MEASURING CONDITIONS AND UNCERTAINTIES FOR THE COMPARISON AND CALIBRATION OF NATIONAL DOSIMETRIC STANDARDS AT THE BIPM*

C. Kessler and D.T. Burns

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Abstract. Information is presented on the experimental conditions used in the x- and gamma-radiation beams at the BIPM for comparisons of national primary standards and calibrations of national secondary standards in terms of air kerma and absorbed dose to water, together with the uncertainties involved in the determination of these dosimetric quantities.

I. Introduction

For each signatory of the Metre Convention and for a given type of measurement, the BIPM works with the National Metrology Institute (NMI) or a laboratory designated nationally for the purpose. For those laboratories that hold national primary standards, the BIPM compares these standards against the BIPM reference standards, either directly using the primary standards in the BIPM reference beams or indirectly through the calibration of transfer instruments by both the BIPM and the NMI. For those that do not hold primary standards, the BIPM calibrates secondary standards that are then normally used as national reference instruments. For this reason, the chambers should be instruments of good quality; in particular with respect to leakage current and both short- and long-term stability.

Comparisons, characterizations and calibrations of ionization chambers are performed at the BIPM in terms of:

- air kerma in the low- (including mammography) and medium-energy x-ray ranges and in ^{60}Co gamma radiation;
- absorbed dose to water in medium-energy x-ray beams and in ^{60}Co gamma radiation;

The present report documents the conditions of measurement at the BIPM, the values for the physical constants and correction factors, and the estimated uncertainties in the determination of the primary quantities and of calibration coefficients.

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 measurements in gamma radiation, the chamber is used with the build-up cap provided. The orientation of the chamber is such that the number, text or line inscribed on the stem faces the radiation source, unless a different orientation is indicated. Parallel-plate chambers are calibrated with the front surface of the chamber casing in the reference plane, unless a different surface is indicated on the chamber, and with the entrance window centred on the beam axis.

All chambers are irradiated for at least thirty minutes, with the appropriate polarizing potential applied to the outer electrode (wall or window), before any measurements are made. If the NMI applies a potential of a given polarity to the collecting electrode, the BIPM will apply the same potential with opposite polarity to the outer electrode.

The leakage current is normally measured before and after each set of measurements and a correction is applied, based on the mean value. A chamber for which the relative leakage current is high, and in particular for which the leakage is also variable, is unsuitable for use as a transfer instrument and might also be considered unsuitable for calibration. In the latter case, a study note is issued.

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, an additional passive enclosure is used to ensure temperature stability below 50 mK. The BIPM reference conditions for air temperature, pressure and relative humidity are T_0 = 293.15 K, P_0 = 101.325 kPa and 50 %, respectively. As the relative humidity is controlled within the range 40 % to 55 %, no humidity correction is applied.

Calibration of national standards: No correction is applied for lack of saturation; the air-kerma rate or absorbed-dose-to-water rate is stated in the certificate. For thimble chamber types calibrated in gamma radiation and in air-kerma for medium-energy x-rays, the radial non-uniformity correction for the BIPM beams is small and is stated in the certificate, although no correction factor is applied. For waterproof thimble chamber types calibrated in terms of absorbed dose to water in medium-energy x-rays, the correction factor at the reference depth will be similar at both laboratories and again no correction factor is applied. In low-energy x-rays, chambers of larger dimensions may be calibrated and the radial uniformity of the beam shows more variation from one laboratory to another. For these reasons, the appropriate correction factor is always applied.

Comparisons of national standards: This depends to some extent on the practice at the NMI and no general statement can be made; the measuring conditions adopted are clearly stated in the comparison report.

III. Comparison and calibration in terms of air kerma (x-rays, ^{60}Co)

The primary standard, transfer chamber or national reference standard is operated in air at the stated reference distance. The ionization current I is determined under the BIPM reference conditions of air temperature, pressure and humidity. The value of I is given by

$$I = I_{\mathrm{exp}}\left(\frac{T}{T_0}\right)\left(\frac{P_0}{P}\right) \tag{1}$$

where I_{exp} is the ionization current measured at temperature T (expressed in K) and pressure P (expressed in kPa).

For a transfer chamber or national reference standard, the calibration coefficient N_K is defined by the relation

$$N_K = \dot{K}_{\mathrm{BIPM}}/I\,, \tag{2}$$

where $\dot{K}_{\mathrm{BIPM}}$ is the air-kerma rate at the reference point, measured with the BIPM standard.

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 and in Tables 7 and 9 for ^{60}Co. 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 denoted by u_i.

IV. Comparison and calibration in terms of absorbed dose to water (x-rays, ^{60}Co)

^{60}Co gamma radiation

When a primary standard is compared directly, the measuring conditions are stated clearly in the comparison report. For indirect comparisons and calibrations, the transfer chamber or national reference standard is placed in its waterproof sleeve (unless calibration of a waterproof chamber without a sleeve is requested) and positioned in the BIPM cubic water phantom of side length 30 cm. Its axis is placed in the reference plane, at the reference depth of 5 g cm^{-2} in water. This depth includes the window of the phantom (PMMA, 0.476 g cm^{-2}) and is corrected for the change in water density with temperature. As well as correctly orienting the chamber, a reference mark on the sleeve (if used) is rotated so as to point towards the radiation source, unless a different orientation is indicated.

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

$$N_{D,\mathrm{w}} = \dot{D}_\mathrm{w} / (I_\mathrm{w} k_\mathrm{win}), \qquad (3)$$

where:

$\dot{D}_\mathrm{w}$ is the absorbed dose rate to water at the reference point, measured using the BIPM standard at a depth of 5 g cm^{-2} in water;

I_w is the ionization current measured using the chamber under the BIPM reference conditions of air temperature, pressure and humidity;

k_win = 0.9997 is a correction factor applied to I_w for the non-equivalence with water of the PMMA window of the phantom (required because a similar factor is applied to the BIPM standard).

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 9 along with their estimated relative uncertainties.

Medium-energy x-ray beams

Only waterproof thimble chamber types are accepted and are measured without a waterproof sleeve. For indirect comparisons and calibrations, the transfer chamber or national reference standard is positioned in the BIPM cubic water phantom of side length 20 cm. Its axis is placed in the reference plane, at the reference depth of 2 g cm^{-2} in water. This depth includes the window of the phantom (PMMA, 0.200 g cm^{-2}). Because of the shallow depth, no correction is required for the change in water density with temperature.

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

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

where:

$\dot{D}_\mathrm{w}$ is the absorbed dose rate to water at the reference point at a depth of 2 g cm^{-2} in the water phantom, determined by the BIPM standard;

I_w is the ionization current measured using the chamber under the BIPM reference conditions of air temperature, pressure and humidity.

At the BIPM, the absorbed dose to water is derived from the air-kerma determination. The conditions of measurement are given in Table 4. The physical constants and correction factors used in the ionometric determination of air kerma and the factor for the conversion to absorbed dose to water are given in Table 5 and their estimated relative uncertainties are given in Table 6.

V. Use of calibration coefficients

A transfer chamber or national reference standard calibrated in the BIPM beam can be used in another beam, taking the calibration coefficients N_K or $N_{D\text{w}}$ to determine K or D_w in that beam, subject to certain provisions as listed below:

(a) The humidity conditions must not differ significantly from those of the calibration at the BIPM. If the relative humidity is outside the range 30 % to 70 %, the recommendations of ICRU Report 90 (ICRU 2016) should be used.

(b) The conditions of measurement must not differ significantly from those of the calibration at the BIPM. Otherwise, additional corrections may be necessary as described by Boutillon *et al* (1993) and Boutillon (1996). 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 with regard to 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.

VI. Comparison and calibration uncertainties

The uncertainties associated with dosimetry measurements made at the BIPM are analysed in accordance with the *Guide to the Expression of Uncertainty in Measurement* (JCGM 2008). The uncertainty budgets for the dosimetry standards are given in Tables 3, 6, 8 and 9. For comparisons, the BIPM standard uncertainties are combined with those associated with the primary or transfer chamber, taking correlation into account, to give the combined standard uncertainty of the comparison results. The detailed uncertainty budgets are given in the comparison report. For the calibration of national reference standards, the BIPM standard uncertainties are combined with the uncertainties associated with the chamber under calibration to give the combined standard uncertainty of the calibration coefficient. This value is given in the calibration certificate.

It is emphasized that the uncertainty associated with BIPM calibrations is a combined *standard* uncertainty without the application of a coverage factor k. This long-standing practice of not applying a coverage factor is maintained to facilitate the combination of the BIPM and NMI uncertainties and thus simplify the subsequent dissemination of the standard to the customers of the NMI.

The BIPM dosimetry measurements fulfil the criteria of Annex G.6.6 of JCGM (2008). In particular, for the purpose of calculating the expanded uncertainty for their end result at a specified level of confidence, an NMI can assume that the effective number of degrees of freedom for a BIPM calibration is sufficient to be able to use a coverage factor $k = 2$ for a level of confidence of approximately 95 %. Any exceptions are noted in the calibration certificate.

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

Conditions of measurement at the BIPM

X-ray tube	W-anode	Mo-anode
Distance between beryllium window of x-ray tube and reference plane of standard	50 cm	60 cm
Beam diameter in reference plane	8.4 cm	10 cm
Beryllium filtration	≈ 3.0 mm	0.8 mm

Reference qualities W-anode x-ray tube [(1)]

X-ray tube voltage / kV	10	30	25	50 (b)	50 (a) [(3)]
Al filtration / mm	0	0.208	0.372	1.008	3.989
Al half-value layer / mm	0.037	0.169	0.242	1.017	2.262
$\bar{\mu}/\rho$ [(2)] / $cm^2\ g^{-1}$	14.84	3.66	2.60	0.75	0.38
air-kerma rate / $mGy\ s^{-1}$	1.00	1.00	1.00	1.00	1.00

Reference qualities Mo-anode x-ray tube [(4)]

X-ray tube voltage / kV	25	28	30	35
Mo filtration / µm	30	30	30	30
Al half-value layer / mm	0.277	0.310	0.329	0.365
$\bar{\mu}/\rho$ [(2)] / $cm^2\ g^{-1}$	2.20	1.99	1.91	1.74
air-kerma rate / $mGy\ s^{-1}$	2.00	2.00	2.00	2.00

Reference qualities W-anode x-ray tube, Mo filter

X-ray tube voltage / kV	23	25	28	30	35	40	50
Mo filtration /µm	60	60	60	60	60	60	60
Al half-value layer / mm	0.332	0.342	0.355	0.364	0.388	0.417	0.489
$\bar{\mu}/\rho$ [(2)] / $cm^2\ g^{-1}$	1.79	1.75	1.70	1.67	1.60	1.53	1.40
air-kerma rate / $mGy\ s^{-1}$	1.00	1.00	1.00	1.00	1.00	1.00	1.00

(1) Recommended by Section I of the CCEMRI (1972, 1975).
(2) Mass attenuation coefficient for air.
(3) The more heavily-filtered of the two 50 kV radiation qualities.
(4) Endorsed by the CCRI (2011).

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

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

Dry air density (273.15 K, 101.325 kPa) = 1.2930 kg m^{-3}

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

W-anode x-ray tube						
Measuring volume FAC-L-01: 1.2004 cm^3						
X-ray tube voltage / kV		10	30	25	50 (b)	50 (a)
Correction factors						
k_{sc}	scattered radiation	0.9962	0.9972	0.9973	0.9977	0.9979
k_{fl}	fluorescence	0.9952	0.9971	0.9969	0.9980	0.9985
k_e	electron loss	1.0000	1.0000	1.0000	1.0000	1.0000
k_{ii}	initial ionization [(2)]	0.9953	0.9968	0.9969	0.9977	0.9980
k_W	energy dependence of W_{air} [(2)]					
k_s	saturation	1.0006	1.0007	1.0007	1.0007	1.0007
k_{pol}	polarity	1.0005	1.0005	1.0005	1.0005	1.0005
k_a	air attenuation [(3)]	1.1957	1.0451	1.0319	1.0091	1.0046
k_d	field distortion	1.0000	1.0000	1.0000	1.0000	1.0000
k_{dia}	diaphragm	0.9999	0.9995	0.9996	0.9989	0.9984
k_p	wall transmission	1.0000	1.0000	1.0000	1.0000	1.0000
k_h	humidity	0.998	0.998	0.998	0.998	0.998
$1-g$	radiative loss	1.0000	1.0000	1.0000	1.0000	1.0000

Mo-anode x-ray tube					
Measuring volume FAC-L-02: 1.2197 cm^3					
X-ray tube voltage / kV		25	28	30	35
Correction factors					
k_{sc}	scattered radiation	0.9977	0.9977	0.9978	0.9978
k_{fl}	fluorescence	0.9975	0.9976	0.9976	0.9977
k_e	electron loss	1.0000	1.0000	1.0000	1.0000
k_{ii}	initial ionization [(2)]	0.9968	0.9968	0.9969	0.9969
k_W	energy dependence of W_{air} [(2)]				
k_s	saturation	1.0015	1.0015	1.0015	1.0015
k_{pol}	polarity	1.0000	1.0000	1.0000	1.0000
k_a	air attenuation [(3)]	1.0269	1.0244	1.0233	1.0212
k_d	field distortion	1.0000	1.0000	1.0000	1.0000
k_{dia}	diaphragm	0.9996	0.9995	0.9995	0.9995
k_p	wall transmission	1.0000	1.0000	1.0000	1.0000
k_h	humidity	0.998	0.998	0.998	0.998
$1-g$	radiative loss	1.0000	1.0000	1.0000	1.0000

(1) Details on the determination of the air-kerma rate are given in Boutillon *et al* (1969); correction factors are described by Burns (2004) and Burns *et al* (2009) for the W-anode qualities and by Kessler *et al* (2010) for the Mo-anode qualities.

(2) Combined values for k_{ii} and k_W adopted from January 2019 (Burns and Kessler 2018).

(3) Values at 293.15 K and 101.325 kPa for an attenuation length of 10.0 cm.

W-anode x-ray tube, Mo filter								
Measuring volume FAC-L-01: 1.2004 cm^3								
X-ray tube voltage / kV		23	25	28	30	35	40	50
Correction factors								
k_{sc}	scattered radiation	0.9974	0.9974	0.9974	0.9974	0.9974	0.9974	0.9975
k_{fl}	Fluorescence	0.9972	0.9972	0.9972	0.9972	0.9973	0.9973	0.9975
k_e	electron loss	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
k_{ii} k_W	initial ionization (2) energy dependence of W_{air} (2)	0.9971	0.9971	0.9971	0.9971	0.9972	0.9972	0.9973
k_s	Saturation	1.0006	1.0006	1.0006	1.0006	1.0006	1.0006	1.0006
k_{pol}	Polarity	1.0005	1.0005	1.0005	1.0005	1.0005	1.0005	1.0005
k_a	air attenuation (3)	1.0218	1.0213	1.0208	1.0203	1.0195	1.0187	1.0170
k_d	field distortion	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
k_{dia}	diaphragm	0.9995	0.9995	0.9995	0.9995	0.9995	0.9995	0.9994
k_p	wall transmission	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
k_h	Humidity	0.998	0.998	0.998	0.998	0.998	0.998	0.998
$1-g$	radiative loss	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

(2) Combined values for k_{ii} and k_W adopted from January 2019 (Burns and Kessler 2018).
(3) Values at 293.15 K and 101.325 kPa for an attenuation length of 10.0 cm.

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

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

Symbol	Parameter / unit	$10^2 \times$ Relative standard uncertainty [(1)] s_i	u_i
Physical constants			
ρ_a	dry air density (0°C, 101.325 kPa) / kg m^{-3}	–	0.01
W/e	mean energy per charge / J C^{-1}	–	0.35 [(2)]
g	fraction of energy lost in radiative processes in air	–	0.01
Correction factors			
k_{sc}	scattered radiation	–	0.03
k_{fl}	fluorescence	–	0.05
k_e	electron loss	–	0.01
$k_{ii}\ k_w$	initial ionization and energy dependence of W_{air} [(2)]	–	0.12
k_s	saturation	0.01	0.01
k_{pol}	polarity	0.01	–
k_a	air attenuation	0.02	0.01
k_d	field distortion	–	0.07
k_{dia}	diaphragm	–	0.03
k_p	wall transmission	0.01	–
k_h	humidity	–	0.03
Measurement of I/υ			
I	ionization current (T, P, air compressibility)	0.02	0.02
υ	volume	0.03	0.05
	positioning of standard	0.01	0.01
Combined uncertainty of the BIPM determination of air-kerma rate [(3)]			
quadratic summation		0.05	0.39
combined relative standard uncertainty		0.39	

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

(2) Value adopted from January 2019 (Burns and Kessler 2018).

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

Conditions of measurement at the BIPM

Distance between focal spot and reference plane of standard: 120 cm

Beam diameter in the reference plane: 9.8 cm

Inherent filtration: ≈ 3 mm Be

Reference depth for absorbed dose measurement: 2 g cm^{-2}

Reference qualities [(1)]

X-ray tube voltage / kV	100	135	180	250
Al filtration / mm	3.431	2.228	2.228	2.228
Cu filtration / mm	–	0.232	0.485	1.570
Al half-value layer / mm	4.030	–	–	–
Cu half-value layer / mm	0.149	0.489	0.977	2.484
$\overline{\mu}/\rho$ [(2)] / cm^2 g^{-1}	0.290	0.190	0.162	0.137
air-kerma rate / mGy s^{-1}	0.50	0.50	0.50	0.50
Absorbed-dose-to-water rate / mGy s^{-1}	0.59	0.71	0.72	0.68

(1) Recommended by Section I of the CCEMRI (1972).
(2) Mass attenuation coefficient for air.

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

Physical constants and correction factors used in the BIPM determination of the air-kerma rate [(1)] and absorbed-dose-to-water rate [(2)] and conversion factor from air kerma to absorbed dose to water

Dry air density (273.15 K, 101.325 kPa) = 1.2930 kg m^{-3}

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

W-anode x-ray tube					
Measuring volume FAC-M-01: 4.6554 cm^3					
X-ray tube voltage / kV		100	135	180	250
Correction factors					
k_{sc}	scattered radiation	0.9952	0.9959	0.9964	0.9974
k_{fl}	fluorescence	0.9985	0.9992	0.9994	0.9999
k_e	electron loss	1.0000	1.0015	1.0047	1.0085
k_{ii} k_W	initial ionization [(3)] energy dependence of W_{air} [(3)]	0.9980	0.9980	0.9981	0.9986
k_s	saturation	1.0010	1.0010	1.0010	1.0010
k_{pol}	polarity	1.0002	1.0002	1.0002	1.0002
k_a	air attenuation [(4)]	1.0099	1.0065	1.0055	1.0047
k_d	field distortion	1.0000	1.0000	1.0000	1.0000
k_{dia}	diaphragm	0.9995	0.9993	0.9991	0.9980
k_p	wall transmission	1.0000	1.0000	0.9999	0.9988
k_h	humidity	0.998	0.998	0.998	0.998
$1-g$	radiative loss	0.9999	0.9999	0.9998	0.9997
Conversion factor from air kerma to absorbed dose to water					
$C_{w,air}$[(2)]		1.1840	1.4294	1.4429	1.3673

(1) Details on the determination of the air-kerma rate are described by Boutillon (1978) and the re-evaluation of the correction factors is described by Burns *et al* (2009).

(2) Details on the determination of the absorbed-dose-to-water rate are described by Burns (2017).

(3) Combined values for k_{ii} and k_W adopted from June 2017 for absorbed dose to water and from January 2019 for air kerma (Burns and Kessler 2018).

(4) Values at 293.15 K and 101.325 kPa for an attenuation length of 28.15 cm.

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

Estimated relative standard uncertainties in the BIPM determination of the air-kerma rate and absorbed-dose-to-water rate

Symbol	Parameter / unit	$10^2 \times$ Relative standard uncertainty [(1)] s_i	u_i
Physical constants			
ρ_a	dry air density (0°C, 101.325 kPa) / kg m^{-3}	–	0.01
W/e	mean energy per charge / J C^{-1}	–	0.35 [(2)]
g	fraction of energy lost in radiative processes in air	–	0.01
Correction factors			
k_{sc}	scattered radiation	–	0.03
k_{fl}	fluorescence	–	0.03
k_e	electron loss	–	0.05
k_{ii} k_W	initial ionization and energy dependence of W_{air} [(2)]	–	0.05
k_s	saturation	0.02	0.01
k_{pol}	polarity	0.01	–
k_a	air attenuation	0.02	0.01
k_d	field distortion	–	0.07
k_{dia}	diaphragm	–	0.03
k_p	wall transmission	0.01	–
k_h	humidity	–	0.03
Measurement of I / υ			
I	ionization current (T, P, air compressibility)	0.02	0.02
υ	volume	0.01	0.05
	positioning of standard	0.01	0.01
Combined uncertainty of the BIPM determination of air-kerma rate			
quadratic summation		0.04	0.37
combined relative standard uncertainty		0.38	

Symbol	Parameter / unit	$10^2 \times$ Relative standard uncertainty [(1)] s_i	u_i
K	air-kerma rate / Gy s^{-1}	0.04	0.37
$C_{w,air}$ [(2)]	conversion factor from air kerma to absorbed dose to water	0.13	0.40
Combined uncertainty of the BIPM determination of absorbed-dose-to-water rate			
quadratic summation		0.14	0.55
combined relative standard uncertainty		0.56	

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

(2) Value adopted from June 2017 for absorbed dose to water and from January 2019 for air kerma (Burns and Kessler 2018).

Table 7. ^{60}Co gamma radiation

Conditions of measurement at the BIPM

Radiotherapy level	
Measurement of air kerma and absorbed dose to water	
Theratron source activity (2017-01-01)	≈ 65 TBq
source type: solid discs of 20 mm diameter	
distance from source centre 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}

(1) The photon fluence rate at the centre of each side of the 10 cm × 10 cm field 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 of the air-kerma rate [(1)], and their estimated relative standard uncertainties

Symbol	Parameter / unit	Value	$10^2 \times$ Relative standard uncertainty [(2)] s_i	u_i
Physical constants				
ρ_a	dry air density (0°C, 101.325 kPa) / kg m^{-3}	1.2930	–	0.01
$(\bar{\mu}_{en}/\rho)_{a,c}$	ratio of mass energy-absorption coefficients	0.9989	0.01	0.04
$s_{c,a}$	ratio of mass stopping powers	0.9928	}	0.08 [(3)]
W/e	mean energy per charge / J C^{-1}	33.97		
g	fraction of energy lost in radiative processes in air	0.0031	–	0.02
Correction factors				
k_g	re-absorption of radiative loss	0.9996	–	0.01
k_h	humidity	0.9970	–	0.03
k_s	saturation	1.0022	0.01	0.02
k_{st}	stem scattering	1.0000	0.01	–
k_{wall}	wall attenuation and scattering	1.0011	}	– [(4)]
k_{an}	axial non-uniformity	1.0020		
k_{rn}	radial non-uniformity	1.0015	–	0.02
Measurement of I/υ				
υ	effective volume / cm^3	6.8855 [(5)]	–	0.08 [(4)]
I	ionization current (T, P, air compressibility)	–	–	0.02
	short-term reproducibility (including positioning and current measurement) [(6)]	–	0.01	–
Combined uncertainty of the BIPM determination of air-kerma rate at 1 m				
quadratic summation			0.02	0.13
combined relative standard uncertainty			0.13	

(1) Details on the determination of air kerma are described by Boutillon *et al* (1973), Burns (2006), Burns *et al* (2007) and the re-evaluation of the standard is described in Burns and Kessler (2018).

(2) s_i represents the relative uncertainty estimated by statistical methods (Type A); u_i represents the relative uncertainty estimated by other methods (Type B).

(3) Uncertainty value for the product $s_{c,a}$ W/e adopted from January 2019 (Burns and Kessler 2018).

(4) The uncertainties for k_{wall} and k_{an} are included in the determination of the effective volume (Burns *et al* 2007).

(5) Standard CH6-1

(6) Over a period of 3 months. The long-term reproducibility over a period of 15 years, u_{rep}, is 0.0004.

Table 9. ^{60}Co gamma radiation

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

Symbol	Parameter / unit	Value	10^2 × Relative standard uncertainty (2) s_i	u_i
Physical constants				
ρ_a	dry air density (0°C, 101.325 kPa) / kg m^{-3}	1.2930	–	0.01
$(\mu_{en}/\rho)_{w,g}$	ratio of mass energy-absorption coefficients	1.1131	–	0.05
W/e	mean energy per charge / J C^{-1}	33.97	–	0.08
$D_{g,air} = s_{g,air} k_{cav}$	product of the ratio of mass stopping powers and cavity perturbation correction	0.9958	0.02	0.13
$\psi_{w,g}$	fluence ratio	1.0037	0.01	0.07
$\beta_{w,g}$	absorbed-dose-to-collision-kerma ratio	0.9998	0.01	0.01
Correction factors				
k_{env}	envelope of the chamber	0.9993	0.01	0.02
k_{win}	entrance window of the phantom	0.9997	0.01	0.01
k_{rn}	radial non-uniformity	1.0056	0.01	0.03
k_s	saturation	1.0021	0.01	0.02
k_h	humidity	0.9970	–	0.03
Measurement of I/υ				
υ	volume / cm^3	6.7928 (3)	–	0.08
I	ionization current (T, P, air compressibility)	–	–	0.02
	short-term reproducibility (including positioning and current measurement) (4)		0.02	–
Combined uncertainty of the BIPM determination of absorbed-dose rate to water				
quadratic summation			0.04	0.18
combined relative standard uncertainty			0.19	

(1) Details on the determination of absorbed dose to water are described by Boutillon *et al* (1993) and the re-evaluation of the standard is described by Burns and Kessler (2018).
(2) s_i represents the relative uncertainty estimated by statistical methods (Type A);
u_i represents the relative uncertainty estimated by other methods (Type B).
(3) Standard CH7-1.
(4) Over a period of 3 months. The long-term reproducibility over a period of 15 years, u_{rep}, is 0.0006.

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