

**Comparison of the air kerma standards of the GUM and the BIPM
in the low- and medium-energy x-ray ranges**

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Abstract

Comparisons between the air kerma standards of the GUM and the BIPM have been performed in low- and medium-energy x-rays by means of transfer instruments. They show an agreement to about 0,5 %, in both energy ranges.

1. Introduction

Indirect comparisons were made between the GUM and the BIPM standards of air kerma in the ranges of 10 kV to 50 kV and 100 kV to 250 kV. The transfer instruments used were a plane-parallel chamber constructed at the GUM for the low-energy range, and a commercial chamber, type NE 2561, for the medium-energy range. The comparisons were made in the reference conditions recommended by the Section I of CCEMRI [1].

The BIPM standards have been described in [2] and [3] and no further details are given in this report. The GUM standards are plane-parallel chambers, whose the characteristics are described below.

2. Comparison in the 10 kV to 50 kV x-ray range

Although indirect comparison is not generally recommended in the low-energy x-ray range, it was acceptable for the present comparison because the transfer chamber is a small plane-parallel chamber of construction similar to that of the GUM standard, and because the radiation qualities used at the GUM are very close to those of the BIPM (Table 1). The air kerma rate at the GUM is about twice that measured at the BIPM, except at 10 kV for which it is lower. This has the effect that the efficiency of ion collection in the transfer chamber is not the same in the two beams. An estimation of this effect made at the BIPM, predicts a change of a few tenths of 0,1 %.

**Table 1. Reference qualities used at the GUM and at the BIPM
(10 kV to 50 kV)**

distance between x-ray tube and reference plane P :		50 cm (GUM and BIPM)			
beam diameter in the plane P :		8,5 cm (GUM) and 9,5 cm (BIPM)			
accelerating potential/kV		10	30	50(b)	50(a) ⁽²⁾
HVL (Al)/mm	GUM	-	0,178	1,007	2,304
	BIPM	0,036	0,176	1,021	2,257
transmission by 20 μ m Al					
BIPM filter C1	GUM	0,6159			
	BIPM	0,6151			
BIPM filter C16	GUM	0,6153			
	BIPM	0,6147			
air attenuation ⁽¹⁾ coefficient/ 10^{-4} cm ⁻¹					
	GUM	180	41,7	9,03	4,61
	BIPM	179	41,5	9,12	4,60

(1) at 101 325 Pa and 20 °C

(2) the most filtered of the two 50 kV radiation qualities

The GUM standard is a plane-parallel chamber with dimensions close to those of the BIPM standard, except that the diameter of the diaphragm is 10 mm at the GUM and 5 mm at the BIPM. Table 2 gives the main characteristics of the GUM standard, its dimensions and correction factors. These factors are very close to those which apply to the BIPM standard.

The transfer chamber used for the comparison has a plate separation of 50 mm and an air-attenuation path-length of 40 mm (Fig. 1). The diaphragm ($\Phi = 10$ mm) is fixed on its support, so it was not possible to make an ionometric comparison with the BIPM diaphragm, as is generally done during a comparison of standards in the low-energy x-ray range. The position of the chamber is easily adjustable in height and direction. It was positioned close to the BIPM standard, on the same lathe bench and its temperature is measured with a thermometer placed on the top of the transfer chamber. The polarization voltage applied was + 2000 V. For the calibration, the x-ray tube was shifted so that the beam axis coincided with that of one chamber or the other. Measurements with the BIPM standard were made immediately before and after the measurements with the transfer chamber, to correct for drift in the x-ray output which still occurs despite the very small variations of the accelerating voltage and x-ray tube current (of the order of 10^{-4}).

**Table 2. Main dimensions of the GUM standard (10 kV to 50 kV)
and correction factors**

	plate separation	69,87 ₅	mm		
	collecting plate width	20,27 ₃	mm		
	collecting plate height	70,41 ₃	mm		
	air path-length	102,2	mm		
	diaphragm diameter	9,995 ₅	mm		
	measuring volume	1,590 ₈	cm ³		
	applied voltage	± 4 000	V		
correction factors		10 kV	30 kV	50 kV(b)	50 kV(a)
k_{sc}	scattered radiation	0,993 8	0,994 4	0,996 0	0,996 1
k_e	electron loss	1,000 0	1,000 0	1,000 1	1,000 3
k_a	air attenuation ⁽¹⁾	1,202 5	1,043 6	1,009 3	1,004 7
k_s	recombination loss	1,000 0	1,000 4	1,000 2	1,000 1
k_d	field distortion	1,000 0	1,000 0	1,000 0	1,000 0
k_1	transmission through diaphragm edge	1,000 0	0,999 9	0,999 9	0,999 8
k_p	transmission through standard walls	1,000 0	1,000 0	1,000 0	1,000 0
k_h	humidity	0,998	0,998	0,998	0,998
k_f	polarity effect	0,999 7	0,999 3	0,999 3	0,999 2

(1) at 101 325 Pa and 20 °C

The transfer chamber was calibrated at the qualities given in Table 1, the calibration factor M being given by

$$M = K_w / I_{trans}$$

where K is the air kerma rate measured with the BIPM standard and I_{trans} is the ionization current measured by the transfer chamber with the BIPM electrometer, normalized to reference conditions (20 °C, 101 325 Pa). The term I_{trans} is corrected for the recombination loss and for the air attenuation on the depth of air between the x-ray tube and the centre of the measuring volume in excess of 59,4 g cm⁻².

The transfer chamber was irradiated for half an hour before each calibration to reduce drift. The leakage current did not exceed $2 \cdot 10^{-4}$ in relative value in most cases and an appropriate correction was made. Once the chamber was stabilized, the standard deviation for a series of five measurements was in the range 0,01 % to 0,05 %, depending on the radiation quality. The total uncertainty of M is estimated to be 0,20 % at the BIPM and 0,26 % at the GUM.

The transfer chamber was calibrated at the GUM at all reference qualities before and after its calibration at the BIPM . The difference found was less than 0,1 %, at each radiation quality and is compatible with the statistical uncertainty. This result confirms the high stability of the transfer chamber and excludes the possibility of damage during its transport to and from the BIPM.

The results of this indirect comparison are given in Table 3. The two determinations of M , obtained at the GUM and the BIPM, agree to about 0,3 % at all radiation qualities. This is an excellent result in view of the estimated uncertainties. A small improvement of about 0,04 % could be made, by taking into account the initial recombination in the GUM standard which has been neglected. It is interesting to note that the variation of M between 10 kV and 50 kV(a), about 1 %, is of the same order of magnitude as that expected from photon scattering and electron loss in the transfer chamber. Indeed, a rough estimate from the results given in Table 3 of [2] suggests a difference in chamber response of about 0,7 % between the two qualities. A more accurate calculation would be a powerful verification of the determination of the correction factors k_{sc} and k_e used for small sized standards.

For comparison, the present results are shown in Fig. 2, together with those of other laboratories. The overall agreement between the various standards is about 0,8 %.

Table 3. Comparison results in the low x-ray range (10 kV to 50 kV)

relative uncertainty of M_{GUM} : 0,26 %
 relative uncertainty of M_{BIPM} : 0,20 %
 uncertainty of M_{GUM}/M_{BIPM} : 0,33 %

accelerating potential /kV	$M_{GUM}^{(1)}$ /Gy μC^{-1}	$M_{GUM}^{(2)}$ /Gy μC^{-1}	M_{BIPM} /Gy μC^{-1}	M_{GUM}/M_{BIPM}
10	-	14,050	14,102	0,996 3
30	14,059	14,066	14,101	0,997 3
50(b)	14,126	14,128	14,173	0,996 8
50(a)	14,221	14,216	14,251	0,997 7

(1) values measured at the GUM before the comparison and (2) afterwards

3. Comparison in the medium-energy x-ray range

The GUM standard is a plane-parallel chamber the dimensions of which are larger than those of the BIPM standard. Table 5 gives its main characteristics, dimensions and correction factors. A commercial chamber was used for the indirect comparison in the medium-energy x-ray range. Its calibration factor varies by less than 2 % between 100 kV and 250 kV. Thus, the influence on the chamber response of a difference between the GUM and BIPM spectra can be disregarded. The radiation qualities used at the GUM are very close to those of the BIPM (Table 4). The air kerma rate at the GUM is more than twice that measured at the BIPM. However, this has no significant effect on the fraction of ions not collected in the transfer chamber since this results only from initial recombination for air kerma rates less than 0,5 mGy/s.

Table 4. Reference qualities used at the GUM and at the BIPM
(100 kV to 250 kV)

distance between x-ray tube
and reference plane P : 100 cm (GUM) and 120 cm (BIPM)
beam diameter in the plane P : 6,0 cm (GUM) and 10,5 cm (BIPM)

accelerating potential/kV		100	135	180	250
HVL(Cu)/mm	GUM	0,157	0,50	1,00	2,48
	BIPM	0,148	0,494	0,99	2,50
air attenuation ⁽¹⁾ coefficient /10 ⁻⁴ cm ⁻¹	GUM	3,44	2,33	2,02	1,67
	BIPM	3,55	2,35	1,98	1,72

(1) at 101 325 Pa and 20 °C

The transfer chamber was positioned on the same lathe bench as the BIPM standard. For the calibration, the x-ray tube was shifted so that the beam axis coincided with the axis of one chamber or the other. The temperature is measured with a thermometer placed near the transfer chamber and outside the beam. The chamber polarization voltage was + 200 V. Measurements with the BIPM standard were made immediately before and after the measurements with the transfer chamber to correct for possible drift in the x-ray output. The transfer chamber was calibrated at the qualities quoted in Table 4.

The transfer chamber was irradiated for half an hour before each calibration to reduce drift. The leakage current was less than $4 \cdot 10^{-4}$ in relative value and an appropriate correction was made. The standard deviation for a series of five measurements was about 0,02 %. The uncertainty of M is estimated as 0,22 % at the BIPM and as 0,26 % at the GUM.

**Table 5. Main dimensions of the GUM standard (100 kV to 250 kV)
and correction factors**

	plate separation/mm	239,9 2			
	collecting plate width/mm	99,88 0			
	collecting plate height/mm	280,5 6			
	air path-length/mm	393,3			
	diaphragm diameter/mm	10,278			
	measuring volume/cm ³	8,287			
	applied voltage/V	± 5 000			
correction factors		100 kV	135 kV	180 kV	250 kV
k_{sc}	scattered radiation	0,993 1	0,994 3	0,995 0	0,995 5
k_e	electron loss	1,000 0	1,000 5	1,001 4	1,003 0
k_a	air attenuation ⁽¹⁾	1,013 6	1,009 2	1,008 0	1,006 6
k_s	recombination loss	1,000 3	1,000 3	1,000 4	1,000 6
k_d	field distortion	1,000 0	1,000 0	1,000 0	1,000 0
k_l	transmission through diaphragm edge	0,999 7	0,999 6	0,999 4	0,999 2
k_p	transmission through standard walls	1,000 0	1,000 0	1,000 0	1,000 0
k_h	humidity	0,998	0,998	0,998	0,998
k_f	polarity effect	0,999 8	0,999 7	0,999 6	0,999 7

(1) at 101 325 Pa and 20 °C

The transfer chamber was calibrated at the GUM at all reference qualities, before and after its calibration at the BIPM. The differences found were less than 0,2 % and are compatible with the statistical uncertainty.

The results of the comparison are given in Table 6. The difference between M_{GUM} and M_{BIPM} is very small at 100 kV, less than 1 σ , but increases slightly with energy up to about 2 σ . This variation, although small, may originate in the value attributed to the correction needed for the electron loss. A small improvement to the agreement between the GUM and the BIPM standards, of the order of 0,05 % at 250 kV, could be obtained re-evaluating the factor k_p , used to correct for the transmission through the diaphragm edge.

Table 6. Comparison results in the medium-energy x-ray range
(100 kV to 250 kV)

relative uncertainty of M_{GUM} : 0,26 %
 relative uncertainty of M_{BIPM} : 0,22 %
 uncertainty of $M_{\text{GUM}}/M_{\text{BIPM}}$: 0,34 %

accelerating potential /kV	$M_{\text{GUM}}^{(1)}$ /Gy μC^{-1}	$M_{\text{GUM}}^{(2)}$ /Gy μC^{-1}	M_{BIPM} /Gy μC^{-1}	$M_{\text{GUM}}/M_{\text{BIPM}}$
100	92,16	92,00	92,22	0,998 5
135	92,91	92,70	93,10	0,996 8
180	93,25	93,12	93,57	0,995 9
250	93,64	93,50	94,09	0,994 4

(1) values measured at the GUM before the comparison and (2) afterwards

For comparison, the present results are shown in Fig. 3, together with those of other laboratories. The overall agreement between the various standards is about 1,2 %.

4. Conclusion

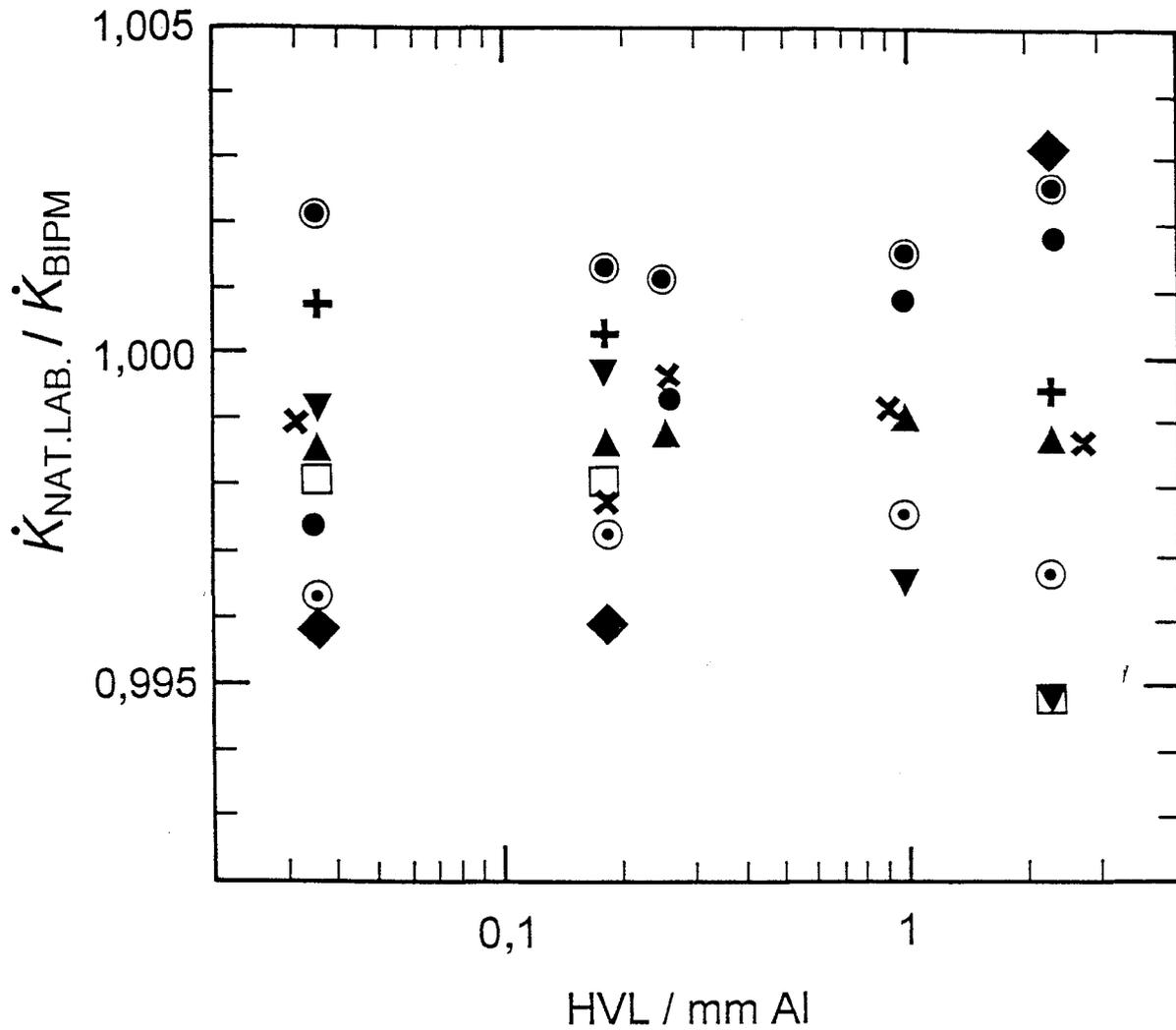
The spread of the results is larger at medium than at low x-ray energies (see Figures 2 and 3). This may be due, at least in part, to the instruments used for indirect comparisons in the medium energy x-ray range. Indeed, laboratories often calibrated these instruments at qualities other than the reference values so that interpolation is necessary, a procedure which increases the uncertainty.

In the low-energy x-ray range, the use of transfer instruments is not recommended and, until now, all comparisons but one were made directly by comparing the standards in the same beam. The present indirect comparison using the GUM transfer instrument gave very good results because it used a free-air chamber similar to a standard, and because the GUM qualities are very close to those of the BIPM.

References

- [1] BIPM, Qualités de rayonnements, in *Com. Cons. Etalons Mes. Ray. Ionisants (Section I)*, 1972, 2, R15 (BIPM, F-92312 Sèvres CEDEX)
- [2] BOUTILLON M., HENRY W.H. and LAMPERTI P.J., Comparison of exposure standards in the 10-50 kV X-ray region, *Metrologia* 5, 1969, pp. 1-11.
- [3] BOUTILLON M., Mesure de l'exposition au BIPM dans le domaine des rayons x de 100 à 250 kV, *Rapport BIPM-78/3* (BIPM, F-92312 Sèvres CEDEX)

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▼	NBS	1966	▲	NPL	1978
+	NRC	1966	⊙	JEN	1979
□	RIV	1968	×	ISS	1985
◆	ETL	1972	●	OMH	1988
			⊙	GUM	1994

Figure 2. Results of the comparisons of air kerma standards made between the BIPM and several national laboratories, in the low-energy x-ray range

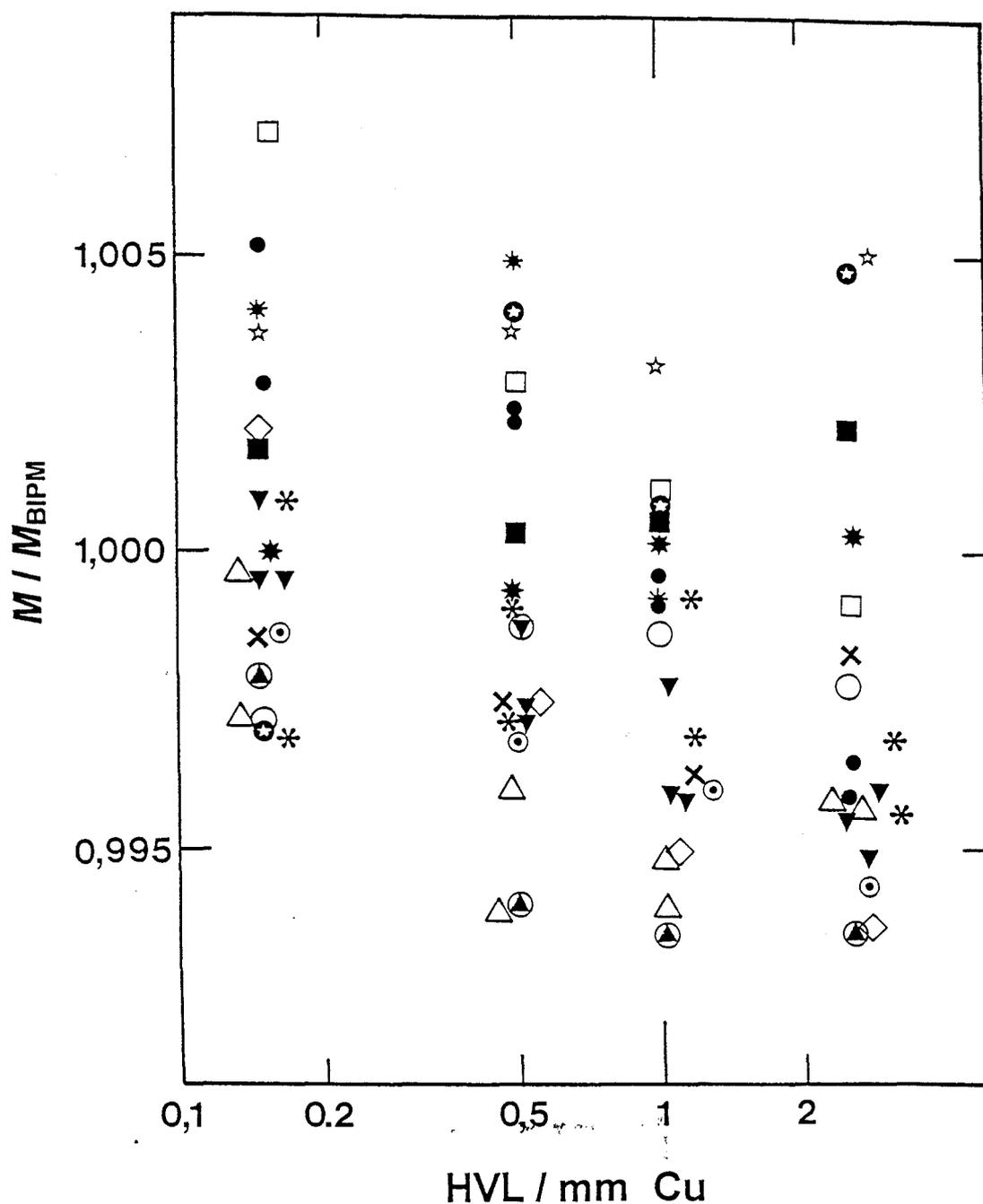


Figure 3. Results of the comparisons of air kerma standards made between the BIPM and several national laboratories, in the medium-energy x-ray range