Rapport BIPM-98/08

BIPM AND COMECON COMPARISONS OF AIR KERMA STANDARDS IN X- AND γ-RADIATION FIELDS

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Abstract
The results of comparisons undertaken by a regional metrology organization at several x- and γ-ray qualities are compared with those of BIPM international comparisons. The results are statistically coherent in most cases.

1. Introduction

One of the main roles of the Ionizing Radiation section of the Bureau International des Poids et Mesures (BIPM) is to promote the world-wide uniformity of dosimetric standards, a task which is of particular importance at radiotherapy levels. Consequently, in the framework of mutual recognition and equivalence proposed by the Comité International des Poids et Mesures (CIPM) [1], Section I of the Consultative Committee for Ionizing Radiation (CCRI(I)) decided to collect the results of dosimetry comparisons of national metrology institutes (NMIs) which have been undertaken by regional metrology organizations (RMOs) and to compare them with those of international comparisons made at the BIPM under the auspices of the CIPM.

This analysis concerns the results of comparisons which were undertaken as projects of the Council for Mutual Economic Assistance (COMECON), an association of countries of Eastern Europe set up in 1949 and disbanded in 1991. The number of participating laboratories is relatively large and the comparisons, made through repeated sets of measurements, cover all the reference radiation qualities (low- and medium-energy x-rays, ^{60}Co and ^{137}Cs γ-rays) proposed by the CCRI(I) to be used for the determination of air kerma in terms of the SI unit, the gray. The general conclusion is that, in view of the estimated uncertainties, the results are statistically coherent. A detailed analysis of the data is presented here.

2. BIPM international comparisons

2.1. *Conditions of measurement*

The international comparisons have been made at the BIPM under reference conditions [2] as recommended by the CCRI. Twenty NMIs have participated in these comparisons (Appendix 1) at all or some of the reference radiation qualities. The standards of air kerma used by the NMIs are plane-parallel free-air ionization chambers in the x-ray ranges (10 kV to 250 kV) and graphite cavity ionization chambers of different shapes at the γ-ray qualities (see for example [3, 4, 5]). Comparisons may be made at the BIPM at any time and consequently the BIPM standards and measuring equipment are verified regularly for long-term stability. Several Shonka chambers have

been calibrated over a period of twenty years or more, at 100 kV and in the ^{60}Co beam. The standard uncertainty of the distribution of their calibration factors during this period is better than 0.05 %. This confirms that, for a given beam quality, all BIPM comparisons are made under very stable conditions of measurement.
As recommended by the CCRI, national standards for the low-energy x-ray range are compared directly with the BIPM standard at the BIPM. In two cases, free-air chambers of small dimensions were used as transfer instruments. In the medium-energy x-ray range, graphite cavity transfer chambers belonging to the NMIs are used. Comparisons in ^{60}Co and ^{137}Cs beams are made either directly using national standards or indirectly using transfer instruments.

2.2. *Results of the BIPM comparisons*

Over the years some NMIs have undertaken two or three comparisons at a given beam quality. Although small changes have been made to the air kerma standards of some of these NMIs, successive results remain within 0.2 % or better, except in a few cases. Only the most recent comparison for a given NMI is considered in the present analysis, however. The combined relative standard uncertainty in the determination of air kerma in the x-ray beams is about 0.2 % at the BIPM and lies in the range from 0.2 % to 0.4 % at the NMIs. At the γ-ray qualities, the standard uncertainty is about 0.4 % at the BIPM and from 0.3 % to 0.6 % at the NMIs. Figure 1 parts (a), (b) and (c) indicate the results obtained in the low- and medium-energy x-ray ranges, and in the ^{60}Co and ^{137}Cs beams. These results, the values of which are given in Table A1 of Appendix 2, are expressed as the ratio

$R_{\mathrm{I,NMI}} = K_{\mathrm{NMI}} / K_{\mathrm{BIPM}}$ for a direct comparison (1a)

or as

$R_{\mathrm{I,NMI}} = N_{K,\mathrm{NMI}} / N_{K,\mathrm{BIPM}}$ for an indirect comparison, (1b)

where N_K is the calibration factor of the transfer instrument in terms of air kerma; see for example [6, 7].

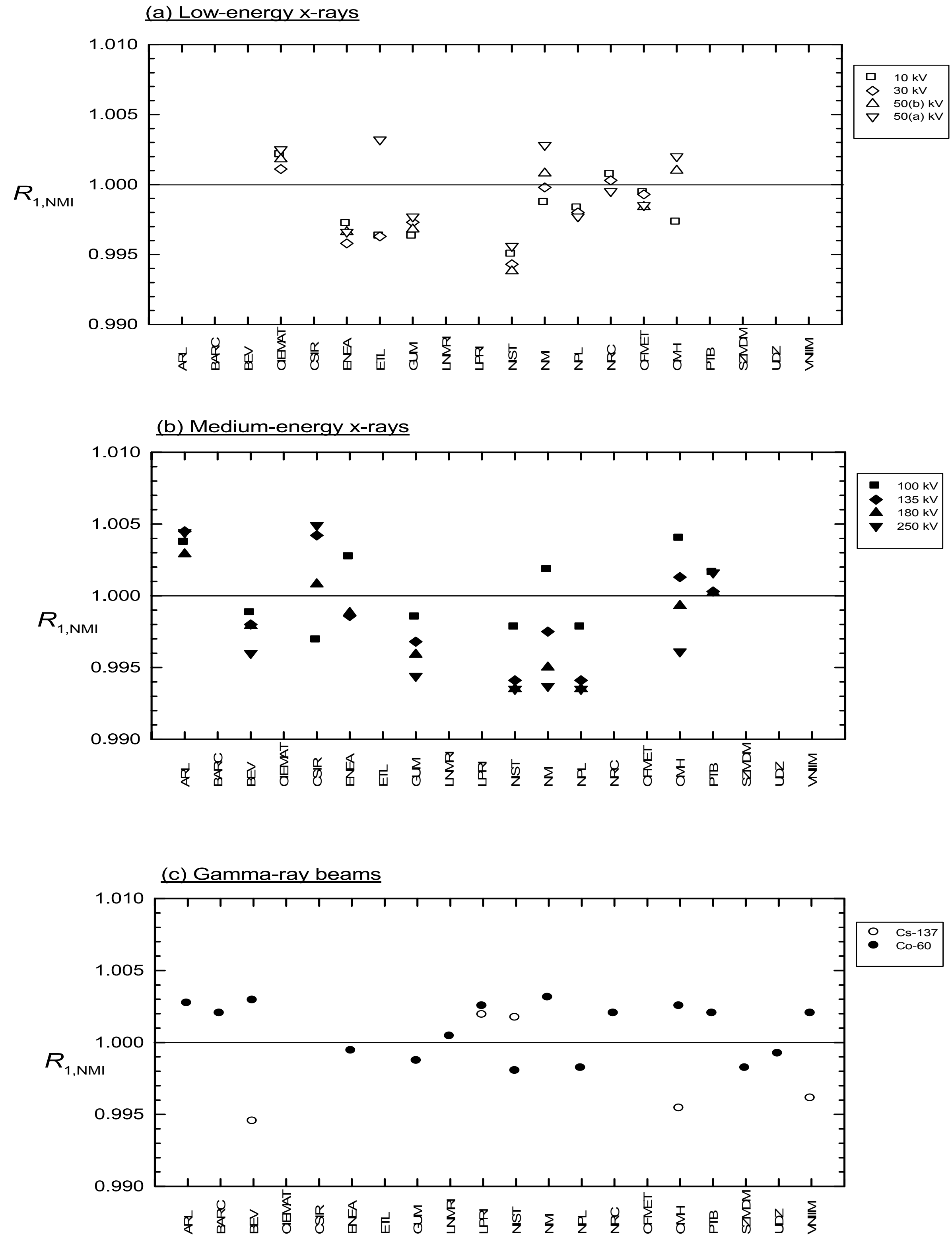
The determinations of air kerma rate during a comparison are correlated through common physical quantities. In evaluating the uncertainty of the comparison result, these correlations are taken into account. The resulting (quadratically summed) standard uncertainty of $R_{\mathrm{I,NMI}}$ is about 0.3 % to 0.5 % for the x-ray beam qualities. The spread of the results at each reference x-ray quality is consistent with this estimate. The resulting uncertainty of $R_{\mathrm{I,NMI}}$ at the ^{60}Co quality is about 0.2 % to 0.3 %, less than that for the x-ray beam qualities because the measurements are strongly correlated for cavity chambers. In the ^{137}Cs beam, where the same chambers are used as for ^{60}Co, the uncertainty of $R_{\mathrm{I,NMI}}$ is slightly higher, 0.3 % to 0.5 %, in part due to the more difficult estimation of wall correction factors [8]. For clarity, these uncertainties are not indicated in Figure 1.

3. COMECON comparisons

3.1 *Conditions of measurement*

During the period 1975 to 1990, three sets of comparisons in x- and γ-ray beams were undertaken in Eastern Europe [9]. Each comparison took one to two years to complete. Seven laboratories (listed in Appendix 1) responsible for the maintenance of national dosimetry standards in six countries participated in the comparisons at all or some of the reference radiation qualities. During this fifteen-year period, some laboratories developed new standards and the correction factors for

Figure 1. Results $R_{1,\mathrm{NMI}}$ of BIPM comparisons



some existing standards were re-evaluated. Only the most recent COMECON comparisons for each laboratory are examined for coherence with the current BIPM international comparison results, while section 4.4 considers the evolution of the COMECON comparisons.

The standards used for the COMECON comparisons are free-air chambers in the x-ray ranges and graphite cavity chambers in the ^{60}Co and ^{137}Cs γ-beams. A pressurized chamber (VNIIM) and a pressurized chamber with a magnetic field (ASMW) were also used in the first comparisons as independent primary standards contributing to the regional mean value. The standard uncertainty in the determination of air kerma is estimated to be in the same range as for the BIPM international comparisons, 0.3 % to 0.5 %.

In the x-ray ranges, all comparisons were indirect. Small free-air chambers and cavity chambers were used as transfer instruments in the low- and medium-energy ranges, respectively. In most cases, comparisons were made by circulating a single transfer instrument amongst the participants. At the γ-ray qualities the comparisons were made by comparing the standard chambers in the radiation beams of the ASMW (1982) and the OMH (1990).

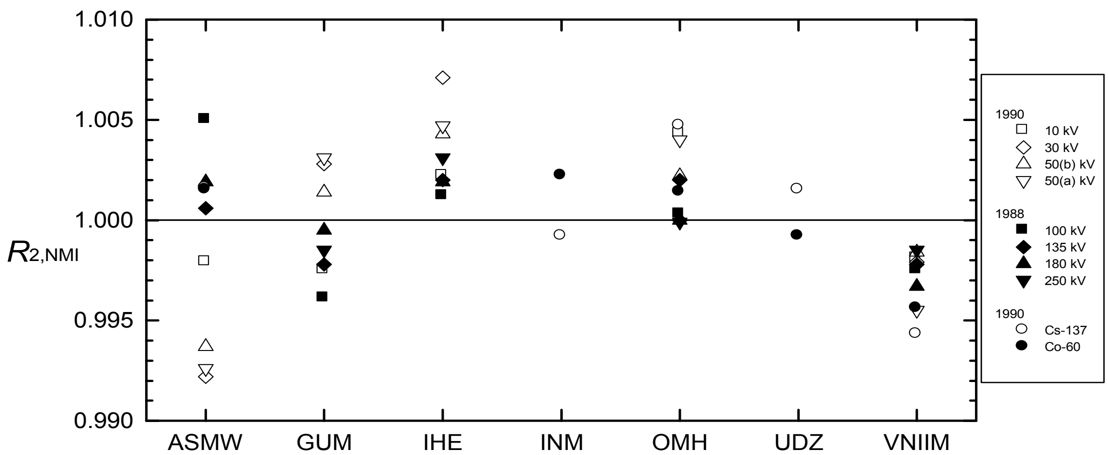
3.2. *Results of the COMECON comparisons*

The results of the most recent COMECON comparisons are given in Figure 2 and in Table A2 of Appendix 2 as the ratio

$$R_{2,\mathrm{NMI}} = N_{K,\mathrm{NMI}} / N_{K,\mathrm{mean}}, \qquad (2)$$

where $N_{K,\mathrm{mean}}$ is the arithmetic mean of the calibration factors determined by the participants for a given radiation quality [9]. At each beam quality, the scatter of the results is consistent with the estimated uncertainties.

Figure 2. Results $R_{2,\mathrm{NMI}}$ of the most recent COMECON comparisons



4. Linking the BIPM and the COMECON results

In order to link the BIPM and the COMECON results, the latter were first expressed in the same form as for the BIPM comparisons by defining the value

$$R_{3,\mathrm{NMI}} = R_{2,\mathrm{NMI}} \times R_{1,\mathrm{link}} / R_{2,\mathrm{link}}, \qquad (3)$$

where the subscript 'link' refers to a laboratory which has participated in both the regional and the BIPM comparisons. This is the case for the GUM and the OMH in the x-ray ranges, and for the OMH, the UDZ and the VNIIM at the γ-ray qualities. Where two (or more) possible linking laboratories exist for a given comparison, the relative position of the results of these laboratories in each comparison can be compared to give an indication of the robustness of the link. Figure 3 shows the ratios between the GUM and the OMH results for the COMECON comparisons and for the BIPM comparisons in the x-ray ranges[1]. Although a mean value of the linking laboratories could have been used, the GUM was chosen as the linking laboratory in the low- and medium-energy x-ray ranges because its comparisons with the BIPM are more recent (1994). The OMH was used as the link at the γ-ray qualities as their BIPM comparisons were also made in 1994. It should be noted that the choice of linking laboratory does not alter the relationship (or degree of equivalence) between one laboratory and another within the COMECON laboratories.

Figure 3. A comparison of the GUM and OMH results obtained in BIPM and COMECON dosimetry comparisons

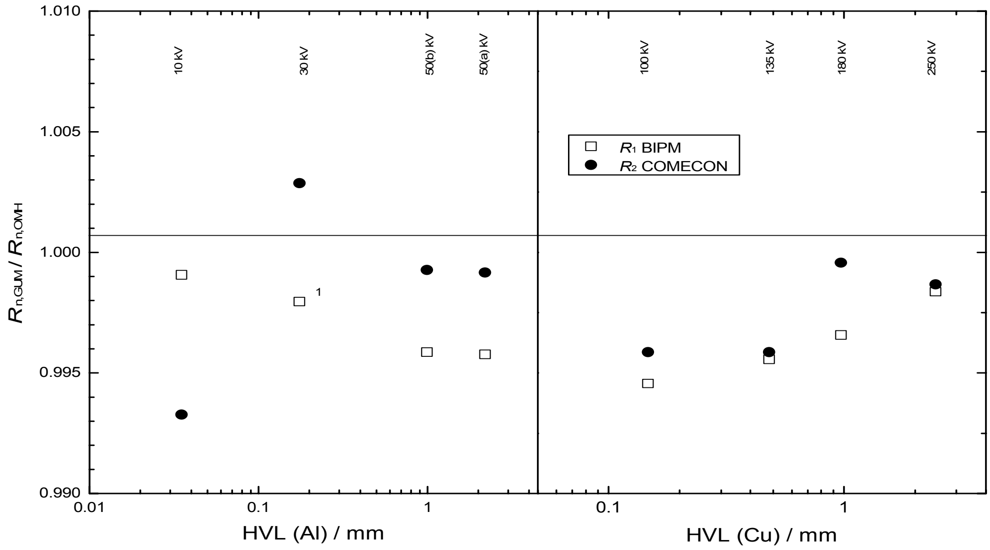


Table 1 gives a summary of the results and indicates the number of participating laboratories for each radiation quality. The arithmetic mean of the $R_{1,NMI}$ values obtained in BIPM international comparisons, R_{BIPM}, and the arithmetic mean of the $R_{3,NMI}$ values obtained in the COMECON comparisons, R_{COM}, are given with their respective standard uncertainties, s_1 and s_2. The radiation quality is expressed as a function of the applied potential to the x-ray tube and the half-value-layer (HVL).

The degree of coherence between the results of BIPM and COMECON comparisons can be assessed by comparing the difference, $d = R_{BIPM} - R_{COM}$, with the uncertainty of this difference, s_d (Table 1). The value of s_d is taken as the quadratic sum of s_1, s_2 and s_{link}, where s_{link} represents the statistical uncertainty of the linking term ($R_{1,link} / R_{2,link}$) in (3). The value of s_{link} is estimated to be 0.1 % in the x-ray ranges and 0.05 % for ^{60}Co and ^{137}Cs.

4.1. *Low-energy x-ray range*

In the low-energy x-ray range, the values for R_{BIPM} and R_{COM} show different trends with beam quality and the ratio s_2/s_1 is higher than one would expect (taking into account the number of participants in each comparison). Possible reasons for the differences could be the stability of the transfer instrument used and differences between the x-ray beams in the COMECON laboratories;

[1] The BIPM comparisons were made at 25 kV for the OMH and at 30 kV for the GUM. For a given NMI, the comparison results at these two qualities are usually very close.

the BIPM comparisons are all carried out in the same BIPM beams. Various parameters can influence the response of a chamber in the low-energy x-ray range [10].

Table 1. Summary of the results

a) Low-energy x-rays (linking laboratory: GUM)

Radiation quality		BIPM comparisons			COMECON comparisons			Coherence
kV	HVL (Al)/mm	No. labs	R_{BIPM}	s_1 / 10^{-3}	No. labs	R_{COM}	s_2 / 10^{-3}	d/s_d
10	0.04	11	0.998 3	0.6	5	0.998 8	1.4	0.3
30	0.18	10	0.998 2	0.7	5	0.994 5	2.5	1.3
50(b)	1.0	8	0.998 7	1.0	5	0.995 4	1.8	1.4
50(a)	2.3	11	0.999 7	0.8	5	0.994 6	2.5	1.8

b) Medium-energy x-rays (linking laboratory: GUM)

Radiation quality		BIPM comparisons			COMECON comparisons			Coherence
kV	HVL (Cu)/mm	No. labs	R_{BIPM}	s_1 / 10^{-3}	No. labs	R_{COM}	s_2 / 10^{-3}	d/s_d
100	0.15	11	1.000 2	0.8	5	1.002 4	1.5	1.1
135	0.50	11	0.999 7	1.0	5	0.999 0	0.9	0.4
180	1.0	11	0.998 4	0.9	5	0.996 4	1.0	1.2
250	2.5	11	0.998 1	1.3	4	0.995 9	1.1	1.1

c) ^{137}Cs and ^{60}Co (linking laboratory: OMH)

Radiation quality	BIPM comparisons			COMECON comparisons			Coherence
	No. labs	R_{BIPM}	s_1 / 10^{-3}	No. labs	R_{COM}	s_2 / 10^{-3}	d/s_d
^{137}Cs	6	0.998 3	1.5	5	0.991 0	1.7	3.1
^{60}Co	17	1.000 8	0.5	5	1.001 1	1.2	0.2

The results from the GUM and the OMH, indicate (Figure 3) that the ratios ($R_{n,GUM}$ / $R_{n,OMH}$) are mostly in agreement, within the uncertainties, in both the COMECON and the BIPM comparisons. However, at the 10 kV beam quality there is a discrepancy which is larger than would be expected from the statistical uncertainties and which results in an inversion of the trend observed at the other beam qualities. However, it can be concluded that in the low-energy x-ray range the coherence (defined as the values of d/s_d) in Table 1 (a) between the COMECON and the BIPM international results is at the level of better than two standard uncertainties, and that the COMECON uncertainties are generally higher than those of the BIPM international comparisons.

4.2. *Medium-energy x-ray range*

In the medium-energy x-ray range, transfer chambers have a relatively flat response with energy and the use of transfer instruments is therefore acceptable. As a check, in Figure 3 the ratio ($R_{n,GUM}$ / $R_{n,OMH}$) is shown to be reasonably constant between 100 kV and 250 kV and has similar values in both COMECON and BIPM international comparisons.

The results given in Table l (b) show that the mean value of d/s_d is approximately equal to 1. The agreement between the two systems of comparison is thus satisfactory and in fact, when taking the number of participants into account, for at least three of the four qualities the standard uncertainty of the COMECON comparison results is smaller than that for the corresponding BIPM comparison.

4.3. ^{60}Co *and* ^{137}Cs

For ^{60}Co, the standard deviations s_1 and s_2 are compatible, taking into account the number of laboratories involved. Table 1 (c) shows that for ^{60}Co the agreement between the COMECON and BIPM comparisons is satisfactory ($d/s_d = 0.2$).

The standard deviations s_1 and s_2 obtained at ^{137}Cs energy are also compatible. They are somewhat larger, however, than the values expected from the estimated individual uncertainties in both comparisons taking into account the number of participants. The increased scatter in the results arises mainly from the empirical determination of the wall correction, the uncertainty of which is probably underestimated [11]. Furthermore, there is some discrepancy between the COMECON and BIPM results as shown by the value of 3.1 obtained for d/s_d in Table 1(c).

Three laboratories, the OMH, the UDZ and the VNIIM, took part in both the BIPM and the COMECON comparisons for ^{60}Co, and two laboratories, the OMH and the VNIIM took part in both comparisons for ^{137}Cs. The ratios $R_{n,UDZ}$ / $R_{n,OMH}$ in Table 2 are consistent between the two comparisons and for the different γ-ray qualities. However, the ratios $R_{n,VNIIM}$ / $R_{n,OMH}$, although in agreement for the BIPM comparisons at both qualities, show a discrepancy of up to 1.1 % between the COMECON and BIPM comparisons. This difference may be due to the use of a new standard by the VNIIM during its recent international comparison at the BIPM; this standard is probably more accurate than that used during the COMECON comparison.

Table 2. Relative results of the NMIs participating in the comparisons for γ-ray qualities

Radiation beam	Comparison	R_{UDZ} / R_{OMH}	R_{VNIIM} / R_{OMH}
^{60}Co	COMECON $R_{2,NMI}$	0.998	0.994
	BIPM $R_{1,NMI}$	0.997	1.000
^{137}Cs	COMECON $R_{2,NMI}$	0.997	0.990
	BIPM $R_{1,NMI}$	-	1.001

4.4. *Evolution of the COMECON comparisons*

Three regional comparisons have been made in Eastern Europe, in 1975, 1981-1982 and in 1988-1990. This emphasizes the effort made by the Eastern laboratories to improve their measurements over the years by means of comparisons. The complete set of COMECON results is presented in Figure 4, where they are linked to the BIPM values through the linking laboratories indicated.

For the low-energy x-ray range, the COMECON comparisons have all been linked through the GUM comparisons with the BIPM carried out in 1994 (Figure 4(a)). The second comparison in 1982 shows a significant improvement in terms of scatter over the first comparison. This was not sustained, however, for the third comparison. In 1988, the OMH also made a direct comparison with the BIPM (as indicated by the points with uncertainty bars on the figure). It is of note that their results from the 1988-1990 regional comparison linked through the GUM to the BIPM agree within the uncertainties with those of the direct comparison.

In the medium-energy x-ray range (Figure 4(b)), the earlier two COMECON comparisons have been linked through the 1994 OMH comparison with the BIPM while the more recent results have been linked to the 1995 GUM comparison with the BIPM. The spread of the results over the three regional comparisons has improved. However, there appears to be a trend with radiation quality. This arises from the distinct trend in the data for the OMH (1975) and the GUM (1994) comparisons with the BIPM although the provisional results of the recent comparison (1998) with the OMH no longer show the previous trend. It had been suggested that the trend was due to the values used for the electron loss correction k_e which vary with the physical dimensions of the standard chambers [12]. Initial calculations made at the BIPM seemed to confirm this [13] but new calculations show that the corrections in use appear to be valid [14].

The results for the γ-ray comparisons are shown in Figure 4 (c) and (d). Here, each COMECON ^{60}Co comparison is linked through the OMH comparison which most recently precedes it, first to a comparison result of 0.997 4 in 1972 then to a result of 1.000 9 in 1986, while the ^{137}Cs comparisons are all linked through the OMH comparison with the BIPM made in 1995. The COMECON comparisons were significantly influenced by the modifications made to national standards. This is particularly evident where pressurized air chambers were originally used as standards, notably at the VNIIM. The subsequent direct comparisons in 1997 of the VNIIM with the BIPM in both ^{137}Cs and ^{60}Co γ-ray beams show satisfactory agreement [7], as indeed do those of the UDZ, the GUM and the OMH.

The results of these successive comparisons and the degree of consistency with the BIPM values demonstrate the positive evolution in the determination of air kerma in Eastern Europe.

5. Discussion

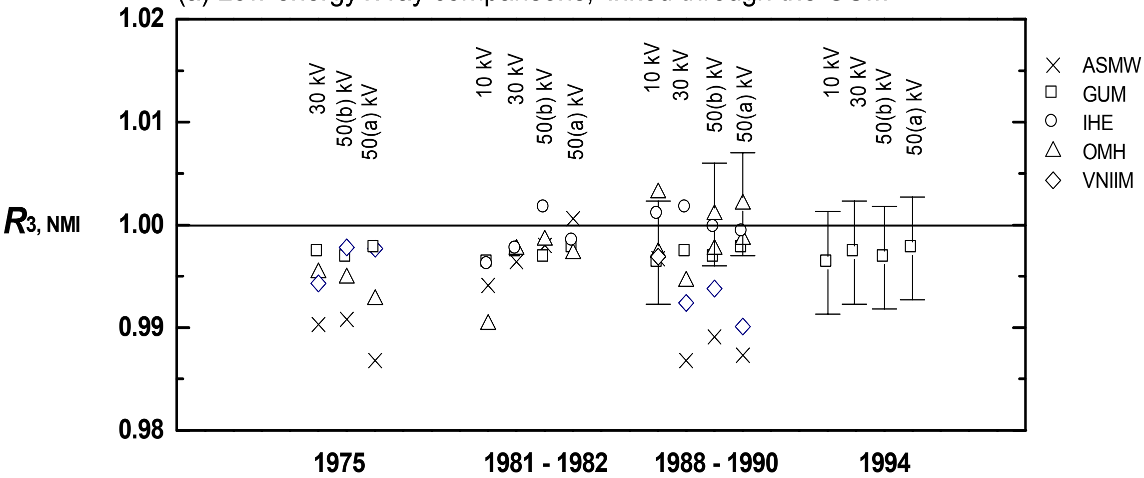
In BIPM international comparisons of air kerma standards, which have been carried out and reported over nearly three decades, national standards are compared with the BIPM standards under the reference conditions recommended by the CCRI. Consequently, the national standards can be reliably compared with each other through the BIPM standards.

The COMECON comparisons generally followed the circular scheme of a regional comparison using transfer standards, and the differences between the conditions of measurement in the various laboratories may have increased the uncertainty of the results. This method requires a relatively short period of time for a given type of comparison, to have confidence in the stability of the transfer standards.

Figure 4. Evolution of COMECON comparisons linked to the international BIPM comparisons

(standard uncertainty bars are indicated for the BIPM comparison results)

(a) Low-energy x-ray comparisons, linked through the GUM



(b) Medium-energy x-ray comparisons, linked through the OMH and the GUM

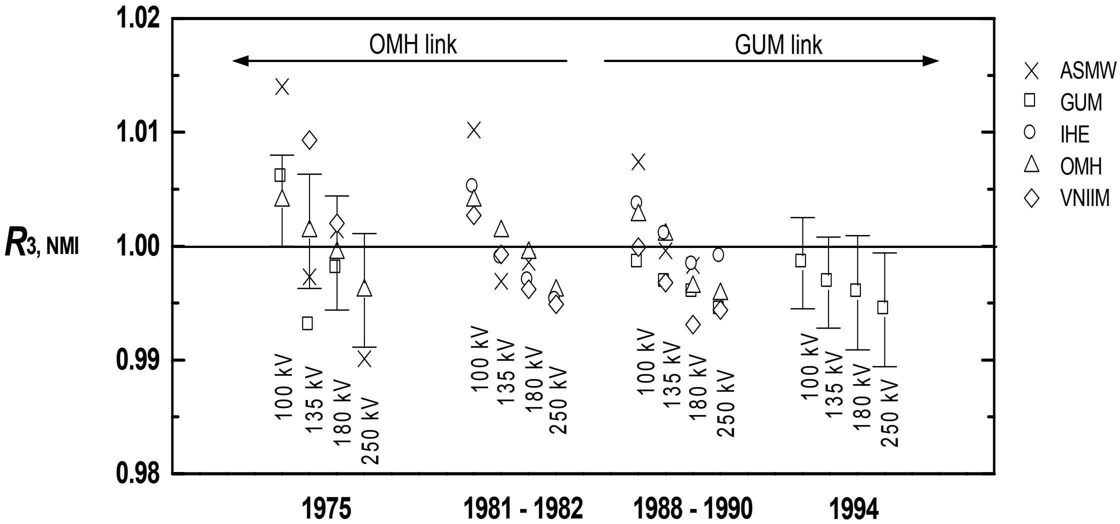
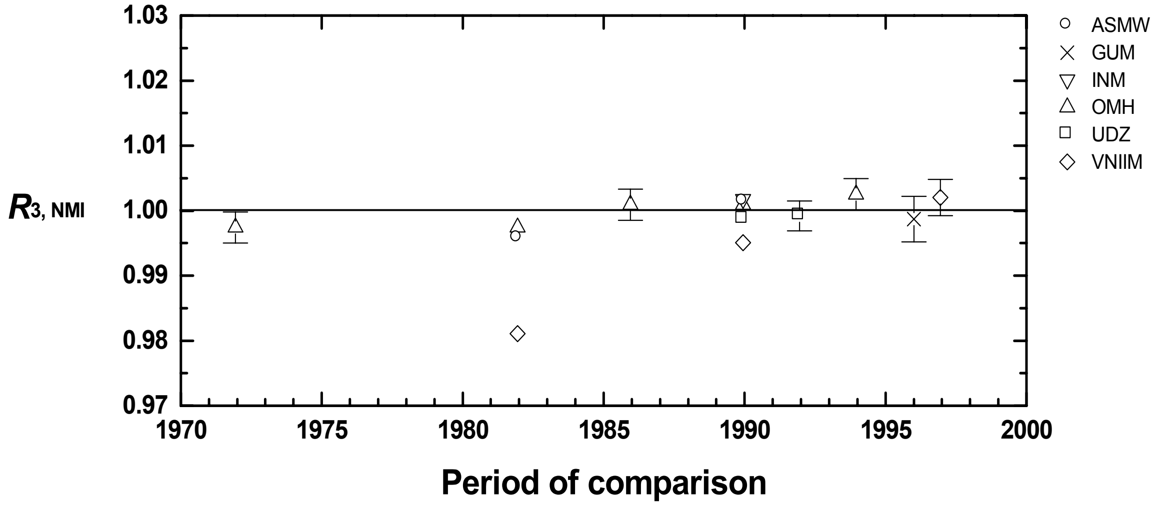
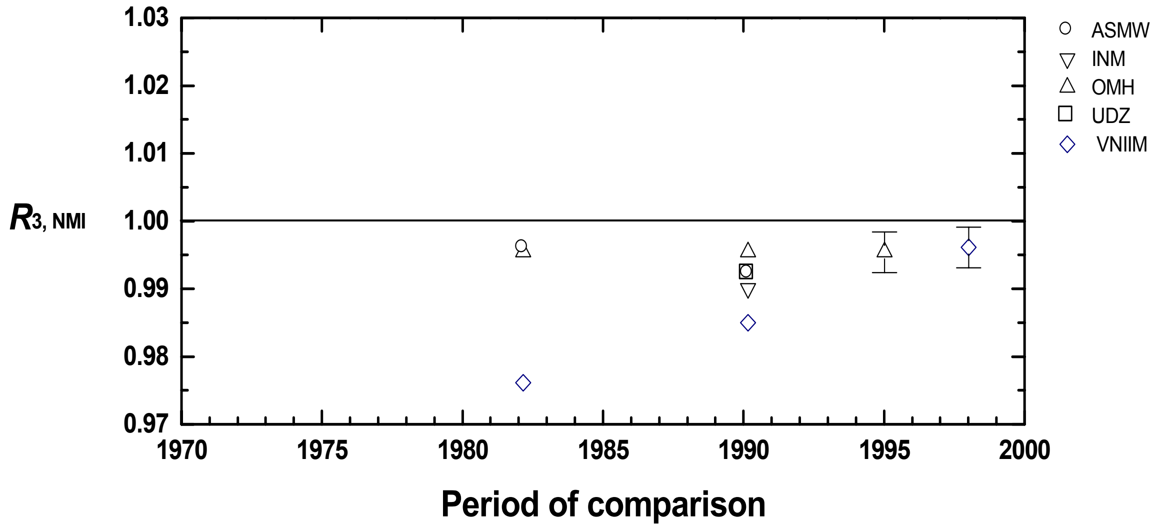


Figure 4 continued

(c) ^{60}Co comparisons linked through the OMH



(d) ^{137}Cs comparisons linked through the OMH



In principle, the results of the most recent COMECON comparisons may be linked to the BIPM international comparisons to deduce the degree of equivalence between each pair of NMIs. Such a calculation requires knowledge of the uncertainty budget for each NMI's determination of air kerma and the uncertainties of the ratios, $R_{2,\mathrm{NMI}}$. Table A3 of Appendix 2 gives an example of how the degrees of equivalence could be presented. The example shows that for the given beam qualities, equivalence is generally achieved at the level of two standard uncertainties. The Mutual Recognition Agreement (MRA) [1] requires the 95 % confidence level to be published. Hence by this criterion the NMIs of the COMECON countries are in satisfactory agreement.

Linking the COMECON results with the wider international community through the appropriate linking laboratory (Table 1) shows that there is coherence at the level of two standard uncertainties for all the energies except for ^{137}Cs. At this energy the agreement is only at the level of three standard uncertainties, which may not be significant given the limited number of participants in both comparisons. However, improvements could be made as mentioned in section 4.3; in particular, a new study of the wall effect is needed [11].

6. Conclusion

The comparisons of national primary air kerma standards of Eastern European countries undertaken under the auspices of the COMECON during the years 1975 to 1990, share many features of the regional comparisons now being considered to establish the degrees of equivalence between NMIs. The COMECON comparisons emphasize the care taken by the laboratories in perfecting their standards and in improving the uniformity of measurements. The results confirm the consistency of the standards within the region and, generally, statistical coherence with the international community. The degrees of equivalence between the NMIs of Eastern Europe and those elsewhere throughout the world are satisfactory even though the link to the international community is not particularly robust. Future regional comparisons should include at least two NMIs with up-to-date international BIPM comparison results to guarantee an unambiguous estimation of these degrees of equivalence, as has been stressed in the documents of the Comité International des Poids et Mesures [1].

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Appendix 1. Participating laboratories

International comparisons

Australian Radiation Laboratory, Yallambie, Australia (ARL)
Bhabha Atomic Research Centre, Trombay, India (BARC)
Bundesamt für Eich- und Vermessungswesen, Vienna, Austria (BEV)
Bureau International des Poids et Mesures (BIPM)
Centre de Investigationes Energéticas, Medioambientales y Tecnológicas, Madrid, Spain (CIEMAT)
Council for Scientific and Industrial Research, Pretoria, South Africa (CSIR)
Ente per la Nuove Tecnologie, I'Energia e l'Ambiente, Rome, Italy (ENEA)
Electrotechnical Laboratory, Tsukuba, Japan (ETL)
Glówny Urzad Miar, Warsaw, Poland (GUM)
D.I. Mendeleyev Institute for Metrology, St Petersburg, Russian Foundation (VNIIM)
Laboratoire Primaire des Rayonnements Ionisants, Saclay, France (BNM-LPRI)
National Institute of Standards and Technology, Gaithersburg, MD, USA (NIST)
Nederlands Meetinstituut, Bilthoven, Netherlands (NMi)
National Physical Laboratory, Teddington, UK (NPL)
Laboratório Nacional de Metrologia das Radiaçoes Ionizantes, Rio de Janeiro, Brazil (LNMRI)
National Research Council of Canada, Ottawa, Canada (NRC)
Orzágos Mérésügyi Hivatal, Budapest, Hungary (OMH)
Physikalisch-Technische Bundesanstalt, Braunschweig, Germany (PTB)
Savezni Zavod za Mere i Dragocene Metale, Belgrade, Yugoslavia (SZMDM)
Ustav Dozimetrie Zareni, Prague, ex-Czechoslovakia (UDZ)

COMECON comparisons

Amt für Standardisierung, Messwesen und Warenprüfung, Berlin, ex-GDR (ASMW)
Glówny Urzad Miar, Warsaw, Poland (GUM)
Institut Higiene a Epidemiologie, Prague, ex-Czechoslovakia (IHE)
Institutul National de Métrologie, Bucharest, Romania (INM)
D.I. Mendeleyev Institute for Metrology, St Petersburg, Russian Foundation (VNIIM)
Orzágos Mérésügyi Hivatal, Budapest, Hungary (OMH)
Ustav Dozimetrie Zareni, Prague, ex-Czechoslovakia (UDZ)

Appendix 2. Results of International and COMECON comparisons

Table A1. Results $R_{1,\mathrm{NMI}}$ of the BIPM international comparisons of air kerma standards

NMI	Year	R_1				Year	R_1				Year	R_1	Year	R_1
		10 kV 0.036[a]	30 kV 0.18[a]	50(b) kV 1.020[a]	50(a) kV 2.26[a]		100 kV 0.15[b]	135 kV 0.49[b]	180 kV 0.99[b]	250 kV 2.50[b]		^{60}Co		^{137}Cs
ARL	-	-	-	-	-	1988	1.003 7	1.004 6	1.002 9	1.004 4	1997	1.002 7	-	-
BARC	-	-	-	-	-	-	-	-	-	-	1975	1.002 0	-	-
BEV	-	-	-	-	-	1982	0.998 8	0.998 0	0.997 9	0.996 0	1995	1.002 9	1995	0.994 5
CIEMAT	1979	1.002 1	1.001 1	1.001 8	1.002 5	-	-	-	-	-	-	-	-	-
CSIR	-	-	-	-	-	1976	0.996 9	1.004 2	1.000 8	1.004 9	-	-	-	-
ENEA	1998	0.997 2	0.995 8	0.996 6	0.996 6	1983	0.998 4	0.997 4	0.996 2	0.995 2	1985	0.999 4	-	-
ETL	1972	0.996 3	0.996 3	-	1.003 2	-	-	-	-	-	-	-	-	-
GUM	1994	0.996 3	0.997 3	0.996 8	0.997 7	1994	0.998 5	0.996 8	0.995 9	0.994 4	1996	0.998 7	-	-
LNMRI	-	-	-	-	-	-	-	-	-	-	1996	1.000 4	-	-
LPRI	-	-	-	-	-	-	-	-	-	-	1993	1.002 5	1995	1.001 9
NIST	1998	0.995 0	0.994 3	0.993 8	0.995 6	1991	1.002 0	1.002 1	1.001 0	0.999 7	1996	0.998 0	1994	1.001 7
NMi	1996	0.998 7	0.999 8	1.000 8	1.002 8	1991	1.001 8	0.997 5	0.995 0	0.993 7	1996	1.003 1	-	-
NPL	1997	0.998 3	0.998 0	-	0.997 7	1982	0.997 8	0.994 0	0.993 5	0.993 5	1982	0.998 2	-	-
NRC	1966	1.000 7	1.000 3	-	0.999 5	-	-	-	-	-	1989	1.002 0	-	-
OFMET	1998	0.999 4	0.999 3	0.998 4	0.998 5									
OMH	1988	0.997 3	-	1.001 0	1.002 0	1975	1.004 0	1.001 3	0.999 4	0.996 1	1994	1.002 5	1994	0.995 4
PTB	-	-	-	-	-	1975	1.001 6	1.000 3	1.000 2	1.001 6	1989	1.002 0	-	-
SZMDM	-	-	-	-	-	-	-	-	-	-	1991	0.998 2	-	-
UDZ	-	-	-	-	-	-	-	-	-	-	1992	0.999 2	-	-
VNIIM	-	-	-	-	-	-	-	-	-	-	1997	1.002 0	1997	0.996 1

[a] Half-value-layer /mm (Al)   [b] Half-value-layer /mm (Cu)

Table A2. Results $R_{2,\mathrm{NMI}}$ of the COMECON comparisons of air kerma standards

NMI	Year	R_2				Year	R_2				Year	R_2	Year	R_2
		10 kV[c]	30 kV[d]	50(b) kV[e]	50(a) kV[f]		100 kV[g]	135 kV[h]	180 kV[i]	250 kV[j]		^{60}Co		^{137}Cs
ASMWM	1990	0.997 9	0.992 2	0.993 7	0.992 6	1988	1.005 0	1.000 6	1.001 9	-	1990	1.001 5	1990	1.001 4
GUM	1990	0.997 5	1.002 8	1.001 4	1.003 1	1988	0.996 1	0.997 8	0.999 5	0.998 5	-	-	-	-
IHE	1990	1.002 2	1.007 1	1.004 3	1.004 7	1988	1.001 2	1.002 0	1.001 9	1.003 1	-	-	-	-
INM	-	-	-	-	-	-	-	-	-	-	1990	1.002 2	1990	0.999 0
OMH	1990	1.004 3	1.000 0	1.002 2	1.004 0	1988	1.000 3	1.002 0	1.000 0	0.999 9	1990	1.001 4	1990	1.004 4
UDZ	-	-	-	-	-	-	-	-	-	-	1990	0.999 2	1990	1.001 3
VNIIM	1990	0.998 1	0.997 9	0.998 4	0.995 5	1988	0.997 5	0.997 8	0.996 7	0.998 5	1990	0.995 6	1990	0.994 0

Half-value-layers

[c] (0.02_8 to 0.04_2) mmAl   [d] (0.16 to 0.19) mmAl

[e] (1.00 to 1.07) mmAl   [f] (2.14 to 2.34) mmAl

Half-value-layers

[g] (0.18 to 0.20) mmCu   [h] (0.45 to 0.51) mmCu

[i] (0.93 to 1.01) mmCu   [j] (2.48 to 2.54) mmCu

Table A3. An example of the degrees of equivalence between the NMIs of the COMECON region

The degree of equivalence is defined as the difference $R_{2,\text{NMIi}} - R_{2,\text{NMIj}}$ and the uncertainty of the difference with a coverage factor of $k = 2$. In the absence of stated uncertainties these are estimated on the basis of BIPM international comparison results.

a) Low-energy x-ray beam at 50(b) kV

	Degree of equivalence $E_{i,j}$			
NMIi	GUM	IHE	OMH	VNIIM
ASMW	-0.007 7 (0.008)	-0.010 6 (0.008)	-0.008 5 (0.008)	-0.004 7 (0.008)
GUM		-0.002 9 (0.008)	-0.000 8 (0.008)	0.003 0 (0.008)
IHE			0.002 1 (0.008)	0.005 9 (0.008)
OMH				0.003 8 (0.008)

b) Medium-energy x-ray beam at 180 kV

	Degree of equivalence $E_{i,j}$			
NMIi	GUM	IHE	OMH	VNIIM
ASMW	0.002 4 (0.006)	0.000 0 (0.006)	0.001 9 (0.006)	0.005 2 (0.006)
GUM		-0.002 4 (0.006)	-0.000 5 (0.006)	0.002 8 (0.006)
IHE			0.001 9 (0.006)	0.005 2 (0.006)
OMH				0.003 3 (0.006)

c) ^{137}Cs γ-ray beam

	Degree of equivalence $E_{i,j}$			
NMIi	INM	OMH	UDZ	VNIIM
ASMW	0.002 4 (0.008)	-0.003 0 (0.008)	0.000 1 (0.008)	0.007 4 (0.008)
INM		-0.005 4 (0.008)	-0.002 3 (0.008)	0.005 0 (0.008)
OMH			0.003 1 (0.008)	0.010 4 (0.008)
UDZ				0.007 3 (0.008)

d) ^{60}Co γ-ray beam

	Degree of equivalence $E_{i,j}$			
NMIi	INM	OMH	UDZ	VNIIM
ASMW	-0.000 7 (0.005)	0.000 1 (0.005)	0.002 3 (0.005)	0.005 9 (0.005)
INM		0.000 8 (0.005)	0.003 0 (0.005)	0.006 6 (0.005)
OMH			0.002 2 (0.005)	0.005 8 (0.005)
UDZ				0.003 6 (0.005)