Comparisons of the standards of air kerma of the BEV and the BIPM for ^{137}Cs and ^{60}Co γ rays

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Abstract
Comparisons of the standards of air kerma of the Bundesamt für Eich- und Vermessungswesen (BEV) and of the Bureau International des Poids et Mesures (BIPM) have been carried out in ^{137}Cs and ^{60}Co radiations. They show that the BEV and BIPM standards agree to within 0,5 % and 0,3 % respectively.

1. Introduction

Comparisons of the standards of air kerma of the Bundesamt für Eich- und Vermessungswesen, Vienna, Austria, and of the Bureau International des Poids et Mesures, have been carried out in ^{137}Cs and ^{60}Co radiations. The standards of air kerma of the BEV are graphite cavity ionization chambers constructed at the Österreichisches Forschungszentrum (ÖFS), Seibersdorf, Austria (type CC01, serial numbers 125 and 132). At the BIPM, the standards are described in [1, 2]. The comparisons took place at the BIPM in June 1995.

For ^{137}Cs, comparisons were made with the two BEV standards (CC01-125 and CC01-132) and with a transfer chamber. This transfer chamber is a spherical secondary-standard ionization chamber also constructed at the ÖFS (type TK-30, serial number 102).

For ^{60}Co, comparisons were made with the same BEV standards. The standards of air kerma for ^{60}Co were last compared in 1994 using chamber CC01-125. The present results agree with those of 1994 to within 0,02 %.

2. Conditions of measurement

The air kerma is determined under the following conditions [3]:
- the distance from source to reference plane is 1 m,
- the field size in air for ^{60}Co 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,
- the field size in air for ^{137}Cs at the reference plane is 11 cm diameter, the photon fluence rate at 3 cm from the centre being 98 % of the photon fluence rate at the centre.

3. Determination of the air kerma

The air kerma rate is determined by

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

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,
$(\mu_{en}/\rho)_{a,c}$ 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 BEV primary and secondary standards are given in Table 1. The volumes were determined mechanically at the BEV. Another determination was made at the BEV for the CC01-125 chamber by filling the cavity with water. The two results are in good agreement (0,01 %).

Table 1. Characteristics of the BEV standards of air kerma.

		CC01-125	CC01-132	TK30-102
		Nominal values / mm		
Chamber	Outer height	19	19	
	Outer diameter	19	19	44
	Inner height	11	11	
	Inner diameter	11	11	38
	Wall thickness	4	4	3
Electrode	Diameter	2,00	2,00	3
	Height	8,97	8,97	
Volume	Air cavity	1,018 7 cm^3	1,017 1 cm^3	30 cm^3
Wall	Materials	ultrapure graphite EK51 Ringsdorf	high purity moulded graphite grade ATJ (Union Carbide)	polyacetal resin DELRIN R500
	Density	1,72 $g \cdot cm^{-3}$	1,80 $g \cdot cm^{-3}$	1,39 $g \cdot cm^{-3}$
	Impurity	$< 1,5 \times 10^{-4}$	$< 8,0 \times 10^{-4}$	
Insulator		PTFE (Teflon)	PTFE (Teflon)	PTFE (Teflon)
Applied voltage		+250 V	+250 V	-300 V

4. Comparison of the air kerma standards for ^{137}Cs radiation

The correction factors for the BEV standards were determined at the BEV. As a check, some measurements concerning the attenuation and scattering in the chamber wall were made again in the BIPM beam. The results agree with the BEV determination well within the uncertainties, as shown in Table 2. The correction factor k_{rn}, for the radial non-uniformity of the BIPM beam over the section of the BEV standard CC01, has been estimated from measurements carried out at the BIPM and is 1,000 4, while that for the transfer chamber TK30 is 1,005 0 [2].

Table 2. Measurements with chamber CC01-132 to determine attenuation and scatter factors for ^{137}Cs.

Additional cap thickness / mm	4	8	12	16
I/I_0 (BEV beam)	0,980 7	0,962 5	0,945 5	0,928 2
I/I_0 (BIPM beam)	0,981 9	0,963 4	0,945 7	0,928 0

The physical constants [4] and the correction factors entering in (1), together with the uncertainties associated with the measurement of $\dot{K}$, are given in Table 3 for the BIPM and BEV standards.

The results of the comparison $R_K = \dot{K}_{\mathrm{BEV}} / \dot{K}_{\mathrm{BIPM}}$ are given in Table 4. The values of $\dot{K}$ refer to an evacuated path length between source and standard at an air temperature of 0 °C. They are given at the reference date of 1995-01-01, 0h UT (the half life of ^{137}Cs is taken as (11 050 ± 40) days [5]). The BIPM value is the mean of measurements which were performed over a period of three months before and after the comparison at the BIPM.

Some of the uncertainties which appear in the BIPM and BEV determinations of the air kerma rate (such as air density, W/e, μ_{en}/ρ, $\bar{g}$, $\bar{s}_{c,a}$ and k_h,) cancel when evaluating the ratio R_K. The uncertainty in the position of each chamber is 0,01 %. The overall uncertainty of R_K is estimated to be 0,28 %.

The mean ratio of the air kerma rates determined by the BEV and the BIPM standards is 0,994 5, which is in fair agreement with the uncertainty of the measurements. The direct and the indirect comparisons for the standard CCO1-132 give the same results, confirming the validity of an indirect calibration in the ^{137}Cs radiation. This is also an indirect check of the accuracy of the correction used for the non-uniformity of the BIPM beam. Indeed, this correction is quite different for the BEV standard and the transfer chamber (0,04 % and 0,50 %, respectively). There is a difference of 0,33 % between the results with the two BEV standards. This value is about twice the expected uncertainty (0,18 %). Although the two chambers are of the same design, they are manufactured from graphite with different specifications. No other explanation has been found for the difference between the measurement results.

Table 3. Physical constants and correction factors entering in the determination of the air kerma rates, $\dot{K}_{\mathrm{BIPM}}$ and $\dot{K}_{\mathrm{BEV}}$, and their estimated relative uncertainties in the BIPM ^{137}Cs beam.

	BIPM values	relative [(1)] uncertainty / % s_i	u_i	BEV values[(2)]	relative [(1)] uncertainty / % s_i	u_i
Physical constants						
dry air density / kg·m^{-3} [(3)]	1,293 0	-	0,01	1,293 0	-	0,01
$(\mu_{en}/\rho)_{a,c}$	0,999 0	-	0,05	0,999 0	-	0,05
$\bar{s}_{c,a}$	1,010 4	-	0,30	1,010 1	-	0,30
W/e	33,97	-	0,15	33,97	-	0,15
$\bar{g}$ fraction of energy lost by bremsstrahlung	0,001 2	-	0,02	0,001 2	-	0,02
Correction factors						
k_s recombination losses	1,001 4	0,01	0,01	1,002 2	0,02	0,02
k_h humidity	0,997 0	-	0,03	0,997 0	-	0,03
k_{st} stem scattering	0,999 8	0,01	-	0,999 3	0,02	0,02
k_{at} wall attenuation	1,054 0	0,01	0,04			
k_{sc} wall scattering (CC01-125)	0,953 5	0,01	0,07	1,018 1	0,02	0,10
k_{sc} wall scattering (CC01-132)				1,019 7	0,02	0,10
k_{CEP} mean origin of electrons	0,997 2	-	0,01	0,999 1	-	0,10
k_{an} axial non-uniformity	0,998 1	-	0,07	1,000 0	-	0,10
k_{rn} radial non-uniformity	1,007 0	0,01	0,03	1,000 4	-	0,03
Measurement of $I/V\rho$						
V volume / cm^3 CC01-125	6,834 4	0,01	0,10	1,018 7	-	0,12
CC01-132				1,017 1	-	0,12
I ionization current		0,03	0,02		0,02	0,05
I_+/I_- polarity correction factor					0,02	-
Uncertainty						
quadratic summation		0,04	0,37		0,04	0,41
combined uncertainty		0,38			0,41	

(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 relate to the chambers CC01-125 and CC01-132 where indicated.

(3) At 101 325 Pa and 273,15 K.

Table 4. Results of the BEV-BIPM comparison of standards of air kerma for ^{137}Cs.

BEV Standard	$\dot{K}_{\mathrm{BEV}}$ [(1)] / µGy·s^{-1}	$\dot{K}_{\mathrm{BIPM}}$ / µGy·s^{-1}	R_K
CC01-125	21,094	21,177	0,996 1 ± 0,002 8
CC01-132	21,025	21,177	0,992 8 ± 0,002 8
TK30-102	21,031	21,177	0,993 1 ± 0,002 8[(2)]

(1) Mean value of a series of 30 to 130 measurements.

(2) Result obtained from calibration of the chamber against CC01-132.

5. Comparison of the air kerma standards for ^{60}Co radiation

Data concerning the comparison of the BEV CC01 standards with the BIPM standard in the ^{60}Co beam are shown in Table 5. They include the physical constants and the correction factors entering in (1) together with the uncertainties associated with the determination of $\dot{K}$ for the cobalt beam [3].

The correction factors for the BEV standard were determined at the BEV. An additional correction factor, k_{rn}, for the radial non-uniformity of the BIPM beam over the section of the BEV standard, has been estimated from [6] its value being 1,000 3.

The result of the comparison $R_K = \dot{K}_{\mathrm{BEV}} / \dot{K}_{\mathrm{BIPM}}$ is given in Table 6. The $\dot{K}$ values refer to an evacuated path length between source and standard. They are given at the reference date of 1995-01-01, 0h UT (the half life of ^{60}Co is taken as (1 925,5 ± 0,5) days [5]). The $\dot{K}_{\mathrm{BIPM}}$ value is the mean of measurements which were performed over a period of three months before and after the comparison at the BIPM. The mean ratio of the air kerma rates determined by the BEV and the BIPM standards is 1,002 9. The result of 1,003 8 for chamber CC01-125 agrees with the value of 1,004 0 obtained in the 1994 comparison well within the uncertainties [7]. This confirms the reproducibility of the measurements of both the BIPM and the BEV standards.

Some of the uncertainties in $\dot{K}$ which appear in the BIPM and BEV determinations (such as air density, W/e, μ_{en}/ρ, $\bar{g}$, $\bar{s}_{\mathrm{c,a}}$ and k_{h},) cancel when evaluating the uncertainty of R_K, which is estimated to be 0,25 %. The mean value of R_K is in agreement with the results of other international comparisons (Figure 1) and in particular with the previous BEV-BIPM comparisons made in 1980 and 1994. This again confirms the stability of the standards.

The results obtained with the two BEV standards are in better agreement when using ^{60}Co radiation than when using ^{137}Cs radiation (compare Tables 4 and 6). The value of $\bar{s}_{\mathrm{c,a}}$ used at the BIPM for ^{60}Co radiation was also used for the two BEV standards. However the value of $\bar{s}_{\mathrm{c,a}}$ used by the BEV for ^{137}Cs radiation is slightly different from that used by the BIPM.

Table 5. Physical constants and correction factors entering in the determination of the air kerma rates, $\dot{K}_{BIPM}$ and $\dot{K}_{BEV}$, and their estimated relative uncertainties in the BIPM ^{60}Co beam.

	BIPM values	relative [(1)] uncertainty / %		BEV values[(2)]	relative [(1)] uncertainty / %	
		s_i	u_i		s_i	u_i
Physical constants						
dry air density / kg·m^{-3} [(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	-	0,30	1,001 0	-	0,30
W/e	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	0,01	0,01	1,002 7	0,02	0,01
k_h humidity	0,997 0	-	0,03	0,997 0	-	0,03
k_{st} stem scattering	1,000 0	0,01	-	0,999 5	0,02	-
k_{at} wall attenuation	1,040 2	0,01	0,04			
k_{sc} wall scattering (CC01-125)	0,971 6	0,01	0,07	1,016 0	0,02	0,10
k_{sc} wall scattering (CC01-132)				1,017 1	0,02	0,10
k_{CEP} mean origin of electrons	0,992 2	-	0,01	0,996 8	-	0,10
k_{an} axial non-uniformity	0,996 4	-	0,07	1,000 0	-	0,10
k_{rn} radial non-uniformity	1,001 6	0,01	0,02	1,000 3	-	0,01
Measurement of $I/V\rho$						
V volume / cm^3 CC01-125	6,811 6	0,01	0,03	1,018 7	-	0,12
CC01-132				1,017 1	-	0,12
I ionization current		0,01	0,02		0,03	0,05
I_+/I_- polarity correction factor					0,02	-
Uncertainty						
quadratic summation		0,02	0,36		0,05	0,41
combined uncertainty		0,36			0,41	

(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 relate to the chambers CC01-125 and CC01-132 where indicated.

(3) At 101 325 Pa and 273,15 K.

Table 6. Results of the BEV-BIPM comparison of standards of air kerma for ^{60}Co.

BEV Standard	$\dot{K}_{BEV}$ [(1)] / mGy·s^{-1}	$\dot{K}_{BIPM}$ / mGy·s^{-1}	R_K
CC01-125	6,030 0	6,007 4	1,003 8 ± 0,002 5
CC01-132	6,019 3	6,007 4	1,002 0 ± 0,002 5

(1) Mean value of 30 measurements.

6. Conclusion

The same BEV standards were used for comparisons in both ^{60}Co and ^{137}Cs radiations. Although the results for a given radiation quality are in good agreement (0,3 % for ^{60}Co and 0,5 % for ^{137}Cs), the difference between R_K (^{60}Co) and R_K (^{137}Cs), of the order of 0,8 %, looks quite high when compared with the uncertainties.

The results of other comparisons using ^{137}Cs are shown in Table 7 together with the corresponding result for ^{60}Co. To obtain these results the OMH used a standard of the same type as that of the BEV, while the comparison of ^{137}Cs with the NIST was made indirectly using a large spherical chamber.

Table 7. Comparison of national laboratory results, $\dot{K}_{\mathrm{Lab}}$ with $\dot{K}_{\mathrm{BIPM}}$.

Laboratory	$\dot{K}_{\mathrm{Lab}}$ / $\dot{K}_{\mathrm{BIPM}}$	
	^{137}Cs	^{60}Co
BEV [7]	0,994 5	1,002 9
OMH [10]	0,995 4	1,002 5
NIST [11]	0,995 1	0,997 3

The values obtained for $\dot{K}_{\mathrm{Lab}}$ for ^{60}Co are consistent to within the estimated uncertainties while those for ^{137}Cs have a tendency to be low. This is an indication that some correction factors related to air kerma measurements in a ^{137}Cs beam may need revision. Of particular importance is the determination of the correction due to the attenuation and scattering in the chamber wall. This correction, for the NIST, OMH and BEV standards, may be underestimated, since it is obtained by extrapolation from measurements made with wall thicknesses far in excess of the maximum range of the electrons. As noted by Rogers and Bielajew [12], such an extrapolation can lead to substantial error, possibly as much as 1 %.

In addition, the three laboratories listed in Table 7 make no correction for the radial non-uniformity of a ^{137}Cs beam. However, experiments made at the BIPM [2] show that this effect may be much more pronounced in a ^{137}Cs beam than in a ^{60}Co beam.

Thus, although the present results for the comparison with the BEV are quite satisfactory, some improvement could still be made concerning the accuracy of the air-kerma determination in a ^{137}Cs beam.

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Figure 1. **NATIONAL COMPARISONS OF AIR KERMA IN ^{60}CO RADIATION.**

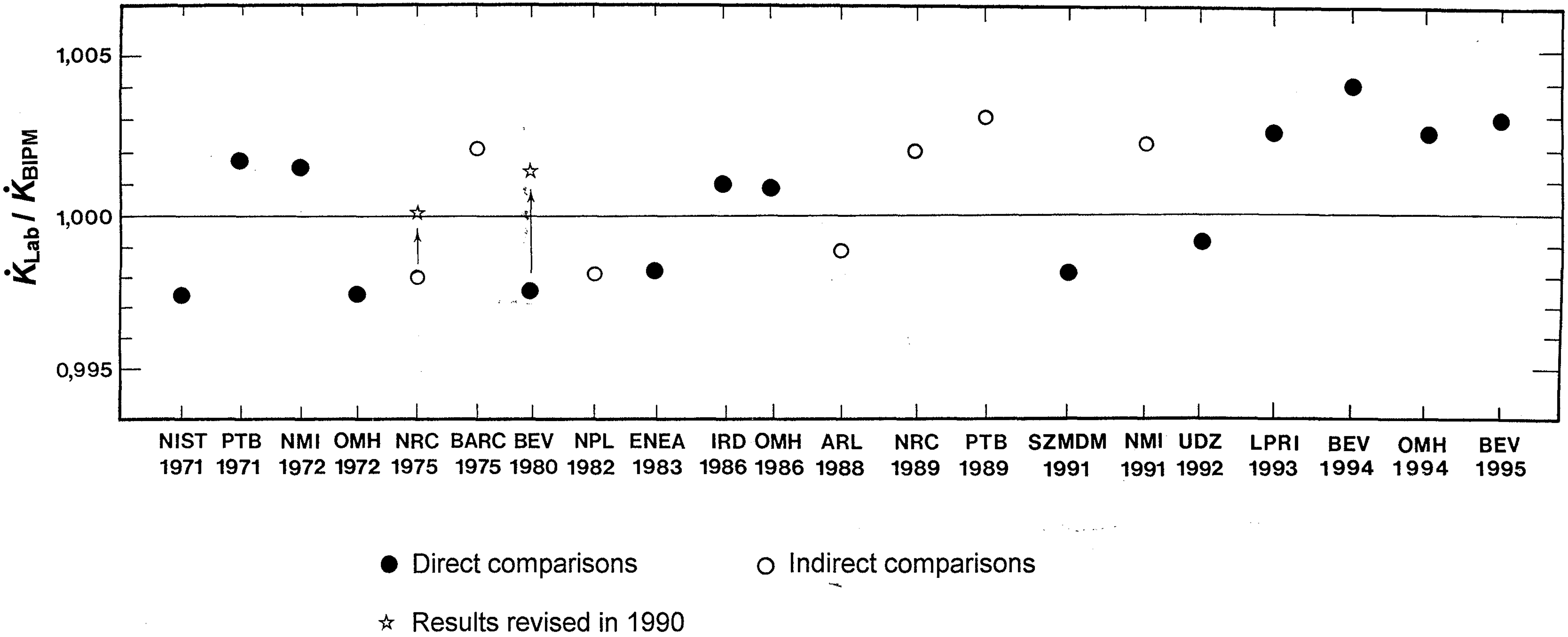

Figure 1. NATIONAL COMPARISONS OF AIR KERMA IN ^{60}CO RADIATION.