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Abstract
A comparison of the standards of air kerma of the Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti of the Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, Italy (ENEA-INMRI) and of the Bureau International des Poids et Mesures (BIPM) has been carried out in ^{60}Co radiation. The comparison result, declared in 2002, is 1.0103 (0.0026). The difference between the ENEA-INMRI and BIPM standards is consistent with the various changes that have been introduced since the previous comparisons that were in agreement within the comparison uncertainties.

1. Introduction

A comparison of the standards of air kerma of the Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti of the Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, Italy, (ENEA-INMRI), and of the Bureau International des Poids et Mesures (BIPM), has been carried out in ^{60}Co radiation. The ENEA-INMRI primary standard of air kerma is a graphite-cavity ionization chamber constructed at the ENEA-INMRI (type C, serial number 3). A similar standard chamber (type C, serial number 1) was used by the ENEA-INMRI as a transfer standard in an indirect comparison as a verification. Details of the standards are given in [1] and in section 2 of this report. The BIPM air kerma standard is described in [2]. The comparison measurements took place at the BIPM in September 1998.

The original result of this comparison has been modified recently. A new determination made at the ENEA-INMRI to take account of the effects of the graphite walls of the standard cavity chamber was declared in January 2001 and published in July 2002 [3].

A previous comparison between the ENEA-INMRI and the BIPM took place in 1983 [4] and a bilateral comparison with the NIST (USA) and the ENEA-INMRI took place in 1994 [5]. The results of these previous comparisons are consistent, when the various changes are taken into account, as discussed later in this report.

2. Determination of the air kerma

The air kerma rate is determined by

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

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,
$(\mu_{en}/\rho)_{a,c}$	is the ratio of the mean mass-energy absorption coefficients of air and graphite,
$\bar{s}_{c,a}$	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 ENEA-INMRI primary standard are given in Table 1.

Table 1. Characteristics of the ENEA-INMRI standard of air kerma

Type	C-ENEA standard chambers	Nominal values
Chamber	Outer height / mm	19
	Outer diameter / mm	19
	Inner height / mm	11
	Inner diameter / mm	11
	Wall thickness / mm	4
Electrode	Diameter / mm	2
	Height / mm	10
Volume	Air cavity / cm^3	1.0243[a]
	relative uncertainty / cm^3	0.0020
	Air cavity / cm^3	1.0222[b]
	relative uncertainty / cm^3	0.0020
Wall	Material	ultrapure graphite
	Density / $g \cdot cm^{-3}$	1.75
	Impurity fraction	$< 1.5 \times 10^{-4}$
Applied tension (both polarities)	Voltage / V	300

a. standard chamber serial number 3

b. standard chamber serial number 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 of the square.

Data concerning the various factors entering in the determination of air kerma in the ^{60}Co beam using the two standards are shown in Table 2. They include the physical constants [6], the correction factors entering in (1), the volume of each chamber cavity and the associated uncertainties. For the BIPM standard, these data are taken from [7]. Also shown in Table 2 are the relative uncertainties in the ratio $R_K = \dot{K}_{\text{ENEA-INMRI}} / \dot{K}_{\text{BIPM}}$.

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

	BIPM values	Relative [(a)] uncertainty		ENEA-INMRI 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)]	1.0007	-	0.11 [(c)]	-	-
W/e	33.97	-		33.97	-		-	-
$\bar{g}$ fraction of energy lost by bremsstrahlung	0.0032	-	0.02	0.0032	-	0.02	-	-
Correction factors								
k_s recombination loss	1.0016	0.01	0.01	1.0018	-	0.05	0.01	0.05
k_h humidity	0.9970	-	0.03	0.9970	-	0.03	-	-
k_{st} stem scattering	1.0000	0.01	-	1.0000	-	0.03	0.01	-
k_{att} wall attenuation	1.0402	0.01	0.04				0.01	0.04
k_{sc} wall scattering	0.9716	0.01	0.07	1.0217	-	0.10	0.01	0.12
k_{CEP} mean origin of electrons	0.9922	-	0.01				-	0.01
k_{an} axial non-uniformity	0.9964	-	0.07	1.0001	-	0.01	-	0.07
k_{rn} radial non-uniformity	1.0016	0.01	0.02	1.0003	-	0.01	0.01	0.02
Measurement of $I/V\rho$								
V volume / cm^3	6.8116	0.01	0.03	1.0243	-	0.20	0.01	0.20
I ionization current		0.01	0.02		0.03	0.06	0.03	0.06
Uncertainty								
quadratic summation		0.03	0.17		0.03	0.27	0.04	0.26
combined uncertainty		0.17			0.27		0.26	

(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*

The correction factors for the ENEA-INMRI standard were determined at the ENEA-INMRI. The polarity effect was about 1.0025 (2), but as all measurements were made with both polarities no corrections were applied. Some measurements concerning the effect of ion recombination and the effect of attenuation and scatter in the chamber walls were repeated in the BIPM beam.

The ratio of the ionization currents obtained with applied voltages of 300 V and 150 V (both polarities) was the same (to less than 4×10^{-4}) for the ENEA-INMRI standard in the ENEA-INMRI beam as in the BIPM beam. This gave a simple estimate of ion recombination loss $k_s = 1.0024$ at the BIPM. However, on measuring the ratio $I_V / I_{V/4}$ [8] in the BIPM beam for a series of different ionization currents, a more precise value of k_s was derived. This value was also equivalent to that for the BIPM transfer chamber of the same size and shape (CC01 serial 122) for an applied voltage of 300 V. Consequently, the correction $k_s = 1.0018$ (0.0005) as measured at the BIPM was applied to the ENEA-INMRI standard in the BIPM beam.

The effect of attenuation and scatter in the graphite walls of the standard chamber is determined conventionally by adding graphite caps of thickness up to 16 mm to the chamber wall (4 mm) of an ENEA-INMRI chamber and extrapolating to zero thickness. This experiment was repeated in the BIPM beam and the result is similar in both the BIPM and the ENEA-INMRI beams (Table 3). Consequently, the correction factor $k_{att.sc} = 1.0159$ (0.0010) deduced from the measurements made at the BIPM would normally be used in the determination of air kerma at the BIPM. This value, together with the correction k_{CEP}, would have given a total correction for wall effects of $k_{wall} = 1.0131$ (0.0022).

However, improvements to replace the traditional extrapolation method have been made recently by the ENEA-INMRI using a technique that involves measurement and analytical calculation [3]. The result of this determination produces a value for the total wall correction ($k_{att}k_{sc}k_{CEP}$) that agrees within the stated uncertainties with the value calculated at the ENEA-INMRI using the Monte Carlo code EGSnrc [9]. This last value of 1.0217 with an uncertainty $u = 0.0010$ in which the statistical uncertainty $s = 0.0002$ was used for the total wall effect. This value is 8.5×10^{-3} higher that the previous experimental value. The new value for k_{wall} agrees well with the value of 1.0219 ($s = 0.0001$) calculated for the same chamber at the NRC (Canada) [10] using the Monte Carlo code EGSnrc.

Table 3. Check measurements with C1-ENEA-INMRI for $k_{att.sc}$ by extrapolation

Number of caps added	0	1	2	3	4
Total wall thickness / mm $\rho = 1.75$ g cm^{-3}	4.00	8.05	12.1	16.15	20.2
Current / pA	36.982	36.413	35.937	35.251	34.647
Ratio in the BIPM beam		0.9838	0.9681	0.9518	0.9356
Ratio in the ENEA-INMRI beam		0.9846	0.9690	0.9535	0.9368

An additional correction factor k_{rn} for the radial non-uniformity of the BIPM beam over the cross-section of the ENEA-INMRI standard has been estimated from [11]; its numerical value is 1.0003.

The result of the comparison $R_K = \dot{K}_{\text{ENEA-INMRI}} / \dot{K}_{\text{BIPM}}$ is given in Table 4. The $\dot{K}_{\text{BIPM}}$ value is the mean of measurements that were performed over a period of one month before and after the present comparison. The ratio of the values of the air kerma rate determined by the ENEA-INMRI and the BIPM standards is 1.0103 with a standard combined uncertainty, u_c, of 0.0026. Some of the uncertainties in $\dot{K}$ which appear in both the BIPM and the ENEA-INMRI 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.

Table 4. Results of the ENEA-INMRI/BIPM comparison of standards of air kerma

Standard C3 ionization current /pA	$\dot{K}_{\text{ENEA-INMRI}}$ (a) / mGy s^{-1}	$\dot{K}_{\text{BIPM}}$ (a) / mGy s^{-1}	R_K	u_c
155.847 (7)	4.0905$_4$	4.0489	1.0103	0.0026

(a) The $\dot{K}$ values refer to an evacuated path length between source and standard and are given at the reference date of 1998-01-01, 0h UTC where the half-life of ^{60}Co is taken as 1925.5 days (u = 0.5 days) [12].

4. Discussion

4.1 Previous ENEA-INMRI comparisons

The present comparison is made using the primary standard chamber serial number C3. In 1983, at the previous air kerma comparison, the ENEA-INMRI standard used was of the same type but with a different serial number, C1, that is now used as a transfer standard. The results obtained with the ENEA-INMRI primary and transfer standard chambers agree at 2×10^{-3}. This difference appears to arise from the difference in the stated volumes of the two standards. Although a difference of about 0.2 % was originally measured in the volumes of the two standard chambers, they each produce the same ionization current (within 4×10^{-4}) whether measured at the ENEA-INMRI or the BIPM. This casts some doubt on the original volume measurement and consequently the uncertainty of the earlier measurement of each chamber's volume has been expanded..

The ionization current produced by the standard chamber C1 in the BIPM beam was used to identify a calibration coefficient that was then compared with one derived from the original data of 1983. The results of 1983 have been updated to account for changes in stopping power ratios in 1985. The results are given in Table 5 and show a relative difference of 1.5×10^{-3} that could be in part due to the change in the ^{60}Co source (and source housing) used for air kerma comparisons at the BIPM during the intervening fifteen years. Taking note of this, it would appear that the ENEA-INMRI C1 chamber has not changed significantly with time.

Table 5. Calibration coefficient for the C1-ENEA chamber.

Measurement laboratory	**BIPM**	**BIPM**
Year	**1985**	**1998**
Calibration coefficient N_K /(Gy/µC) at 0 °C	26.00_4	25.97_7
Uncertainty of N_K	0.04	0.04

An indirect comparison between the ENEA-INMRI and the NIST held in 1994, using two transfer chambers of the NIST, produced a mean comparison result for the ratio ENEA-INMRI/NIST of 1.0004 (0.0051) [5]. The NIST compared their standard with the BIPM in 1996, again indirectly using the same two transfer chambers, and this gave a result for the ratio NIST/BIPM of 0.9980 (0.0040) [13]. Using these two values, a comparison result between the ENEA-INMRI and the BIPM can be deduced as 0.9984. This agrees within one standard uncertainty (0.0040) both with the previous result of the updated 1983 comparison and the original result of the 1998 direct comparison of 0.9988 that was obtained before the corrections for the beam (axial and radial) non uniformity and wall effects were implemented.

Table 6. Previous comparison results for the ENEA-INMRI/BIPM

Year	1983	1983 corrected for Δ	1985 update using ICRU $\bar{s}_{c,a}$	1996 inferred from the ENEA-INMRI/NIST of 1994
ENEA-INMRI/BIPM	0.9982	0.9985	0.9994	0.9984
Uncertainty u_c	0.0040	0.0040	0.0040	0.0051

4.2 Discussion regarding k_{wall} effects

For more than 10 years there have been intensive discussions on wall correction factors for cavity ionization chambers determined with an experimental extrapolation method versus those calculated using Monte Carlo methods [14, 15, 10]. There has also been considerable debate over the corrections for non-uniformity and the point of measurement [16, 17].

The majority of the national metrology institutes (NMIs) currently use wall correction factors that have been determined by the linear extrapolation method. Both experimental and theoretical results have been provided in recent years which strongly support the validity of calculated wall correction factors and for certain chamber types these calculated values differ significantly from those obtained by linear extrapolation of experimental data to zero wall thickness. This is particularly the case for the cylindrical cavity chambers that are used as primary air kerma standards by some NMIs. In some cases, the differences amount to 50 % of the correction itself [18].

During the 14th CCRI(I) meeting in 1999, the various approaches for determining wall and axial non-uniformity correction factors for graphite-cavity standards were discussed in detail [19]. It became apparent that several NMIs were actively re-evaluating their correction factors for ^{60}Co air kerma standards including their uncertainties at the time of the meeting. It was agreed to set up a working group (WG) to study the implications of using correction factors for ^{60}Co air kerma standards based on Monte Carlo methods. The members of the WG include the BNM-LNHB (France), NIST, NMi (The Netherlands), NPL (UK) and the BIPM. The NRC agreed to act as a consultant and submit to the working group a paper that it intended to publish on this topic. Furthermore it was decided that before publishing results in the key comparison database (KCDB), which shows the degrees of equivalence between the NMIs, the BIPM would ask the NMIs to review their uncertainty budgets for air kerma standards in ^{60}Co gamma radiation. It was further suggested that the method of determining the correction factors (e.g. Monte Carlo or experimental, particularly linear extrapolation) should be identified in the KCDB together with a statement on the implications of differences between the two methods with respect to the uncertainty [19].

The debate continued during the 15th CCRI(I) meeting in 2001 and several NMIs produced documents [18, 20-23] describing the work undertaken since the 1999 meeting. Significant contributions were made to the debate on wall correction factors for cavity chambers. As a consequence, it was agreed that the WG evaluate the information available and make recommendations on the procedure to ensure that the results to be entered in the KCDB are valid.

The results of comparisons at the BIPM with standards of a similar type to that of the ENEA-INMRI are shown in Figure 1 (in green). The OMH (Hungary) has already declared a new value for its air kerma standard [20], as has the PTB (Germany) [24]. The SZMDM (Yugoslavia) and the NCM (Bulgaria), both of which have made comparisons recently with the BIPM [25, 26], have also changed their method of k_{wall} determination, using Monte Carlo calculations.

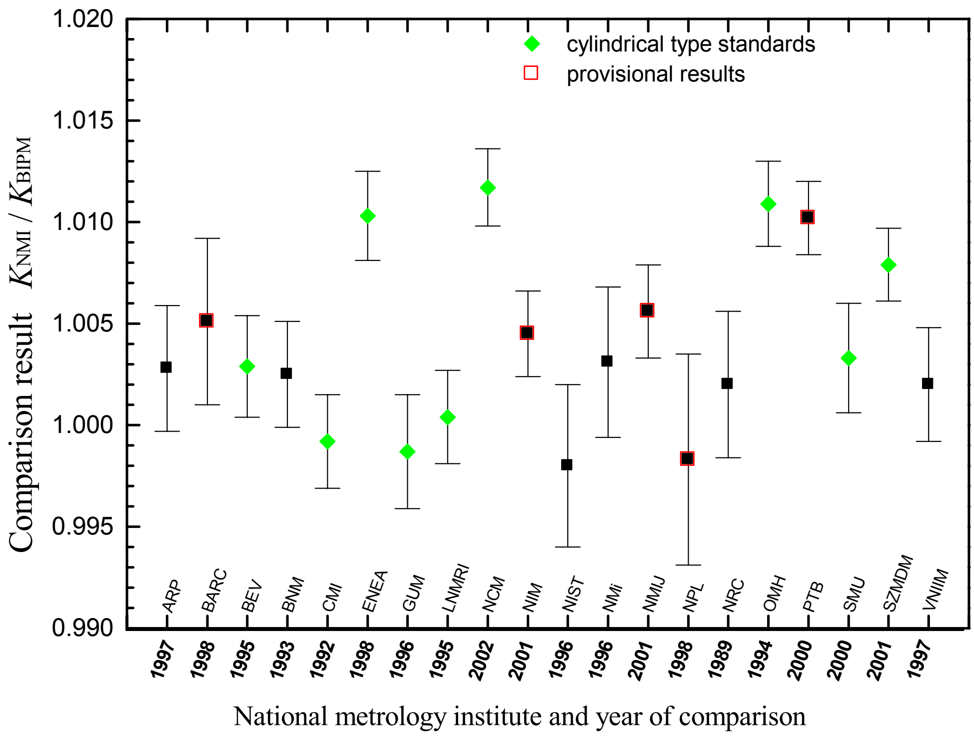
The BIPM is making calculations of the equivalent factors for its standard to verify its determination of air kerma. Any future new result will need to be approved and implemented at a date to be confirmed by the Consultative Committee for Ionizing Radiation (CCRI).

5. Conclusion

The ENEA-INMRI standard for air kerma in ^{60}Co gamma radiation compared with the BIPM air kerma standard gives a comparison result of 1.0103 (0.0026). The comparison with the other national standards can be seen in Figure 1. The standard deviation of all the international comparison results is equal to 4.3×10^{-3}. The results of comparisons at the BIPM with standards of a similar type to that of the ENEA-INMRI are shown as green diamonds. The standard deviation of this group of comparison results is 5.2×10^{-3} compared to the whole set of comparison results. In the green diamond group there now appear to be two sets of results, each of which is self-consistent within the estimated uncertainties, but different from each other by about 1 %. The set with the higher values has re-evaluated its wall correction factor on changing from the traditional extrapolation method. However, some of the other NMIs with differently shaped standards have always used Monte Carlo calculations but their results are more consistent with the lower group.

In principle, these results will be used as the basis of the entries in Appendix B of the KCDB set up under the CIPM Mutual Recognition Arrangement [27]. All the NMIs that have previously used experimental extrapolation methods to determine wall correction factors are currently checking their factors, using various Monte Carlo codes or other methods. It is anticipated that it will be a further ten months before all the NMIs will be ready for their results to be entered into the BIPM key comparison database (KCDB). In the meantime, the BIPM is also reviewing its experimental and calculated results for the wall corrections of its primary standard as indeed is the ENEA-INMRI.

Figure 1 International air kerma comparison results



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