this comparison the measurements made with the ITN standard were not corrected for leakage. The reasons are explained below and give rise to an uncertainty component of 3×10^{-4} included in Table 3.

Leakage measurements. Three sets of 30 measurements were made with the ITN standard in the reference beam, the chamber being repositioned each time. On each occasion, the leakage was measured for one minute both before and after the ionization current measurements. The mean value of the measured leakage current was 0.6 fA; while not large in absolute terms, this represents 1×10^{-3} of the ionization current. Correcting for leakage in the usual manner, the statistical relative standard uncertainty of the mean current arising from these three measurements would be 4×10^{-4}. However, if no leakage correction is applied, the corresponding uncertainty is only 6×10^{-5}. The relative change in the mean ionization current with and without leakage correction is 3×10^{-4}.

Comparison in two beams. While the chamber was positioned in the ^{137}Cs small diameter beam, measurements were also made using another collimator which defines a circular beam 20 cm in diameter at the reference plane. When each set of measurements was corrected using the appropriate radial non-uniformity correction, better agreement between the results for the two beams was achieved when no leakage corrections were made.

5. Results

The values of the ionization currents measured at the BIPM for the ITN standard are given in Table 5. These values are corrected for decay from the measurement date to the reference date using the half-life 10976 (29) days [10], and normalized to the reference conditions of air temperature 273.15 K and pressure 101.325 kPa. No humidity correction has been applied as the BIPM laboratory is controlled at 50 % relative humidity.

The evaluation of the air kerma rate at the BIPM measured with the ITN primary standard, $\dot{K}_{\mathrm{ITN}}$, is obtained from (1) using the data in Table 3 and the mean measured ionization current in the BIPM beams.

Table 5. Ionization currents measured with the ITN standard at the BIPM

^{137}Cs radiation beams, values are given in pA				Mean values	100 s*
Small field	0.58637	0.58630	0.58633	0.58633	0.006
Large field	0.61425	0.61426	–	0.61425	0.001

* relative statistical standard uncertainties in the measurements

The $\dot{K}_{\mathrm{BIPM}}$ value is taken from the mean of the four measurements made around the period of the comparison. The air kerma rate was verified immediately before the comparison measurements. The $\dot{K}_{\mathrm{BIPM}}$ values refer to an evacuated path length between source and standard and are given at the reference date of 2008-01-01, 0 h UTC. The half-life of ^{137}Cs is taken as 10976 (u = 29 days) [10].

The comparison results are given in Table 6 together with their uncertainties. As some constants (such as air density, W/e, $\bar{\mu}_{\mathrm{en}}/\rho$, $\bar{g}$, $\bar{s}_{c,a}$ and k_h) are derived from the same basic data in both laboratories, the uncertainty in R_K is due only to the uncertainties in the correction factors, the volumes of the standards, the ionization currents measured and the distance to the source, the values of which are also given in Table 3. The relative uncertainty in the position of each chamber at the BIPM is less than 0.01 %.

Table 6. Results of the direct comparison of standards for air kerma

^{137}Cs beam	$\dot{K}_{\mathrm{ITN}}$ /µGy s^{-1}	$\dot{K}_{\mathrm{BIPM}}$ /µGy s^{-1}	R_K	100 u_c
Small field	15.747	15.723	1.0015	0.0021
Large field	16.492	16.475	1.0010	0.0021

The mean ratio of the values of the air kerma rate determined by the ITN and the BIPM standards in the ^{137}Cs beam taken from Table 6 is 1.0013 with a combined uncertainty u_c of 0.0021

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_B, is taken as the key comparison reference value (KCRV), for each of the CCRI radiation qualities [11]. 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 $D_i = (K_i - K_{Bi})/ K_{Bi})) = R_{Ki} - 1$ (3)

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

$$U_i = 2\, u_i. \qquad (4)$$

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

Consequently, the degree of equivalence of the ITN with the KCRV is given in Table 7.

Table 7. Degree of equivalence with the KCRV for the ITN in the BIPM.RI(I)-K5 comparison

	D_i	U_i
	/ (mGy/Gy)	
ITN	**1.3**	**4.2**

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

$$D_{ij} = D_i - D_j = R_i - R_j \qquad (5)$$

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

$$u_{ij}{}^2 = u_{c,i}{}^2 + u_{c,j}{}^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_i^2 - \sum_k \left(f_k u_{k,\mathrm{corr}}\right)_j^2 \qquad (6)$$

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 GUM 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 currently being re-evaluated for all the NMIs that have taken part in the BIPM.RI(I)-K5 ongoing comparison in the light of the imminent change to the BIPM standard and the changes since original publication of the individual NMI standards. Once this has been achieved, the revised result for the ITN will be included in a summary report to be published in the KCDB together with the other results [12].

7. Conclusion

The ITN standard for air kerma in ^{137}Cs gamma radiation compared with the present BIPM air kerma standard gives a comparison result of 1.0013 (0.0021). This satisfactory result will be included in the KCDB together with the other NMI results that are currently being re-evaluated.

References

[1] Allisy-Roberts P.J., Burns D.T., Kessler C., Cardoso J., 2009, Comparison of the standards for air kerma of the ITN (Portugal) and the BIPM for ^{60}Co γ-rays, *Metrologia, 2009, 46, Tech. Suppl., 06007*

[2] Boutillon M. and Niatel M.-T., A study of a graphite cavity chamber for absolute measurements of ^{60}Co gamma rays, 1973, *Metrologia*, **9**, 139-146.

[3] Boutillon M., Allisy-Roberts P.J., Measurement of air kerma and ambient dose equivalent in a ^{137}Cs beam, 1996, *Rapport BIPM-96/7*, 12 pp.

[4] Kessler C., Burns D.T. and Allisy-Roberts P.J., 2009, Re-evaluation of the BIPM standard for air kerma in ^{137}Cs gamma radiation, *Metrologia*, 46 (2009), L24-L25.

[5] Allisy-Roberts P.J., Burns D.T., Kessler C., Measuring conditions used for the calibration of ionization chambers at the BIPM, 2007, *Rapport BIPM-07/06*, 20 pp.

[6] *Comité Consultatif pour les Étalons de Mesures des Rayonnements Ionisants*, Constantes physiques pour les étalons de mesure de rayonnement, 1985, *CCEMRI Section (I)*, **11**, R45.

[7] Witzani J., 2003, Monte Carlo calculation of wall correction factors for the air kerma standards of the BEV for ^{137}Cs and ^{60}Co γ rays. CCRI(I)/03-11.

[8] Rogers D.W.O. and Treurniet J. Monte Carlo calculated wall and axial non-uniformity corrections for primary standards of air kerma, 1999, *NRCC Report PIRS–663*, and *CCRI 14th meeting document* CCRI(I)/99-26, 25 pp.

[9] Boutillon M. Volume recombination parameter in ionization chambers, 1998, *Phys.Med.Biol.* **43**, 2061-2072.

[10] Bé M.-M., Chisté V, Dulieu C., Browne E., Baglin C., Chechev V., Kuzmenco N., Helmer R., Kondev F., MacMahon D., Lee K.B., 2006, Table of Radionuclides (Vol. 3 – A = 3 to 244) *Monographie BIPM-5*.

[11] Allisy P.J., Burns D.R., Andreo P., International framework of traceability for radiation dosimetry quantities, *Metrologia*, 2009, **46(2)**, S1-S8

[12] Allisy P.J., Burns D.F., Kessler, C., Summary report of the BIPM.RI(I)-K5 ^{137}Cs dosimetry comparisons, *Metrologia*, 2009, 46, *Tech. Suppl.*, 06XXX (in preparation)