Comparison of the standards of air kerma of the LNMRI and the BIPM for ^{60}Co γ rays

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Abstract
A second comparison of the standards of air kerma of the Laboratório Nacional de Metrologia das Radiações Ionizantes, Rio de Janeiro, Brazil and of the Bureau International des Poids et Mesures has been carried out in ^{60}Co radiation. It shows that the LNMRI and BIPM standards agree closely, as was the case for the first comparison in 1986.

1. Introduction

In 1993, the CCEMRI(I) recommended that ionizing radiation dosimetry standards should be compared at least every 10 years. Following this recommendation, a comparison of the standards of air kerma of the Laboratório Nacional de Metrologia das Radiações Ionizantes (LNMRI), Rio de Janeiro, Brazil, and of the Bureau International des Poids et Mesures (BIPM), has been carried out in ^{60}Co radiation. The LNMRI standard used in the comparison is a graphite cylindrical cavity ionization chamber, type CC01, constructed at the Österreichisches Forschungszentrum (ÖFS), Austria and is one of the two standards brought to the BIPM in 1986. The BIPM standard is described in [1].

The comparison took place at the BIPM in October 1995. The present results agree with the 1986 comparison and show that the standards of the two laboratories remain in close agreement.

2. The LNMRI standard

The main characteristics of the LNMRI primary standard are listed in Table 1. The volume was determined by the ÖFS with an uncertainty of 0,1 %.

Table 1. Characteristics of the LNMRI standard for air kerma.

LNMRI standard		CCO1-110
		Nominal value / mm
Chamber	Outer height	19
	Outer diameter	19
	Inner height	11
	Inner diameter	11
	Wall thickness	4
Electrode	Diameter	2
	Height	10
Volume	Air cavity	1,017 6 cm^3
Wall	Materials	ultrapure graphite EK51 Ringsdorff
	Density	1,71 $g \cdot cm^{-3}$
	Impurity	< 1,5 x 10^{-4}
Insulator		polyethylene
Applied voltage	Both polarities	250 V

3. Conditions of measurement

The air kerma is determined under the following conditions [2]:

- the centre of the chamber is placed at the reference point,
- the distance from source to reference plane is 1 m,
- the field size in air at the reference plane is 10 cm x 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 of the square.

4. Determination of the air kerma

The air kerma rate is determined from

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

where

I/m is the mass ionization current 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 energy lost by bremsstrahlung,

$(\mu_{\text{en}}/\rho)_{\text{a,c}}$ 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.

5. Correction factors relating to the air kerma standards

Since the last comparison in 1986, the BIPM has changed its ^{60}Co source (6 TBq) to one of higher activity (170 TBq). Thus, some of the correction factors applicable to the BIPM standard, namely for axial and radial non-uniformity of the beam, incomplete ion collection, distance to the source, stopping power ratio and chamber wall effect, have been modified to take into account the differences between the two beams in cross section (circular and square), air kerma rate (0,12 mGy s^{-1} and 6 mGy s^{-1}), and energy spectrum (the ratio of energy fluences of the scattered and unscattered photons is 8 % and 14 %, respectively). Corresponding changes have also been estimated for some of the correction factors relating to the LNMRI standard during the comparison. They are described briefly in the following paragraphs:

- *radial non-uniformity* (k_{rn}). The new correction factors for the two standards are deduced from the experimental work described in [3].

- *incomplete ion collection* (k_s). Previous measurements made at the BIPM with different cavity chambers allow accurate determination of the changes in the correction factors for the two standards [4].

- *stopping power ratio* ($\bar{s}_{c,a}$). Recalculations of the stopping power ratios of the two standards take into account the electron spectrum in the graphite chamber wall when using the new ^{60}Co source.

- *axial non-uniformity* of the beam (k_{an}). The axial non-uniformity correction has been recalculated for the BIPM standard taking into account the change in the reference distance (1,12 m to 1,0 m) and the change in the attenuation coefficient of graphite μ_c, resulting from the difference in photon spectrum. The LNMRI does not apply a correction for this effect.

- *wall effect* ($k_w = k_{sc} \times k_{at} \times k_{CEP}$). The correction factors for attenuation and scattering in the graphite walls were determined experimentally for the two standards in 1986 [5] by measuring the effect of adding graphite to the chamber wall. The change in the values of k_{sc} and k_{at}, due to the change in the spectrum, was evaluated for the BIPM standard by a Monte-Carlo calculation. The factor k_{CEP} was also modified as a result of the changes in the reference distance and in μ_c.

For the LNMRI standard, the 1986 value for the combined correction factor k_w is used as no new experimental data is available for this chamber. Some Monte-Carlo calculations for the correction factors for this standard have been made by Rogers and Bielajew [6,7] and give a value for k_w of 1,020 0. This is 0,74 % more than the value estimated from measurements and is explained partly by the linear extrapolation technique used to obtain the factor. In 1986, k_w and the correction for the centre for electron production were assessed as a single value at the LNMRI. Nowadays it is felt appropriate to separate the k_{CEP}, as it is derived in a different way. For this standard, a value for k_{CEP} which assumes that the mean centre is at 0,78 mm from the inner cavity wall of CC01 type chambers, has been used [8].

- *stem scattering* (k_{st}) The correction for scattering from the stem has been measured for each standard and does not differ significantly from unity.

The overall effect of the changes since 1986 is to reduce the value for the BIPM standard by 0,02 % and, neglecting the change in the wall effect, increase that for the LNMRI standard by 0,09 %.

The values of the physical constants [9] and the correction factors entering in equation (1) are shown in Table 2 for both standards.

Table 2. Physical constants and correction factors entering in the determination of the air kerma rates, $\dot{K}_{\mathrm{BIPM}}$ and $\dot{K}_{\mathrm{LNMRI}}$, and their estimated relative uncertainties in the BIPM ^{60}Co beam.

	BIPM values	BIPM relative uncertainty[1]		LNMRI values	LNMRI relative uncertainty[1]		$R_{\dot{K}}$ relative uncertainty[1]	
		$100\,s_i$	$100\,u_i$		$100\,s_i$	$100\,u_i$	$100\,s_i$	$100\,u_i$
Physical constants								
dry air density / kg·m^{-3}	1,293 0	-	0,01	1,293 0	-	0,01	-	-
$(\mu_{en}/\rho)_{a,c}$	0,998 5	-	0,05	0,998 5	-	0,05	-	-
$\bar{s}_{c,a}$	1,001 0 1,000 3[2]	-	0,30	1,001 1 1,000 7[2]	-	0,30	-	0,01
W/e / (J·C^{-1})	33,97	-	0,15	33,97	-	0,15	-	-
$\bar{g}$ fraction of energy lost by bremsstrahlung	0,003 2	-	0,02	0,003 2	-	0,02	-	-
Correction factors								
k_s recombination losses	1,001 6 1,001 5[2]	0,007	0,01	1,002 3[3] 1,002 2[2]	0,01	0,01	0,01	0,01
k_h humidity	0,997 0	-	0,03	0,997 0	-	0,03	-	-
k_{st} stem scattering	1,000 0	0,01	-	1,000 0	-	0,01	0,01	0,01
k_{at} wall attenuation	1,040 2 1,038 9[2]	0,01	0,04	1,015 5			0,01	0,06
k_{sc} wall scattering	0,971 6 0,973 5[2]	0,01	0,07	1,012 5[2]	0,01	0,08[3]	0,01	0,11
k_{CEP} mean origin of electrons	0,992 2 0,992 5[2]	-	0,01	0,997	-	0,10	-	0,10
k_{an} axial non-uniformity	0,996 4 0,996 8[2]	-	0,07	1,000	-	0,07	-	0,10
k_{rn} radial non-uniformity	1,001 6 1,001 3[2]	0,01	0,02	1,000 3 1[2]	-	0,02	0,01	0,03
V volume / cm^3	6,811 6	0,01	0,03	1,017 6	-	0,10	0,01	0,10
I ionization current / pA		0,01	0,02	229,383	0,03	0,05	0,03	0,05
I_+/I_- polarity correction factor		-	-		0,02	-	0,02	-
Uncertainty								
quadratic summation		0,02	0,36		0,04	0,39	0,04	0,23
combined uncertainty		0,36			0,39		0,23	

(1) Expressed as a 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) Values used in 1986 which are different to 1995.
(3) Values obtained by De Almeida *et al* [10].

6. Results of the comparison

The values of the air kerma rate (see Table 3) refer by convention to an evacuated path length between source and standard and are given at the reference date of 1995-01-01, 0h UT (the half life of ^{60}Co is taken as (1 925,5 d, σ = 0,5 d) [11]). The value used for the linear attenuation coefficient of air was 7,5 10^{-3} m^{-1} in 1986 and 7,8 10^{-3} m^{-1} in 1995.

The $\dot{K}_{\mathrm{BIPM}}$ value is the mean of 8 series of 60 measurements which were performed over the four months before and immediately after the measurements with the LNMRI standard.

Temperature and pressure corrections are made for each measurement. The temperature was controlled and did not fluctuate more than 0,05 °C during the whole series of 60 measurements made with the LNMRI standard. The humidity was between 42 % and 45 % during the measurements and the correction factor remains unchanged at the CCEMRI(I) recommended value [12].

The result of the comparison $R_{\dot{K}} = \dot{K}_{\mathrm{LNMRI}} / \dot{K}_{\mathrm{BIPM}}$ is given in Table 3. Some of the uncertainties in $\dot{K}$ which appear in both the BIPM and LNMRI 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 $R_{\dot{K}}$ (see Table 2). The ratio of the air kerma rates determined by the LNMRI and the BIPM standards is 1,000 5 with σ = 0,002 3. The present result for $R_{\dot{K}}$ agrees with the value obtained in the 1986 comparison well within the statistical uncertainties.

Table 3. Results of the LNMRI-BIPM comparisons.

Year of comparison	LNMRI Standard	$\dot{K}_{\mathrm{LNMRI}}$ / $\mathrm{mGy \cdot s^{-1}}$	$\dot{K}_{\mathrm{BIPM}}$ / $\mathrm{mGy \cdot s^{-1}}$	$R_{\dot{K}} = \dot{K}_{\mathrm{LNMRI}} / \dot{K}_{\mathrm{BIPM}}$
1986	CC01-108	0,120 98	0,120 82	1,001 3 σ = 0,002 6
	CC01-110	0,120 89	0,120 82	1,000 6 σ = 0,002 6
1995	CC01-110	6,010 2	6,007 7	1,000 4 σ = 0,002 3

7. Conclusion

The result of the present comparison shows close agreement between the LNMRI and the BIPM standards for ^{60}Co, within the estimated uncertainties. This result confirms the good agreement observed in 1986 and the stability of the two standards.

The results of comparisons in ^{60}Co radiation using standards of the same type (CC01 and ND1005) as that used by the LNMRI are shown in Table 4. As can be seen, they agree to within ± 0,2 %. Since the correction factors are very similar for all these chambers, the differences observed in the results derive mainly from the volume determinations. However, the SZMDM result appears rather low. This laboratory, however, applies a correction for axial non-uniformity of $3 \cdot 10^{-3}$, whereas the others used a value of $2 \cdot 10^{-4}$ or less.

Table 4. Comparison of $\dot{K}_{\mathrm{lab}}$ with $\dot{K}_{\mathrm{BIPM}}$ for national standards of the same type.

Laboratory	$R_{\dot{K}} = \dot{K}_{\mathrm{lab}} / \dot{K}_{\mathrm{BIPM}}$ ^{60}Co
LNMRI present work	1,000 4
BEV [13]	1,002 9
OMH [14]	1,002 5
UDZ [15]	0,999 2
SZMDM [16]	0,998 2

The results of all the international comparisons of air kerma in ^{60}Co radiation made at the BIPM are shown in Figure 1. The results obtained using CC01 type standards are in good agreement with the results of comparisons made with other types of standard. The standard deviation of these 24 national laboratory comparisons is 0,2 %.

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Figure 1

NATIONAL COMPARISONS OF AIR KERMA IN ^{60}Co RADIATION