Comparison of air kerma and exposure standards of ARL and BIPM for X rays (100 to 250 kV) and ^{60}Co gamma radiation

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Abstract

The comparison performed between the air kerma and exposure standards of the Australian Radiation Laboratory and the Bureau International des Poids et Mesures for medium-energy X rays and ^{60}Co gamma radiation is reported. For X rays, the results show a discrepancy of 0.4 %, whereas for ^{60}Co gamma radiation there is no significant difference.

1. Introduction

An indirect comparison between the air kerma and exposure standards of the Australian Radiation Laboratory (ARL), Yallambie, Australia, and of the Bureau International des Poids et Mesures (BIPM) has been performed in the medium-energy X rays and in the ^{60}Co gamma radiation. The comparison took place at the BIPM in April 1988. For the X rays the ARL standard is a free-air chamber; for ^{60}Co ARL has constructed a graphite cavity chamber similar to that of the BIPM standard.

2. Conditions of measurement

For the comparison two transfer cavity chambers (thimble type and graphite wall) belonging to the ARL and manufactured by Nuclear Enterprises Ltd. (serial numbers NE 2561-070 and NE 2561-194) were used.

The results are given in terms of the ratio R of the calibration factors determined at ARL and at BIPM.

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The calibration factors N_X and N_K are defined by the relations

$$N_X = \dot{X}/I \quad \text{and}$$

$$N_K = \dot{K}/I ,$$

where $\dot{X}$ and $\dot{K}$ are the exposure rate and the air-kerma rate measured with the standard of each laboratory and I is the ionization current measured with an ARL transfer chamber.

The ionization current I is given for the reference conditions 293.15 K (20 °C) and P_o = 101 325 Pa

$$I = I_{exp} \frac{T}{293.15} \frac{P_o}{P} ,$$

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

The collecting voltage applied to the transfer chamber is −200 V. I is corrected neither for humidity nor for ion recombination.

During the calibration the position of the transfer chamber was such that the number inscribed on its stem was pointed towards the radiation source. At the BIPM the chamber was irradiated for half an hour before commencing the measurements. The relative humidity was (55 ± 3) % and the air temperature (20.5 ± 0.5) °C. At the ARL the chamber was similarly positioned and pre-irradiated. The room temperature ((20.0 ± 0.5) °C) was constant to 0.1 °C during any set of measurements. The relative humidity was (49 ± 6) % and the results were assumed to apply at 50 %.

In addition, measurements of the ionization current have been performed with the two chambers, using a ^{90}Sr reference source. They took place at ARL before and after the comparison, and at BIPM.

Details about the measurements and the results are given in the following tables.

a) Medium-energy X rays

- Tables 1 and 2 - Conditions of measurement at the BIPM and the ARL,
- Table 3 - Physical constants entering in the determination of $\dot{X}$ and $\dot{K}$,
- Table 4 - Correction factors applied to the standards,
- Tables 5 and 6 - Uncertainties involved in the determination of exposure rate and air kerma rate,
- Tables 7 and 8 - Calibration factors of the transfer chambers determined at the ARL and at the BIPM,

- Tables 9 and 10 - Results of the comparison and analysis of the uncertainties,

- Table 11 - Comparison with the results of the 1979 comparison.

b) ^{60}Co gamma radiation

- Table 12 - Physical constants and correction factors entering in the determination of $\dot{X}$ and $\dot{K}$,

- Table 13 - Uncertainties in the determination of exposure rate and air kerma rate,

- Tables 14 and 15 - Results of the comparison and analysis of the uncertainties.

c) ^{90}Sr reference source

- Table 16 - Comparison of measurements of ionization current at ARL and at BIPM.

In the 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 u_j and correspond also to one standard deviation.

3. Results

a) Medium-energy X rays

The mean values of the calibration factors for the two transfer chambers are 0.3 to 0.5 % higher at the ARL than at the BIPM (Table 9).

At the BIPM no long-term variation has been observed in the measurement of the ionization current of the two chambers.

An indirect comparison had already been performed in 1979, using one of these chambers (NE 2561-070) as a transfer instrument. At this time the agreement between the calibration factors determined at the ARL and at the BIPM was better than 0.2 %. The difference between the value of R obtained during the two comparisons is 0.4 % at 100, 135 and 180 kV and 0.7 % at 250 kV (Table 9).

Since 1979 the calibration conditions at the ARL have slightly changed: the distance between the X-ray tube and the reference plane is 140 cm instead of 120 cm and the diameter of the beam is 9.5 cm instead of 10.5 cm; however, this probably does not account for the above difference. However, changes have been made to the charge measuring system used with the X-ray beam. In addition, since 1979 the equipment has been completely relocated. As a result some of the calibration conditions may have changed slightly. These changes may account for some of the difference.

b) ^{60}Co gamma radiation

The calibration factors determined for the chamber NE 2561-070 at the ARL and at the BIPM are in good agreement (better than 0.1 %).

The chamber NE 2561-194 had to be calibrated on a single day at BIPM. A drift of 0.4 % was observed for a few hours at the beginning of the measurements. The BIPM calibration factor, determined when the ionization current seemed to be stable, differs from the value obtained at ARL by 0.5 %. It would have been preferable to extend the measurements over a longer period.

c) ^{90}Sr reference source

As can be seen in Table 16, the ratio of the ionization currents measured at ARL and at BIPM, with chamber 070, does not differ significantly from unity and shows a good stability over a period of about 10 years. The measurements performed with chamber 194 have shown some instabilities.

No significant difference between the measuring devices of BIPM and ARL can thus be observed.

4. Conclusion

For medium-energy X rays, the results of this comparison show a discrepancy between the values of the calibration factors of the transfer chambers, as determined at ARL and BIPM. In view of the observed change in the response of chamber NE 2561-070 since 1979, further studies on the stability of the instruments will be needed. For ^{60}Co gamma radiation, the reported good agreement confirms the adequacy of the standard cavity chamber constructed at ARL.

Table 1

X rays (100 to 250 kV)

Conditions of measurement at BIPM

Distance between focal spot and reference plane: 120 cm
Beam diameter in reference plane of diaphragm: 10.5 cm

X-ray tube voltage (kV)	100	135	180	250
Current (mA)	5	5	5	5
Additional filtration*	1.2037 mm Al	0.2321 mm Cu	0.4847 mm Cu	1.5701 mm Cu
Half-value thickness	4.027 mm Al or 0.148 mm Cu	0.494 mm Cu	0.990 mm Cu	2.500 mm Cu
Air attenuation coefficient, μ/ρ (cm^2/g)	0.300	0.198	0.167	0.145

* The inherent filtration is approximately 2.3 mm Al.

Table 2

X rays (100 to 250 kV)

Conditions of measurement at ARL

Distance between focal spot and reference plane: 140 cm
Beam diameter in reference plane of diaphragm: 9.5 cm

X-ray tube voltage (kV)	100	135	180	250
Current (mA)	10	10	10	10
Additional filtration*	1.17 mm Al	0.21 mm Cu + 1.04 mm Al	0.42 mm Cu + 1.17 mm Al	1.57 mm Cu + 1.17 mm Al
Half-value thickness	0.14 mm Cu	0.48 mm Cu	1.09 mm Cu	2.72 mm Cu
Air attenuation coefficient, μ/ρ (cm^2/g)	0.325	0.234	0.189	0.173

* The inherent filtration is approximately 2.5 mm Al.

Table 3

X rays (100 to 250 kV)

Physical constants entering in the determination of $\dot{X}$ and $\dot{K}$ at BIPM and ARL

Dry air density (273.15 K, 101 325 Pa)	1.292 99 kg/m^3 *			
W/e **	33.97 J/C			
Fraction $\overline{g}$ ** of energy lost by bremsstrahlung:				
voltage	100 kV	135 kV	180 kV	250 kV
$\overline{g}$	$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$3 \cdot 10^{-4}$

* Value used by ARL: 1.292 9 kg/m^3

** See ref. [1].

Table 4

X rays (100 to 250 kV)

Correction factors applied to the ARL and BIPM air kerma and exposure standards

X-ray tube voltage (kV)	100		135		180		250	
	ARL	BIPM	ARL	BIPM	ARL	BIPM	ARL	BIPM
scattered radiation, k_{sc}	0.9945	0.9948	0.9957	0.9962	0.9961	0.9967	0.9964	0.9969
electron loss, k_e	1.0000	1.000	1.0011	1.0023	1.00313	1.0052	1.00528	1.0078
recombination losses, k_s	1.00007	1.0004	1.00006	1.0006	1.00008	1.0005	1.00009	1.0003
air attenuation, k_a	1.0117	1.0100	1.0084	1.0066	1.0068	1.0056	1.0062	1.0048
field distortion, k_d	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
transmission through edges of diaphragm, k_l	0.9999	0.9999	0.9997	0.9997	0.9994	0.9997	0.9995	0.9996
transmission through walls of standard, k_p	1.0000	1.0000	1.0000	1.0000	0.99991	0.9999	0.99969	0.9998
humidity, k_h	0.99779 to 0.99824	0.998	0.99779 to 0.99824	0.998	0.99779 to 0.99824	0.998	0.99779 to 0.99824	0.998

Table 5

X rays (100 to 250 kV)

Estimated relative uncertainties in BIPM exposure rate and air kerma rate (standard deviation, in %)

X-ray tube voltage (kV)	100		135		180		250	
	s_i	u_j	s_i	u_j	s_i	u_j	s_i	u_j
Physical constants								
dry air density (273,15 K, 101 325 Pa)		⩽ 0.01		⩽ 0.01		⩽ 0.01		⩽ 0.01
W/e		0.15		0.15		0.15		0.15
$\bar{g}$ } for air kerma		-		-		-		-
Correction factors applied to the standard								
scattered radiation, k_{sc}		0.07		0.07		0.07		0.07
electron loss, k_e		0.03		0.03		0.06		0.1
recombination losses, k_s	0.01	⩽ 0.01	0.017	⩽ 0.01	0.01	⩽ 0.01	0.013	⩽ 0.01
air attenuation, k_a	0.017	⩽ 0.01	0.017	⩽ 0.01	0.01	⩽ 0.01	0.01	⩽ 0.01
field distortion, k_d		0.07		0.07		0.07		0.07
transmission through edges of diaphragm, k_l		⩽ 0.01		⩽ 0.01		⩽ 0.01		⩽ 0.01
transmission through walls of standard, k_p		⩽ 0.01		⩽ 0.01		⩽ 0.01		⩽ 0.01
humidity, k_h		0.03		0.03		0.03		0.03
Measurement of $I/v\rho$								
measurement volume, v	0.007		0.007		0.007		0.007	
ionization current, I / corrections concerning ρ (temperature, pressure)	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01
Uncertainty on $\dot{X}_{BIPM}$								
quadratic sum	0.03	0.11	0.03	0.11	0.03	0.12	0.03	0.14
combined uncertainty	0.11		0.11		0.12		0.15	
Uncertainty on $\dot{K}_{BIPM}$								
quadratic sum	0.03	0.18	0.03	0.18	0.03	0.19	0.03	0.21
combined uncertainty	0.19		0.19		0.19		0.21	

Table 6

X rays (100 to 250 kV)

Estimated relative uncertainties in ARL exposure rate and air kerma rate
(standard deviation, in %)

X-ray tube voltage (kV)	100		135		180		250	
	s_i	u_j	s_i	u_j	s_i	u_j	s_i	u_j
Physical constants								
dry air density (273.15 K, 101 325 Pa)		0.01		0.01		0.01		0.01
W/e, $\bar{g}$ for air kerma		0.15		0.15		0.15		0.15
Correction factors applied to the standard								
scattered radiation, k_{sc}	0.01	0.1	0.01	0.1	0.01	0.1	0.01	0.1
electron loss, k_e		0.03		0.03		0.03		0.07
recombination losses, k_s	0.03	-	0.03	-	0.03	-	0.03	-
air attenuation, k_a	0.1		0.05		0.05		0.05	
field distortion, k_d	0.03		0.03		0.03		0.03	
transmission through edges of diaphragm, k_l		0.01		0.01		0.01		0.01
transmission through walls of standard, k_p		≤ 0.01		≤ 0.01		≤ 0.01		≤ 0.01
humidity, k_h		0.05		0.05		0.05		0.05
Measurement of $I/v\rho$								
measurement volume, v	0.03		0.03		0.03		0.03	
ionization current, I; corrections concerning ρ (temperature, pressure)	0.015	0.02	0.015	0.02	0.015	0.02	0.015	0.02
Uncertainty on $\dot{X}_{ARL}$								
quadratic sum	0.11	0.12	0.07	0.12	0.07	0.12	0.07	0.13
combined uncertainty	0.16		0.14		0.14		0.15	
Uncertainty on $\dot{K}_{ARL}$								
quadratic sum	0.11	0.19	0.07	0.19	0.07	0.19	0.07	0.20
combined uncertainty	0.22		0.20		0.20		0.21	

Table 7

X rays (100 to 250 kV)

N_X and N_K, calibration factors determined at ARL for the transfer chambers NE 2561-070 and 2561-194

X-ray tube voltage	$\dot{X}_{ARL}$ *	$\dot{K}_{ARL}$ *	Chamber NE 2561-070 * (a)		(b)		Chamber NE 2561-194 * (a)		(b)		Relative uncertainty** (st. dev., in %)	
			N_X	N_K	N_X	N_K	N_X	N_K	N_X	N_K		
(kV)	(µA/kg)	(mGy/s)	(mg^{-1})	(Gy/µC)	(mg^{-1})	(Gy/µC)	(mg^{-1})	(Gy/µC)	(mg^{-1})	(Gy/µC)	on N_X	on N_K
100	18.4	0.625	2.680	91.05	2.680	91.05	2.668	90.64	2.670	90.71	0.17	0.23
135	15.7	0.533	2.712	92.14	2.713	92.17	2.693	91.49	2.698	91.66	0.15	0.22
180	24.0	0.815	2.720	92.42	2.722	92.48	2.699	91.70	2.702	91.81	0.15	0.22
250	28.5	0.968	2.730	92.77	2.736	92.97	2.708	92.02	2.712	92.15	0.16	0.22

* Each value of the calibration factors is an average value based on 3 to 9 determinations, each determination being composed of at least five separate measurements.
The values in columns (a) and (b) were determined before and after calibration at BIPM, respectively.
The standard deviation of the ionization current for the transfer chambers is of the order of 0.03 %.
The difference between the values given in columns (a) and (b) is systematic. This may indicate changes in the instruments due to air travel.

** See Table 10 for a detailed analysis of uncertainties.

Table 8

X rays (100 to 250 kV)

N_X and N_K, calibration factors determined at BIPM for the transfer chambers NE 2561-070 and 2561-194

X-ray tube voltage (kV)	Date	$\dot{X}_{BIPM}$* (μA/kg)	$\dot{K}_{BIPM}$* (mGy/s)	Chamber NE 2561-070			Chamber NE 2561-194			Relative uncertainty** (st. dev., in %)	
				Ionization current* (pA)	N_X (mg^{-1})	N_K (Gy/μC)	Ionization current* (pA)	N_X (mg^{-1})	N_K (Gy/μC)	on N_X	on N_K
100	1988-04-14	6.2975	0.21395	2.359	2.670	90.70				0.12	0.19
		6.2995	0.21402				2.369	2.659	90.34		
135	1988-04-15	6.1410	0.20863	2.275	2.700	91.71				0.12	0.19
		6.1395	0.20857				2.284	2.688	91.31		
180	1988-04-18	8.8341	0.30016	3.256	2.713	92.19				0.13	0.20
		8.8345	0.30017				3.283	2.691	91.44		
250	1988-04-19	11.450	0.38906	4.208	2.721	92.47				0.15	0.22
		11.451	0.38911				4.248	2.695	91.59		

The correction for the leakage current of the transfer chambers was less than 0.1 %.
The standard deviation of the ionization current of a transfer chamber was of the order of 0.03 %.

* Each value given in this column is an average based on 30 measurements.
** See Table 10 for a detailed analysis of uncertainties.

Table 9

X rays (100 to 250 kV)

Results of the ARL-BIPM comparison

$R = (N_X)_{ARL}/(N_X)_{BIPM} = (N_K)_{ARL}/(N_K)_{BIPM}$

X-ray tube voltage (kV)	Chamber 2561-070			Chamber 2561-194		
	$(N_X)_{ARL}$ (mg^{-1})	$(N_X)_{BIPM}$ (mg^{-1})	R *	$(N_X)_{ARL}$ (mg^{-1})	$(N_X)_{BIPM}$ (mg^{-1})	R *
100	2.680	2.670	1.0037 ± 0.0021	2.669	2.659	1.0038 ± 0.0021
135	2.7125	2.700	1.0046 ± 0.0019	2.696	2.688	1.0030 ± 0.0019
180	2.721	2.713	1.0029 ± 0.0020	2.7005	2.691	1.0035 ± 0.0020
250	2.733	2.721	1.0044 ± 0.0022	2.710	2.695	1.0056 ± 0.0022

* See Table 10 for a detailed analysis of uncertainties

Table 10

X rays (100 to 250 kV)

Estimated relative uncertainty on the ratio
$R = (N_X)_{ARL}/(N_X)_{BIPM} = (N_K)_{ARL}/(N_K)_{BIPM}$
(standard deviation, in %)

X-ray tube voltage (kV)	100		135		180		250	
	s_i	u_j	s_i	u_j	s_i	u_j	s_i	u_j
ARL								
Measurement of exposure	0.11	0.12	0.07	0.12	0.07	0.12	0.07	0.13
Measurement of air kerma	0.11	0.19	0.07	0.19	0.07	0.19	0.07	0.20
Measurement of the ionization current of chambers NE 2561-070 and NE 2561-194	0.03	0.04	0.03	0.04	0.03	0.04	0.03	0.04
Measurement of distance		0.03		0.03		0.03		0.03
Use of monitor chamber	0.01		0.01		0.01		0.01	
Uncertainty on $(N_X)_{ARL}$								
Quadratic sum	0.11	0.13	0.08	0.13	0.08	0.13	0.08	0.14
Combined uncertainty	0.17		0.15		0.15		0.16	
Uncertainty on $(N_K)_{ARL}$								
Quadratic sum	0.11	0.20	0.08	0.20	0.08	0.20	0.08	0.21
Combined uncertainty	0.23		0.22		0.22		0.22	
BIPM								
Measurement of exposure	0.03	0.11	0.03	0.11	0.03	0.12	0.03	0.14
Measurement of air kerma	0.03	0.18	0.03	0.18	0.03	0.19	0.03	0.21
Measurement of the ionization current of chambers NE 2561-070 and NE 2561-194	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.02
Measurement of the distance		0.02		0.02		0.02		0.02
Uncertainty on $(N_X)_{BIPM}$								
Quadratic sum	0.04	0.11	0.04	0.11	0.04	0.12	0.04	0.14
Combined uncertainty	0.12		0.12		0.13		0.15	
Uncertainty on $(N_K)_{BIPM}$								
Quadratic sum	0.04	0.18	0.04	0.18	0.04	0.19	0.04	0.21
Combined uncertainty	0.19		0.19		0.20		0.22	
Uncertainty on R *								
Quadratic sum	0.12	0.17	0.09	0.17	0.09	0.18	0.09	0.20
Combined uncertainty	0.21		0.19		0.20		0.22	

* The uncertainties on W/e and g entering in the uncertainty of N_K do not contribute to the uncertainty on $(N_K)_{ARL}/(N_K)_{BIPM}$.

Table 11

X rays (100 to 250 kV)

Comparison of 1979 and 1988 values of N_X (chamber NE 2561-070)

X-ray tube voltage (kV)	$(N_X)_{1988}/(N_X)_{1979}$	
	at ARL	at BIPM
100	1.0011	0.9970
135	1.0030	0.9985
180	1.0035	1.000
250	1.0031	0.9963

Table 12

^{60}Co gamma radiation

Physical constants and correction factors
entering in the determination of $\dot{X}$ and $\dot{K}$ at BIPM and ARL

Physical constants		BIPM	ARL
dry air density (273.15 K, 101 325 Pa) (kg/m^3)		1.292 99	1.292 9
$\bar{s}_{C,a}$ *		1.000 3	1.000 4
W/e * (J/C)		33.97	33.97
fraction $\bar{g}$ * of energy lost by bremsstrahlung		$3.2 \cdot 10^{-3}$	$3.2 \cdot 10^{-3}$
$(\mu_{en}/\rho)_a/(\mu_{en}/\rho)_C$ **		0.998 5	0.998 7
Correction factors applied to the standard			
air compressibility,	k_z	1.000 2	1.000
recombination losses,	k_s	1.001 5	1.000 37
humidity,	k_h	0.997 0	0.997 0 to 0.997 2
stem scattering,	k_{st}	1.000 0	0.998 6
wall attenuation,	k_{at}	1.038 9	1.037 7
mean origin of electrons,	k_{CEP}	0.992 5	0.992 2
wall scattering,	k_{sc}	0.973 5	0.970 3
axial non-uniformity,	k_{an}	0.996 8	0.996 3
radial non-uniformity,	k_{rn}	1.001 3	1.003 0

* See ref. [1].

** See ref. [2].

Table 13

^{60}Co gamma radiation

Estimated relative uncertainties in the exposure rate and air kerma rate (for BIPM and ARL), and in the ratio of the exposure (or air kerma) rates for the two laboratories

(standard deviation, in %)

	BIPM		ARL		ARL/BIPM	
	s_i	u_j	s_i	u_j	s_i	u_j
Physical constants						
dry air density (273.15 K, 101 325 Pa)		≤ 0.01		0.01		-
$\bar{s}_{C,a}$ (for exposure)		0.2		0.3		-
$\bar{s}_{C,a}$ W/e } (for air kerma)		0.11		0.11		-
$\bar{g}$ } (for air kerma)		0.02		0.02		-
$(\mu_{en}/\rho)_a/(\mu_{en}/\rho)_C$		0.05		0.1		-
Correction factors applied to the standard						
recombination losses, k_s	0.007	≤ 0.01	0.01		0.01	0.01
humidity, k_h		0.03		0.05		-
stem scattering, k_{st}		0.01	0.02		}	
wall attenuation, k_{at}		0.04		0.15	}	
mean origin of electrons, k_{CEP}		0.01		0.05	}	
wall scattering, k_{sc}		0.07		0.10	0.04	0.29
axial non-uniformity, k_{an}		0.07		0.2	}	
radial non-uniformity, k_{rn}		0.02	0.03		}	
Measurement of I/vρ						
measurement volume, v	0.011	0.03	0.05		0.05	0.03
ionization current, I } corrections concerning ρ (temperature, pressure)	0.018	0.01	0.04	0.02	0.04	0.02
Uncertainty on $\dot{X}$						
quadratic sum	0.02	0.24	0.07	0.42		
combined uncertainty	0.24		0.43			
Uncertainty on $\dot{K}$						
quadratic sum	0.02	0.17	0.07	0.32		
combined uncertainty	0.17		0.33			
Uncertainty on $\dot{X}_{ARL}/\dot{X}_{BIPM}$ and $\dot{K}_{ARL}/\dot{K}_{BIPM}$						
quadratic sum					0.08	0.29
combined uncertainty					0.30	

Table 14

^{60}Co gamma radiation

Result of the ARL-BIPM comparison $R = (N_X)_{ARL}/(N_X)_{BIPM} = (N_K)_{ARL}/(N_K)_{BIPM}$

N_X and N_K, calibration factors of transfer chambers NE 2561-070 and 2561-194

	Date of measurement (1988)	Ionization current* (pA)	$\dot{X}$ (µA/kg)	$\dot{K}$ (mGy/s)	N_X (mg^{-1})	N_K (Gy/µC)	Relative uncertainty** (st. dev., in %) on N_X	on N_K	R
Chamber NE 2561-070									
at ARL	March/April	32.420	89.606	0.3054	2.764	94.19	0.43	0.34	1.0005 ± 0.0031
at BIPM	12 April	0.9888	2.7269	0.09293	2.758	93.98	0.24	0.18	
	20 April	0.9872	2.7262	0.09291	2.762	94.12	0.24	0.18	
at ARL	July	32.499	89.672	0.3056	2.759	94.03	0.43	0.34	
Chamber NE 2561-194									
at ARL	March/April	32.934	89.606	0.3054	2.721	92.72	0.43	0.34	0.9954 ± 0.0033
at BIPM	13 April	0.9970	2.7260	0.09290	2.734	93.18	0.26	0.20	
at ARL	July	32.945	89.672	0.3056	2.722	92.76	0.43	0.34	

* At BIPM the correction for the leakage current of the transfer chambers was up to 0.2 %. Each value given in this column is an average based on about 60 measurements for chamber NE 2561-070 (standard deviation = 0.03 %) and 30 measurements for chamber NE 2561-194 (standard deviation = 0.1 %).

At ARL the leakage current corrections were negligible. The values were obtained over several days and are all corrected to the common date of 1 April 1988. They represent the mean of 5 determinations each based on 30 measurements for the values taken pre-BIPM, and the mean of 19 determinations based on 10 measurements for those taken post-BIPM.

** See Table 15 for a detailed analysis of uncertainties.

Table 15

^{60}Co gamma radiation

Estimated relative uncertainties of the calibration factors N_X and N_K (determined at ARL and BIPM), and of $R = (N_X)_{ARL}/(N_X)_{BIPM} = (N_K)_{ARL}/(N_K)_{BIPM}$

(standard deviation, in %)

	ARL		BIPM		ARL/BIPM	
	s_i	u_j	s_i	u_j	s_i	u_j
Measurement of exposure	0.07	0.42	0.02	0.24	0.08*	0.29*
Measurement of air kerma	0.07	0.32	0.02	0.17		
Measurement of ionization current of chambers NE 2561-070 and NE 2561-194	0.06	0.04	0.03**	0.03	0.07	0.05
Measurement of distance	-	0.02	-	0.01	-	0.02
Uncertainty on N_X						
Quadratic sum	0.09	0.42	0.04	0.24		
Combined uncertainty	0.43		0.24			
Uncertainty on N_K						
Quadratic sum	0.09	0.32	0.04	0.17		
Combined uncertainty	0.34		0.18			
Uncertainty on R						
Quadratic sum					0.11	0.29
Combined uncertainty					0.31	

* See Table 13.

** For chamber 194 this uncertainty amounts to 0.1 % to take into account the drift of the ionization current at the time of the calibration. The relative uncertainties on N_X and N_K determined at BIPM are 0.26 % and 0.20 %, respectively, and that on R is 0.33 %.

Table 16

Comparison of the ionization currents measured at ARL and at BIPM with the ^{90}Sr reference source

	I_{ARL} (pA) (1)	I_{ARL} (pA) (2)	I_{BIPM} (pA)	I_{ARL}/I_{BIPM}*
Chamber 070	29.377 ± 0.002	29.378 ± 0.003	29.384 ± 0.015	0.9998 ± 0.0005
Chamber 194	30.032 ± 0.004	30.006 ± 0.015	30.068 ± 0.015	0.9984 ± 0.0007

The values of the ionization current are given for 1988-04.01.

The values in columns (1) and (2) were determined before and after the measurements at BIPM, respectively.

The uncertainties represent one standard deviation (1σ).

* In 1979 this ratio was 1.0004 for chamber 070.

References

[1] BIPM, Constantes physiques pour les étalons de mesure de rayonnement, in BIPM Com. Cons. Etalons Mes. Ray. Ionisants, Section (I) 11, 1985, p. R 45 (Offilib, 75240 Paris Cedex 05)

[2] Hubbell, J.H., Photon mass attenuation and energy-absorption coefficients from 1 keV to 20 MeV, Int. J. Appl. Radiat. Isot. 33, 1982, pp. 1269-1290.

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