Rapport BIPM-96/1

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 g-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 have no primary standard. It works with a single laboratory in each country for a given type of measurement. The calibrated instruments are then 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 entering in the determination of these quantities.

II. Calibration in terms of air kerma (x rays, ^{60}Co, ^{137}Cs)

The transfer chamber is operated in air, with its axis in the reference plane. It is provided with its build-up cap for calibration in g radiation. For the calibration, the position of the chamber is such that the number inscribed on its stem points towards the radiation source, unless another specific centering indication is given. The chamber is irradiated for about half an hour before beginning of measurements. The calibration factor N_K is defined by the relation

$$N_K = K_{BIPM} / I \ , \qquad (1)$$

where K_{BIPM} is the air kerma rate, measured with the BIPM standard, and I is the ionization current of the transfer chamber in the reference conditions of temperature and pressure (T_0 = 20 °C and P_0 = 101 325 Pa). 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 (close to 20 °C) and pressure P. The value of I is given at the ambient humidity which, at the BIPM, lies in the range 40 % to 60 % in relative value.

No correction is applied to the chamber response for ion recombination, nor for the non-uniformity of the BIPM beam. However, these effects are mentioned, when appropriate.

- Calibration factor in terms of exposure, N_X. The calibration factor for exposure is given by

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

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

Details about the conditions of measurement at the BIPM and the uncertainties in the determination of K_{BIPM} are given in Tables 1 to 6 for x rays, in Tables 7 and 8 for ^{60}Co and in Tables 11 and 12 for ^{137}Cs. In these tables, the relative uncertainties estimated by statistical methods (type A) are denoted by s_i and correspond to one standard deviation; the relative uncertainties estimated by other means (type B) are designated by u_i and also correspond to one standard deviation.

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

The transfer chamber is placed in its waterproof sheath and located in the BIPM water phantom (30 cm x 30 cm x 30 cm). Its axis is placed in the reference plane, at the depth of 5 g cm^{-2} in water. This depth includes the front face of the phantom (in perspex, 0,476 g cm^{-2}). The position of the chamber is such that the number inscribed on its stem and the mark on the sheath point towards the radiation source. The water temperature is about 20 °C. The chamber is irradiated before measurement.

The calibration factor, N_W, is determined using the relation

$$N_w = D_w / (I_W\, k_{pf}) \quad , \qquad (4)$$

where

- D_W is the absorbed dose rate to water measured by the BIPM standard at a point on the beam axis in the reference plane, at a depth of 5 g cm^{-2} in water;
- I_W is the ionization current measured by the transfer chamber under reference conditions (2). The value of I_W is given at the ambient humidity which, at the BIPM, lies in the range 40 % to 60 % in relative value.
- k_{pf} = 0,999 6 is a correction factor applied to I_W for the non-equivalence with water of the perspex front face of the phantom.

No correction is applied to the chamber response for ion recombination, or for the non-uniformity of the BIPM beam. An indication of these effects is given, however, when appropriate.

The conditions of measurement at the BIPM are given in Table 7. The physical constants and correction factors entering in the ionometric determination of the absorbed dose rate to water at 5 g cm^{-2} and their estimated relative uncertainties are given in Table 9.

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

The transfer chamber is located in air, with its axis in the reference plane. The chamber is positioned so that the number inscribed on its stem is pointed towards the radiation source. The chamber is irradiated before the beginning of the measurement.

The calibration factor, N_H, is determined using the relation

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

where

- H^* is the ambient dose equivalent rate. For ^{60}Co radiation, H^* is measured by the BIPM standard. For ^{137}Cs, 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 reference conditions (T_0 = 20 °C, P_0 = 101 325 Pa). The ionization current, I_H , is corrected neither for humidity, nor for ion recombination nor for radial non-uniformity of the beam.

The conditions of measurement at the BIPM are given in Tables 7 and 11 for ^{60}Co and ^{137}Cs, respectively. The physical constants and correction factors entering in the ionometric determination of the ambient dose equivalent and their estimated relative uncertainties are given in Tables 10 and 13 for ^{60}Co and ^{137}Cs radiation, respectively.

V. Use of calibration factors

Subject to some provisions, a secondary standard calibrated in the BIPM beam can be used in another beam, taking the calibration factors N_K, N_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, 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 air kerma calibration,
- 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, 14].

Table 1. X rays (10 kV to 50 kV)
Conditions of measurement at the BIPM

Distance between beryllium window of x-ray tube and the reference plane: 50 cm
beam diameter in the reference plane: 9,5 cm
air filtration : 59,4 mg/cm^2; beryllium filtration: ¶ 2,9 mm

Reference qualities (recommended by Section I of CCEMRI [7,8])

x-ray tube voltage/kV		10	25	30	40(3)	50(a)(4)	50(b)
filtration	/mm Al	0	0,373	0,208	3,989	3,989	1,007
	/mm Cu	-	-	-	0,212	-	-
HVL(1)	/mm Al	~0,036	0,250	0,176	2,73	2,257	1,021
	/mm Cu	-	-	-	0,086	-	-
m/r(2)	/cm^2 g^{-1}	15,1	2,57	3,50	0,33	0,39	0,79
air kerma rate	/mGy s^{-1}	0,57	1,12	3,33	0,02	0,34	1,56

(1) half-value layer
(2) air attenuation coefficient
(3) ISO quality
(4) the most filtered of the two 50 kV radiation qualities

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

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

Dry air density (273,15 K, 101 325 Pa) =1,293 0 kg/m^3

W/e = 33,97 J/C

measuring volume : 0,30358 cm^3

x-ray tube voltage/kV		10	25	30	40	50(a)	50(b)
Correction factors							
k_{sc}	scattered radiation	0,994 4	0,995 7	0,995 6	0,997 4	0,997 1	0,996 6
k_e	electron loss	1,000 0	1,000 0	1,000 0	1,000 0	1,000 0	1,000 0
k_s	ion collection	1,000 5	1,000 5	1,000 7	1,000 5	1,000 5	1,000 6
k_a	air attenuation[2]	1,192 1	1,030 9	1,042 4	1,003 9	1,004 6	1,009 2
k_d	field distortion	1,000 0	1,000 0	1,000 0	1,000 0	1,000 0	1,000 0
k_1	transmission through edges of diaphragm	1,000 0	1,000 0	1,000 0	1,000 0	1,000 0	1,000 0
k_p	transmission through walls of standard	1,000 0	1,000 0	1,000 0	1,000 0	1,000 0	1,000 0
k_h	humidity	0,998	0,998	0,998	0,998	0,998	0,998
$1-g$	bremsstrahlung	1,000 0	1,000 0	1,000 0	1,000 0	1,000 0	1,000 0

(1) details on the determination of the air kerma rate can be found in [9]
(2) values at 20 °C and 101 325 Pa

Table 3. x rays (10 kV to 50 kV)

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

		$100\, s_i$ [1]	$100\, u_i$
Physical constants			
dry air density (273,15 K, 101 325 Pa)		–	µ0,01
W/*e*	-		0,15
g	-		µ0,01
Correction factors			
k_{sc}	scattered radiation	-	0,07
k_e	electron loss	–	µ0,01
k_s	recombination losses	0,02	0,01
k_a	air attenuation	0,03 (0,06) [2]	µ0,01
k_d	field distortion	-	0,07
k_1	transmission through edges of diaphragm	-	µ0,01
k_p	transmission through walls of standard	µ0,01	
k_h	humidity	-	0,03
Measurement of *I*/*v*r			
v	volume	0,03	0,05
I	ionization current		
	correction concerning r (temperature, pressure, air compressibility)	0,03 (0,1)	0,02
Relative uncertainty on K_{BIPM}			
quadratic sum		0,06 (0,12)	0,19
combined uncertainty		0,20 (0,23)	

[1] s_i represents the relative uncertainty estimated by statistical methods, type A, u_i represent the relative uncertainty estimated by other means, type B.

[2] The values within parentheses apply only to the ISO quality (40 kV).

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

Conditions of measurement at 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 CCEMRI [7,8])

x-ray tube voltage/kV		100	135	180	250
additional filtration /	mm Al	1,204	-	-	-
	mm Cu	-	0,232	0,484	1,570
half-value layer /	mm Al	4,027	-	-	-
	mm Cu	0,148	0,494	0,990	2,500
m/r [(1)] /	$cm^2\ g^{-1}$	0,300	0,198	0,167	0,145
air kerma rate /	$mGy\ s^{-1}$	0,214	0,210	0,300	0,390

(1) air-attenuation coefficient

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

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

Dry air density (273,15 K, 101 325 Pa) =1,293 0 kg/m^3

W/e = 33,97 J/C

measuring volume : 4,655 4 cm^3

x-ray tube voltage/kV		100	135	180	250
Correction factors					
k_{sc}	scattered radiation	0,994 8	0,996 2	0,996 7	0,996 9
k_e	electron loss	1,000 0	1,002 3	1,005 2	1,007 8
k_s	ion collection	1,000 4	1,000 6	1,000 5	1,000 3
k_a	air attenuation	1,010 0	1,006 6	1,005 6	1,004 8
k_d	field distortion	1,000 0	1,000 0	1,000 0	1,000 0
k_1	transmission through edges of diaphragm	0,999 9	0,999 7	0,999 7	0,999 6
k_p	transmission through walls of standard	1,000 0	1,000 0	0,999 9	0,998 8
k_h	humidity	0,998	0,998	0,998	0,998
1-g	bremsstrahlung	0,999 9	0,999 9	0,999 8	0,999 7

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

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

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

		100 s_i	100 u_i
Physical constants			
Dry air density (273,15 K, 101 325 Pa)		–	µ0,01
W/*e*		-	0,15
g		-	µ0,01
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	µ0,01
k_d	field distortion	-	0,07
k_1	transmission through edges of diaphragm	-	µ0,01
k_p	transmission through walls of standard	µ0,01	
k_h	humidity	-	0,03
Measurement of *I*/*v*r			
v	volume	0,01	0,05
I	ionization current correction concerning r (temperature, pressure, air compressibility)	0,03	0,02
Relative uncertainty on K_{BIPM}			
quadratic sum		0,05	0,22
combined uncertainty			0,22

Table 7. ^{60}Co gamma radiation

Conditions of measurement at BIPM

Measurement of air kerma and absorbed dose	
source activity (1995-01-01)	~ 70 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 x 10 cm
reference depth for absorbed dose measurement	5 g/cm^2
Measurement of ambient dose equivalent	
source activity (1995-01-01)	~ 0,6 TBq
source dimensions	
diameter	0,5 mm
length	0,6 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 x 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 entering in the BIPM determination[(1)] of the air kerma rate, and estimated relative standard uncertainties

		value	100 s_i	100 u_i
Physical constants				
dry air density / kg m^{-3} (273,15 K, 101 325 Pa)		1,293 0	-	µ 0,01
$(m_{en}/r)_a/(m_{en}/r)_c$		0,998 5	-	0,05
stopping power ratio $s_{c,a}$[(2)]		1,001 0	-	0,3
W/e	(J C^{-1})	33,97	-	0,15
g (fraction of energy lost by bremsstrahlung)		$3{,}2 \cdot 10^{-3}$	-	0,02
Correction factors				
k_s	recombination losses	1,001 5	0,01	µ 0,01
k_h	humidity	0,997 0	-	0,03
k_{st}	stem scattering	1,000 0	0,01	
k_{at}	wall attenuation	1,039 8	0,01	0,04
k_{CEP}	mean origin of electrons	0,992 2	-	0,01
k_{sc}	wall scattering	0,972 0	0,01	0,07
k_{an}	axial non-uniformity	0,996 4	-	0,07
k_{rn}	radial non-uniformity	1,001 6	0,01	0,02
Measurement of I/vr				
v	volume / cm^3	6,802 8[(3)]	0,01	0,03
I	ionization current			
corrections concerning r (temperature, pressure, air compressibility)			0,01	0,02
Relative uncertainty on K_{BIPM}				
quadratic sum			0,02	0,36
combined uncertainty				0,36

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

(2) the uncertainty of the stopping power ratio is estimated to be the same for air kerma and absorbed dose determination (see [12]). The present value supersedes the one quoted in the Rapport BIPM-91/5

(3) standard CH5-1

Table 9. ^{60}Co gamma radiation

Physical constants and correction factors entering in the BIPM ionometric determination[(1)] of the absorbed dose rate to water at 5 g/cm^2, and estimated relative uncertainties

			$100\, s_i$	$100\, u_i$
Physical constants				
dry air density / kg m^{-3} (273,15 K, 101 325 Pa)		1,293 0	-	≤ 0,01
$(\mu_{en}/\rho)_w/(\mu_{en}/\rho)_c$		1,1125[(2)]	0,01[(2)]	0,14[(2)]
$s_{c,a}$		1,003 0	-	0,3
W/e / J C^{-1}		33,97	-	0,15
Correction factors				
k_p	perturbation correction	1,110 7	-	0,17
k_{ps}	polythene envelope of the chamber	0,999 4	0,01	0,01
k_{pf}	front face of the phantom	0,999 6	-	0,01
k_{rn}	radial non-uniformity	1,005 1	0,01	0,03
k_s	recombination losses	1,001 5	0,01	0,01
k_h	humidity	0,997 0	-	0,03
Measurement of $I/v\mathtt{r}$				
v	volume / cm^3	6,881 0[(3)]	0,19	0,03
I	ionization current			
corrections concerning $\mathtt{r}$ (temperature, pressure air compressibility)			0,01	0,02
Relative uncertainty on $(D_W)_{BIPM}$				
quadratic sum			0,19	0,38
combined uncertainty			0,43	

(1) details on the determination of absorbed dose to water can be found in [12]

(2) included in the uncertainties for k_p

(3) standard CH4-1

Table 10. ^{60}Co gamma radiation

Physical constants and correction factors entering in the BIPM determination[1] of the ambient dose equivalent rate, and estimated relative uncertainties

Physical constants		value	100 s_i	100 u_i
dry air density / kg m^{-3} (273,15 K, 101 325 Pa)		1,293 0	-	µ 0,01
$(m_{en}/r)_w/(m_{en}/r)_c$		1,110 9	-	0,10
$s_{c,a}$		1,001 0	-	0,3
W/e	(J C^{-1})	33,97	-	0,15
Q (quality factor)		1		
Correction factors				
k_p	perturbation	0,9931	-	0,16
k_s	recombination losses	1,001 4	0,01	µ 0,01
k_h	humidity	0,997 0	-	0,03
k_{st}	stem scattering	1,000 0	0,01	
k_{rn}	radial non-uniformity	1,000	-	0,01
Measurement of I/vr				
v	volume / cm^3	6,868 1 [2]	0,01	0,03
I	ionization current			
corrections concerning r (temperature, pressure, air compressibility)			0,02	0,02
Relative uncertainty on H^*_{BIPM}				
quadratic sum			0,03	0,39
combined uncertainty				0,39

[1] details on the determination of the ambient dose equivalent can be found in [13]

[2] standard CH2

Table 11. ^{137}Cs gamma radiation

Conditions of measurement at BIPM

Source activity (1995)	~ 1 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 12. ^{137}Cs gamma radiation

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

Physical constants		value	100 s_i	100 u_i
dry air density / kg m^{-3} (273,15 K, 101 325 Pa)		1,293 0	-	µ 0,01
$(m_{en}/r)_a/(m_{en}/r)_c$		0,999 0	-	0,05
$s_{c,a}$		1,010 4	-	0,3
W/e / J C^{-1}		33,97	-	0,15
g (fraction of energy lost by bremsstrahlung)		0,001 2	-	0,02
Correction factors				
k_s	recombination losses	1,001 4	0,01	µ 0,01
k_h	humidity	0,997 0	-	0,03
k_{st}	stem scattering	0,999 8	0,01	
k_{at}	wall attenuation	1,054 0	0,01	0,04
k_{CEP}	mean origin of electrons	0,997 2	-	0,01
k_{sc}	wall scattering	0,953 5	0,01	0,15
k_{an}	axial non-uniformity	0,998 1	-	0,07
k_{rn}	radial non-uniformity	1,007 0	0,01	0,03
Measurement of I/vr				
v	volume / cm^3	6,834 4 [(2)]	0,01	0,10
I	ionization courant			
corrections concerning r (temperature, pressure, air compressibility)			0,03	0,02
Relative uncertainty on K_{BIPM}				
quadratic sum			0,04	0,40
combined uncertainty			0,40	

(1) details on the determination of the air kerma rate can be found in [14]

(2) standard CH5-2

Table 13. ^{137}Cs gamma radiation

Estimated relative uncertainties entering in the BIPM determination(1) **of the ambient dose equivalent rate**

Parameters	100 s_i		100 u_i
air kerma rate K_{BIPM}	0,04		0,40
ratio H^*/K (2)	-		0,45
Relative uncertainty on H^*_{BIPM}			
quadratic sum	0,04		0,60
combined uncertainty		0,60	

(1) details on the determination of the ambient dose equivalent rate H^* can be found in [15],

(2) the calculated value of the ratio H^*/K for the BIPM beam is 1,216 1 Sv/Gy.

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