COOMET.RI(I))-K1 comparison of national measurement standards of air kerma for ^{60}Co γ radiation

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Abstract:

Results are presented of the COOMET key comparison of the national measurement standards of air kerma for ^{60}Co γ radiation. Participants of the comparison were PTB (Germany, pilot institute), VNIIM (Russia), SMU (Slovakia), BelGIM (Belarus), CPHR (Cuba) and RMTC (Latvia). PTB, VNIIM and SMU had previously taken part in a key comparison with the Bureau International de Poids et Mesures (BIPM) and operated as link laboratories in order to evaluate the degree of equivalence of the participants results with the key comparison reference value. These data form the basis of the results entered into the BIPM key comparison database for comparison COOMET.RI(I)-K1.

1. Introduction

This report describes the COOMET regional key comparison of national measurement standards of air kerma for ^{60}Co γ radiation according to the CIPM Mutual Recognition Arrangement [1]. Results will be published in Appendix B of the BIPM key comparison database (KCDB) using the identifier COOMET.RI(I)-K1. This is the first comparison of this kind within the COOMET region. Six National Metrology Institutes (NMIs), listed in Table 1, took part in the comparison. The key comparison reference value (KCRV) in this area is defined to be the realization of the unit of air kerma by the BIPM primary standard. Three participants of the current comparison, namely PTB [2], SMU [3] and VNIIM [4] previously took part in the BIPM.RI(I)-K1 key comparison and their results can be used to link the participants results to the KCRV. The national standards of Cuba and Latvia are traceable to BIPM, that of Belarus is traceable to VNIIM.

The procedure of the comparison is described in the next chapter. The results are presented in chapter 3. The evaluation of the results leading to the values of the degrees of equivalence of the participant’s results with respect to the KCRV and the degrees of equivalence between pairs of the participant’s results is given in chapter 4. After the completion of the Draft B report there was a significant change in the defined KCRV. Therefore it was necessary to adjust the results of this comparison accordingly. The adjustment procedure and the corresponding final results are presented in chapter 5. A summary and conclusion is given in chapter 6.

Table 1. Participants of the comparison COOMET.RI(I)-K1

NMI	Country	Contact person	E-mail of contact person
BelGIM	Belarus	Valery S. Milevsky	milevsky@belgim.by
CPHR	Cuba	Gonzalo Walwyn Salas	gonzalo@cphr.edu.cu
PTB	Germany	Ludwig Büermann	ludwig.bueermann@ptb.de
RMTC	Latvia	Antons Lapenas	alap@latnet.lv
SMU	Slovakia	Jozef Dobrovodsky	dobrovodsky@smu.gov.sk
VNIIM	Russia	Alexandr V. Oborin	khia@vniim.ru

2. Procedure of the comparison

The comparison was conducted indirectly. Three ionization chambers of different volumes (1 cm^3, 0.6 cm^3, 0.3 cm^3) were used as transfer chambers and were calibrated in terms of air kerma in the participant's ^{60}Co reference radiation fields under reference conditions as described below. The main technical data of the three transfer standards for the comparison are listed in Table 2. All chambers were manufactured by PTW and are otherwise in use as secondary standards at PTB. The reference points of the chambers are located on the chamber axis at a distance *d* from the top. Values of *d* are given in Table 2. The chambers were aligned in the beam with the mark on the stem facing the radiation source. The chambers had a PTW-M type connector. All chambers were provided with PMMA build-up caps which were applied for the measurements at ^{60}Co γ radiation. The build-up caps were marked at the height of the reference points.

Table 2. Main technical data of the transfer chambers

Type	Serial Number	Sensitive volume (nominal)	Chamber high voltage	Leakage	Wall material	*d*
M23331	607	1 cm^3	400 V	< 5*10^{-15} A	PMMA	11,5 mm
M30001	107	0.6 cm^3	400 V	< 5*10^{-15} A	PMMA	13 mm
M23332	275T	0.3 cm^3	400 V	< 5*10^{-15} A	PMMA	9,5 mm

The source to chamber distance (reference point of the chamber from the focus point of the ^{60}Co source) was 100 cm. The air kerma rates of the collimated ^{60}Co radiation beams at the participant's sites were always greater than 0.8 mGy/s yielding an ionization current of about 8 pA for the 0.3 cm^3 chamber. The beam cross sections at the reference planes were about 100 cm^2. The transfer chambers were placed in the laboratory at least 12 hours before the measurements were started in order to let them adjust to the climatic conditions. The leakage currents were measured and subtracted from the signal currents. The leakage currents of the transfer chambers did not exceed 5*10^{-15} A. A complete measurement consisted of at least 10 repeated single measurements and the mean value was taken as the result. The relative percentage Type A standard uncertainty of the repeated measurements did not exceed 0.05%. The calibration coefficients for the transfer chambers were measured at both chamber polarities (pos. and neg.) and the averages of these were given in terms of air kerma per unit charge in units of Gy/C referring to standard conditions of air temperature, pressure and relative humidity of T = 293.15 K, P = 101.325 kPa and h = 50 %. The relative air humidity was between 20 % and 80 % during the calibrations. If not, a correction to h = 50 % was applied. Participants did not apply any correction for the incomplete charge collection. The uncertainties were given in accordance with the ISO Guide to the expression of uncertainties in measurements [5].

A star-shaped circulation of the chambers between PTB and the participants was conducted. After each participant's calibration PTB repeated their calibration to monitor the constancy of the chamber response during the comparison. The chambers stayed at the participant's site for no longer than 2 weeks. The results were reported to the coordinator within 4 weeks after the calibration. The comparison started in August 2005 with the PTB measurements and ended in June 2006 with the measurements at SMU. The schedule of the comparison is listed in Table 3.

Table 3. Time schedule of the comparison

Participant	Date of calibration at the participants site	Constancy measurements at PTB
PTB, Germany	August-2005	
BelGIM, Belarus	September-2005	October-2005
VNIIM, Russia	December-2005	January-2006
CPHR, Cuba	February-2006	March-2006
RMTC, Latvia	April-2006	April-2006
SMU, Slovakia	June-2006	June-2006

3 Results

3.1 Constancy of the transfer chambers

The constancy check measurements started with the measurements at PTB in August 2005 and were repeated at both polarities each time when the chambers returned to PTB after the participant's measurements. The last stability check measurements were done in June 2006. The results are summarized in Table 4. The mean values of both polarities were calculated and are also listed in the table. Mean values of the calibration coefficients of each transfer chamber were calculated and then used to normalize the single values. Results are shown in Figure 1. From the figure it appears that one of the transfer chambers, namely of type M23331, behaved unstably and was consequently not used for the evaluation of comparison results. Fortunately, the other two chambers were stable to within about ±0.1% and hence they were suitable to be used as transfer standards.

Table 4. Summary of the calibration coefficients in units of 10^7 Gy/C obtained from the repeated measurements at PTB during the course of the comparison.

Chamber	Polarity	Aug 05	Oct 05	Jan 06	Mar 06	Apr 06	Jun 06
M23331	pos	2.693	2.693	2.731	2.703	2.724	2.699
	neg	2.700	2.697	2.734	2.709	2.723	2.705
M30001	pos	4.960	4.956	4.958	4.954	4.964	4.962
	neg	4.968	4.957	4.957	4.965	4.976	4.973
M23332	pos	9.793	9.793	9.780	9.776	9.781	9.792
	neg	9.772	9.762	9.788	9.773	9.798	9.776
M23331	mean	2.697	2.695	2.733	2.706	2.724	2.702
M30001	mean	4.964	4.957	4.958	4.960	4.970	4.967
M23332	mean	9.782	9.778	9.784	9.775	9.790	9.784

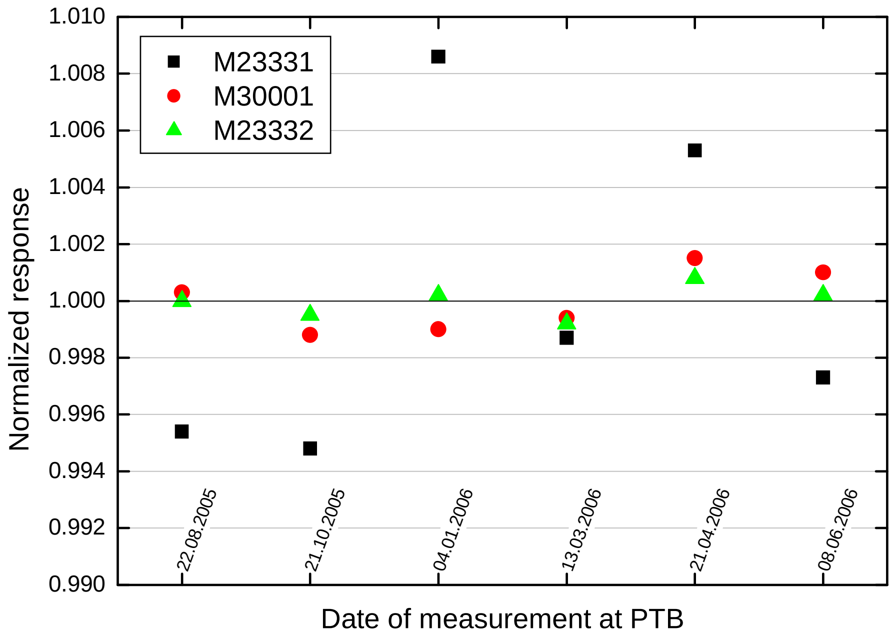

Figure 1. Calibration coefficients of the three transfer chambers normalized to their mean values as obtained from the constancy check measurements at PTB during the comparison.

3.2 Results of the participants

The calibration coefficients obtained by the participants for both polarities are listed in Table 5 together with the mean values of both polarities and the relative and absolute standard uncertainties reported by the participants. Note that the results of the transfer chamber type M23331 are not shown because the chamber was found to be unstable during the course of comparison. The results are also shown in Figures 2 and 3.

Table 5. Summary of the calibration coefficients and their standard uncertainties as reported by the participants.

		PTB Aug 05	BELGIM Sep 05	VNIIM Nov 05	CPHR Feb 06	RMTC Mrz 06	SMU May 06
Air kerma rate	/ mGy/s	0.82	12.68	8.664	6.9	9.77	5.27
M30001	pos	4.9600	4.96	4.8850	4.932	4.900	4.9659
	neg	4.9678	4.96	4.8900	4.927	4.899	4.9735
M23332	pos	9.7929	9.76	9.6370	9.661	9.632	9.7720
	neg	9.7718	9.73	9.6490	9.672	9.635	9.7721
M30001	mean	4.964	4.96	4.8875	4.9295	4.8993	4.970
.	rel. unc	0.21%	1.13%	0.41%	0.50%	0.50%	0.35%
	abs unc.	0.0104	0.056	0.0200	0.0246	0.0245	0.0174
M23332	mean	9.782	9.745	9.643	9.6665	9.6335	9.772
	rel. unc.	0.21%	1.13%	0.41%	0.50%	0.50%	0.35%
	abs. unc.	0.0205	0.110	0.0395	0.0483	0.0482	0.0342

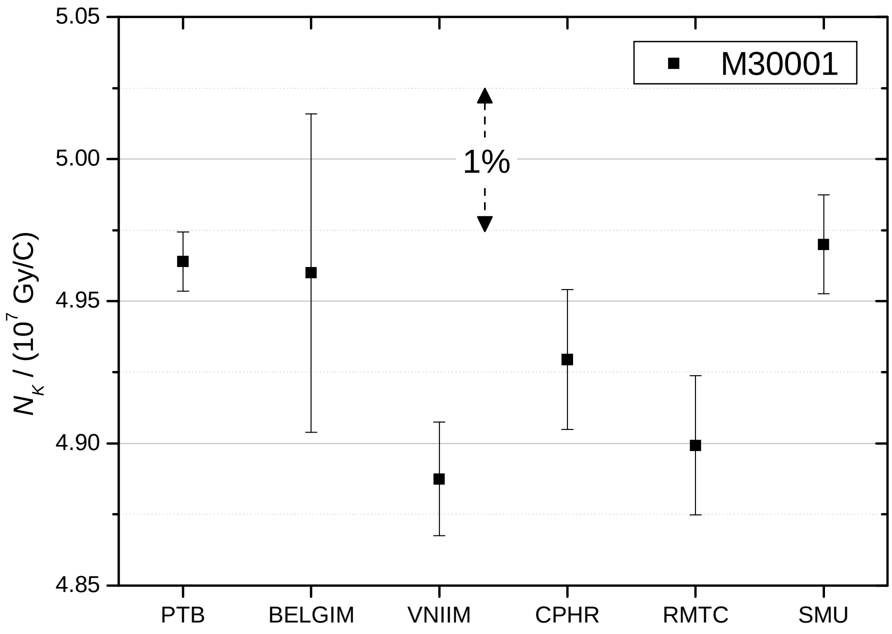

Figure 2. Calibration coefficients and associated standard uncertainties obtained by the participants for the transfer chamber of type M30001.

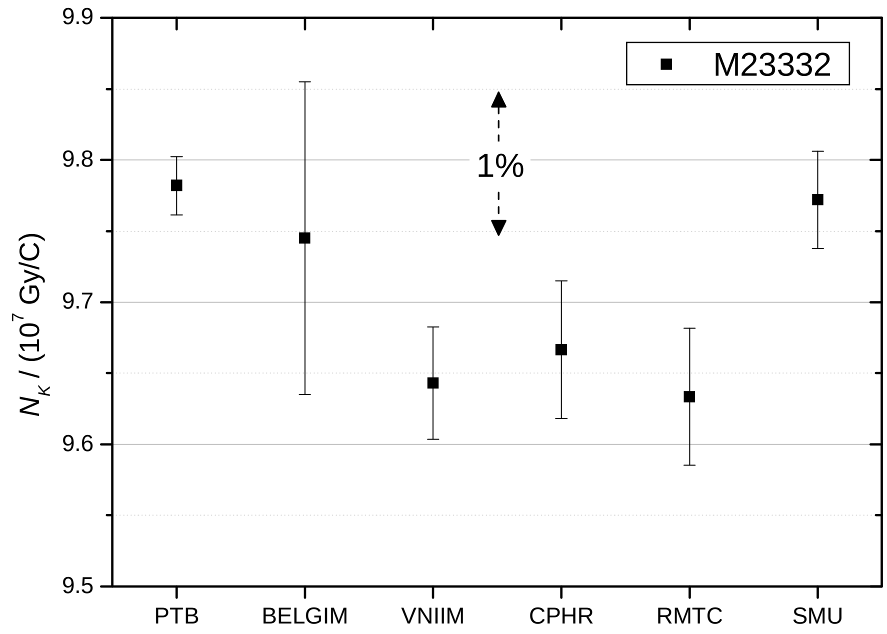

Figure 3. Calibration coefficients and associated standard uncertainties obtained by the participants for the transfer chamber of type M23332.

The ratios of the calibration coefficients of the two chambers obtained at each participant's site were calculated. Such ratios reflect in essence the ratio of the currents of the two transfer chambers measured in the ^{60}Co reference fields of the participants because the value of the air kerma rate cancels. The results normalized to the mean value of all participants are shown in Figure 4. The relative standard deviation of the mean value was 0.0018. From the figure it can be seen that the values are consistent within 0.3%.

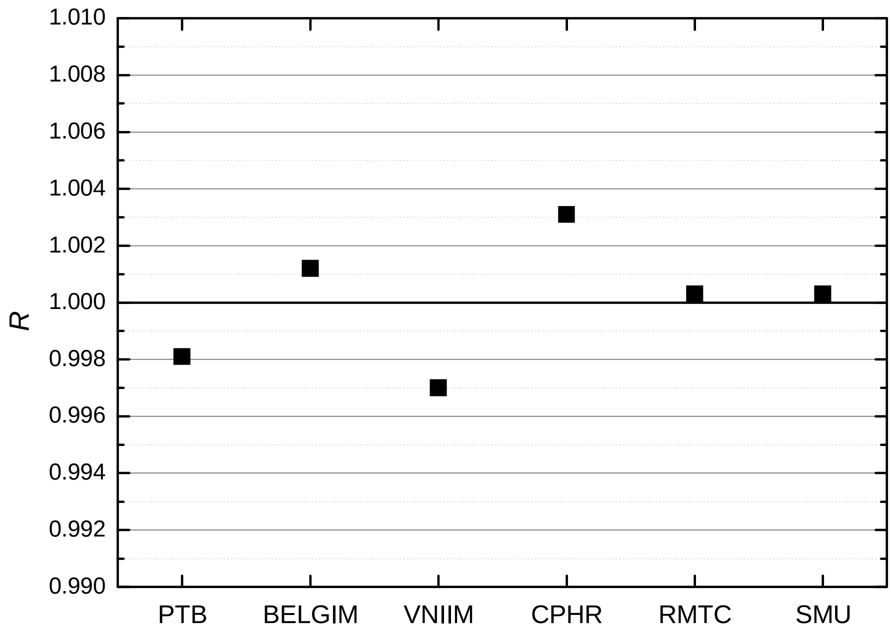

Figure 4. Ratio *R* of the calibration coefficients of the transfer chambers M30001 and M23332 measured by the participants, normalized to the mean value.

The uncertainties of the calibration coefficients given by the participants are summarized in Table 6. The national standard of Belarus (BelGIM) is traceable to the VNIIM, that of Cuba (CPHR) was calibrated by the IAEA whose standard is traceable to the BIPM and that of Latvia (RMTC) was calibrated at the Swedish Radiation Protection Centre (SSI) whose standard is also traceable to the BIPM. The complete uncertainty budgets of the primary standards of the three link laboratories are given in the corresponding key comparison reports [2-4] and that of the BIPM is given in [6] and will therefore not be repeated here. The standard uncertainties in Table 6 are divided into three components which are (i) the uncertainties of the physical constants used by the primary standards to which the national standards are traceable, (ii) other uncertainty components of the national standards and (iii) uncertainties due to the calibration procedures. All the primary standards involved in this comparison use the same values for the physical constants of the average energy spent by an electron of charge *e* to produce an ion pair in dry air, the dry air density, the fraction of electron energy lost in bremsstrahlung production in air, the ratio of the mean mass-energy absorption coefficients of air and graphite and the ratio of the mean stopping powers of graphite and air. Correlations due to these interrelations were taken into account in the evaluation of the uncertainties of the comparison results as described in the next chapter. The large relative uncertainty of the BelGIM standard is due to the standard uncertainty of the calibration coefficient of 1% given in the VNIIM calibration certificate.

Table 6. Comparison of the relative standard uncertainties in % of the calibration coefficients. The components from the physical constants, other components of the air kerma standards and the calibration procedures are given separately.

Institute traceable to	PTB primary	SMU primary	VNIIM primary	BelGIM VNIIM	CPHR IAEA->BIPM	RMTC SSI->BIPM
Standard (phys. constants)	0.12	0.12	0.34	0.34	0.12	0.12
Standard (other components)	0.13	0.27	0.23	0.94	0.45	0.39
Calibration procedure	0.12	0.18	0.06	0.52	0.17	0.29
Quadratic Summation	0.21	0.35	0.41	1.13	0.50	0.50

4 Evaluation of the degree of equivalence

The comparison results of the bilateral key comparisons of the three link laboratories with the BIPM are given in the BIPM reports [2,3,4] by the ratios R_K of the air kerma rates measured with the standards of the NMI to those measured with the BIPM standard in the same ^{60}Co radiation field at the BIPM:

$$R_{K,\mathrm{NMI}} = \dot{K}_{\mathrm{NMI}} / \dot{K}_{\mathrm{BIPM}} \quad (1)$$

R_K values obtained by equation (1) are referenced in the following as direct results. Values of R_K and the corresponding uncertainty, $u(R_K)$, of the link laboratories, taken from the comparison reports, are summarized in Table 7.

Table 7. Direct results of the link laboratories PTB [2], SMU [3], and VNIIM [4].

	PTB	VNIIM	SMU
R_K	1.0099	1.0020	1.0033
$u(R_K)$	0.0018	0.0028	0.0027

In the current comparison, the SMU used the wall correction factor, k_{wall}=1.0191(9) for their CC01-type standard cavity chamber, which is different from that used in the key comparison with the BIPM, where k_{wall}=1.0109(10) was applied. As a consequence, for the evaluation of the results of this report R_K =1.0114(27) was used as the direct result of SMU, which was calculated as 1.0033*1.0191/1.0109. Such a change in the wall correction factor for CC01-type chambers was first introduced by the MKEH, the Hungarian National Metrology Institute [7,8]. Note that this change in the direct result of SMU will not affect the linking results because it cancels in equation (2).

The BIPM value of the air kerma rate is regarded as the KCRV. The participant's results of the current comparison are linked to the KCRV using the link laboratories (PTB, VNIIM and SMU), who participated in both - the current regional and the BIPM key comparison, using the following equation:

$$R'_{K,\mathrm{NMI}} = R_{K,\mathrm{LINK}} \frac{N_{K,\mathrm{NMI}}}{N_{K,\mathrm{LINK}}} \quad (2)$$

$R_{K,\mathrm{LINK}}$ is the direct result of the link laboratory as defined in equation (1), $N_{K,\mathrm{NMI}}$ and $N_{K,\mathrm{LINK}}$ are the calibration coefficients of the participating NMI and link laboratory obtained from the current comparison. The R'_K values obtained by equation (2) are referenced in the following as indirect results. As there are three link laboratories, each of them can be used to evaluate indirect R'_K values for all other participants including those of the other two link laboratories, which in turn can be compared with the direct results, R_K, by the ratio R:

$$R = \frac{R'_{K,\mathrm{NMI}}}{R_{K,\mathrm{NMI}}} \qquad (3)$$

Ideally, R should be equal to one. This offers the possibility to check the consistency of the direct and indirect results of the three link laboratories.

For the evaluation of the uncertainties it was important to take into account the correlations which become clear from the above equations. The uncertainties of the direct results of equation (1) were taken from the reports [2-4]. In equation (2) the uncertainties of the physical constants and of the correction factor for air humidity of the standards of the NMI and the link laboratory cancel as well as the uncertainties of the correction factors and the volume determination of the standard of the link laboratory. In equation (3) the uncertainties of the correction factors and the volume determination of the BIPM standard cancel. Uncertainty evaluations were based on the numbers given in Table 6.

The results of the evaluations according to the equations (2) and (3) are given in the Tables 8, 9 and 10, where PTB, VNIIM and SMU were chosen as link laboratories, respectively. As there were always two values of R'_K obtained from the two transfer chambers, the mean value of both was taken as the final result, also given in the tables.

Before these results can be used for further evaluations, it should be checked whether the indirect results of the link laboratories are consistent with the direct results. Figure 5 shows the ratios R of the indirect and direct results according to equation (3). It appears that, within the uncertainties, the values obtained for PTB and SMU are consistent with each other, i.e. $R = 1$. However, the values R of VNIIM differ by up to about -0.006 or -0.007 from 1 if SMU or PTB is used to link the direct and indirect results which is much more than the standard uncertainties. Consequently, the ratios R of SMU and PTB are greater than 1 by about 0.006 and 0.007 if VNIIM is the link laboratory. It was therefore decided, to use only PTB and SMU as link laboratories for the final evaluation.

Table 8. Values of R'_K (see equation (2)) of the participants, if PTB is the link laboratory.

	PTB	BELGIM	VNIIM	CPHR	RMTC	SMU
R'_K (M30001)		1.0091	0.9944	1.0029	0.9967	1.0111
$u(R'_K)$		0.0111	0.0029	0.0051	0.0051	0.0036
R'_K (M23332)		1.0060	0.9955	0.9979	0.9945	1.0088
$u(R'_K)$		0.0111	0.0029	0.0051	0.0051	0.0036
R'_K (mean value)		1.0076	0.9949	1.0004	0.9956	1.0100
$u(R'_K)$		0.0096	0.0025	0.0044	0.0044	0.0031
R_K (direct result)	1.0099		1.0020			1.0114
$u(R_K)$	0.0018		0.0028			0.0027
$R = R'_K / R_K$			0.9929			0.9986
$u(R)$			0.0007			0.0030

Table 9. Values of R'_K (see equation (2)) of the participants, if VNIIM is the link laboratory.

	PTB	BELGIM	VNIIM	CPHR	RMTC	SMU
R'_K (M30001)	1.0177	1.0169		1.0106	1.0044	1.0189
$u(R'_K)$	0.0023	0.0113		0.0051	0.0051	0.00360
R'_K (M23332)	1.0165	1.0126		1.0044	1.0010	1.0154
$u(R'_K)$	0.0023	0.0126		0.0051	0.0051	0.0036
R'_K (mean value)	1.0171	1.0147		1.0075	1.0027	1.0171
$u(R'_K)$	0.0020	0.0098		0.0044	0.0044	0.0031
R_K (direct result)	1.0099		1.0020			1.0114
$u(R_K)$	0.0018		0.0028			0.0027
$R = R'_K / R_K$	1.0071					1.0057
$u(R)$	0.0020					0.0032

Table 10. Values of R'_K (see equation (2)) of the participants, if SMU is the link laboratory.

	PTB	BELGIM	VNIIM	CPHR	RMTC	SMU
R'_K (M30001)	1.0102	1.0094	0.9947	1.0032	0.9971	
$u(R'_K)$	0.0039	0.0119	0.0042	0.0060	0.0060	
R'_K (M23332)	1.0125	1.0086	0.9980	1.0005	0.9971	
$u(R'_K)$	0.0039	0.0118	0.0042	0.0060	0.0060	
R'_K (mean value)	1.0113	1.0090	0.9964	1.0018	0.9971	
$u(R'_K)$	0.0034	0.0103	0.0036	0.0052	0.0052	
R_K (direct result)	1.0099		1.0020			1.0114
$u(R_K)$	0.0018		0.0028			0.0027
$R = R'_K / R_K$	1.0014		0.9944			
$u(R)$	0.0030		0.0028			

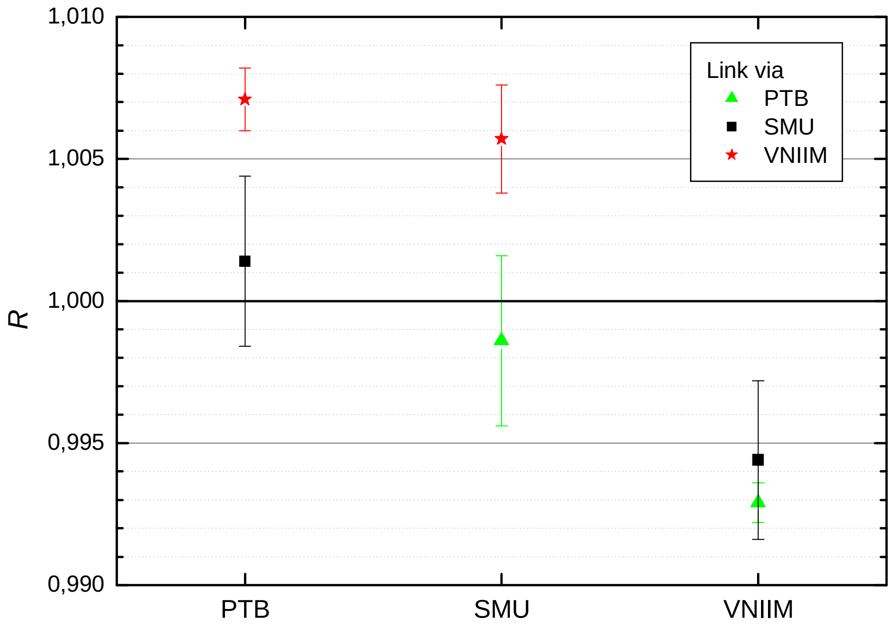

Figure 5. The ratios, *R*, of the indirect and direct results obtained for the three link laboratories. Consistency is reflected by values *R* = 1.

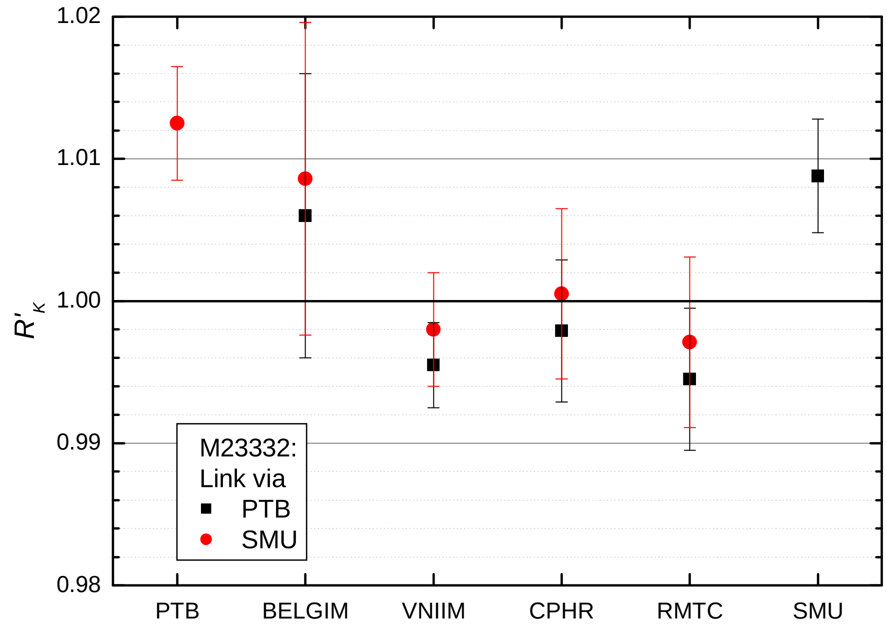

Figure 6. Comparison of the results R'_K obtained from the link laboratories PTB and SMU based on the results of the transfer chamber type M23332.

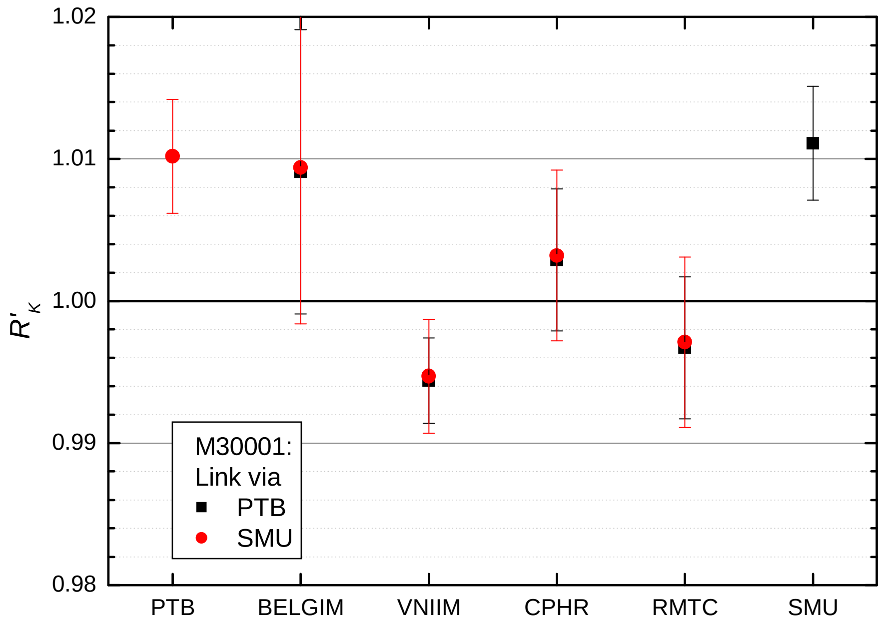

Figure 7. Comparison of the results R'_K obtained from the link laboratories PTB and SMU based on the results of the transfer chamber type M30001.

Figure 6 and 7 show the results R'_K of the participating laboratories obtained respectively with the transfer chambers M23332 and M30001 when PTB and SMU are used as link laboratories. The mean values R'_K of the values of both transfer chambers were taken as the final results and are summarized in Table 11 and shown in Figure 8.

Table 11. Summary of the final results of the ratios R'_K obtained indirectly according to equation (2), using PTB and SMU as link laboratories. The last two rows contain the mean values from both numbers and for comparison also the direct results of the link laboratories, written in italic letters.

NMI Traceability	PTB primary	BELGIM VNIIM	VNIIM primary	CPHR BIPM	RMTC BIPM	SMU primary
R'_K via PTB		1.0076	0.9949	1.0004	0.9956	1.0100
$u(R'_K)$ via PTB		0.0096	0.0025	0.0044	0.0044	0.0032
R'_K via SMU	1.0113	1.0090	0.9964	1.0018	0.9971	
$u(R'_K)$ via SMU	0.0034	0.0103	0.0036	0.0052	0.0051	
R'_K (mean) or R_K	*1.0099*	1.0083	*1.0020*	1.0011	0.9964	*1.0114*
$u(R'_K)$ or $u(R_K)$	*0.0018*	0.0100	*0.0028*	0.0048	0.0048	*0.0027*

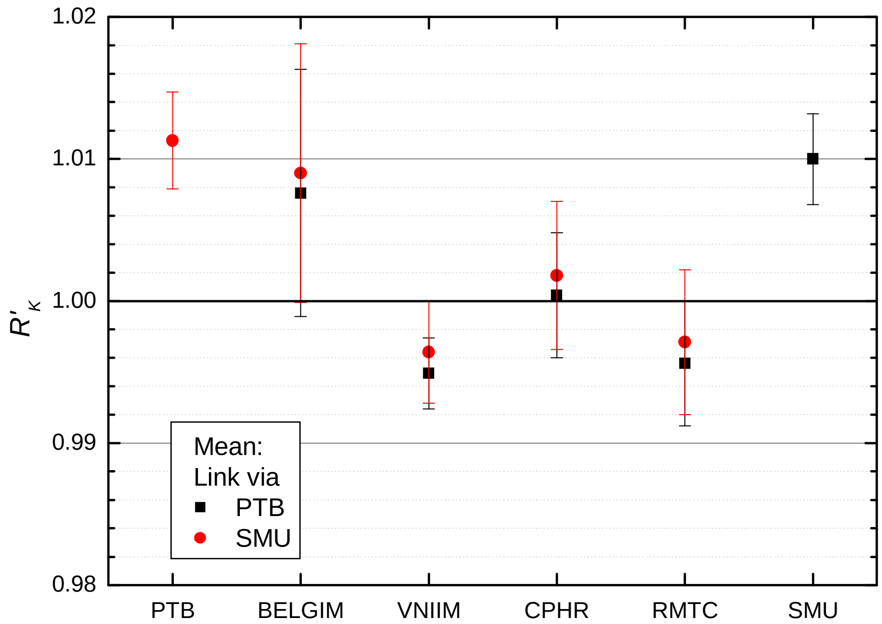

Figure 8. Comparison of the final results R'_K obtained from the link laboratories PTB and SMU based on the results of the mean values of the two transfer chambers.

Due to the fact that the BIPM realization of the unit of air kerma is used to define the KCRV, the degree of equivalence of the laboratory *i* with respect to the KCRV is effectively given by the difference $D_i = R_{K,i} - 1$ and its expanded uncertainty U_i. The values obtained in this way using the values of R'_K or R_K of the last two rows in Table 11 are summarized in columns 2 and 3 of Table 12 together with their expanded uncertainty, U_i. Note that the values of the three link laboratories are those obtained previously from the direct comparisons with the BIPM and only these are listed in Table 12 for the purpose of comparison. The numbers characterizing the degrees of equivalence with the KCRV are also shown in Figure 9. The degrees of equivalence between pairs of laboratories *i* and *j* were calculated according to the differences $D_{ij} = D_i - D_j$ as well as their corresponding expanded uncertainties according to $U_{ij} = 2(u_i^2 + u_j^2)^{1/2}$. The resulting values are also given in Table 12.

Table 12. The degree of equivalence of each laboratory *i* with respect to the reference value, given by the pair of terms D_i and its expanded uncertainty U_i, and the degree of equivalence between laboratory *i* and *j* given by the pair of terms $D_{ij} = D_i - D_j$, and the corresponding expanded uncertainty U_{ij}.

	Lab *j*		BELGIM		CPHR		RMTC		VNIIM		SMU		PTB	
	D_i	U_i	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
Lab *i*	$/10^{-2}$		$/10^{-2}$		$/10^{-2}$		$/10^{-2}$		$/10^{-2}$		$/10^{-2}$		$/10^{-2}$	
BELGIM	**0.83**	2.00			**0.72**	2.22	**1.19**	2.22	**0.63**	2.08	**-0.31**	2.07	**-0.16**	2.03
CPHR	**0.11**	0.97	**-0.72**	2.22			**0.47**	1.36	**-0.09**	1.12	**-1.03**	1.11	**-0.88**	1.03
RMTC	**-0.36**	0.96	**-1.19**	2.22	**-0.47**	1.36			**-0.56**	1.11	**-1.50**	1.10	**-1.35**	1.03
VNIIM	**0.20**	0.56	**-0.63**	2.08	**0.09**	1.12	**0.56**	1.11			**-0.94**	0.78	**-0.79**	0.67
SMU	**1.14**	0.54	**0.31**	2.07	**1.03**	1.11	**1.50**	1.10	**0.94**	0.78			**0.15**	0.65
PTB	**0.99**	0.36	**0.16**	2.03	**0.88**	1.03	**1.35**	1.03	**0.79**	0.67	**-0.15**	0.65		

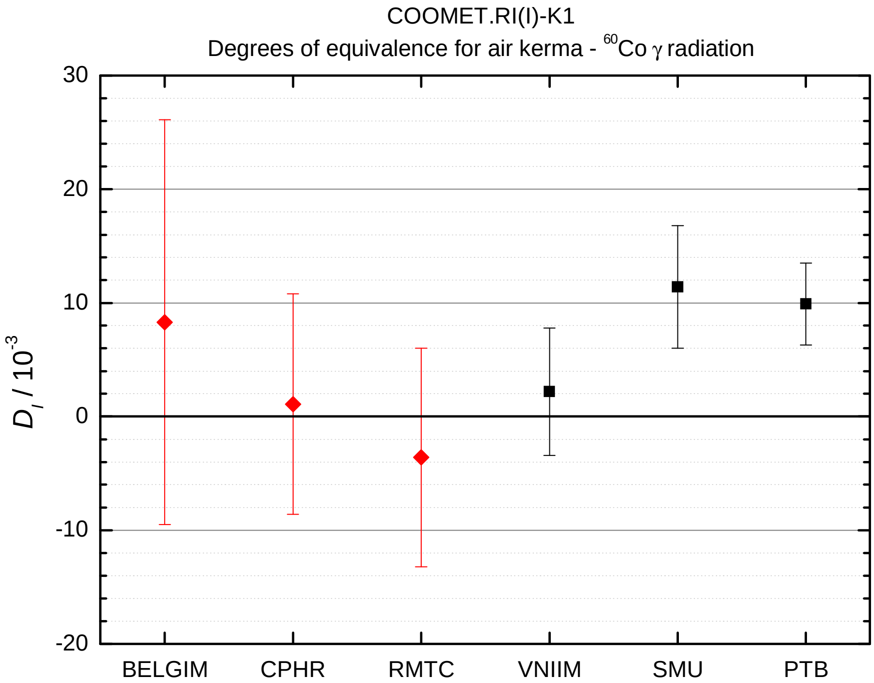

Figure 9. Graph of degrees of equivalence with the KCRV for air kerma at ^{60}Co γ radiation. The values of BelGIM, CPHR and RMTC are indirect results of this work, the others are direct results taken from the corresponding BIPM reports [2-4].

From Figure 9 it can be seen that the values of PTB and SMU agree well with each other but are about 1% above the KCRV. This result could be expected because it is consistent with the results of a similar comparison between the PTB and MKEH air kerma standards at ^{60}Co gamma radiation [9]. Both, MKEH and SMU use cavity chambers of the same type ND1005. The reasons for the discrepancies of the PTB and MKEH standards compared with the BIPM standard are well known and were already discussed in detail in the corresponding comparison reports [2, 7, 8, 9]. The results of CPHR and RMTC are consistent because their standards are traceable to the BIPM standard which, by definition, is the KCRV. The result of BelGIM reflects a larger deviation from the VNIIM to which their standard is traceable but is still consistent within the uncertainty. VNIIM is currently in the process to establish a new primary standard and it is planned to perform a key comparison with the BIPM in the near future. Nevertheless the reasons for the discrepancies found here between the indirect and direct comparison results should be examined.

5 Final results adjusted to the recent changes in the KCRV and decisions in the KCWG

The results of the comparison as presented in Table 12 and shown in Figure 9 were evaluated soon after the end of the comparison in October 2006 (Draft A) and finally agreed by the participants. The Draft B report of this comparison was agreed by the COOMET TC 1.9 on its meeting in September 2007 in Bratislava. At that time the final report of the BIPM.RI(I)-K1 was in preparation. Therefore it was decided by TC 1.9 to wait for this final report and then to adjust the results accordingly.

In November 2007 the BIPM published its re-evaluation of their standard for air kerma in ^{60}Co gamma radiation [10] which resulted in an increase in the BIPM determination of air kerma rate by the factor 1.0054. The final report for BIPM.RI(I)-K1 [11] was published in October 2007. The Key Comparison Working Group of the CCRI(I) confirmed at its meeting in April 2008 that, for these dosimetry comparisons, D_{i} is defined as the difference between the air kerma measured by a participating national metrology Institute (NMI), $K_{\mathrm{a},i}$, and the KCRV, $K_{\mathrm{a,BIPM}}$, divided by the KCRV. That is,

$$D_i = (K_{\mathrm{a},i} - K_{\mathrm{a,BIPM}}) / K_{\mathrm{a,BIPM}} = K_{\mathrm{a},i} / K_{\mathrm{a,BIPM}} - 1 = R_i - 1 \quad (4)$$

where the index, *i*, is used to identify the NMI and $R_i = K_{\mathrm{a},i} / K_{\mathrm{a,BIPM}}$ which can be identified with $R_{K,\mathrm{NMI}}$ defined in equation (1) for air kerma rates. R_i for each NMI can be found by multiplying $R_{i=LINK}$ by $N_{\mathrm{K,NMI}}/N_{\mathrm{K,LINK}}$ which can be identified with $R'_{K,\mathrm{NMI}}$ defined in equation (2) and reported in Table 11. Further it was agreed, that according to this new definition, D_{i} should be given in units of mGy/Gy.

The uncertainties, $u_{R,i}$ of R_{i} were re-calculated according to the methods described in the final report SIM.RI(I)-K1 [12] where the following equation was used:

$$u_{R,i}^2 = u_i^2 + u_{BIPM}^2 + u_r^2 + u_{stab}^2 - \sum_k (f_k u_i(k))^2 - \sum_k (f_k u_{BIPM}(k))^2 \quad (5)$$

u_i is the relative uncertainty of the transfer chamber calibration coefficient reported by NMI *i*, $u_i(k)$ a particular component, *k*, u_{BIPM} is the relative uncertainty associated with the BIPM standard, $u_{BIPM}(k)$ a particular component, *k*, u_r is the relative uncertainty of the link through PTB and SMU, u_{stab} is the relative uncertainty due to the long term stability of the transfer chambers. The last two terms account for any correlated quantities between the NMI and the BIPM, where the factor f_k is the correlation coefficient. u_r was estimated from the values of the ratios *R* defined in equation (3) and shown in Figure 5 at 0.1%. u_{stab} was estimated at 0.08% from the relative standard deviation of the calibration coefficients obtained from the repeated measurements at PTB as described in 3.1.

The degree of equivalence, D_{ij}, between any pair of NMIs, *i* and *j*, is given by

$$D_{ij} = D_i - D_j = R_i - R_j \quad (6)$$

The uncertainty u_{ij}, of D_{ij} was calculated according to the methods described in the final report SIM.RI(I)-K1 [12] where the following equation was used:

$$u_{ij}^2 = u_i^2 + u_j^2 + 2u_{stab}^2 - \sum_k (f_k u_i(k))^2 - \sum_k (f_k u_j(k))^2 \quad (7)$$

The notation is similar to that used in equation (5). It is noted that u_{stab} enters twice in equation (7), once for each laboratory.

In the following it is described how the results of this comparison shown in Table 12 and Figure 9 were adjusted in order to make them consistent with the results now published in the final report of BIPM.RI(I)-K1 [11] and in the KCDB.

5.1 Adjustments of the results of the comparison of a given NMI with the KCRV

The direct key comparison results of the three link laboratories (PTB, SMU and VNIIM) are now published in the KCDB and differ from the former values shown in Table 12. The differences D_{i} as defined in eq. (4) of all three laboratories were reduced by 0.0054 in accordance with the changes in the defined KCRV. In addition, the value D_{i} of the VNIIM was increased by 0.0096 according to their recently announced increase in the determination of the air kerma at the VNIIM [13]. The SMU has not yet announced the increase of the wall correction factor of their standard as described in chapter 4 although they already used it in the current comparison. Therefore this change is not included in the current KCDB and is not presented as a result of the current comparison. However, the SMU intends to introduce this change in the near future and they will announce this change in time. Please note that the results obtained for the laboratories to be linked to the KCRV via the link laboratory SMU are not affected by changes in the wall correction factor of the SMU standard because it cancels as can be seen from equation (2). The values of the expanded uncertainties U_i remain the same except that for VNIIM, which reduces from 5.5 mGy/Gy to 5.2 mGy/Gy as a consequence of the introduced changes in their standards [13].

The comparison results of the three secondary standard laboratories were adjusted as follows. The national standard of the BelGIM is directly traceable to the VNIIM standard and will reflect the same changes after the next re-calibration. Accordingly, the D_{i} value of the BelGIM shown in Table 12 was decreased by 0.0054 and increased by 0.0096. The national standards of the CPHR and the RMTC are traceable to the international standard of the BIPM and will reflect the same changes after the next re-calibration. Taking this into account means that the differences D_{i} shown in Table 12 remain unchanged for these two laboratories and need not to be adjusted in contrast to the corresponding calibration coefficients which will be increased by the factor of 1.0054. It is strongly recommended that all the three secondary laboratories (BelGIM, CPHR and RMTC) re-calibrate their national standards as soon as possible. If this is not possible, they should change their current calibration coefficients accordingly. The uncertainties U_i were re-calculated according to equation (5). Results are shown in Table 13. They deviate not much from the values shown in Table 12.

5.2 Adjustments of the results of the comparison of any pair of NMIs

The differences D_{ij} were re-calculated with the new values of D_i as explained in 5.1. The corresponding values of the uncertainties U_{ij} of the comparisons between any pair of the link laboratories VNIIM, SMU and PTB were adopted from the published KCDB which were evaluated according to the methods described in the final report BIPM.RI(I)-K1 [11]. They appear to be decreased compared to the values shown in Table 12 because the uncertainties related to the BIPM measuring instrument ($u_{\mathrm{BIPM,instr}}$ = 0.12%) were removed and the uncertainties in the wall correction factors of a pair of standards were regarded as being correlated if both of them were calculated using Monte Carlo methods. The corresponding expanded uncertainties U_{ij} between all other pairs of the current comparison were re-calculated according to equation (7). Results are shown in Table 13. They deviate not much from the values shown in Table 12.

5.3 Final results

The final results of this work adjusted as described above in order to be consistent with the results published in the KCDB are given in Table 13 and shown in Figure 10. This values are suggested for publication in the KCDB.

Table 13. The degree of equivalence of each laboratory *i* with respect to the reference value, given by the pair of terms D_i and its expanded uncertainty U_i, and the degree of equivalence between laboratory *i* and *j* given by the pair of terms $D_{ij} = D_i - D_j$, and the corresponding expanded uncertainty U_{ij}.

	Lab *j*		BELGIM		CPHR		RMTC		VNIIM		SMU		PTB	
	D_i	U_i	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
Lab *i*	/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)		/(mGy/Gy)	
BELGIM	12.5	21.8			11.4	23.7	16.1	23.7	6.3	21.4	14.6	22.3	8.0	21.9
CPHR	1.1	9.7	-11.4	23.7			4.7	13.5	-5.1	10.7	3.2	10.8	-3.4	10.1
RMTC	-3.6	9.7	-16.1	23.7	-4.7	13.5			-9.8	10.7	-1.5	10.8	-8.1	10.1
VNIIM	6.2	5.2	-6.3	21.4	5.1	10.7	9.8	10.7			8.3	6.5	1.7	5.3
SMU	-2.1	5.4	-14.6	22.3	-3.2	10.8	1.5	10.8	-8.3	6.5			-6.6	5.4
PTB	4.5	3.6	-8.0	21.9	3.4	10.1	8.1	10.1	-1.7	5.3	6.6	5.4		

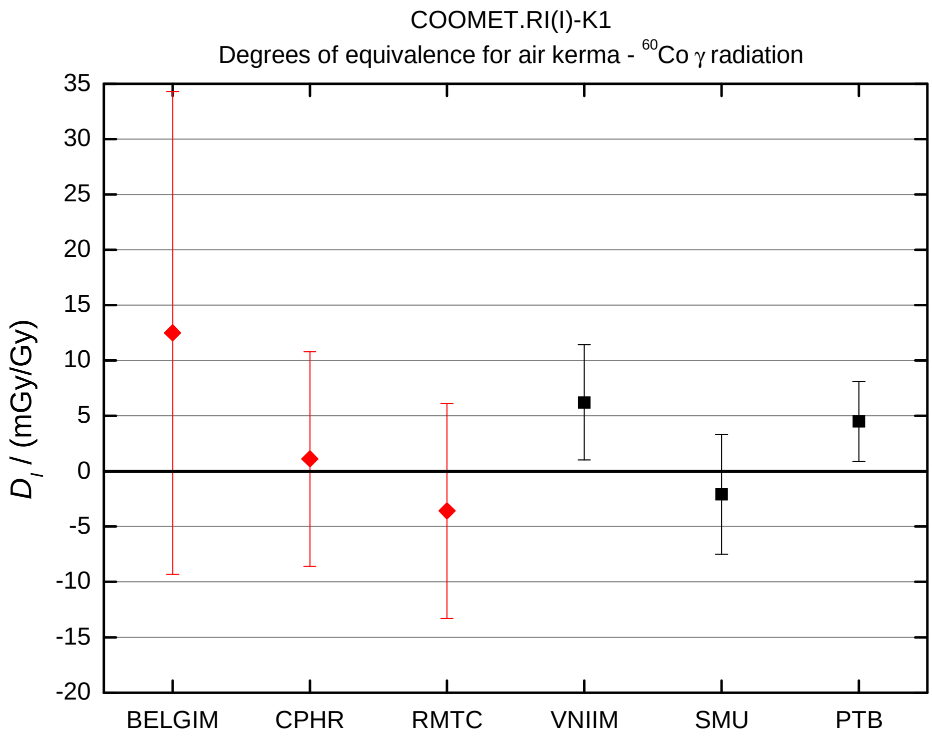

Figure 10. Graph of degrees of equivalence with the KCRV for air kerma at ^{60}Co γ radiation. The values of BelGIM, CPHR and RMTC are indirect results of this work, the others are adopted from the direct results taken from the final report for BIPM.RI(I)-K1 [11].

6 Summary and conclusion

The national measurement standards of air kerma for ^{60}Co γ radiation of the National Metrology Institutes of Belarus (BELGIM), Cuba (CPHR) and Latvia (RMTC) were successfully linked to the current KCRV. The estimated relative standard uncertainty of the comparison between any pair of laboratories ranged from 0.3 % to 1.1 %. The largest discrepancy between any of two laboratories was 1.6 %. The results are published in Appendix B of the MRA under the identifier COOMET.RI(I)-K1.

7 References

[1] MRA: *Mutual Recognition Arrangement of national measurement standards and of calibration and measurement certificates issued by national metrology institutes,* International Committee for Weights and Measures, 1999.

[2] Allisy-Roberts P.J., Burns D.T., Büermann L., Kramer H.-M., Comparison of the standards for air kerma of the PTB and the BIPM for ^{60}Co and ^{137}Cs gamma radiation, *Rapport BIPM-2005/10.*

[3] Allisy-Roberts P.J., Burns D.T., Gabris F., Dobrovoský, Comparison of the standards of air kerma of the SMU Slovakia and the BIPM for ^{60}Co γ rays, *Rapport BIPM-2002/04.*

[4] Allisy-Roberts P.J., Boutillon M., Villevalde N.D., Oborin A.V., Yurjatin E.N., Comparison of the standards of air kerma of the VNIIM and the BIPM for ^{60}Co γ rays, *Rapport BIPM-1998/3.*

[5] Guide to the Expression of Uncertainty in Measurement 2nd edn (Geneva: International Organization for Standardization) 1995 ISBN 92-67-10188

[6] Allisy-Roberts P.J., Burns D.T., Kessler C., Measuring conditions used for the calibration of ionization chambers at the BIPM, *Rapport BIPM-2004/17*.

[7] Csete I., New correction factors for the OMH air kerma standards for ^{137}Cs and ^{60}Co radiation, 2001, *CCRI(I) 15th meeting document CCRI(I)01-03*.

[8] Kessler C., Roger P., Burns D.T, Allisy-Roberts P.J., Machula G., Csete I., Rabus H., Comparison of the standards for air kerma of the OMH and the BIPM for ^{60}Co gamma radiation, *Rapport BIPM-2006/07*.

[9] Csete I. , Büermann L., Kramer H.-M., Comparison of the PTB and OMH air kerma standards for ^{60}Co and ^{137}Cs gamma radiation, 2002, *PTB Report Dos-40*.

[10] Burns D. T., Allisy-Roberts P. J. and Kessler C., Re-evaluation of the BIPM international standard for air kerma in ^{60}Co gamma radiation, 2007, Metrologia 44 L53–L56

[11] Allisy-Roberts P. J., Burns D. T. and Kessler C., Summary of the BIPM.RI(I)-K1 comparison for air kerma in ^{60}Co gamma radiation, 2007, Metrologia 44, 06006

[12] Ross C. K., Shortt K. R., Saravi M., Meghzifene A., Tovar V. M., Barbosa R. A., Da Silva C. N., Carrizales L. and Seltzer S. M., Final Report of the SIM ^{60}Co Air-Kerma Comparison, 2008, Metrologia 45, Tech. Suppl., 06010

[13] Kharitonov I. A. Oborin A. V. and Villevalde A. Y., Changes to the VNIIM air kerma primary standard, 2007, Metrologia 44, L71-L72