Rapport BIPM-01/04

MEASURING CONDITIONS USED FOR THE CALIBRATION OF IONIZATION CHAMBERS AT THE BIPM*

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Abstract. Information on the experimental conditions used at the BIPM in the x- and γ-radiation beams for the calibration of secondary standards in terms of air kerma, absorbed dose in water, and ambient dose equivalent, is assembled and presented together with the uncertainties involved in the determination of these dosimetric quantities.

I. Introduction

The BIPM calibrates secondary standards (ionization chambers) for countries which are Member States of the Metre Convention. It works with a single, designated laboratory in each country for a given type of measurement. The calibrated instruments are then normally used as national references. For this reason, the chambers should be instruments of good quality, in particular with respect to leakage currents and both short- and long-term stability. Their calibration factors must not vary significantly with the conditions of irradiation.

Calibrations of ionization chambers are performed at BIPM

- in terms of air kerma in the low- and medium-energy x-ray ranges and in ^{60}Co and ^{137}Cs gamma radiations,
- in terms of absorbed dose to water in ^{60}Co gamma radiation,
- in terms of ambient dose equivalent in ^{60}Co and ^{137}Cs gamma radiations.

The present report documents the conditions of measurement at the BIPM, the physical constants, and the estimated uncertainties of the factors used in the determination of these quantities.

II. General remarks

The reference plane is specified in terms of a distance from the radiation source or, in the case of low-energy x-rays, from the beam exit window. The reference point is the intersection of the beam axis with the reference plane.

For chamber types other than parallel plate, the chamber is positioned with its axis in the reference plane and with the stated point of measurement of the chamber at the reference point. For calibration in γ-radiation the chamber is used with the build-up cap provided. The orientation of the chamber is such that the number or text inscribed on the stem is facing the radiation source, unless a different orientation is indicated. Parallel-plate chambers are calibrated with the front surface of the collecting volume in the reference plane and with the circular entrance window centred on the beam axis.

All chambers are irradiated for at least thirty minutes, with the polarizing potential applied, before any measurements are made. The leakage current is normally measured before and after each set of measurements and a correction applied based on the mean value.

The irradiation facilities at the BIPM are temperature controlled (close to 20 °C) at the level of around 100 mK. For air kerma measurements in ^{60}Co and ^{137}Cs, an additional, passive enclosure is used to give temperature stability below 50 mK. The BIPM reference conditions for air temperature and pressure are T_0 = 20 °C and P_0 = 101 325 Pa, respectively. Relative humidity is controlled within the range 47 % to 53 % and consequently no humidity correction is applied.

No corrections are applied to the chamber response for ion recombination, or for the non-uniformity of the BIPM beams. However, these effects are mentioned, when appropriate.

III. Calibration in terms of air kerma (X-rays, ^{60}Co, ^{137}Cs)

The transfer chamber is operated in air at the stated reference distance. The calibration factor N_K is defined by the relation

$$N_K = \dot{K}_{\mathrm{BIPM}} / I \,, \qquad (1)$$

where $\dot{K}_{\mathrm{BIPM}}$ is the air kerma rate at the reference point, measured with the BIPM standard, and I is the ionization current of the transfer chamber under the BIPM reference conditions of air temperature and pressure. The value of I is given by

$$I = I_{exp} \,(TP_0)/(T_0 P) \;, \qquad (2)$$

where I_{exp} is the ionization current measured at temperature T and pressure P.

The calibration factor for exposure, N_X, is given by

$$N_X = N_K \,(1-g)/(W/e) \,, \qquad (3)$$

where g is the fraction of electron energy lost by bremsstrahlung [1], W is the mean energy expended to produce an ion pair in dry air, and e is the electron charge [1,2].

Details of the conditions of measurement at the BIPM and the uncertainties in the determination of $\dot{K}_{\mathrm{BIPM}}$ are given in Tables 1 to 6 for x-rays, in Tables 7 and 8 for ^{60}Co and in Tables 9 and 10 for ^{137}Cs. In these tables, the relative standard uncertainties estimated by statistical methods (Type A) are denoted by s_i and those estimated by other means (Type B) are designated by u_i.

IV. Calibration in terms of absorbed dose to water (^{60}Co)

The transfer chamber is placed in its waterproof sleeve and positioned in the BIPM water phantom of side 30 cm. Its axis is placed in the reference plane, at the depth of 5 g cm^{-2} in water. This depth includes the window of the phantom (PMMA, 0.476 g cm^{-2}). As well as correctly orienting the chamber, the mark on the sleeve is rotated so as to point towards the radiation source.

The calibration factor, $N_{D,\mathrm{w}}$, is determined using the relation

$$N_{D,\mathrm{w}} = \dot{D}_{\mathrm{w}} / (I_{\mathrm{w}} k_{\mathrm{pf}}) \,, \qquad (4)$$

where
$\dot{D}_{\mathrm{w}}$ is the absorbed dose rate to water at the reference point, measured by the BIPM standard at a depth of 5 g cm^{-2} in water;
I_{w} is the ionization current measured by the transfer chamber under the BIPM reference conditions of air temperature and pressure;
k_{pf} = 0.9996 is a correction factor applied to I_{w} for the non-equivalence with water of the PMMA window of the phantom. The conditions of measurement at the BIPM are given in Table 7. The physical constants and correction factors used in the ionometric determination of the absorbed dose rate to water at 5 g cm^{-2} are given in Table 11 along with their estimated relative uncertainties.

V. Calibration in terms of ambient dose equivalent (^{60}Co, ^{137}Cs)

The transfer chamber is positioned in air, with its axis in the reference plane.

The calibration factor, N_H is determined using the relation

$$N_H = \dot{H}^* / I_H \quad , \qquad (5)$$

where

$\dot{H}^*$ is the ambient dose equivalent rate. For ^{60}Co radiation, $\dot{H}^*$ is measured by the BIPM standard. For ^{137}Cs, $\dot{H}^*$ is deduced by calculation from the measurement of air kerma rate,

I_H is the ionization current measured by the transfer chamber under the BIPM reference conditions of air temperature and pressure.

The conditions of measurement at the BIPM are given in Tables 7 and 9 for ^{60}Co and ^{137}Cs, respectively. The physical constants and correction factors used in the ionometric determination of the ambient dose equivalent are given in Tables 12 and 13 for ^{60}Co and ^{137}Cs radiation, respectively.

VI. Use of calibration factors

Subject to certain provisions, a secondary standard calibrated in the BIPM beam can be used in another beam, taking the calibration factors N_K , $N_{D,\mathrm{w}}$ or N_H , obtained from (1), (4) and (5), respectively, to determine *K*, *D* or *H* in that beam.

(a) The humidity conditions must not differ significantly from those of the calibration at BIPM. Otherwise, if the relative humidity is outside the range 30 % to 70 %, the curves given in [3] should be used.

(b) The conditions of measurement must not as a whole differ significantly from those of the calibration at the BIPM. Otherwise, additional corrections may be necessary (see for example [4] and [5]). Particular attention should be paid to:

- the radiation quality, particularly in the x-ray range;
- the distance from the source;
- the dimensions of the radiation field, in particular as regards the radiation scattered by the stem and the support, for calibration in terms of air kerma;
- the intensity of the ionization current which can produce a change in the ion recombination;
- the radial non-uniformity of the beam over the cross-section of the chamber [6, 7].

Table 1. X-rays (10 kV to 50 kV)

Conditions of measurement at the BIPM

Distance between beryllium window of x-ray tube and reference plane of standard: 50 cm
Beam diameter in the reference plane: 9.5 cm
Air filtration : 59.4 mg cm^{-2} (50 cm at 20 ºC and 100 kPa); beryllium filtration: ≅ 3.2 mm

Reference qualities (recommended by Section I of CCEMRI [8,9])

X-ray tube voltage /kV	10	30	25	50(b)	50(a)[3]
filtration /(mm Al)	0	0.208	0.372	1.008	3.989
HVL[1] /(mm Al)	0.0368	0.169	0.242	1.017	2.262
μ/ρ [2] /(cm^2 g^{-1})	14.83	3.66	2.60	0.75	0.38
air kerma rate /(mGy s^{-1})	1.00	1.00	1.00	1.00	1.00

[1] half-value layer
[2] air attenuation coefficient
[3] the more-filtered of the two 50 kV radiation qualities

Table 2. X-rays (10 kV to 50 kV)

Physical constants and correction factors used in the BIPM determination[1] of the air kerma rate

Dry air density (273.15 K, 101 325 Pa) =1.2930 kg m^{-3}

W/e = 33.97 J C^{-1}

Measuring volume: 1.200 41 cm^3

	X-ray tube voltage /kV	10	30	25	50(b)	50(a)
Correction factors						
k_{sc}	scattered radiation	0.9944	0.9956	0.9957	0.9966	0.9971
k_e	electron loss	1.0000	1.0000	1.0000	1.0000	1.0000
k_s	ion collection	1.0006	1.0007	1.0007	1.0007	1.0007
k_a	air attenuation[2]	1.1956	1.0451	1.0319	1.0091	1.0046
k_d	field distortion	1.0000	1.0000	1.0000	1.0000	1.0000
k_l	transmission through edges of diaphragm	1.0000	1.0000	1.0000	1.0000	1.0000
k_p	transmission through walls of standard	1.0000	1.0000	1.0000	1.0000	1.0000
k_h	humidity	0.998	0.998	0.998	0.998	0.998
$1-g$	bremsstrahlung	1.0000	1.0000	1.0000	1.0000	1.0000

[1] details on the determination of the air kerma rate can be found in [10]

[2] values at 20 °C and 101 325 Pa

Table 3. X-rays (10 kV to 50 kV)

Estimated relative standard uncertainties in the BIPM determination of air kerma rate

		100 s_i [(1)]	100 u_i
Physical constant			
dry air density		-	0.01
(273.15 K, 101 325 Pa)			
W/e	/(J C^{-1})	-	0.15
g		-	0.01
Correction factors			
k_{sc}	scattered radiation	-	0.07
k_e	electron loss	-	0.01
k_s	recombination losses	0.02	0.01
k_a	air attenuation	0.03	0.01
k_d	field distortion	-	0.07
k_l	transmission through edges of diaphragm	-	0.01
k_p	transmission through walls of standard	0.01	
k_h	humidity	-	0.03
Measurement of $I/v\rho$			
v	volume /cm^3	0.03	0.05
I	ionization current correction concerning ρ (temperature, preassure, air compressibility)	0.03	0.02
Relative standard uncertainty in $\dot{K}_{BIPM}$			
quadratic sum		0.06	0.19
combined uncertainty			0.20

(1) s_i represents the relative standard Type A uncertainty, estimated by statistical methods;
u_i represents the relative standard Type B uncertainty, estimated by other means.

Table 4. X-rays (100 kV to 250 kV)

Conditions of measurement at the BIPM

Distance between focal spot and reference plane: 120 cm

Beam diameter in the reference plane: 10.5 cm

Inherent filtration: ≅ 2.3 mm Al

Reference qualities (recommended by Section I of the CCEMRI [8])

X-ray tube voltage /kV	100	135	180	250
additional filtration /(mm Al)	1.203	-	-	-
/(mm Cu)	-	0.232	0.485	1.570
half-value layer /(mm Al)	4.027	-	-	-
/(mm Cu)	0.148	0.494	0.990	2.500
μ/ρ [(1)] /(cm^2 g^{-1})	0.299	0.198	0.167	0.145
air kerma rate /(mGy s^{-1})	0.21	0.20	0.29	0.38

[(1)] air attenuation coefficient

Table 5. X-rays (100 kV to 250 kV)

Physical constants and correction factors used in the BIPM determination[(1)] of the air kerma rate

Dry air density (273.15 K, 101 325 Pa) =1.2930 kg m^{-3}

W/e = 33.97 J C^{-1}

Measuring volume: 4.6554 cm^3

	X-ray tube voltage /kV	100	135	180	250
Correction factors					
k_{sc}	scattered radiation	0.9948	0.9962	0.9967	0.9969
k_e	electron loss	1.0000	1.0023	1.0052	1.0078
k_s	ion collection	1.0005	1.0005	1.0005	1.0005
k_a	air attenuation	1.0100	1.0066	1.0056	1.0049
k_d	field distortion	1.0000	1.0000	1.0000	1.0000
k_l	transmission through edges of diaphragm	0.9999	0.9998	0.9997	0.9996
k_p	transmission through walls of standard	1.0000	1.0000	0.9999	0.9988
k_h	humidity	0.998	0.998	0.998	0.998
$1-g$	bremsstrahlung	0.9999	0.9999	0.9998	0.9997

[(1)] details on the determination of the air kerma rate can be found in [11]

Table 6. X-rays (100 kV to 250 kV)

Estimated relative standard uncertainties in the BIPM determination of air kerma rate

		100 s_i[(1)]	100 u_i
Physical constant			
dry air density (273.15 K, 101 325 Pa)		-	0.01
W/e	/(J C^{-1})	-	0.15
g		-	0.01
Correction factors			
k_{sc}	scattered radiation	-	0.07
k_e	electron loss	-	0.10
k_s	recombination losses	0.02	0.01
k_a	air attenuation	0.03	0.01
k_d	field distortion	-	0.07
k_l	transmission through edges of diaphragm	-	0.01
k_p	transmission through walls of standard	0.01	-
k_h	humidity	-	0.03
Measurement of $I/v\rho$			
v	volume /cm^3	0.01	0.05
I	ionization current correction concerning ρ (temperature, preassure, air compressibility)	0.03	0.02
Relative standard uncertainty in $\dot{K}_{BIPM}$			
quadratic sum		0.05	0.22
combined uncertainty		0.22	

[(1)] s_i represents the relative standard Type A uncertainty, estimated by statistical methods;
u_i represents the relative standard Type B uncertainty, estimated by other means.

Table 7. ^{60}Co gamma radiation

Conditions of measurement at the BIPM

Measurement of air kerma and absorbed dose	
source activity (2000-01-01) (approximate value)	45 TBq
source dimensions	
diameter	20 mm
length	5.6 mm
contribution of incident scattered radiation (in terms of energy fluence)	14 %
distance from source to reference plane	1 m
beam section in the reference plane[(1)]	10 cm × 10 cm
reference depth for absorbed dose measurement	5 g cm^{-2}
Measurement of ambient dose equivalent	
source activity (2000-01-01) (approximate value)	0.4 TBq
source dimensions	
diameter	5 mm
length	5.6 mm
contribution of incident scattered radiation (in terms of energy fluence)	8 %
distance from source to reference plane	3.5 m
beam diameter in the reference plane	74 cm

[(1)] The photon fluence rate at the centre of each side of the 10 cm × 10 cm square is 50 % of the photon fluence rate at the centre of the square.

Table 8. ^{60}Co gamma radiation

Physical constants and correction factors used in the BIPM determination[(1)] of the air kerma rate, and their estimated relative standard uncertainties

Physical constant		**value**	100 s_i	100 u_i
dry air density /(kg m^{-3}) (273.15 K, 101 325 Pa)		1.2930	-	0.01
$(\mu_{en}/\rho)_a/(\mu_{en}/\rho)_c$		0.9985	-	0.05
stopping power ratio $\bar{s}_{c,a}$		1.0010	-	0.11[(2)]
W/e	/(J C^{-1})	33.97	-	
g	fraction of energy lost by bremsstrahlung	3.2×10^{-3}	-	0.02
Correction factors				
k_s	recombination losses	1.0015	0.01	0.01
k_h	humidity	0.9970	-	0.03
k_{st}	stem scattering	1.0000	0.01	-
k_{at}	wall attenuation	1.0398	0.01	0.04
k_{CEP}	mean origin of electrons	0.9922	-	0.01
k_{sc}	wall scattering	0.9720	0.01	0.07
k_{an}	axial non-uniformity	0.9964	-	0.07
k_{rn}	radial non-uniformity	1.0016	0.01	0.02
Measurement of $I/v\rho$				
v	volume /cm^3	6.8028[(3)]	0.01	0.03
I	ionization current correction concerning ρ (temperature, preassure, air compressibility)		0.01	0.02
Relative standard uncertainty in $\dot{K}_{BIPM}$				
quadratic sum			0.03	0.17
combined uncertainty			0.17	

(1) details on the determination of air kerma rate can be found in [12]

(2) the uncertainty of the product of the stopping power ratio and W/e is estimated to be the same for determinations of air kerma and absorbed dose [13]. The present value supersedes that quoted in the Rapport BIPM-96/1, as agreed by the CCRI in 1999 [14]

(3) standard CH5-1

Table 9. ^{137}Cs gamma radiation

Conditions of measurement at the BIPM

Measurement of air kerma and absorbed dose	
source activity (2001) (approximate value)	0.9 TBq
source dimensions	
diameter	12 mm
length	23 mm
contribution of incident scattered radiation (in terms of energy fluence)	30 %
Measurement of air kerma	
distance from source to reference plane	1 m
beam diameter in the reference plane	11 cm or 20 cm
Measurement of ambient dose equivalent	
distance from source to reference plane	3 m
beam diameter in the reference plane	60 cm

Table 10. ^{137}Cs gamma radiation

Physical constants and correction factors used in the BIPM determination(1) of the air kerma rate, and their estimated relative standard uncertainties

Physical constant		**value**	100 s_i	100 u_i
dry air density /(kg m^{-3}) (273.15 K, 101 325 Pa)		1.2930	-	0.01
$(\mu_{en}/\rho)_a/(\mu_{en}/\rho)_c$		0.9990	-	0.05
stopping power ratio $\bar{s}_{c,a}$		1.0104	-	0.11(2)
W/e	/(J C^{-1})	33.97	-	
g	fraction of energy lost by bremsstrahlung	0.0012	-	0.02
Correction factors				
k_s	recombination losses	1.0014	0.01	0.01
k_h	humidity	0.9970	-	0.03
k_{st}	stem scattering	0.9998	0.01	-
k_{at}	wall attenuation	1.0540	0.01	0.04
k_{CEP}	mean origin of electrons	0.9972	-	0.01
k_{sc}	wall scattering	0.9535	0.01	0.15
k_{an}	axial non-uniformity	0.9981	-	0.07
k_{rn}	radial non-uniformity	1.0070	0.01	0.03
Measurement of $I/v\rho$				
v	volume /cm^3	6.8344 (3)	0.01	0.10
I	ionization current correction concerning ρ (temperature, preassure, air compressibility)		0.03	0.02
Relative standard uncertainty on $\dot{K}_{BIPM}$				
quadratic sum			0.04	0.24
combined uncertainty			0.24	

(1) details on the determination of the air kerma rate can be found in [7]

(2) the uncertainty of the product of the stopping power ratio and W/e is estimated to be the same for air kerma and absorbed dose determination [13]. The present value supersedes that quoted in the Rapport BIPM-96/1, as agreed by the CCRI in 1999 [14]

(3) standard CH5-2

Table 11. ^{60}Co gamma radiation

Physical constants and correction factors used in the BIPM ionometric determination[(1)] of the absorbed dose rate to water at 5 g cm^{-2}, and their estimated relative standard uncertainties

		value	100 s_i	100 u_i
Physical constant				
dry air density /(kg m^{-3})		1.2930	-	0.01
(273.15 K, 101 325 Pa)				
$(\mu_{en}/\rho)_w/(\mu_{en}/\rho)_c$		1.1125[(2)]	0.01[(2)]	0.14[(2)]
stopping power ratio $\bar{s}_{c,a}$		1.0030	-	0.11[(3)]
W/e /(J C^{-1})		33.97	-	
Correction factors				
k_p	perturbation correction	1.1107	0.05	0.17
k_{ps}	polythene envelope of the chamber	0.9994	0.01	0.01
k_{pf}	front face of the phantom	0.9996	-	0.01
k_{rn}	radial non-uniformity	1.0051	0.01	0.03
k_s	recombination losses	1.0015	0.01	0.01
k_h	humidity	0.9970	-	0.03
Measurement of $I/v\rho$				
v	volume /cm^3	6.8810[(4)]	0.19	0.03
I	ionization current correction concerning ρ (temperature, preassure, air compressibility)		0.01	0.02
positioning			0.03	-
Relative standard uncertainty in $(\dot{D}_w)_{BIPM}$				
quadratic sum			0.20	0.21
combined uncertainty			0.29	

(1) details on the determination of absorbed dose to water can be found in [13]

(2) included in the uncertainties for k_p

(3) the uncertainty of the product of the stopping power ratio and *W/e* is estimated to be the same for determinations of air kerma and absorbed dose [13]. The present value supersedes that quoted in the Rapport BIPM-96/1, as agreed by the CCRI in 1999 [14]

(4) standard CH4-1

Table 12. ^{60}Co gamma radiation

Physical constants and correction factors used in the BIPM determination(1) of the ambient dose equivalent rate, and their estimated relative standard uncertainties

Physical constant		**value**	100 s_i	100 u_i
dry air density /(kg m^{-3}) (273.15 K, 101 325 Pa)		1.2930	-	0.01
$(\mu_{en}/\rho)_w/(\mu_{en}/\rho)_c$		1.1109	-	0.10
stopping power ratio $\bar{s}_{c,a}$		1.0010	-	0.11(2)
W/e	/(J C^{-1})	33.97	-	
Q	(quality factor)	1		
Correction factors				
k_p	perturbation	0.9931	-	0.16
k_s	recombination losses	1.0014	0.01	0.01
k_h	humidity	0.9970	-	0.03
k_{st}	stem scattering	1.0000	0.01	-
k_{rn}	radial non-uniformity	1.000	-	0.01
Measurement of $I/v\rho$				
v	volume /cm^3	6.8116(3)	0.01	0.03
I	ionization current correction concerning ρ (temperature, preassure, air compressibility)		0.02	0.02
Relative standard uncertainty in $(\dot{H}^*)_{BIPM}$				
quadratic sum			0.03	0.22
combined uncertainty			0.23	

(1) details on the determination of the ambient dose equivalent can be found in [15]

(2) the uncertainty of the product of the stopping power ratio and W/e is estimated to be the same for determinations of air kerma and absorbed dose [13]. The present value supersedes that quoted in the Rapport BIPM-96/1, as agreed by the CCRI in 1999 [14]

(3) standard CH2

Table 13. ^{137}Cs gamma radiation

Estimated relative standard uncertainties used in the BIPM determination[(1)]
of the ambient dose equivalent rate

Parameters	100 s_i	100 u_i
air kerma rate $\dot{K}_{\mathrm{BIPM}}$	0.04	0.24
ratio $\dot{H}^*/\dot{K}$ [(2)]	-	0.45
Relative standard uncertainty in $(\dot{H}^*)_{\mathrm{BIPM}}$		
quadratic sum	0.04	0.51
combined uncertainty		0.51

[(1)] details on the determination of the ambient dose equivalent rate $\dot{H}^*$ can be found in [16]

[(2)] the calculated value of the ratio $\dot{H}^*/\dot{K}$ for the BIPM beam is 1.2161 Sv Gy^{-1}

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