Comparison of the air kerma standards of the OFMET and the BIPM in the low-energy x-ray range

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Abstract A direct comparison between the air kerma standards of the OFMET and the BIPM has been performed in the low-energy x-ray range. The results show that the standards are in close agreement, better than 0.2 %, at the five reference radiation qualities.

1. Introduction

A direct comparison was made between the OFMET and the BIPM standards of air kerma under the low-energy x-ray range (10 kV to 50 kV). The comparison took place in July 1998, in the reference conditions recommended by the Section I of CCEMRI [1].

2. Determination of the air kerma rate

The air kerma rate is determined by the relation

$$\dot{K} = (I / m)\,(W / e)\,(1 - g)^{-1}\ \Pi\, k_i\ ,$$

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,
g is the fraction of electron energy lost by bremsstrahlung,
$\Pi\, k_i$ is the product of the correction factors to be applied to the standard.

The values of the physical constants used for the determination of the air kerma rate are given in Table 1.

Table 1. Physical constants entering in the determination of the air kerma rate.

Air density [a]	1.2930 kg m^{-3}	s = 0.01 % [b]
1 - g	1.0000	s < 0.01 %
W/e	33.97 JC^{-1}	s = 0.15 %

a. at 101 325 Pa and 273.15 K.
b. s is the relative standard uncertainty.

The BIPM standard is described in [2] and its correction factors are listed in [3]. The diameter of the BIPM diaphragm used for the present comparison is 10 mm in place of the usual 5 mm diaphragm, to match that of the OFMET. The correction for recombination loss has been changed accordingly. The OFMET standard is a free-air ionization chamber, the dimensions of which are similar to those of the NPL standard. They are given in Table 2 together with the relative standard uncertainties, s. The OFMET standard, the details of which can be found in [4], has already been linked to the BIPM standard through the calibration of a transfer instrument [5] and it has been compared previously with the NPL standard [4].

Table 2. Main dimensions of the OFMET standards.

dimensions	value	s x 100
Plate separation/mm	62.5	-
Collecting plate width/mm	20.3113	0.015
Air path length/mm	90.09	0.06
Diaphragm diameter/mm	10.0045	0.005
Measuring volume/cm^3	1.5967	0.018
Applied voltage/V	1500	-

3. Measuring conditions

The radiation qualities used at the BIPM for the comparison are those recommended by the CCEMRI(I) [1] and are given in Table 3 together with the corresponding radiation qualities used at the OFMET, which are slightly different. The correction factors applied to the OFMET standard are listed in Table 4 together with their associated uncertainties.

Table 3. Radiation qualities at the OFMET and the BIPM.

distance between x-ray tube and reference plane = 50 cm.
beam diameter in the reference plane = 8 cm (OFMET) and 4.5 cm (BIPM).

Accelerating potential/kV	OFMET	9.3	23	31.6	49.2	-
	BIPM	10	25	30	50 (1)[a]	50 (2)[a]
HVL(Al)/mm	OFMET	0.036	0.250	0.350	1.000	-
	BIPM	0.036	0.250	0.176	1.021	2.257
μ_{air}[b] /10^{-4} cm^{-1}	OFMET	196	29	22	8.4	-
	BIPM	176	30.4	41.5	9.12	4.60
air kerma rate /mGy s^{-1}	OFMET	2.6	6.1	11.4	11.0	-
	BIPM	0.57	1.12	3.33	1.56	0.34

a. The filtrations for qualities 50 kV(1) and 50 kV(2) are 1 mm Al and 4 mm Al, respectively.
b. Air attenuation coefficient at 100.00 kPa and 20 °C.

Table 4. Correction factors of the OFMET standard.

	Accelerating potential/kV	10	25	30	50 (1)	50 (2)	s^a x 100	
							Type A	Type B
k_{sc}	Scattered radiation	0.9949	0.9971	0.9968	0.9979	0.9987	-	0.10
k_e	Electron loss	1.0000	1.0000	1.0000	1.0000	1.0000	-	-
k_s	Ion recombination	1.0006	1.0008	1.0015	1.0010	1.0006	0.04	0.01
k_d	Field distortion	1.0004	1.0004	1.0004	1.0004	1.0004	-	0.01
k_l	Aperture transmission	1.0000	1.0000	1.0000	1.0000	1.0000	-	<0.01
k_p	Wall transmission	1.0000	1.0000	1.0000	1.0000	1.0000	0.01	-
k_h	Humidity	0.998	0.998	0.998	0.998	0.998	-	0.03
k_{pol}	Polarity effect	0.9995	0.9995	0.9995	0.9995	0.9995	0.02	-

a. s represents the relative standard uncertainty, obtained by statistical means (type A) or other means (type B).

For the measurements, the OFMET standard was positioned close to the BIPM standard and its temperature measured with an OFMET thermistor. The polarization voltage was 1500 V (negative polarity). For the comparison, the x-ray tube was displaced so that the beam axis coincided with that of one standard or the other. Measurements with the OFMET standard were made immediately before and after the measurements with the BIPM standard, to correct for drift in the x-ray output which still occurs despite the good stability of the accelerating voltage and x-ray tube current.

The standards were irradiated before each series of measurement to reduce the current leakage. The leakage current of the OFMET standard did not exceed 0.01 % in relative value and an appropriate correction was made. The relative standard deviation of the mean of a series of five measurements was less than 2×10^{-4} for both standards, at each radiation quality.

4. Preliminary work

4.1. *Wall transmission of the OFMET standard.* The wall transmission of the OFMET standard was checked at the highest quality, 50(2) kV, by measuring the current leakage with and without the beam on, a thick lead plug being placed in front of the diaphragm. The net current resulting from radiation leakage was negligible, less than 1 fA.

4.2. *Comparison of air-attenuation coefficient.* During a comparison, the measured air attenuation coefficient of the BIPM beam is used to determine the correction for air attenuation along the path length between the defining plane and the centre of the collecting volume of both standards. This correction is very large at low energy. Measurements of air attenuation were made using a special OFMET ionization chamber provided with two collecting plates separated by 9.01 cm. At the quality 10 kV, the air attenuation for this distance was 14.61 %. The corresponding value determined by the BIPM method [2] is 14.64 %, in very close agreement. This result ensures the equivalence of the two methods. Unfortunately, no comparison of air attenuation coefficients was possible at other radiation qualities because of the lack of time.

4.3. *Diaphragm comparison.* A comparison between the OFMET and the BIPM diaphragms (Φ = 10 mm) was made at the quality 30 kV, using the OFMET chamber. The values of $(I/\Phi^2)_{OFMET}$ and $(I/\Phi^2)_{BIPM}$, where I is the ionization current, are in acceptable agreement, their ratio being 1.0005 (s = 0.0002).

4.4. *Polarity effect of the* OFMET *standard.* The polarity effect of the OFMET standard, was measured at the OFMET (1.000) by measuring the ionization currents I_+ and I_- obtained at positive and negative polarities. The polarity effect was checked at the BIPM at the quality 30 kV, and ratio I_+ / I_- was equal to 0.9990 (s = 0.0002). A value of 0.9995 has been attributed to the correction factor k_p during the present comparison. It was suggested that measurements at the OFMET should be made at the two polarities to check the stability of the chamber.

4.5. *Correction for recombination loss.* The experimental determination of k_s for the OFMET standard was not completed at the time of the comparison (measurements were made for one polarity alone). Hence, the OFMET has adopted the results of [6]. For the same voltage of 1500 V applied to the standards, the values of k_s are given by

$k_s(\text{OFMET}) = 1 + 0.00046 + 5.40 \cdot 10^{-6}\, I$ and
$k_s(\text{BIPM}) = 1 + 0.00051 + 8.88 \cdot 10^{-6}\, I$,

where the mean ionization current I, = $\frac{1}{2}(I_+ / I_-)$, is expressed in pA.

5. Results of the comparison

The results of the comparison are given in Table 5 and their associated uncertainties in Table 6. The relative total standard uncertainty of the air kerma rate is estimated to be 2×10^{-3} at the two laboratories. The uncertainty on the ratio $K_{\text{OFMET}}/K_{\text{BIPM}}$ takes into account the correlations between the measurements of both quantities (uncertainty of type B of the ionization current, humidity correction and physical constants). The correlations between the values of k_{sc} and k_e of the two standards, which are calculated from the same set of data, are not taken into account. The two standards agree within 0.1 % at all radiation qualities. This lies well within the estimated uncertainties, suggesting that the latter may have been too pessimistic.

The results obtained with the values of k_{sc}(BIPM) recently calculated by D.T. Burns [7] are also given in Table 5. The difference between the two standards then increases to 0.2 %, which is still within the uncertainties.

Table 5. Comparison results in the low x-ray range.

Accelerating potential/kV		10	25	30	50 (1)[a]	50 (2)[a]
$k_{sc\ \text{BIPM}}$	Previous value	0.9944	0.9957	0.9956	0.9956	0.9971
	New value	0.9958	0.9968	0.9967	0.9967	0.9979
$K_{\text{OFMET}}/K_{\text{BIPM}}$	(1)	0.9991	0.9994	0.9993	0.9994	0.9985
	(2)	0.9977	0.9983	0.9982	0.9983	0.9977

a. With previous or (2) with new values of k_{sc} for the BIPM standard.

Table 6. Relative uncertainties ascribed to the results of the comparison.

	BIPM standard		OFMET standard	
Relative uncertainty x 100	Type A	Type B	Type A	Type B
Volume	0.03	0.05	~~0.15~~ 0.015	0.005
Ionization current	0.02	0.02	0.02	0.02
Positioning	0.02	-	0.02	-
Physical factors	-	0.15	-	0.15
Correction factors	0.037	0.104	0.05	0.11
Quadratic summation	0.069	0.190	0.06	0.19
$s\,(K_{\text{LAB}})$	0.20		0.20	
$s\,(K_{\text{OFMET}} / K_{\text{BIPM}})$	0.18*			

*$s(\text{ratio}) = [s(K_{\text{OFMET}})^2 + s(K_{\text{BIPM}})^2 - 2\,\Sigma\,(s_{\text{com}})^2]^{1/2}$, where s_{com} are the common uncertainties affecting both K_{OFMET} and K_{BIPM}

6. Discussion and conclusion

The results of the present comparison are encouraging and their very small variation with radiation quality ensures a good coherence in the determination of the correction factors made in both laboratories.
The OFMET standard was previously compared with the NPL standard in 1992 [4] and the NPL and BIPM standards were compared in 1978 and 1997 [8]. The inferred OFMET/BIPM values, through these crossed comparisons, are given in Table 7 together with the present direct values. The overall agreement is remarkable and strengthens the coherence of the measurements made in these three laboratories.

Table 7. Results of OFMET-NPL-BIPM comparisons.

kV	*HVL* / *mm*	NPL/BIPM[1] 1978 / 1997	NPL/OFMET 1993	OFMET/BIPM[a] inferred values	OFMET/BIPM[b] present work
8.5	0.024	-	0.9996	-	-
10	0.036	0.9985 / 0.9983	1.0006	0.9978	0.9991
11.5	0.05	-	0.9989	-	-
16	0.10	-	0.9991	-	-
30	0.176	0.9986 / 0.9980	-		0.9993
25	0.25	0.9988 / 0.9995	0.9988	1.0003	0.9994
41	0.50	-	0.9987	-	-
50 (1)	1.00	0.9989 / -	0.9983	1.0006	0.9994
50 (2)	2.25	0.9989 / 0.9977	-	-	0.9985
mean		0.9987	0.9991	0.9993	0.9991

a. The previous values of k_{sc} (BIPM) are used for comparison purposes

For information, the results of comparisons made at the BIPM in the low-energy x-ray range are given in Annex 1.

7. Aknowledgement

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Annex 1. Results R [a] of the international comparisons of air kerma standards in the low-energy x-ray range.

$R = K_{LAB} / K_{BIPM}$

radiation quality	kV	10	25	30	50 (1)	50 (2)
	HVL(Al) / mm	0.036	0.250	0.176	1.021	2.257
Laboratory	Date	R	R	R	R	R
CIEMAT	1979	1.0021	1.0013	1.0011	1.0018	1.0025
ISS	1985	0.9986	0.9987	0.9975	0.9989	0.9989
ETL	1972	0.9958	-	0.9960	1.0031	-
GUM	1994	0.9963	-	0.9973	0.9968	0.9977
NIST	1966 1998[b]	0.9976 0.9941	-	0.9989 0.9961	0.9966 0.9968	0.9948 0.9938
NMi[c]	1966 1996	0.9964 0.9986	- -	0.9964 0.9998	- 1.0028	0.9948 1.0009
NPL	1978 1997[b]	0.9985 0.9983	0.9988 0.9995	0.9986 0.9980	0.9989 -	0.9989 0.9977
NRC	1966	1.0007	-	1.0003	0.9997	-
OFMET	1998	0.9991	0.9994	0.9993	0.9994	0.9985
OMH[d]	1988	0.9973	0.9994	-	1.0020	1.0010

a. With previous values of k_{sc}(BIPM).

b. Provisional values.

c. The correction factor k_{sc} was first modified in 1972 by Somerwil (experimental study [9]). Both correction factors k_{sc} and k_e have recently been redetermined by calculation (Grimbergen and van Dick, to be published).

d. A first comparison in 1979 is not considered here.

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