Final Report of the SIM ^{60}Co Absorbed-Dose-to-Water Comparison

(KCDB Entry SIM.RI(I)-K4)

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C. K. Ross and K. R. Shortt (NRC, Canada; pilot laboratory)

M. Saravi (CNEA, Argentina)
A. Meghzifene (IAEA)
V. M. Tovar (ININ, Mexico)
R. A. Barbosa and C. N. da Silva (IRD, Brazil)
L. Carrizales[1] (LSCD, Venezuela)
S. M. Seltzer (NIST, USA)

Report prepared by Carl Ross, Ionizing Radiation Standards,
National Research Council, Ottawa, Canada K1A 0R6

Tel: 613-993-9352, ext. 233
Fax: 613-952-9865
E-mail: carl.ross@nrc-cnrc.gc.ca

[1]F. Gutt was head of the laboratory when the measurements were made at the Venezuelan SSDL in 2002

Abstract

Transfer chambers were used to compare the standards for ^{60}Co absorbed dose to water maintained by seven laboratories. Six of the laboratories were members of the Sistema Interamericano de Metrología (SIM) regional metrology organization while the seventh was the International Atomic Energy Agency (IAEA) laboratory in Vienna. The National Research Council (NRC) acted as the pilot laboratory for the comparison. Because of the participation of laboratories holding primary standards, the comparison results could be linked to the key comparison reference value maintained by the Bureau International des Poids et Mesures (BIPM). The results for all laboratories were within the expanded uncertainty (two standard deviations) of the reference value. The estimated relative standard uncertainty on the comparison between any pair of laboratories ranged from 0.6 % to 1.4 %. The largest discrepancy between any two laboratories was 1.3 %.

1 Introduction

A comparison of standards for ^{60}Co absorbed dose to water was carried out between seven laboratories. Six of the laboratories were national metrology institutes (NMIs) and members of the Sistema Interamericano de Metrología (SIM) regional metrology organization. The seventh was the International Atomic Energy Agency (IAEA) laboratory in Vienna. The National Research Council (NRC, Canada) was the pilot laboratory for the comparison, which took place between 2000 and 2002. The comparison was carried out using three transfer ionization chambers that were circulated among the laboratories. Two of the laboratories (the National Institute of Standards and Technology (NIST) and the NRC) maintain primary standards for absorbed dose to water and their participation in the comparison allows the results to be linked to the key comparison data base (KCDB) [1] of the Mutual Recognition Arrangement of the International Committee for Weights and Measures (CIPM MRA) [2].

This report describes the protocol used for the comparison and presents the results in tabular and graphical form. It describes how previous comparisons between the NRC and the BIPM and between the NIST and the BIPM can be used to link the data of this comparison to the key comparison reference value. The degree of equivalence is calculated for each laboratory with respect to the reference value as well as the degree of equivalence between any pair of laboratories.

2 Participating Laboratories

The participating laboratories are listed in Table 1.

Table 1 Listing of the laboratories that participated in the absorbed-dose-to-water comparison. The NIST and the NRC are primary standards laboratories, while the others operate as secondary standards laboratories.

Laboratory		Country
CNEA	Comisión Nacional de Energía Atómica	Argentina
IAEA	International Atomic Energy Agency	-
ININ	Instituto Nacional de Investigaciones Nucleares	Mexico
IRD[1]	Instituto de Radioproteçao e Dosimetria	Brazil
LSCD[2]	Laboratorio Secundario de Calibración Dosimetrica	Venezuela
NIST	National Institute of Standards and Technology	United States
NRC	National Research Council	Canada

[1]The designated institute for the CIPM MRA is known as the Laboratório Nacional de Metrologia das Radiações Ionizantes (LNMRI).

[2]Note that Venezuela has not yet signed the CIPM MRA.

3 Transfer Chambers

Three Exradin A12 ionization chambers were used in the comparison with serial numbers 101, 149 and 150. These are cylindrical chambers constructed from C552 plastic and are intrinsically waterproof. The main characteristics of the A12 ionization chamber are summarized in Table 2. No electrometer was provided with the chambers so each laboratory was responsible for their own measurement of the electrical current or charge arising from the ion pairs produced in the air cavity.

Table 2. Characteristics of the cylindrical A12 ionziation chamber.

Characteristic		Nominal value
Dimensions	Inner diameter	6.1 mm
	Wall thickness	0.5 mm
	Cavity length	24.7 mm
	Tip to center of collecting volume	12.9 mm
Electrode	Diameter	1.0 mm
	Height	21.6 mm
Volume	Air cavity	0.65 cm^3
Wall	Material	C552 plastic
	Density	1.76 g cm^{-3}
Buildup cap	Material	C552 plastic
	Thickness	2.7 mm
Applied voltage		300 V
Sign of collected charge		Positive

4 Calibration Coefficients

The comparison of the absorbed-dose-to-water standards was made indirectly by comparing the calibration coefficients, $N_{\mathrm{D,w}}$, of the three transfer chambers as determined by the individual laboratories. The calibration coefficient is given by

$$N_{\mathrm{D,w}} = \dot{D}_{\mathrm{w}} / \dot{Q} \ , \qquad (1)$$

where $\dot{Q}$ is the charge per unit time or current, I , due to positive ions produced in the cavity gas when the delivered absorbed dose to water rate is $\dot{D}_{\mathrm{w}}$. All laboratories were asked to report values of $N_{\mathrm{D,w}}$ that would apply if positive charge were collected. Each chamber was positioned so that the centre of its sensitive volume was at the reference point and $\dot{D}_{\mathrm{w}}$ is the absorbed dose to water that would be delivered to the reference point in the absence of the chamber. In order to get the current, I , from the measured current, I_{m} , a number of corrections must be considered. These include:

Leakage current: This is the current measured when the primary radiation field is blocked. For all the chambers at all the laboratories, the leakage current was less than 0.01 % of the current measured when the chamber was exposed to the ^{60}Co beam. In practice, the measured leakage current includes contributions from background radiation.

Recombination: No correction for recombination was applied. The volume recombination is negligible for absorbed dose to water rates less than 15 mGy s^{-1} for this chamber type and polarizing voltage and the initial recombination will be the same for all the laboratories.

Temperature and pressure normalization: For all the laboratories, the measured ionization current of the transfer chambers was normalized to a temperature of 295.15 K and a pressure of 101.325 kPa. (This is consistent with normal practice at the NIST and the NRC but several of the other laboratories would normally use a reference temperature of 293.15 K.)

Humidity: None of the laboratories applied a correction to their measured current (or charge) for humidity. As long as the relative humidity is within the range from 10 to 80 % for all the laboratories, the effect on the chamber calibration coefficient of variations in the humidity is less than 0.1 %.

Radial non-uniformity: It was assumed than any correction for radial non-uniformity would be similar for all the ^{60}Co beams and thus need not be applied when comparing calibration coefficients.

5 Absorbed-Dose-to-Water Standards

The absorbed-dose-to-water standards of the secondary laboratories are all traceable to the absorbed-dose-to-water standard maintained by the BIPM. Three of the laboratories (the CNEA, the IAEA and the IRD) have their secondary standards calibrated directly by the BIPM. The other two (the ININ and the LSCD) have their chambers calibrated at the IAEA, which in turn is traceable to the BIPM.

The NIST standard for ^{60}Co absorbed dose to water is based on a water calorimeter operating at room temperature [3-5]. The NRC standard is also based on a water calorimeter but it is operated at 4 °C [6,7]. The BIPM standard is based on a graphite cavity chamber of pancake geometry [8,9] and this is the standard to which the secondary laboratories are traceable.

Results of recent comparisons between the BIPM and several NMIs, including the NIST and the NRC, are given in [9].

6 Chamber Calibrations

The chambers were circulated among the various laboratories as follows: the NRC to the IAEA; the IAEA to the NRC; the NRC to the CNEA; the CNEA to the IRD; the IRD to the NRC; the NRC to the LSCD; the LSCD to the ININ; the ININ to the NRC; the NRC to the NIST; the NIST to the IAEA; the IAEA to the NRC. By having the chambers return several times to the NRC, their stability could be verified.

The conditions under which the chambers were calibrated were similar at all of the laboratories. The calibrations were carried out in a suitable water phantom provided by each laboratory. Because the A12 ionization chamber is waterproof, it can be mounted directly in water. The center of the chamber was positioned at a depth of 5 cm. The surface of the water was positioned approximately 1 m from the ^{60}Co source and the field size was approximately 10 cm by 10 cm at 1 m. The polarizing voltage was set to 300 V and laboratories were asked to report values of $N_{D,w}$ that would apply if positive charge were collected. None of the laboratories used a shutter or source transfer system to define the irradiation time. Instead, each chamber was irradiated continuously during the measurement session and the charge accumulated by the electrometer was measured at well-defined times.

7 Results

The calibration coefficients, $N_{D,w}$, obtained by the different laboratories for each of the three transfer chambers are given in Table 3. The chambers were calibrated on two separate occasions at the IAEA and on five separate occasions at the NRC. The values reported in Table 3 for these laboratories are the averages of the repeated calibrations. The ratios of the calibration coefficients for each laboratory to that of the NRC are given in columns 3, 5 and 7. The mean values of the ratios for the three chambers and for each of the laboratories are given in the final column. The spread of these mean values is about 1.3 %.

Table 3. The absorbed-dose-to-water calibration coefficients, expressed in mGy/nC, obtained by each laboratory for each ionization chamber are given in columns 2, 4 and 6. Columns 3, 5 and 7 report the ratio of the calibration coefficient for a given NMI to that of the NRC while column 8 gives the mean value of the ratio for all three chambers.

Laboratory	#101		#149		#150		Mean
CNEA	49.38	0.9994	50.08	0.9972	49.27	0.9996	0.9987
IAEA	49.40	0.9998	50.19	0.9994	49.36	1.0014	1.0002
ININ	49.76	1.0071	50.57	1.0070	49.53	1.0049	1.0063
IRD	50.12	1.0144	50.57	1.0070	49.96	1.0136	1.0116
LSCD	49.28	0.9974	50.11	0.9978	49.38	1.0018	0.9990
NIST	49.34	0.9986	50.16	0.9988	49.23	0.9988	0.9987
NRC	49.41	1.0000	50.22	1.0000	49.29	1.0000	1.0000

The ratios of the calibration coefficients obtained by each laboratory for each chamber to that obtained by the NRC are shown graphically in Figure 1. Ideally, all three calibration-coefficient ratios for each laboratory should be approximately the same. Instead, differences of up to 0.8 % are apparent. Calibrations were repeated at the NRC five times during the course of the comparison, and these results are shown in Figure 2. The calibration coefficients for the three chambers were always consistent to better than 0.15 %. Thus, the differences apparent in Figure 1 are probably not due to changes in chamber response due to transport.

8 Uncertainties

Each laboratory reported the key components that contributed to their uncertainty budget, and the results are summarized in Table 4. The uncertainty on the primary standards as reported by the NIST and the NRC are listed in the row labeled “$N_{D,w}$ of reference chamber”. Components 2, 3, 5 and 6 in this section of the table have already been incorporated into their respective overall uncertainty. However, there will be a component due to source decay because both NIST and NRC use the ^{60}Co half-life to track the absorbed dose rate as a function of time.

Figure 1. Graphical summary of the absorbed-dose-to-water calibration coefficients reported by each laboratory to that of the NRC for each of the ionization chambers.

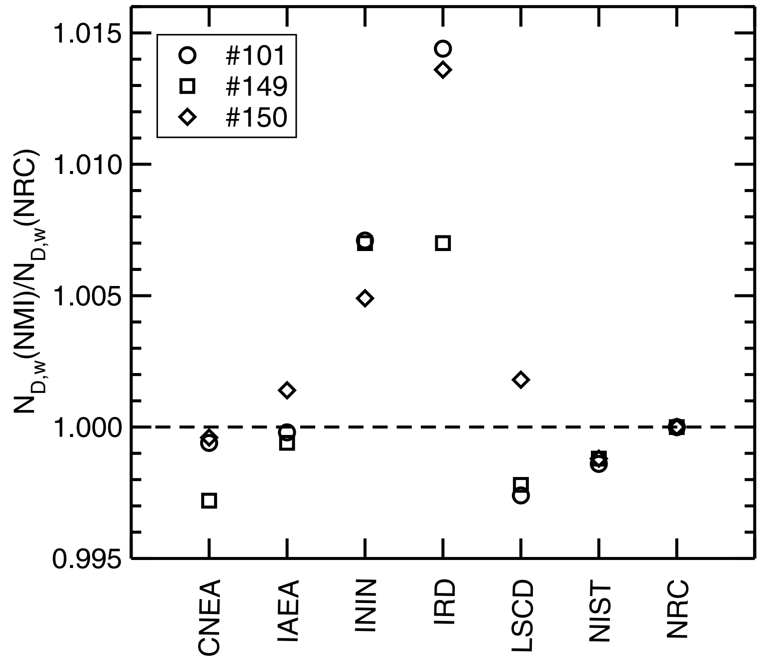
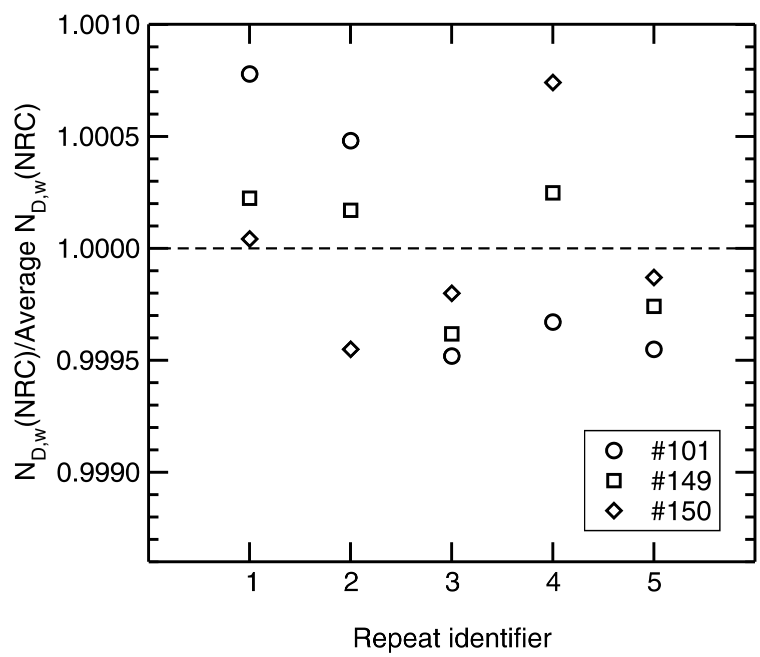


Figure 2. Summary of the results obtained for repeated chamber calibrations at the NRC. The calibration coefficient for each chamber's repeat measurement is shown with respect to the average of all five calibration coefficients.



The ionization-chamber current is obtained by all of the laboratories by measuring the charge collected in a known time interval. Most of the laboratories assume the uncertainty of the measured time interval is negligible and that the uncertainty of the current is dominated by the uncertainty of the charge. If the laboratory reported separate uncertainties for the charge and time, they have been combined in quadrature to obtain the uncertainty of the current.

9 Degrees of Equivalence

Two of the laboratories participating in the present comparison (the NRC and the NIST) maintain primary standards for absorbed dose to water and have participated in previous comparisons with the BIPM. Thus, we can link the results of this comparison to the absorbed-dose-to-water standard maintained by the BIPM. For the NIST, using the comparison results reported in [9] gives 0.9984(51) for $D_{\mathrm{w,NIST}} / D_{\mathrm{w,BIPM}}$, while the corresponding result for the NRC is 0.9976(51). Note that $D_{\mathrm{w,NIST}}$, $D_{\mathrm{w,BIPM}}$ and, more generally, $D_{\mathrm{w,NMI}}$, are the values of the absorbed dose to water that would be reported by each national standard for identical irradiation conditions. The numbers in parentheses represent the standard uncertainties of the last two digits of the ratios. Although both the NIST and the NRC could be used as the link, in what follows, we have used the NRC result which is more robust as they measured the chambers five times. This also enables the NIST to update their 1997 comparison value in the KCDB.

Table 4. Summary of the standard uncertainty estimates reported by the various laboratories participating in the comparison.

		Relative standard uncertainty (%)													
	Source of uncertainty	CNEA		IAEA		ININ		IRD		LSCD		NIST		NRC	
		A	B	A	B	A	B	A	B	A	B	A	B	A	B
	Related to dose to water rate														
1	$N_{D,w}$ of ref. chamber	-	0.43	-	0.3	-	1.1	-	0.3	-	0.5	0.16	0.32	0.21	0.35
2	Long-term stability of ref. chamber	-	0.07	-	0.23	0.31	-		0.2	-	0.1	-	-	-	-
3	Positioning of ref. chamber	-	-	-	0.1	-	-	0.01	0.1	-	0.05	-	-	-	-
4	Source decay	-	-	-	-	-	0.01	-	-	-	-	-	0.05	-	0.02
5	Temperature and pressure		0.04	0.03	0.1	-	0.02		0.39	0.03	0.04	-	-	-	-
6	Charge	0.02	0.3	0.05	0.1	0.05	-	0.01	0.11	0.05	0.1	-	-	-	-
	Related to the transfer instrument														
7	Chamber positioning	-	0.08	-	0.1	-	0.06	0.01	0.09	-	0.05	0.03	-	0.03	-
8	Temperature, pressure, humidity	-	0.04	0.03	0.1	-	0.02	-	0.40	0.03	0.04	0.04	0.06	0.04	0.06
9	Charge	0.02	0.3	0.05	0.1	0.05	0.30	0.03	0.29	0.05	0.1	0.02	-	0.06	0.06
	Quadratic summation	0.03	0.62	0.08	0.45	0.32	1.14	0.03	0.75	0.08	0.54	0.17	0.33	0.22	0.36
	Combined standard uncertainty	**0.62**		**0.46**		**1.18**		**0.75**		**0.55**		**0.37⇒0.6**[a]		**0.42**	

[a] The overall uncertainty on absorbed dose-to-water calibrations by the NIST was increased to 0.6 % in 2001, due to uncertainty related to the field size [5].

In this comparison, each NMI reported calibration coefficients. However, the calibration coefficients are proportional to the absorbed dose to water as determined by the national standard of the NMI, so ratios of calibration coefficients will be equal to absorbed-dose-to-water ratios. In the following, any absorbed-dose-to-water ratio can be replaced by the numerical value of the equivalent ratio of calibration coefficients.

The CCRI meeting in 1999 agreed that, in an absorbed-dose-to-water key comparison, the BIPM value of the comparison quantity would be taken as the key comparison reference value (KCRV). Furthermore, the Key Comparison Working Group of the CCRI(I) confirmed at its meeting in April 2008 that, for these dosimetry comparisons, the degree of equivalence, D_i , is defined as the difference between the absorbed dose to water measured by a participating NMI and the KCRV, divided by the KCRV and the expanded uncertainty of this difference. That is,

$$D_i = (D_{\mathrm{w},i} - D_{\mathrm{w,BIPM}}) / D_{\mathrm{w,BIPM}} = D_{\mathrm{w},i} / D_{\mathrm{w,BIPM}} - 1 = R_i - 1, \quad (2)$$

where the index, *i*, is used to identify the NMI and

$$R_i = D_{\mathrm{w},i} / D_{\mathrm{w,BIPM}}. \quad (3)$$

R_i for each NMI can be found by multiplying $N_{\mathrm{Dw,NMI}} / N_{\mathrm{Dw,NRC}}$ as reported in Table 3 by $D_{\mathrm{w,NRC}} / D_{\mathrm{w,BIPM}}$, as given above.

The uncertainty, $u_{\mathrm{R},i}$, of R_i is obtained by combining the uncertainty of the calibration coefficients reported by the NMI, the absorbed-dose-to-water uncertainty of the BIPM standard and the uncertainty of the link through the ratio $D_{\mathrm{w,NRC}} / D_{\mathrm{w,BIPM}}$, including the effects of correlations between the laboratories. We denote by u_i the overall relative uncertainty reported by a particular NMI of its calibration coefficient and by $u_i(k)$ a particular component, *k*, of the uncertainty.

We use u_r to denote the relative uncertainty of the link through $D_\mathrm{w,NRC} / D_\mathrm{w,BIPM}$ and u_stab to denote the uncertainty due to the long term stability of the transfer chambers. Then

$$u_{\mathrm{R},i}^2 = u_i^2 + u_\mathrm{BIPM}^2 + u_\mathrm{r}^2 + u_\mathrm{stab}^2 - \sum_k (f_k u_i(k))^2 - \sum_k (f_k u_\mathrm{BIPM}(k))^2, \quad (4)$$

where the last two terms account for any correlated quantities between the NMI and the BIPM. The factor, f_k, which can range from zero to unity, accounts for the possibility that the quantities are not fully correlated.

The only correlated quantity between the various NMIs and the BIPM is the BIPM calibration coefficient of the national secondary standards. All of the secondary standards laboratories participating in this comparison are traceable to the BIPM and thus the uncertainty associated with the BIPM absorbed-dose-to-water standard must be subtracted. Reference [10] gives a value of 0.29 % for this quantity and f_k is taken to be unity.

At first sight, one might set u_r to 0.51 %, which is the uncertainty given earlier for $D_\mathrm{w,NRC} / D_\mathrm{w,BIPM}$. However, the uncertainty of the link through the NRC to the BIPM standard depends only on the stability of the results obtained using transfer chambers and not on any estimate of how well either laboratory can determine the absorbed dose to water. According to [10] a reasonable estimate for u_r is 0.11 %.

The value for u_stab was obtained as recommended by Burns and Allisy-Roberts [11] by calculating the standard deviation of the repeated measurements at the NRC for each of the chambers. The data are shown graphically in Figure 2 and give values of the relative standard deviation for each of the chambers of 0.06 %, 0.03 % and 0.05 %. The mean value of 0.05 % was used for u_stab. It may be that some of the uncertainty attributed to u_{stab} is already included in the uncertainties quoted by the NMIs. We have not tried to quantity these effects.

The standard uncertainty of D_i is approximately equal to the relative uncertainty of R_i because R_i is close to unity. By convention, the uncertainty, U_i, associated with D_i is given as twice the standard uncertainty. Values for D_i and U_i are given in the shaded columns of Table 5 and are shown in graphical form in Figure 3.

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

$$D_{ij} = D_i - D_j = R_i - R_j, \tag{5}$$

with expanded uncertainty U_{ij}.The standard uncertainty of D_{ij} is given to a very good approximation by

$$u_{ij}^2 = u_i^2 + u_j^2 + 2 \cdot u_{\mathrm{stab}}^2 - \sum_k (f_k u_i(k))^2 - \sum_k (f_k u_j(k))^2, \tag{6}$$

where the notation is similar to that used with equation (4). The form of equation (6) may seem surprising because it involves only the relative uncertainties, u_i and u_j, of the NMI absorbed-dose-to-water disseminations and there is no term related to the uncertainty of $D_{\mathrm{w,BIPM}}$. This follows by making the reasonable assumption that, for purposes of estimating the uncertainties, all of the absorbed-dose-to-water values can be considered equal. Note that u_{stab} enters twice in equation (6) (once for each laboratory) but only once in equation (4).

One correlation to be considered when evaluating equation (6) is due to the fact that all the secondary standard calibration coefficients are traceable to the BIPM. Thus, the uncertainty contributed by the BIPM absorbed-dose-to-water standard must be subtracted. Its value is taken to be 0.29 % [10] and the correlation is assumed to be complete ($f_k = 1$). A second correlation is due to the heat defect for water, which is common to the water calorimeters operated by the NIST and the

NRC, and its contribution to the uncertainty must be subtracted (0.30 %). In this case, f_k is taken to be 0.7 [9].

Values for D_{ij} and its associated expanded uncertainty are given in Table 5 for each pair of laboratories participating in the comparison. The largest discrepancy between any pair of laboratories is almost 1.3 %. However, in no case is the degree of equivalence between any pair of laboratories larger than the expanded uncertainty.

10 Conclusions

A comparison of absorbed-dose-to-water standards has been carried out between seven laboratories. The participating laboratories included the IAEA and six NMIs that are members of the SIM regional metrology organization. Three ionization chambers were circulated among the seven laboratories and each laboratory was asked to provide calibration coefficients and associated uncertainties. The ionization chambers were returned several times to NRC during the comparison and they showed satisfactory stability.

Because two laboratories maintaining primary standards for absorbed dose to water participated in the comparison, and because these laboratories have participated in earlier comparisons with the BIPM, the results of all the laboratories participating in this comparison could be compared to the key comparison reference value maintained by the BIPM. For results to be included in the KCDB, the participant must be a signatory to the CIPM MRA and, unfortunately, this is not yet the case of Venezuela.

The difference in each result with respect to the KCRV, expressed as a fraction, was calculated for each laboratory and in each case this difference was smaller than the expanded uncertainty, indicating that each laboratory has a satisfactory realization of the gray for ^{60}Co absorbed dose to water.

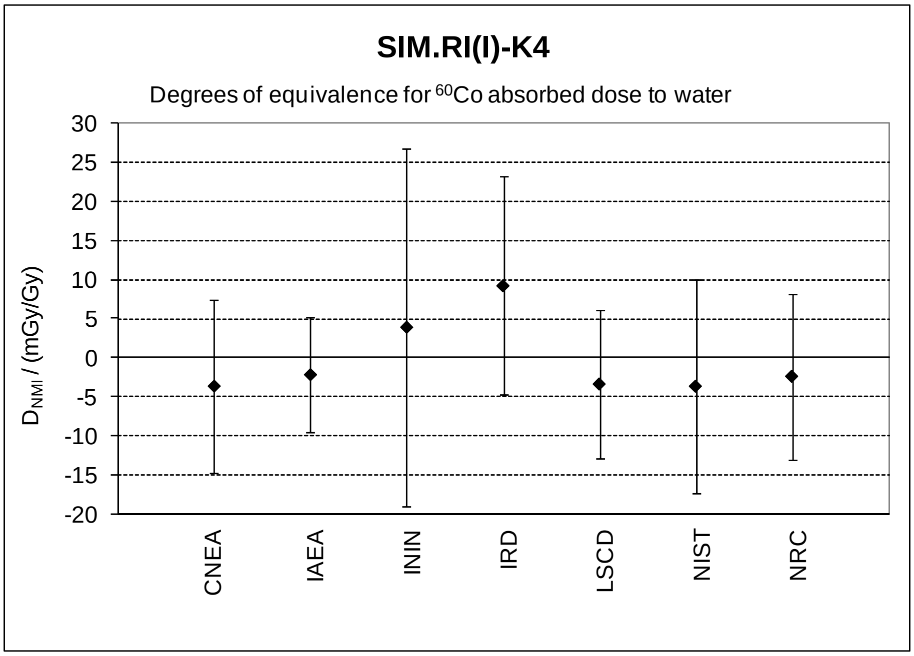
The largest discrepancy between any pair of laboratories was almost 1.3 %. This suggests that there is still room for improvement in disseminating the ^{60}Co absorbed dose to water, as the uncertainties associated with the transfer system are almost negligible.

Table 5. The degree of equivalence of each laboratory with respect to the reference value is given in the shaded columns. The degree of equivalence is the difference between the value obtained by a particular NMI and that obtained by the BIPM, divided by the BIPM value, along with the expanded uncertainty on this fractional difference. The degrees of equivalence between any pair of laboratories are given in the rest of the table.

Lab *i* ⇓ / Lab *j* ⇒			CNEA		IAEA		ININ		IRD		LSCD	
	D_i /(mGy/Gy)	U_i	D_{ij} /(mGy/Gy)	U_{ij}	D_{ij} /(mGy/Gy)	U_{ij}	D_{ij} /(mGy/Gy)	U_{ij}	D_{ij} /(mGy/Gy)	U_{ij}	D_{ij} /(mGy/Gy)	U_{ij}
CNEA	**-3.7**	11.2			**-1.5**	13.2	**-7.6**	25.4	**-12.9**	17.7	**-0.3**	14.5
IAEA	**-2.2**	7.5	**1.5**	13.2			**-6.1**	24.0	**-11.4**	15.6	**1.2**	11.8
ININ	**3.9**	23.0	**7.6**	25.4	**6.1**	24.0			**-5.3**	26.8	**7.3**	24.8
IRD	**9.2**	14.0	**12.9**	17.7	**11.4**	15.6	**5.3**	26.8			**12.6**	16.8
LSCD	**-3.4**	9.7	**0.3**	14.5	**-1.2**	11.8	**-7.3**	24.8	**-12.6**	16.8		
NIST	**-3.7**	13.5	**0.0**	17.3	**-1.5**	15.2	**-7.6**	26.5	**-12.9**	19.3	**-0.3**	16.3
NRC	**-2.4**	10.5	**1.3**	15.0	**-0.2**	12.5	**-6.3**	25.1	**-11.6**	17.2	**1.0**	13.9

Lab *i* ⇓ / Lab *j* ⇒			NIST		NRC	
	D_i /(mGy/Gy)	U_i	D_{ij} /(mGy/Gy)	U_{ij}	D_{ij} /(mGy/Gy)	U_{ij}
CNEA	**-3.7**	11.2	**0.0**	17.3	**-1.3**	15.0
IAEA	**-2.2**	7.5	**1.5**	15.2	**0.2**	12.5
ININ	**3.9**	23.0	**7.6**	26.5	**6.3**	25.1
IRD	**9.2**	14.0	**12.9**	19.3	**11.6**	17.2
LSCD	**-3.4**	9.7	**0.3**	16.3	**-1.0**	13.9
NIST	**-3.7**	13.5			**-1.3**	13.5
NRC	**-2.4**	10.5	**1.3**	13.5		

Figure 3. Graphical representation of the degrees of equivalence for the various laboratories participating in the comparison. The degree of equivalence is the difference between the value obtained by a particular NMI and that obtained by the BIPM, divided by the BIPM value, along with the expanded uncertainty on this fractional difference. The expanded uncertainty corresponds to twice the standard uncertainty.



11 Acknowledgements

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