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of the PTB and the BIPM for ^{60}Co and ^{137}Cs gamma radiation

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Abstract

Direct comparisons of the standards for air kerma of the Physikalisch-Technische Bundesanstalt (PTB, Germany) and of the Bureau International des Poids et Mesures (BIPM) were carried out in the ^{60}Co and ^{137}Cs radiation beams of the BIPM in 2000. The results, expressed as ratios of the PTB and the BIPM standards for air kerma, indicate a relative difference in ^{60}Co of 9.9×10^{-3} with a combined standard uncertainty of 1.8×10^{-3}, and in ^{137}Cs of 6.4×10^{-3} with a combined standard uncertainty of 2.8×10^{-3}. The earlier comparisons in ^{60}Co γ rays made in 1971 (direct) and 1989 (indirect) resulted in an agreement of the two standards within 2×10^{-3}. The differences obtained now are due to the application of new correction factors for wall effects and point source non-uniformity of the beam, k_{wall} and k_{pn}, for the PTB standards, which were calculated using Monte Carlo methods.

Introduction

The last direct comparison of the air kerma standards of the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany and the Bureau International des Poids et Mesures (BIPM) for ^{60}Co gamma radiation dates back to 1971. An indirect comparison was carried out for ^{60}Co air kerma in 1989. Hitherto, no comparison was made for ^{137}Cs air kerma. The PTB produced and put into operation, in 2000, a set of new standard cavity ionization chambers. Special emphasis was given to the mechanical measurements of the cavity volume. Some essential changes were made concerning some of the correction factors (see section 3). For these reasons and the fact that the last comparison dated more than 10 years previously, a direct comparison of the standards for air kerma in ^{60}Co and ^{137}Cs gamma radiation of the PTB and the BIPM was carried out in December 2000 in the BIPM ^{60}Co and ^{137}Cs radiation beams.

The air kerma standard of the PTB for ^{60}Co and for ^{137}Cs is the mean response of three graphite cavity ionization chambers of different shapes and volumes (from about 0.55 cm^3 to about 6.14 cm^3). The PTB standards are described in [1]. The BIPM standards are parallel-plate graphite cavity ionization chambers as described in [2, 3].

2. Determination of the air kerma

For the BIPM standards and the PTB standards, the air kerma rate is determined from

$$\dot{K} = (I/m)(W/e)(1-\bar{g})^{-1}(\bar{\mu}_{en}/\rho)_{a,c}\,\bar{s}_{c,a}\Pi k_i \quad (1)$$

where

I	is the ionization current measured for the mass m of air in the cavity,
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 in bremsstrahlung production,
$(\bar{\mu}_{\mathrm{en}}/\rho)_{\mathrm{a,c}}$	is the ratio of the mean mass-energy absorption coefficients of air and graphite,
$\bar{s}_{\mathrm{c,a}}$	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
	$= k_{\mathrm{s}}\, k_{\mathrm{h}}\, k_{\mathrm{st}}\, k_{\mathrm{sc}}\, k_{\mathrm{at}}\, k_{\mathrm{CEP}}\, k_{\mathrm{an}}\, k_{\mathrm{m}}$ for the BIPM standard
	$= k_{\mathrm{s}}\, k_{\mathrm{h}}\, k_{\mathrm{st}}\, k_{\mathrm{wall}}\, k_{\mathrm{pn}}\, k_{\mathrm{bn}}$ for the PTB standard

The values of the physical data used in (1) are consistent with the CCEMRI(I) 1985 recommendations [4] and the correction factors needed for ^{60}Co and ^{137}Cs radiation are also shown in Tables 1 to 4 for both the PTB and the BIPM standards, together with their associated uncertainties.

3. Air kerma standards at the PTB since 1970

From 1970 until fairly recently, the PTB has used a set of three cavity ionization chambers that are different in shape and size [5, 6] as their air kerma standard. Two were cylindrical type chambers (denoted as PTB(a) and PTB(b) in reference [5]) and the third (denoted as PTB(c) in reference [5]) is a parallel-plate type chamber. These standards were directly compared with the BIPM standard for ^{60}Co air kerma in 1971 and the results were published in 1975 [5]. An indirect comparison of the air kerma standards of the PTB and the BIPM was carried out for ^{60}Co air kerma in 1989 and the results were published in 1993 [7]. The mean values of the dose-rate ratios measured with the PTB and BIPM standards at BIPM in terms of exposure rate in 1971 and air kerma rate in 1989 were 1.0017(50) and 1.002(2), respectively. However, two chambers of the original set (which was designed, machined and constructed at the PTB about 35 years ago) have since been broken.

Consequently, in 1998 the PTB decided to fabricate a new set of standards with exactly the same dimensions but with improvements in design, materials and manufacturing process. The designation of the new set is HRK-1 and HRK-2 for the two cylindrical, and HRK-3 for the parallel-plate chamber. Special emphasis was given to the mechanical measurements and determination of the chamber volumes. The density of the high purity graphite material used for the walls and electrodes is 1.775 g/cm^3, and the insulating material is MAKROLON $(C_{16}H_{14}O_3)_n$. A set of build-up caps is available for all chambers, more details are given elsewhere [1]. Measurements in ^{137}Cs beams are made using the bare chambers with 2 mm wall thickness. In ^{60}Co beams an additional build-up cap of thickness 1 mm is added in order to obtain a total wall thickness of 3 mm. The main dimensions and characteristics of the PTB chambers involved in this comparison are summarized in Table 5.

Table 1. Physical constants and correction factors with their estimated relative uncertainties of the BIPM standard for the ^{60}Co and ^{137}Cs gamma radiation beams at the BIPM

BIPM standard		^{137}Cs values	^{137}Cs uncertainty[1] 100 s_i	^{137}Cs uncertainty[1] 100 u_i	^{60}Co values	^{60}Co uncertainty[1] 100 s_i	^{60}Co uncertainty[1] 100 u_i
Physical Constants							
ρ_0	dry air density[2] /kg m^{-3}	1.2930		0.01	1.2930		0.01
$(\mu_{en}/\rho)_{a,c}$		0.9990		0.05	0.9985		0.05
$\bar{s}_{c,a}$		1.0104		0.11[3]	1.0010		0.11[3]
W/e	J/C	33.97			33.97		
$\bar{g}$	bremsstrahlung loss	0.0012		0.02	0.0032		0.02
Correction factors:							
k_s	recombination losses	1.0014	0.01	0.01	1.0015	0.01	0.01
k_h	humidity	0.9970		0.03	0.9970		0.03
k_{st}	stem scattering	0.9998	0.01		1.0000	0.01	
k_{at}	wall attenuation	1.0540	0.01	0.04	1.0398	0.01	0.04
k_{sc}	wall scattering	0.9535	0.01	0.15	0.9720	0.01	0.07
k_{cep}	mean origin of electrons	0.9972		0.01	0.9922		0.01
k_{an}	axial non-uniformity	0.9981		0.07	0.9964		0.07
k_{rn}	radial non-uniformity[4]	1.0011	0.01	0.03	1.0016	0.01	0.02
V	chamber volume[5] /cm^3	6.8344	0.01	0.01	6.8028	0.01	0.03
I	ionization current / pA		0.03	0.02		0.01	0.02
Relative standard uncertainty							
quadratic summation			0.04	0.24		0.02	0.17
combined uncertainty			**0.24**			**0.17**	
Relative standard uncertainty neglecting contributions from physical constants and k_h							
quadratic summation			0.04	0.18		0.02	0.12
combined uncertainty			**0.18**			**0.12**	

(1) 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

(2) At 101 325 Pa and 273.15 K

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

(4) For the 20 cm diameter ^{137}Cs beam

(5) BIPM standards CH5-3 and CH5-1in ^{137}Cs and ^{60}Co respectively [14].

Table 2. Physical constants and correction factors with their estimated relative uncertainties of the PTB HRK-1 standard for the ^{60}Co and ^{137}Cs gamma radiation beams at the BIPM

PTB: HRK-1		^{137}Cs values	^{137}Cs uncertainty[1] 100 s_i	^{137}Cs uncertainty[1] 100 u_i	^{60}Co values	^{60}Co uncertainty[1] 100 s_i	^{60}Co uncertainty[1] 100 u_i
Physical Constants							
ρ_0	dry air density[2] /kg m^{-3}	1.2930		0.01	1.2930		0.01
$(\mu_{en}/\rho)_{a,c}$		0.9990		0.05	0.9985		0.05
$\bar{s}_{c,a}$		1.0104		0.30	1.0010		0.11[3]
W/e	J/C	33.97		0.15	33.97		
$\bar{g}$	bremsstrahlung loss	0.0012		0.02	0.0032		0.02
Correction factors:							
k_s	recombination losses[4]	1.0030	0.05	0.05	1.0030	0.05	0.05
k_h	humidity	0.9970		0.03	0.9970		0.03
k_{st}	stem scattering	0.9983	0.05		0.9986	0.05	
k_{wall}	wall effects	1.0094	0.01	0.05	1.0097	0.01	0.05
k_{pn}	point source non-uniformity	1.0013	0.05	0.05	1.0005	0.03	0.05
k_{bn}	radial beam non-uniformity[4]	1.0001		0.01	1.0001		0.05
V	chamber volume /cm^3	0.5539	0.05		0.5539	0.05	
I	ionization current / pA		0.15	0.02		0.02	0.02
Relative standard uncertainty							
quadratic summation			0.18	0.36		0.09	0.16
combined uncertainty			**0.40**			**0.19**	
Relative standard uncertainty neglecting contributions from physical constants and k_h							
quadratic summation			0.18	0.10		0.09	0.10
combined uncertainty			**0.21**			**0.14**	

(1) 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

(2) At 101 325 Pa and 273.15 K

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

(4) In the BIPM beams

Table 3. Physical constants and correction factors with their estimated relative uncertainties of the PTB HRK-2 standard for the ^{60}Co and ^{137}Cs gamma radiation beams at the BIPM

PTB: HRK-2		^{137}**Cs**			^{60}**Co**		
		values	uncertainty(1)		values	uncertainty(1)	
			100 s_i	100 u_i		100 s_i	100 u_i
Physical Constants							
ρ_0	dry air density(2) /kg m^{-3}	1.2930		0.01	1.2930		0.01
$(\mu_{en}/\rho)_{a,c}$		0.9990		0.05	0.9985		0.05
$\bar{s}_{c,a}$		1.0104		0.30	1.0010		0.11(3)
W/e	J/C	33.97		0.15	33.97		
$\bar{g}$	bremsstrahlung loss	0.0012		0.02	0.0032		0.02
Correction factors:							
k_s	recombination losses(4	1.0022	0.05	0.05	1.0022	0.05	0.05
k_h	humidity	0.9970		0.03	0.9970		0.03
k_{st}	stem scattering	0.9978	0.05		0.9982	0.05	
k_{wall}	wall effects	1.0135	0.01	0.05	1.0134	0.01	0.05
k_{pn}	point source non-uniformity	1.0006	0.05	0.05	1.0002	0.04	0.05
k_{bn}	radial beam non-uniformity(4)	1.0002		0.05	1.0002		0.05
V	chamber volume /cm^3	1.5190	0.03		1.5190	0.03	
I	ionization current / pA		0.03	0.02		0.03	0.02
Relative standard uncertainty							
quadratic summation			0.10	0.36		0.09	0.16
combined uncertainty			**0.37**			**0.19**	
Relative standard uncertainty neglecting contributions from physical constants and k_h							
quadratic summation			0.10	0.10		0.09	0.10
combined uncertainty			**0.14**			**0.14**	

(1) 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

(2) At 101 325 Pa and 273.15 K

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

(4) In the BIPM beams

Table 4. Physical constants and correction factors with their estimated relative uncertainties of the PTB HRK-3 standard for the ^{60}Co and ^{137}Cs gamma radiation beams at the BIPM

PTB: HRK-3		^{137}Cs			^{60}Co		
		values	uncertainty[1]		values	uncertainty[1]	
			100 s_i	100 u_i		100 s_i	100 u_i
Physical Constants							
ρ_0	dry air density[2] /kg m^{-3}	1.2930		0.01	1.2930		0.01
$(\mu_{en}/\rho)_{a,c}$		0.9990		0.05	0.9985		0.05
$\bar{s}_{c,a}$		1.0104		0.30	1.0010		0.11[3]
W/e	J/C	33.97		0.15	33.97		
$\bar{g}$	bremsstrahlung loss	0.0012		0.02	0.0032		0.02
Correction factors:							
k_s	recombination losses[4]	1.0011	0.05	0.05	1.0011	0.05	0.05
k_h	humidity	0.9970		0.03	0.9970		0.03
k_{st}	stem scattering	0.9989	0.05		0.9992	0.05	
k_{wall}	wall effects	0.9980	0.01	0.05	1.0004	0.01	0.05
k_{pn}	point source non-uniformity	1.0018	0.04	0.05	1.0015	0.03	0.05
k_{bn}	radial beam non-uniformity[4]	1.0011		0.05	1.0016		0.05
V	chamber volume /cm^3	6.138	0.08		6.138	0.08	
I	ionization current / pA		0.03	0.02		0.03	0.02
Relative standard uncertainty							
quadratic summation			0.12	0.36		0.12	0.16
combined uncertainty			**0.38**			**0.20**	
Relative standard uncertainty neglecting contributions from physical constants and k_h							
quadratic summation			0.12	0.10		0.12	0.10
combined uncertainty			**0.16**			**0.15**	

(1) 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

(2) At 101 325 Pa and 273.15 K

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

(4) In the BIPM beams

Table 5. The main dimensions and characteristics of the new PTB cavity chambers

PTB chamber	**HRK-1**	**HRK-2**	**HRK-3**
shape	cylinder	cylinder	parallel-plate
Dimensions /mm			
outer height	24	24	8.5
outer diameter	10	14	48
inner height	20	20	4.5
inner diameter	6	10	44
minimum wall thickness	2	2	2
electrode diameter	1	2	40
electrode height	17.5	16	0.5
volume of air cavity /cm^3	0.5539	1.519	6.138
applied voltage (both polarities)	100 V	200 V	100 V

The PTB correction factors for recombination losses, k_s, were determined from the extrapolation $U \to \infty$ of the $I/I_0(U^{-1})$ plot, where U is the applied polarizing voltage, I is the measured ionization current if U is applied, and I_0 is the ionization current if U_0, the normal operating voltage is applied. The influence of the stem scattering was measured with dummy stems and corrected for by applying k_{st}. The correction factors for the radial non-uniformity of the beam, designated as k_{bn}, were calculated from measured beam profiles in the radial direction.

Special emphasis was given to the remaining correction factors, k_{wall} and k_{pn}, which correct for scattering and attenuation of photons in the wall of the chamber and for the point source non-uniformity of the beam. The wall correction factor is often written as $k_{wall} = k_{at}\, k_{sc}\, k_{cep}$, where k_{at} and k_{sc} account for attenuation and scattering of photons in the wall and k_{cep} accounts for the fact that the centre of electron production is upstream of where the energy is deposited in the chamber cavity. A common way to determine k_{wall} is to measure the ionization chamber response as a function of the wall thickness using build-up caps and then to extrapolate linearly to zero wall thickness. The value obtained this way is then multiplied by a calculated value of k_{cep}. This method of extrapolation was used hitherto at the PTB. An alternative way is to calculate k_{wall} with Monte Carlo methods ([8], and references therein). Recent investigations of Büermann *et al* [9] strongly support the use of calculated k_{wall} and k_{pn} values and were therefore used for the new PTB standards involved in this comparison.

Cavity theory is valid for parallel incidence of the radiation beam. However, real ^{60}Co and ^{137}Cs radiation sources more closely resemble a point source, although this is also an approximation. The associated deviations due to this effect were formerly accounted for by k_{an}, the correction factor for the axial beam non-uniformity. Bielajew [10,11] developed an analytic theory for cavity ionization chambers which includes k_{pn}, the point-source non-uniformity correction factor, which essentially replaces k_{an}. For the new PTB standards, the approach of Rogers *et al* [8] is followed who calculated k_{pn} as the ratio of the dose deposited in the cavity, corrected for wall effects in the parallel radiation case and for the case of a point source at a given distance from the centre of the cavity.

The correction factors k_{wall} and k_{pn} were calculated using the Monte Carlo Code CAVRZnrc [12], and the results are listed in the Tables 1 to 4. More details of the calculations are given elsewhere [9], with a comparison between results obtained using the traditional methods described above and those obtained using Monte Carlo calculations.

It is important to note that the application of the new calculated correction factors leads to a mean increase of the air kerma response of the PTB cavity chambers of 0.95 % for ^{60}Co γ-rays and 0.86 % for ^{137}Cs γ-rays. The old and new correction factors and the differences are summarized in Table 6. It should be noted, that the application of the calculated value of k_{pn} instead of k_{an} used hitherto leads to more significant changes than the use of the calculated instead of the extrapolated wall correction factors. This is particularly true for the parallel-plate chamber HRK-3. These changes have now been implemented for the PTB standard and are disseminated as presented in [13].

Table 6. Comparison of old and new correction factors for the PTB cavity chambers

^{60}Co beams									
chamber	HRK-1			HRK-2			HRK-3		
	old	new	Δ	old	new	Δ	old	new	Δ
$k_{at}k_{sc}$	1.0130			1.0133			1.0078		
k_{cep}	0.9940			0.9940			0.9940		
k_{wall}	1.0069	1.0097	0.0028	1.0072	1.0134	0.0062	1.0018	1.0004	-0.0014
k_{an}(old); k_{pn} (new)	0.9955	1.0005	0.0050	0.9925	1.0002	0.0077	0.9933	1.0015	0.0082
total difference			0.0078			0.0139			0.0068
mean of total differences:					**0.0095**				

^{137}Cs beams									
chamber	HRK-1			HRK-2			HRK-3		
	old	new	Δ	old	new	Δ	old	new	Δ
$k_{at}k_{sc}$	1.0089			1.0092			1.0047		
k_{cep}	0.9980			0.9980			0.9980		
k_{wall}	1.0069	1.0094	0.0025	1.0072	1.0135	0.0063	1.0027	0.9980	-0.0047
k_{an}(old); k_{pn} (new)	0.9957	1.0013	0.0056	0.9928	1.0006	0.0078	0.9936	1.0018	0.0082
total difference			0.0081			0.0141			0.0035
mean of total differences:					**0.0086**				

4. Experimental conditions

The three PTB standards were placed in turn in the two BIPM radiation beams. The reference conditions of measurement used at the BIPM [14] and the PTB are given in Table 7.

At the BIPM, an insulating cabin was used to minimize temperature fluctuations and during a series of measurements in the ^{60}Co beam the air temperature was stable to better than 0.005 °C, while in the ^{137}Cs beam it was better than 0.05 °C. The air temperature was stable to better than 0.1 °C at the PTB.

Table 7. Measurement conditions at the BIPM and the PTB

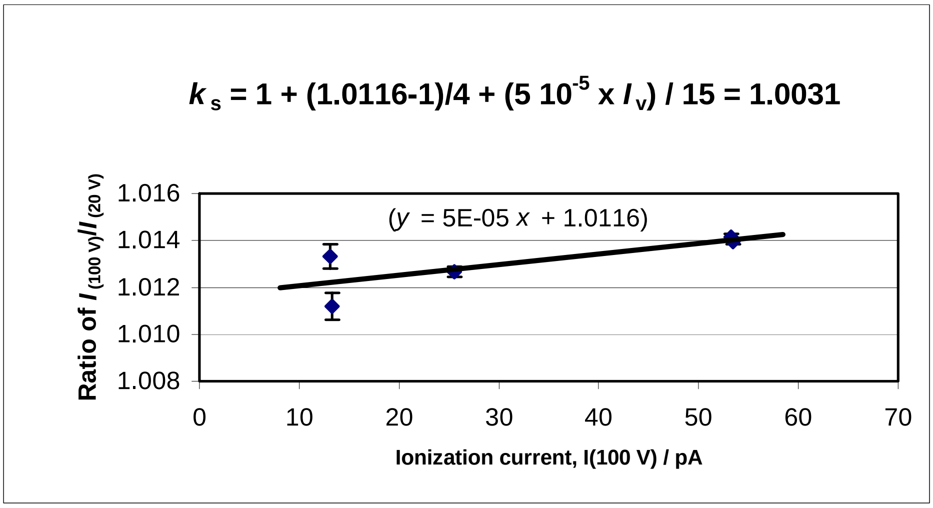
Parameter	^{137}Cs		^{60}Co	
	BIPM	PTB	BIPM	PTB
Position of the centre of the standard chamber	1 m from the source	1 m from the source	1 m from the source	1 m from the source
Beam cross-section	Φ = 20 cm	Φ = 20 cm	10 cm × 10 cm	Φ = 17 cm
Nominal $\dot{K}$	20 μGy s^{-1}	700 μGy s^{-1}	3 mGy s^{-1}	0.7 mGy s^{-1}
Incident scatter in terms of energy fluence	30 %	not evaluated	14 %	18 % (source no. 2)
Humidity range /%	50 ± 5	50 ± 10	50 ± 5	50 ± 10
Temperature / °C	20.8 to 21.9	19.5 to 20.5	20.4 to 20.7	19.5 to 20.5
Pressure / kPa	100.1 to 101.6	100.5 to 101.6	99.9 to 100.7	100.5 to 101.6
Measurement of charge	Keithley electrometer	Keithley electrometer	Keithley electrometer	Keithley electrometer

The ionization current measured from each PTB standard was corrected for the leakage current. The relative correction was less than 10^{-4} at the BIPM for ^{60}Co, and 10^{-3} in the ^{137}Cs beam where the air kerma rate is 100 times less than that in the ^{60}Co beam. It is important to note that the PTB chamber HRK-2 had a relative leakage current correction of around 10^{-2} in the ^{137}Cs beam. It was therefore decided in this case to use only the HRK-1 and HRK-3 results for the comparison. Each of the standards was re-positioned three times to measure the air kerma rate in the ^{60}Co beam and at least twice in the ^{137}Cs beam.

Some measurements were made to confirm the PTB correction of 1.0030 for ion recombination in the chamber HRK-1 at the BIPM as this standard has the highest correction factor for this effect. The value obtained at the BIPM using the Niatel method described in [15] is 1.0031 (0.0003) which is in agreement with the PTB evaluation. Figure 1 shows the BIPM experimental results.

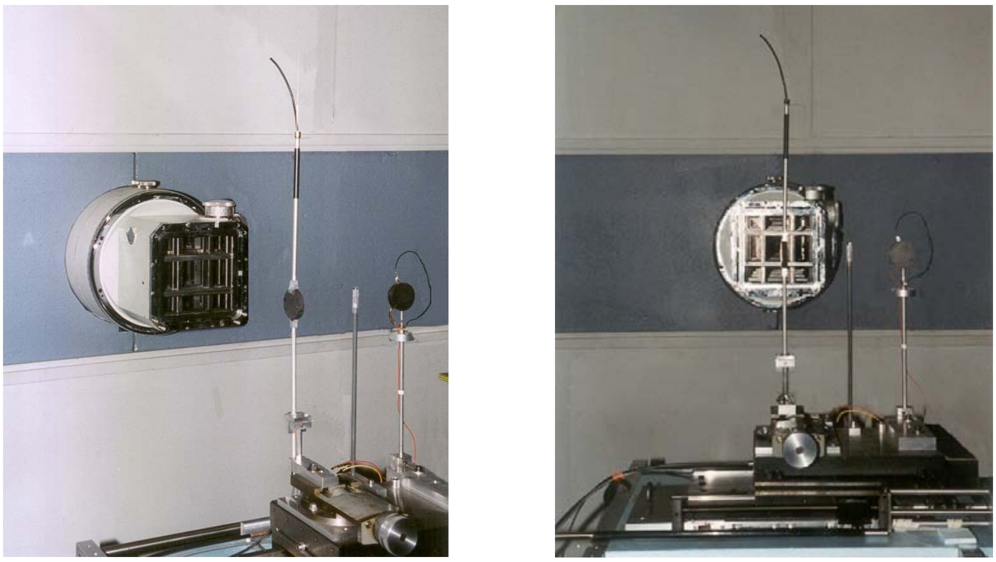
Some measurements were also made to identify the effect of different attenuation and scatter effects in the walls of the standard HRK-3 when irradiated at different angles of radiation incidence. The calculated values of k_{wall} predict a decrease of the response of the parallel-plate type chamber by about 11 % if the chamber is irradiated at an angle of 90° (radial incidence) with respect to the normal (axial) incidence. The values measured at the PTB reflected a decrease of about 10 %. At the BIPM, measurements were made with the HRK-3 at 90° and at 270° yielding a mean decrease of the response of 8.5 %. It is interesting that this significant change in response is predicted by the calculated wall correction factor. It would not be appropriate to apply the traditional method of extrapolation to such a geometry. This is discussed in more detail by Büermann *et al* [9]. The different values obtained for the decrease of the response measured in the PTB and the BIPM beams might be explained by (i) a dependence of k_{wall} on the size and geometry of the source, which are different at the PTB and the BIPM, and/or (ii) by the experimental difficulty in positioning the parallel-plate chamber with its curved surface perpendicular to the beam. Experiments have shown that the response of the chamber varies significantly between 85° and 95°. Effects due to extended sources were not simulated in the Monte Carlo calculations, where a point source was assumed.

Figure 1 Recombination measurements made at the BIPM for the HRK1 standard



A measurement was made at the BIPM to confirm the effect of an additional stem. This was made while the HRK-3 chamber was in the rotated position. Figure 2 shows the experimental arrangement. The measured effect was of the order of 5×10^{-4} which is similar to that measured at the PTB with the chamber in its normal position.

Figure 2 Experimental arrangement for radial irradiation of the HRK3. The photographs also show the dummy stem in place for the relative measurement of the stem effect. (The BIPM standard is on the right hand side of each photograph.)



The stability of the PTB standards was confirmed by measurements made at the PTB after their return. Agreement for each standard was within 3×10^{-4} of its previous value.

In 2005, during a comparison of absorbed dose to water standards at the BIPM, the opportunity was taken to re-measure the air kerma rate at the BIPM using the PTB standard HRK-3.

5. Results and discussion

The values of the measured ionization current from each standard are given in Table 8. These values are corrected for leakage and for decay from the measurement date to the reference date, and normalized to the reference conditions of air temperature 273.15 K and pressure of 101.3 kPa.

The comparison results are given by,

$$R_{\dot{K}} = \dot{K}_{\mathrm{PTB}} / \dot{K}_{\mathrm{BIPM}} , \qquad (2)$$

where $\dot{K}$ is the value of the air kerma rate at the BIPM measured by the PTB and BIPM standards, respectively. The results are given in Table 9 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 Tables 1 to 4. The uncertainty in the position of each chamber at the BIPM is less than 0.01 %.

Table 8. Ionization currents measured with the PTB standards at the BIPM

^{60}Co radiation, values are given in pA				Mean values	100 s*
HRK1	65.611	65.616	65.636	65.621	0.02
HRK2	179.20_4	179.25_2	179.22_6	179.23	0.01
HRK3	731.73	731.87	731.86	731.82	0.01
^{137}Cs radiation, values are given in pA					
HRK1	0.411 61	0.411 17	–	0.411 39	0.05
HRK3	4.6040	4.6036	4.6039	4.6038	0.02

* relative statistical uncertainties in the measurements

Each air kerma value for the PTB standards is derived from the mean of the measurement series in Table 8 using the physical constants and correction factors given in Tables 2 to 4. The BIPM air kerma value is the mean of measurements made over several months before and after the comparison.

The current measured with the HRK3 in October 2005, under the same conditions as in 2000 but with a reference date of 01/01/2005, was 378.82 pA. This gives a value for air kerma of 1.6271 mGy/s using the data in Table 4, which produces a comparison result of 1.0087 (18). The difference between this value and the 2000 comparison value of 1.0094 (18) is of the order of the expanded combined statistical uncertainties of the ionization currents of the two standards from Tables 1 and 4, of 6×10^{-4}.

Table 9. Results of the comparisons of standards for air kerma

Beam	PTB chamber	$\dot{K}_{\mathrm{PTB}}$ /mGy s^{-1}	$\dot{K}_{\mathrm{BIPM}}$ /mGy s^{-1}	R_K	100 u_c
^{60}Co	HRK1	3.1486	3.1141	1.0111	0.18
	HRK2	3.1430	3.1141	1.0093	0.18
	HRK3	3.1433	3.1141	1.0094	0.19
Mean values		**3.1450**	**3.1141**	**1.0099**	**0.18**

Beam	PTB chamber	$\dot{K}_{\mathrm{PTB}}$ /μGy s^{-1}	$\dot{K}_{\mathrm{BIPM}}$ /μGy s^{-1}	R_K	100 u_c
^{137}Cs	HRK1	19.899	19.760	1.0070	0.29
	HRK3	19.872	19.760	1.0057	0.26
Mean values		**19.886**	**19.760**	**1.0064**	**0.28**

The values of $\dot{K}$ refer to an evacuated path length between source and standard. They are given at the reference date of 2000-01-01: 0 h UT (the half life of ^{60}Co is taken as 1925.5 (0.5) days [16]) and of ^{137}Cs is taken as 11050 (40) days [17].

Table 9 shows that the PTB and the BIPM standards of air kerma differ by about 5 times the standard uncertainty in the ^{60}Co beam. Compared to the last comparison of air kerma in ^{60}Co gamma radiation (see section 3) R_K has increased by about 0.8 %.

The difference between the standards is just over twice the standard uncertainty in the ^{137}Cs beam. This was the first comparison of the PTB and BIPM standards for ^{137}Cs and therefore no previous value is available. However, the reason for the discrepancy obtained in the result is probably also due to the differences in k_{wall} and k_{pn} between Monte Carlo calculations and experimental determinations, as for those obtained in ^{60}Co γ radiation.

In the last two years, the BIPM has also made Monte Carlo calculations of the wall corrections and other factors for its ^{60}Co standard to verify its determination of air kerma [18]. The effect that this would have on the present comparison result is shown in Table 10. However, any new result needs to be approved and implemented at a date to be confirmed by the CCRI, probably in 2007. Similar evaluations for ^{137}Cs are in hand and the values given in the lower part of Table 10 for ^{137}Cs are currently based on [8].

Table 10. Changes to the results if the Monte Carlo calculated correction factors are used for the BIPM standard

Correction factor	^{60}Co		
	present	new [18]	ratio
k_{wall}	1.0028 (8)	1.0012 (2)	0.9984
k_{an}	0.9964 (7)	1.0027 (3)	1.0063
total difference*			1.0046
***R*$_K$ (new)**	**1.0053 (18)**		

*including other small changes [18]

Correction factor	^{137}Cs		
	present	new [8]	ratio
k_{wall}	1.0022 (15)	0.9999 (2)	0.9968
k_{an}	0.9981 (7)	1.0018 (4)	1.0037
total difference			1.0005
***R*$_K$ (new)**	**1.0059 (28)**		

For both ^{60}Co and ^{137}Cs beams, the changes due to the re-evaluation of k_{an} are more significant than the changes due to the calculated k_{wall} correction factors. However, there remains a systematic difference between the PTB and BIPM air kerma standards of, at least, 0.5 % for both ^{60}Co and ^{137}Cs beams. A similar difference of about 0.5 % was also found in the analyses made by Rogers et al [8] for many other national standards. No satisfactory explanation has been identified as yet for such a difference and the BIPM is currently investigating possible causes. Although the MC evaluated correction factors differ by about 0.2 % for the two similar parallel-plate cavity standards of the PTB and the BIPM, this would actually increase the overall difference between the two standards.

5.1 Analysis of the BIPM ongoing ^{60}Co air kerma comparisons

The results of air kerma comparisons in ^{60}Co at the BIPM are currently being re-evaluated, taking into account the effect of changes being made in many national standards following the recommendations of the Consultative Committee for Ionizing Radiation (CCRI) [19]. The NRC (Canada), OMH (Hungary), PTB (Germany) and the BEV (Austria) have already declared new values for their air kerma standard [20, 21 13, 22]. The SZMDM (Yugoslavia), the NCM (Bulgaria) and the ENEA (Italy), all of which have made comparisons recently with the BIPM [23, 24, 25], have also changed their previous method of k_{wall} determination, now using Monte Carlo calculations. The NMi and the LNMRI/IRD have recently confirmed their earlier comparison results [26, 27] but are in the process of recalculating wall effects for their primary standard, the latter of which has a similar shape and size to the OMH standard.

In the meantime, the other comparisons that have been made are being reviewed, such as for the NIST (USA) [28], and once the evaluations have been updated and the results approved by the CCRI(I), they will be published in the BIPM key comparison database (KCDB) that was set up under the CIPM Mutual Recognition Arrangement [29]. The comparison identifier is known as the BIPM.RI(I)-K1 key comparison.

5.2 BIPM ongoing ^{137}Cs air kerma comparisons

Several other national laboratories have also made ^{137}Cs comparisons with the BIPM [30] and the PTB result is not inconsistent with the other results. However, it is of note that the air kerma determinations in a ^{137}Cs beam made by the national metrology institutes are currently undergoing re-evaluation and at present have a greater spread of results than for ^{60}Co radiation beams. Once the results have been re-evaluated, they will be the subject of a summary report and the results will be placed in the KCDB under comparison identifier BIPM.RI(I)-K5.

6. Conclusion

The PTB standard for air kerma in ^{60}Co gamma radiation compared with the present BIPM air kerma standard gives a comparison result of 1.0099 (18). Although this is significantly different from the earlier comparisons with the BIPM, it compares favourably with other primary standards for which the wall and point-source non-uniformity correction factors have now been calculated using Monte Carlo methods.

In principle, all the comparison results of the national metrology institutes (NMIs) and designated laboratories will be used as the basis of the entries in Appendix B of the KCDB set up under the CIPM MRA. 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 expected that all the NMIs will be ready for their results to be entered into the BIPM KCDB by the end of 2005. In the meantime, the BIPM has also reviewed its experimental and calculated results for the wall and other correction factors for its primary standard. This re-evaluation of the BIPM primary standard will be published in the open literature before formal adoption.

The ^{137}Cs air kerma standards of the PTB and BIPM have been compared for the first time. The result for this comparison, R_K = 1.0064 (28), differs by more than the expanded uncertainties. The reasons for this difference are also related to the calculation of new correction factors as discussed for the ^{60}Co comparison.

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