Comparison of the standards of air kerma and of absorbed dose of the LPRI and the BIPM for ^{60}Co γ rays

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Abstract
Comparisons between the standards of air kerma, absorbed dose to graphite and absorbed dose to water of the Laboratoire Primaire des Rayonnements Ionisants and of the Bureau International des Poids et Mesures have been carried out in the ^{60}Co radiation. They show an agreement of 0,3 % and 0,1 % between the standards of air kerma and absorbed dose, respectively.

1. Introduction

Comparisons of the standards of air kerma, absorbed dose to graphite and absorbed dose to water of the Laboratoire Primaire des Rayonnements Ionisants (LPRI), Saclay, France, and of the Bureau International des Poids et Mesures (BIPM), have been carried out in ^{60}Co radiation.
The standard of air kerma of the LPRI is a cavity ionization chamber constructed at the LPRI [1] and the standard of absorbed dose to graphite of the LPRI is a quasi-adiabatic calorimeter constructed at the LPRI [2]. The LPRI derives the absorbed dose to water from its calorimetric determination of absorbed dose to graphite by means of measurements with a transfer chamber in graphite and in water [3]. At the BIPM, the standards are graphite cavity chambers (see [4,5]).
The comparisons took place at the BIPM in December 1993. The standards of absorbed dose to graphite had already been compared in 1977.

2. Conditions of measurement

Air kerma and absorbed dose are determined under conditions defined by the Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants (CCEMRI) [6] :
- the distance from source to reference plane is 1 m,
- the field size in air at the reference plane is 10 cm x 10 cm, the photon fluence rate at the centre of each side of the square being 50 % of the photon fluence rate at the centre of the square,
- the reference depth for absorbed dose measurements is 5 $g \cdot cm^{-2}$.

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3. Comparison of the air kerma standards

The air kerma rate is determined by

$$\dot{K} = \frac{I}{m}\frac{W}{e}\frac{1}{1-\bar{g}}\left(\frac{\mu_{en}}{\rho}\right)_{a,c}\bar{s}_{c,a}\Pi k_i \ , \qquad (1)$$

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,

$\bar{g}$ is the fraction of energy lost by bremsstrahlung,

$(\mu_{en}/\rho)_{a,c}$ is the ratio of the mean mass-energy absorption coefficients of air and graphite,

$\bar{s}_{c,a}$ is the ratio of the mean stopping powers of graphite and air,

Πk_i is the product of the correction factors to be applied to the standard.

For the LPRI standard, the physical constants and the correction factors entering in (1) and the uncertainties associated with the measurements of $\dot{K}$ are given in Table 1 of the present report. Table 7 of [7] gives this data for the BIPM standard.

The collecting voltage applied to the LPRI standard is ± 800 V. The polarity effect I_- / I_+ is equal to 1,000 7.

The LPRI and the BIPM used their own equipment for the measurement of the ionization current I. A comparison of the two measuring devices was performed at the BIPM and shows no significant difference ($< 1\ 10^{-4}$).

The LPRI determined the correction factors applying to its standard for the ^{60}Co beam of the BIPM. These concern corrections due to the wall (k_{at}, k_{sc}, k_{CEP}), stem scattering (k_{st}) and recombination losses (k_s). The values of these factors measured at the BIPM agree to better than 0,1 % with those used at the LPRI.
The correction factor k_{rn}, for the radial non-uniformity of the BIPM beam over the section of the LPRI standard was estimated from [8].

The result of the comparison $R_K = \dot{K}_{LPRI}/\dot{K}_{BIPM}$ is given in Table 2. The $\dot{K}$ values refer to an evacuated path length between source and standard. They are given at the reference date of 1993-01-01, 0h UT (the half life of ^{60}Co is taken as (1 925,5 ± 0,5) days [9]).

The air kerma rates determined by the LPRI and BIPM standards are in good agreement. Their ratio R_K is 1,002 5. Some of the uncertainties in $\dot{K}$ which appear in both determinations (such as air density, W/e, μ_{en}/ρ, $\bar{g}$, $\bar{s}_{c,a}$, k_h, ...) cancel when evaluating the uncertainty of R_K, which is estimated to be 0,26 %. A detailed analysis is given in Table 2.

Table 1. Physical constants and correction factors entering in the determination of the air kerma rate, $\dot{K}_{LPRI}$, for the BIPM ^{60}Co beam.

The uncertainties are given as standard deviations (in %).

			$\dot{K}_{LPRI}$ values	$\dot{K}_{LPRI}$ uncertainty s_i	$\dot{K}_{LPRI}$ uncertainty u_j	$\dot{K}_{LPRI} / \dot{K}_{BIPM}$ uncertainty* s_i	$\dot{K}_{LPRI} / \dot{K}_{BIPM}$ uncertainty* u_j
Physical constants							
dry air density (293,15 K, 101 325 Pa)		($kg{\cdot}m^{-3}$)	1,204 7		< 0,01		
$(\mu_{en}/\rho)_a / (\mu_{en}/\rho)_c$ [10]			0,999 0		0,07		
$\bar{s}_{c,a}$ [10]			1,002 0		0,20		0,03
W/e [10]		($J{\cdot}C^{-1}$)	33,97		0,15		
$\bar{g}$ fraction of energy lost by bremsstrahlung			0,003 0		0,02		
Correction factors							
k_s	recombination losses		1,000 5		0,03	0,01	0,03
k_h	humidity		0,997		0,03		
k_{st}	stem scattering		0,998 7		0,04		0,04
k_{at}	wall attenuation	}					
k_{sc}	wall scattering	}	1,021 3		0,20	0,03	0,22
k_{CEP}	mean origin of electrons		0,994 0		0,06		0,06
k_{an}	axial non-uniformity		1,000 0		0,05		0,09
k_{rn}	radial non-uniformity		1,000 3		0,01		
Measurement of $I/v\rho$							
v	volume	(cm^3)	9,477 1		0,03	0,01	0,04
I	ionization current			0,01	0,07	0,02	0,07
Uncertainty in $\dot{K}_{LPRI}$							
	by quadratic summation			0,01	0,35		
	combined uncertainty			0,35			
Uncertainty in $\dot{K}_{LPRI} / \dot{K}_{BIPM}$							
	by quadratic summation					0,04	0,26
	combined uncertainty					0,26	

* See Table 7 of ref. [7] for a detailed analysis of the uncertainty in $\dot{K}_{BIPM}$.

Table 2. Result of the LPRI-BIPM comparison of standards of air kerma

$\dot{K}_{LPRI}$* ($mGy{\cdot}s^{-1}$)	$\dot{K}_{BIPM}$ ($mGy{\cdot}s^{-1}$)	$\dot{K}_{LPRI} / \dot{K}_{BIPM}$
7,834	7,815	1,002 5 ± 0,002 6

* Mean value of 5 measurements.

4. Comparison of the absorbed dose to graphite standards

The main characteristics of the LPRI calorimeter are given in Table 3.

Table 3. Characteristics of the LPRI graphite calorimeter

Core	diameter	(mm)	16
	length	(mm)	3
	mass	(g)	1,117 7
	graphite density	($g\cdot cm^{-3}$)	1,85
Gap widths*	gap 1	(mm)	1,12
	gap 2	(mm)	1,19
	gap 3	(mm)	1,00
Depth from the entrance window to the middle plane of the core		($g\cdot cm^{-2}$)	2,249 9
Phantom	section	(mm^2)	300 x 300
	length	(mm)	200
	graphite density	($g\cdot cm^{-3}$)	1,76

* Width of lateral gaps : 2 mm.

The absorbed dose rate $(\dot{D}_d)_{\mathrm{LPRI}}$ at depth d is given by the relation

$$(\dot{D}_d)_{\mathrm{LPRI}} = \frac{(L_c)_d}{m} F_{\mathrm{el}} \Pi k_i \ , \qquad (2)$$

where

$(L_c)_d$ is the calorimeter reading at depth d ; the values refer to an evacuated path length between source and phantom and to the reference date 1993-01-01, 0h UT,

F_{el} is the electrical calibration factor,

m is the mass of the core,

Πk_i is the product of the correction factors to be applied to the calorimetric measurements.

The numerical values of the terms entering in (2) are given in Table 4, together with their uncertainties. The correction factors were determined at the LPRI, except for k_6 and k_9 which account for gaps in the calorimeter and the radial non-uniformity of the BIPM ^{60}Co beam over the section of the core. These are taken from [11] and [8], respectively.
The calorimetric measurements of absorbed dose to graphite were performed at the BIPM at two depths, 4,551 $g\cdot cm^{-2}$ and 9,710 $g\cdot cm^{-2}$.

Detailed information on the determination of the absorbed dose rate to graphite $(\dot{D}_d)_{\mathrm{BIPM}}$ at a depth d in the BIPM phantom is given in [12].
The value at 5,000 $g\cdot cm^{-2}$, $(\dot{D}_5)_{\mathrm{BIPM}}$, is the mean of measurements performed over a period of three months before and after the LPRI calorimetric measurements at the BIPM, with $(\dot{D}_5)_{\mathrm{BIPM}}$= 7,3850 $mGy\cdot s^{-1}$. The values of $(\dot{D}_d / \dot{D}_5)_{\mathrm{BIPM}}$ for the two depths of comparison are given in Table 5.

Table 4. Quantities and correction factors entering in the LPRI calorimetric measurement of the absorbed dose rate in graphite at depth *d*, and estimated relative uncertainties (1σ, in %)

			numerical value	uncertainty s_i	uncertainty u_j
Measured quantity					
L_c					
α_{rad}	temperature rise signal by radiation			0,05*	
Δt_{rad}	irradiation time				0,005
m	mass of the core	(g)	1,117 7		0,02
F_{el}					
P_{el}	electrical calibration power				0,015
α_{el}	temperature rise signal by electrical energy				0,02
Δt_{el}	calibration time				0,005
Correction factors					
k_1	impurities		0,998 9		0,10
k_2	heat loss (temperature gradient)		1,000 0		0,05
k_3	heat defect		1,000 0		0,10
k_4	depth of point of measurement		1,000 0		0,10
k_5	distance		1,000 3		0,01
k_6	vacuum gaps		see Table 5		0,08
k_7	entrance foil attenuation		1,000 4		0,01
k_8	axial non-uniformity		1,000 0		
k_9	radial non-uniformity in the BIPM beam		see Table 5		0,01
Uncertainty in $(\dot{D}_d)_{LPRI}$					
	by quadratic summation			0,06	0,20
	combined uncertainty			0,21	

* At 5 g cm^{-2} (see Table 5).

Measurements were carried out at the BIPM to estimate the effect of the differences between the LPRI and BIPM phantoms (dimensions, graphite thickness behind the reference plane, graphite density). For this purpose, a LPRI graphite transfer chamber inserted in a graphite disc was placed successively in the phantoms of the LPRI and of the BIPM at several depths near to 5 g·cm^{-2} and 10 g·cm^{-2}. The results show that the difference between measurements in the two phantoms can be of 0,1 % and 0,3 % at 5 g·cm^{-2} and 10 g·cm^{-2}, respectively. In view of the uncertainty in these results, no correction is applied to the experimental result of the comparison which is given, at depth *d*, by

$$R_d = \frac{(\dot{D}_d)_{LPRI}}{(\dot{D}_d)_{BIPM}} \quad . \tag{3}$$

The values of R_d are listed in Table 5 and their uncertainties in Table 6. They indicate that the two standards are in very good agreement, within their uncertainties. One can note that R_d agrees also very well with the values obtained during the 1977 comparison (R_5 = 0,999 9 and R_{10} = 1,001 1 [13]).

Table 5. Result of the LPRI-BIPM comparison of standards of absorbed dose to graphite

Depth d (g·cm^{-2})	LPRI correction factors k_6	k_9	$(\dot{D}_d)_{LPRI}$* (mGy·s^{-1})	σ** (%)	$(\dot{D}_d / \dot{D}_5)_{BIPM}$	$(\dot{D}_d)_{BIPM}$ (mGy·s^{-1})	R_d
4,551	1,005 2	1,000 4	7,480	0,05	1,013 4	7,484	0,999 5
9,710	1,008 9	1,000 9	6,272	0,06	0,850 1	6,278	0,999 0

* Mean value of 15 calorimetric runs at each depth.
** Statistical uncertainty.

Table 6. Estimated relative uncertainties in the comparison result, R_d (1σ, in %)

	uncertainty s_i	u_j
Determination of $(\dot{D}_d)_{BIPM}$		
ionometric measurement of absorbed dose rate in graphite, at 5 g·cm^{-2} (see Table 1 of [11])	0,01	0,26
interpolation on BIPM depth dose curve, $(\dot{D}_d / \dot{D}_5)_{BIPM}$		0,05
Determination of $(\dot{D}_d)_{LPRI}$		
calorimetric measurement of absorbed dose rate in graphite, $(\dot{D}_d)_{LPRI}$ (see Table 3)	0,06	0,20
Comparison conditions		
difference in the LPRI and BIPM graphite phantoms		0,10
measurement of distance from source to detectors		0,03
Uncertainty in R_d		
by quadratic summation	0,06	0,35
combined uncertainty	0,35	

5. Comparison of the absorbed dose to water standards

The comparison was made at the reference depth of 5,000 g·cm^{-2}. The absorbed dose to water is determined at the LPRI by transfer from absorbed dose to graphite using a graphite cavity chamber, type NE 2571.

In the BIPM beam, this chamber was first placed in the LPRI graphite phantom with its centre at a depth of 5,042 g·cm^{-2}. With its equilibrium cap fitted, and embeded in its waterproof envelope, it was then placed in the BIPM water phantom (30 cm x 30 cm x 30 cm) with its centre at a depth of 5,000 g·cm^{-2}.

The absorbed dose rate in water, $(\dot{D}_W)_{LPRI}$, is thus given by the relation

$$(\dot{D}_W)_{LPRI} = (\dot{D}_C)_{LPRI} \frac{I_W}{I_C} k_{pf} k_{stop} k_{wall} k_{cav} (\frac{\mu_{en}}{\rho})_{w,c} \beta_{w,c} \quad , \qquad (4)$$

where

$(\dot{D}_C)_{LPRI}$	is the absorbed dose rate to graphite at the depth of 5,042 g·cm^{-2} determined with the LPRI calorimetric standard,
I_C	is the ionization current measured by the transfer chamber, with its centre at the depth of 5,042 g·cm^{-2}, in the LPRI graphite phantom,
I_W	is the ionization current measured by the transfer chamber, in the conditions described above,
k_{pf}	is a correction factor which accounts for the non-equivalence of the perspex front face of the BIPM phantom with water [7],
k_{stop}	is the ratio of the graphite to air stopping power ratios in the water and graphite phantoms,
k_{wall}	is the ratio of the wall perturbation factors in the water and graphite phantoms,
k_{cav}	is the ratio of the cavity perturbation factors in the water and graphite phantoms,
$(\mu_{en}/\rho)_{w,c}$	is the ratio of the mean mass-energy absorption coefficients of water and graphite in the water phantom,
$\beta_{w,c}$	is the ratio of the kerma factors in water and graphite, in the water phantom.

Detailed information on the ionometric determination of the absorbed dose rate to water $(\dot{D}_W)_{BIPM}$ at 5 g·cm^{-2} in the BIPM phantom is given in [5].

The physical constants and correction factors entering in the determination of the absorbed dose rate to water, together with their uncertainties, are given in [5] for the BIPM standard and in Table 7 for the LPRI standard.

The $(\dot{D}_W)_{BIPM}$ value is the mean value of measurements performed over a period of three months, before and after the present comparison at the BIPM, with $(\dot{D}_W)_{BIPM}$ = 7,820 mGy·s^{-1} at 5,000 g·cm^{-2}.

The result of the comparison (Table 8) is given by

$$R_W = \frac{(\dot{D}_W)_{LPRI}}{(\dot{D}_W)_{BIPM}} \quad . \qquad (5)$$

The standards are in good agreement, within their uncertainties. The various contributions to the total uncertainty in R_W are given in Table 9. The uncertainties in $(\mu_{en}/\rho)_{w,c}$ and $\beta_{w,c}$ which appear in both determinations of $\dot{D}_W$ cancel when evaluating the uncertainty of R_W which is estimated to be 0,50 %.

Table 7. Physical constants and correction factors entering in the LPRI determination of the absorbed dose rate to water at 5 g·cm^{-2} and estimated relative uncertainties (1σ, in %)

	numerical value	uncertainty s_i	uncertainty u_j
Determination of $(\dot{D}_c)_{LPRI}$ in LPRI phantom			
calorimetric measurement of absorbed dose rate in graphite at 4,551 g·cm^{-2} (see Table 4) (mGy·s^{-1})	7,480 0	0,05	0,20
interpolation on LPRI depth dose curve $(\dot{D}_{5,042} / \dot{D}_{4,551})_{BIPM}$	0,985 8		0,02
Transfer chamber at 5,042 g·cm^{-2} in graphite			
measurement of ionization current		0,01	0,03
measurement of distance			0,01
measurement of depth in graphite			0,05
Transfer chamber at 5,000 g·cm^{-2} in water			
measurement of ionization current		0,01	0,03
measurement of distance			0,02
measurement of depth in water			0,03
Transfer from graphite to water			
k_{stop}	1,000 0		0,03
k_{wall}	1,009 7		} 0,20
k_{cav}	1,002 0		} 0,20
$(\mu_{en}/\rho)_{w,c}$	1,112 5		0,15
$\beta_{w,c}$	1,001 5		0,06
Uncertainty in $(\dot{D}_W)_{LPRI}$			
by quadratic summation		0,05	0,34
combined uncertainty		0,34	

Table 8. Result of the LPRI-BIPM comparison of standards of absorbed dose to water at 5,000 g·cm^{-2}

$(\dot{D}_W)_{LPRI}$ (mGy·s^{-1})	$(\dot{D}_W)_{BIPM}$ (mGy·s^{-1})	R_W	Relative uncertainty (1σ, in %)
7,811	7,820	0,998 8	0,50

Table 9. Estimated relative uncertainties in the comparison result, R_W (1σ, in %)

	uncertainty s_i	uncertainty u_j
Determination of $(\dot{D}_W)_{BIPM}$		
ionometric measurement of absorbed dose rate to water at 5 g·cm^{-2} (see [5])*	0,20	0,35
Determination of $(\dot{D}_W)_{LPRI}$		
(see Table 7)*	0,05	0,30
Uncertainty in R_W		
by quadratic summation	0,21	0,46
combined uncertainty	0,50	

* Without the uncertainties in $(\mu_{en}/\rho)_{w,c}$ and $(\beta)_{w,c}$ which are common to LPRI and BIPM.

5. Conclusion

These comparisons show a very good agreement between the standards of the LPRI and the BIPM which is of order 0,3 % for the standards of air kerma and of order 0,1 % for the standards of absorbed dose. The comparison of absorbed dose to graphite confirms the excellent agreement between the standards of absorbed dose to graphite of the LPRI and the BIPM obtained in 1977.
It should be noted that the results of the other comparisons of absorbed dose to water show that the values obtained with methods based on graphite [14, 15, 16,17] agree within the estimated uncertainties. That the results agree so well is due in part to the correlations between the different determinations because of the use of the same physical constants.

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