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Supplementary comparison CCRI(I)-S2 of standards for absorbed dose to water in ^{60}Co gamma radiation at radiation processing dose levels

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Abstract

Eight national standards for absorbed dose to water in ^{60}Co gamma radiation at the dose levels used in radiation processing have been compared over the range from 1 kGy to 30 kGy using the alanine dosimeters of the NIST and the NPL as the transfer dosimeters. The comparison was organized by the Bureau International des Poids et Mesures, who also participated at the lowest dose level using their radiotherapy-level standard for the same quantity. The national standards are in general agreement within the standard uncertainties, which are in the range from 1 to 2 parts in 10^2. Evidence of a dose rate effect is presented and discussed briefly.

1. Introduction

At its meeting in May 2007, Section I of the Consultative Committee for Ionizing Radiation (CCRI) proposed a supplementary comparison of the high-dose standards for absorbed dose to water in ^{60}Co gamma radiation among the national laboratories operating standards and services in this field. This comparison, denoted CCRI(I)-S2 and organized by the Bureau International des Poids et Mesures (BIPM), follows a similar comparison carried out in 1999 [1]. Part of the motivation for a new comparison was published evidence of a dose rate dependence in alanine dosimetry [2].

Eight laboratories offering high-dose irradiation services took part in the comparison: the Czech Metrology Institute Inspectorate for Ionizing Radiation (CMI-IIR, Czech Republic), the Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti (ENEA-INMRI, Italy), the Laboratoire National Henri Becquerel (LNE-LNHB, France), the National Institute of Metrology (NIM, China), the National Institute of Standards and Technology (NIST, USA), the National Physical Laboratory (NPL, UK), the High Dose Reference Laboratory of the Danish Technical University (Risø-HDRL, Denmark) and the Institute for Physical-Technical and Radiotechnical Measurements, Rostekhregulirovaniye of Russia (VNIIFTRI, Russian Federation). All laboratories hold primary standards with the exception of the CMI-IIR and the Risø-HDRL, who hold secondary standards traceable to the BIPM and the NPL, respectively. In addition, the BIPM, although it does not offer a high-dose service, took part at the lowest dose level (1 kGy) to provide a direct link to the international reference for absorbed dose to water in ^{60}Co. Two transfer dosimeters were used for the comparison; the alanine/ESR dosimetry system of the NIST [3, 4] and that of the NPL [5, 6].

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2. High-dose standards and transfer dosimeters

For each of the participants, the basis of the ^{60}Co standard for absorbed dose to water and the means of transfer of the dosimetry to an industrial irradiator are summarized in Table 1. Also given in the table are the nominal dose rate and the combined relative standard uncertainty u_{lab} of the mean absorbed dose to water D_{w} over the dimension of each alanine transfer dosimeter, as stated by each laboratory. The detailed uncertainty budgets are given in Appendix I.

Table 1. Basis of the estimates of absorbed dose to water at the various laboratories.

Laboratory	Standard of absorbed dose to water in ^{60}Co reference radiotherapy field	Transfer to high-dose irradiator	Nominal dose rate / Gy s^{-1}	u_{lab} / %	Reference
BIPM	Primary standard ionization chamber	-[a]	0.007	0.31	[7]
CMI-IIR	Secondary standard ionization chamber[b]	Ionization chamber	0.36	2.2	[8]
ENEA-INMRI	Graphite calorimeter + thick-walled ionization chamber	Dichromate dosimeter via Fricke dosimeter in calibration irradiator	1.2	1.9	[9, 10]
LNE-LNHB	Graphite calorimeter + ionization chamber and Fricke dosimeter	Alanine dosimeter	2.7	0.9	[11]
NIM	Fricke dosimeter	-[a]	0.17	1.4	[12]
NIST	Water calorimeter	Alanine dosimeter	3.1[c]	0.6	[3, 4]
NPL	Graphite calorimeter + scaling theorem	Alanine dosimeter	2.2	1.1	[5, 6]
Risø-HDRL	-	Alanine dosimeter[d]	1.8	1.4	[13]
VNIIFTRI	-	Polystyrene calorimeter[e]	2.4	0.7	[14, 15]

a No irradiator employed; alanine transfer dosimeters irradiated directly in ^{60}Co reference field.

b The CMI-IIR is traceable to the BIPM through radiotherapy-level calibration.

c For the NIST irradiation of the NPL alanine, two dosimeters (one at 1 kGy and one at 30 kGy) were irradiated using a second irradiator in which the dose rate is 0.6 Gy s^{-1}.

d The Risø-HDRL alanine dosimeter system is directly traceable to the NPL.

e The VNIIFTRI standard is a polystyrene calorimeter operating directly at high dose levels. The conversion to absorbed dose to water uses tabulated mass energy-absorption coefficients.

The NIST alanine dosimeters for use in ^{60}Co are supplied in watertight cylindrical holders 12.3 mm in diameter and 29 mm in length, each vial containing four pellets. The relative standard uncertainty associated with the calibration of the NIST alanine dosimeters is 0.9 % and the dosimeter-to-dosimeter reproducibility, relevant to its use as a transfer dosimeter, is 0.4 %. The NPL alanine dosimeters are also supplied in cylindrical holders, 11.5 mm in diameter and 17 mm in length; these are not normally watertight but can be made so on request. The relative standard uncertainty associated with the calibration of NPL alanine dosimeters is 1.2 % and the reproducibility is 0.5 %.

3. Comparison procedure

A protocol for the comparison was issued in December 2008 and each national laboratory sent information on its irradiation protocol to the NIST and the NPL (*via* the BIPM) in advance of the irradiations. Each laboratory was sent, in late January 2009, eleven alanine transfer dosimeters from the NIST and eleven from the NPL. Of each set of eleven, two were irradiated to each of four nominal dose levels: 1 kGy, 5 kGy, 15 kGy and 30 kGy (note that, in order that the comparison remains blind, laboratories were instructed to give doses in the region of, but not precisely equal to, the nominal dose levels). Of the three remaining control dosimeters for each set, two were irradiated before issue (to 1 kGy and 15 kGy) and the third remained unirradiated. For the BIPM, a similar arrangement was used, but because of the low dose rate of the reference ^{60}Co radiotherapy-level field at the BIPM irradiations were only feasible for the 1 kGy dose level.

Irradiations at all laboratories took place in the three-week period beginning 9 February 2009. The dosimeters were returned immediately to the issuing laboratories with information on irradiation temperatures but no information on dose estimates. All laboratories sent their irradiation dose estimates to the BIPM for analysis, along with information on the basis of the dose and uncertainty estimates. The issuing laboratories sent their measured alanine doses to the BIPM by the end of April 2009.

The irradiation geometry was not specified in detail in the protocol; each irradiating institute used their normal arrangement. This policy was adopted so that the dose estimates be representative of those routinely disseminated by each institute, rather than modified for the purpose of the present comparison. All laboratories other than the ENEA-INMRI, CMI-IIR, NIM and the BIPM employed a laboratory-scale self-shielded irradiator. The ENEA-INMRI irradiated the dosimeters in a large pool-type irradiation facility and the CMI-IIR in a small industrial facility. The NIM and the BIPM irradiated the alanine dosimeters in a water phantom under their reference conditions in ^{60}Co.

4. Results and discussion

The results are given in Tables 2 and 3 for the NIST and NPL dosimeters, respectively. The dose estimates include a correction for differences from the stated reference temperature (correcting upwards for temperatures below this value). The results using the NIST dosimeters are summarized in Figure 1, expressed for each dosimeter i as the ratio $R_{i,\mathrm{NIST}}$ of the irradiating laboratory dose estimate relative to the NIST estimate for that dosimeter. The uncertainty bars represent the combined standard uncertainty of the laboratory and the NIST dose estimates. Despite evidence for the CMI-IIR and the ENEA-INMRI of a systematic difference for each pair of dosimeters at a given dose level, such differences are within the stated uncertainties and no deviations from unity larger than the expanded uncertainty ($k = 2$) are observed. The results for the Risø-HDRL closely match those of the NPL, to whom the Risø-HDRL is traceable. The results for the CMI-IIR at the 1 kGy dose level are consistent with those of the BIPM, to whom they are traceable.

For each of the four dose levels, the relative standard deviation of the results for $R_{i,\mathrm{NIST}}$ is in the range from 1.3 % to 1.7 %. Recalling the values for the standard uncertainty u_{lab} given in Table 1, this level of agreement is consistent with the stated standard uncertainties. Nevertheless, there is evidence of a trend with dose level, particularly for the laboratories with relatively low dose rates (the CMI-IIR and the NIM). This behaviour is discussed in [2]. Similar conclusions can be drawn from the results for the NPL dosimeters, shown in Figure 2, although the trend with dose level is less marked.

Table 2. Results for the NIST dosimeters

T_{ref} = 24 °C, 0.14 %/K at 1 kGy
0.11 %/K at 5 kGy, 15 kGy, 0.12 %/K at30 kGy

Irradiating lab	Dosim ref	Lab est / kGy	Temp / °C	NIST est / kGy
CMI-IIR	7	1.0	17.5	0.999
	8	0.97	18.5	0.962
	5	5.0	18.0	4.984
	6	5.0	18.0	4.866
	3	15.0	17.0	14.803
	4	15.0	17.0	14.375
	1	30.0	17.0	28.809
	2	30.0	17.0	29.259
ENEA-INMRI	15	0.99	16.0	1.033
	16	1.00	16.0	1.021
	13	4.98	16.0	5.135
	14	5.03	16.0	5.091
	11	14.92	16.0	15.282
	12	15.07	16.0	15.167
	9	29.84	16.0	30.430
	10	30.15	16.0	30.267
LNE-LNHB	17	1.003	20.1	1.002
	18	1.003	19.9	1.001
	19	5.002	20.5	4.942
	20	5.007	20.1	4.950
	21	15.000	21.2	14.810
	22	15.000	20.4	14.811
	23	30.010	20.8	29.479
	24	30.000	21.5	29.491
NIM	33	1.045	20.0	1.056
	34	1.013	20.0	1.029
	35	5.225	20.0	5.231
	36	5.067	20.0	5.025
	37	15.68	20.0	15.626
	38	15.20	20.0	15.033
	39	31.35	20.0	30.320
	40	30.40	20.0	29.601
VNIIFTRI	60	1.073	19.5	1.080
	58	1.073	19.5	1.082
	59	5.363	17.0	5.417
	61	16.092	17.0	16.258
	64	16.093	17.0	16.273
	63	16.09	17.0	16.272
	57	32.182	17.0	32.379
	62	32.178	17.0	32.257
Risø-HDRL	49	1.00	25.0	1.005
	50	1.00	25.0	1.015
	51	4.80	25.0	4.849
	52	4.80	25.0	4.816
	53	16.0	25.0	16.000
	54	16.0	25.0	16.159
	55	29.0	25.0	29.016
	56	29.0	25.0	28.855
NPL	47	0.9987	25.0	1.015
	48	0.9987	25.0	1.014
	45	5.020	25.0	5.053
	46	5.020	25.0	5.063
	43	15.08	25.0	15.248
	44	15.08	25.0	15.196
	41	30.15	25.0	30.074
	42	30.15	25.0	30.152
BIPM	65	1.0163	19.4	1.028
	66	1.0169	19.4	1.025

Table 3. Results for the NPL dosimeters

T_{ref} = 25 °C, 0.14 %/K at all dose levels

Irradiating lab	Dosim ref	Lab est / kGy	Temp / °C	NPL est / kGy
CMI-IIR	1386	1.0	17.5	0.989
	1387	0.97	18.5	0.948
	1384	5.0	18.0	4.913
	1385	5.0	18.0	4.883
	1382	15.0	17.0	14.723
	1383	15.0	17.0	14.540
	1380	30.0	17.0	29.149
	1381	30.0	17.0	28.958
ENEA-INMRI	1394	0.99	16.0	1.019
	1395	1.00	16.0	1.025
	1392	4.97	16.0	5.065
	1393	5.03	16.0	5.092
	1390	14.92	16.0	15.320
	1391	15.07	16.0	15.228
	1388	29.84	16.0	30.332
	1389	30.15	16.0	30.576
LNE-LNHB	1396	1.002	19.8	0.989
	1397	1.001	19.8	0.990
	1398	5.003	19.4	4.905
	1399	5.004	19.7	4.909
	1400	15.000	19.6	14.671
	1401	15.000	20.8	14.680
	1402	30.000	19.4	29.442
	1403	30.000	20.9	29.525
NIM	1404	1.045	20.0	1.071
	1405	1.013	20.0	1.040
	1406	5.225	20.0	5.358
	1407	5.067	20.0	5.133
	1408	15.68	20.0	15.913
	1409	15.20	20.0	15.097
	1410	31.35	20.0	31.055
	1411	30.40	20.0	30.038
VNIIFTRI	1428	1.074	19.5	1.083
	1433	1.074	19.5	1.082
	1429	5.363	17.0	5.386
	1432	5.363	17.0	5.378
	1430	16.089	17.0	16.252
	1435	16.091	17.0	16.236
	1431	32.179	17.0	32.393
	1434	32.180	17.0	32.393
Risø-HDRL	1420	1.00	25.0	1.002
	1421	1.00	25.0	1.005
	1422	4.80	25.0	4.807
	1423	4.80	25.0	4.775
	1424	16.0	25.0	15.935
	1425	16.0	25.0	16.061
	1426	29.0	25.0	28.886
	1427	29.0	25.0	28.938
NIST	1412	1.00	23.7	0.997
	1413	1.00	23.8	0.990
	1414	5.00	23.7	4.946
	1415	5.00	23.8	4.948
	1416	15.00	23.8	14.920
	1417	15.00	23.6	14.906
	1418	30.00	23.5	29.380
	1419	30.00	23.6	29.711
BIPM	1508	1.0143	19.4	1.021
	1509	1.0130	19.4	1.020

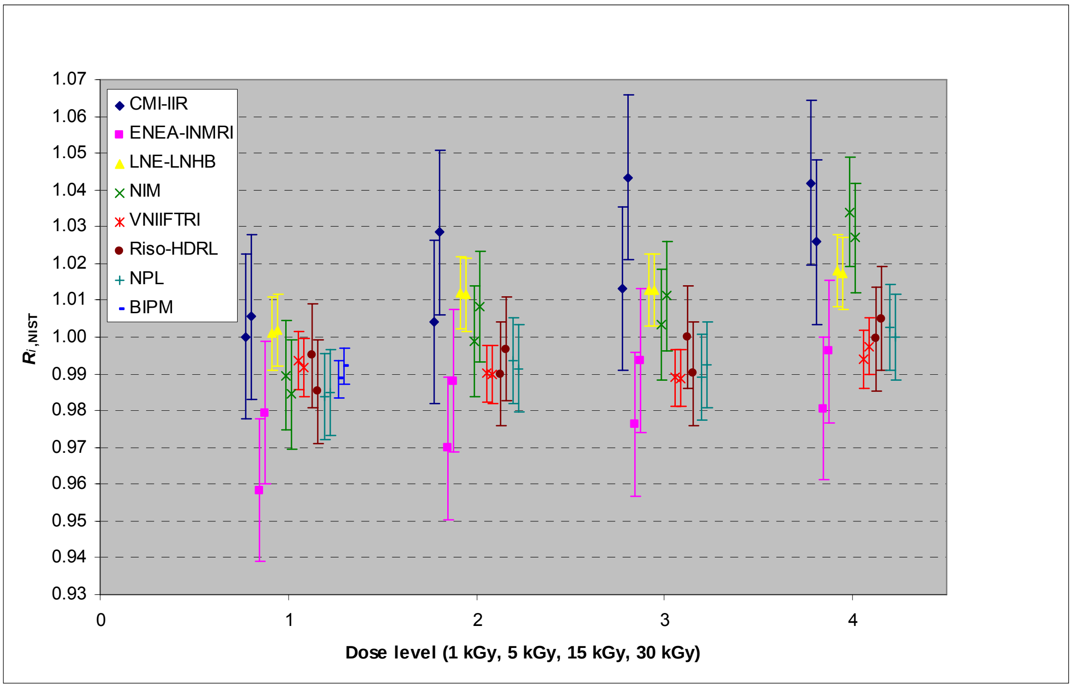

Figure 1. Comparison results using the NIST alanine transfer dosimeters, expressed as the ratio $R_{i,\mathrm{NIST}}$ of the dose estimate of the irradiating laboratory relative to that of the NIST, for the four stated dose levels. The uncertainty bars represent the combined standard uncertainty of the laboratory dose estimate and the reproducibility of the NIST alanine dosimeter (0.4 %).

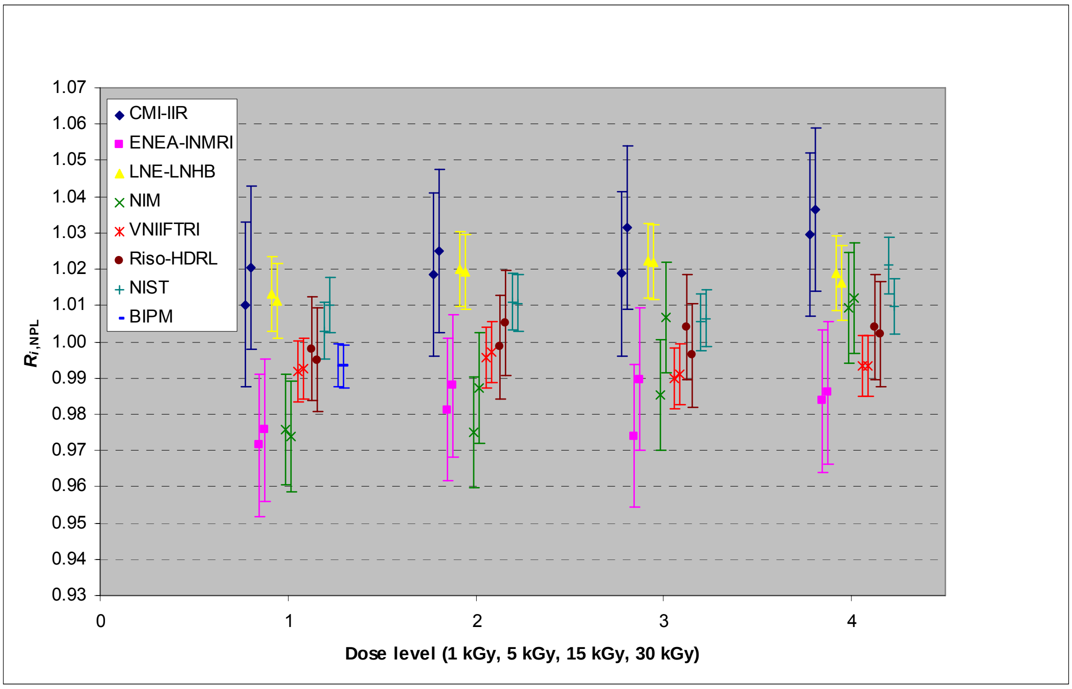

Figure 2. Comparison results using the NPL alanine transfer dosimeters, expressed as the ratio $R_{i,\mathrm{NPL}}$ of the dose estimate of the irradiating laboratory relative to that of the NPL, for the four stated dose levels. The uncertainty bars represent the combined standard uncertainty of the laboratory dose estimate and the reproducibility of the NPL alanine dosimeter (0.5 %).

The consistency of the NPL and NIST results can be studied by evaluating the ratio $R_{\mathrm{NPL,NIST}}$ as the ratio of the mean value of $R_{i,\mathrm{NIST}}$ to the mean value of $R_{i,\mathrm{NPL}}$ for each laboratory at each dose level, as shown in Figure 3. Here, the uncertainty bars represent the combined standard uncertainty of the NPL and NIST alanine dosimeters and do not include a component of uncertainty arising from the measurements at the participating laboratories. The results for each dose level, with the exception of those of the NIM, form a self-consistent set; there is evidence of a slight systematic effect with dose level amounting to around 1 % in total. The results for the NIM show a possible systematic difference in the treatment of the NPL and NIST dosimeters. Nevertheless, there is no significant deviation from unity in the ratio $R_{\mathrm{NPL,NIST}}$.

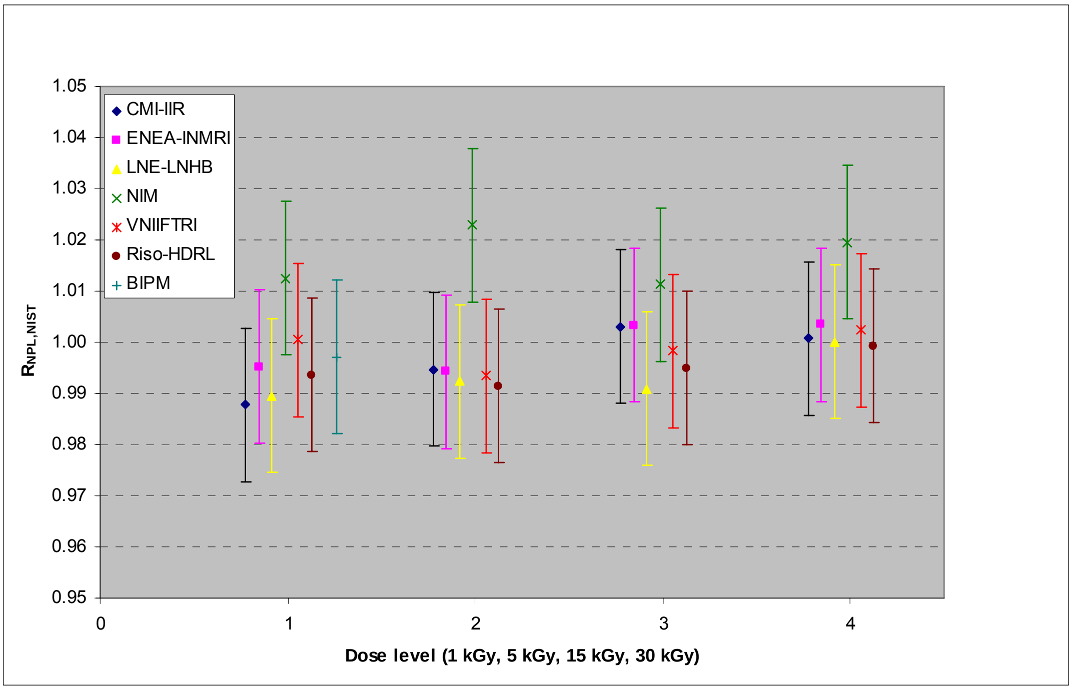

Figure 3. Ratio of the NPL to NIST dose estimates derived from the results $R_{i,\mathrm{NPL}}$ and $R_{i,\mathrm{NIST}}$ for each irradiating laboratory. The uncertainty bars represent the combined standard uncertainty.

5. CIPM MRA and equivalence

In the BIPM key comparison database [16], the present comparison is registered as the supplementary comparison CCRI(I)-S2 and this report is referenced in Appendix B. Although no formal degrees of equivalence are registered for supplementary comparisons, the following analysis results in a set of values, one for each laboratory at each dose level, that characterizes the extent to which the laboratories are in agreement.

For each dose level, all twenty-eight values for $R_{i,\mathrm{NIST}}$ and $R_{i,\mathrm{NPL}}$ are combined to give their unweighted mean value R_{ref} and its statistical standard uncertainty u_{ref} [1]. Each such value is taken to represent the reference value for that dose level. The four results for each laboratory at each dose level (that is, two values for $R_{i,\mathrm{NIST}}$ and two for $R_{i,\mathrm{NPL}}$) are reduced to their mean value R_i. Note that the NIST and the NPL each have only two results for each dose level (the NIST irradiation of two NPL alanine dosimeters and *vice-versa*). The results for each dose level are then expressed as normalized differences from the reference value,

$$D_i = (R_i - R_{\mathrm{ref}}) / R_{\mathrm{ref}}, \qquad (1)$$

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[1] For the evaluation of $\underline{u}_{\mathrm{ref}}$, the number of degrees of freedom is taken to be eight, rather than twenty-eight, because only eight laboratories contribute to the results.

and the expanded uncertainty U_i of each D_i evaluated using the coverage factor $k = 2$. The uncertainty for each laboratory includes the laboratory standard uncertainty u_{lab} from Table 1 and the standard uncertainty u_{ref} of the reference value, which is close to 0.5 % for each of the four dose levels. This value of 0.5 %, which arises from an unweighted analysis of the values for $R_{i,\text{NIST}}$ and $R_{i,\text{NPL}}$ for a given dose level, is very close to the value obtained if a weighted mean is used. In other words, the internal and external uncertainty estimates are very similar, which indicates a self-consistent data set. The BIPM results are not included in the reference value for 1 kGy and are used only to verify that the reference value $R_{\text{ref}} = 0.9928$ for 1 kGy (with statistical standard uncertainty 0.005) is consistent with the BIPM result $R_i = 0.9918$ for 1 Gy (with combined standard uncertainty 0.0037). The results for D_i and U_i are presented in Table 4 and shown graphically in Figure 4.

Table 4. Results for D_i and U_i, expressed in Gy per kGy.

Dose level / kGy	D_i, U_i / (Gy/kGy)	CMI-IIR	ENEA-INMRI	LNE-LNHB	NIM	VNIIF TRI	Risø-HDRL	NPL	NIST
1	D_i	16	-22	14	-12	0	1	-8	14
5	D_i	19	-18	16	-8	-7	-3	-8	11
15	D_i	25	-19	15	0	-12	-4	-11	4
30	D_i	24	-22	8	11	-14	-6	-8	6
	U_i	46	40	23	32	19	30	26	19

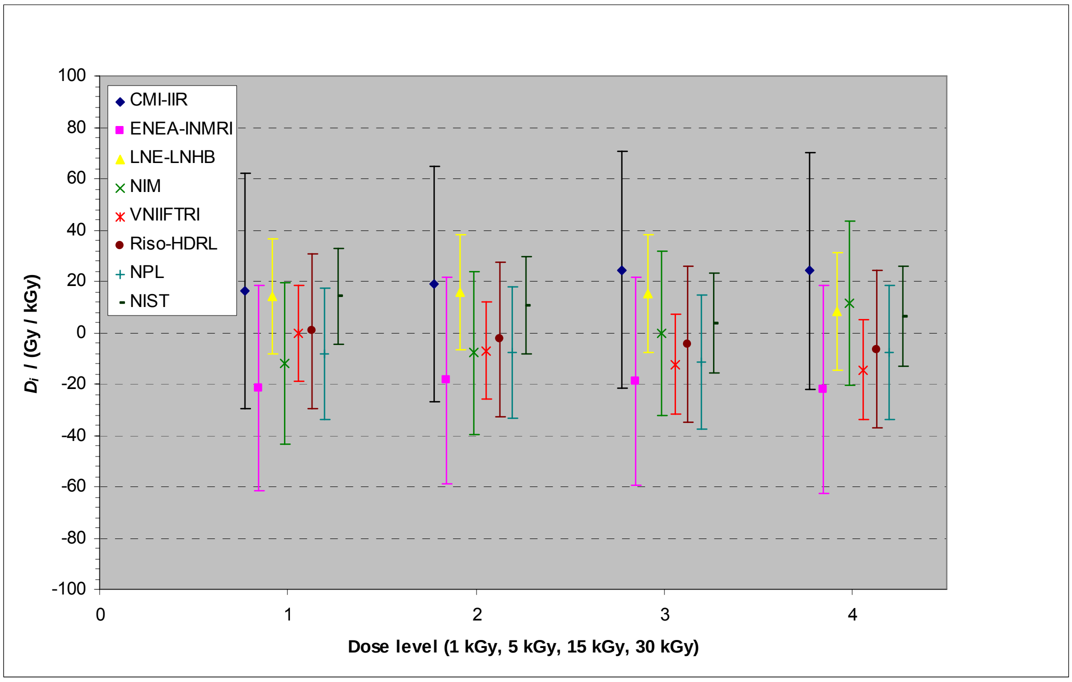

Figure 4. The normalized differences D_i, in Gy per kGy, with respect to the reference value for the comparison, for each laboratory and each dose level. The uncertainty bars represent the expanded uncertainty U_i of these differences (with coverage factor $k = 2$).

6. Discussion and conclusions

The results demonstrate that the national high-dose standards of the participating laboratories are in general agreement within the standard uncertainties, which are in the range from 0.7 % to 2.2 %. Nevertheless, for those laboratories with an absorbed-dose rate that is low in relation to the dose rate at which the alanine dosimeters are calibrated, there is evidence of a trend in the results with dose level. This effect has been seen in previous work [2] and is demonstrated by the analysis presented in Figure 5. Here, the parameter S for each laboratory represents the slope, in percent per kGy, of the values for $R_{i,\mathrm{NIST}}$ from Figure 1, and separately for $R_{i,\mathrm{NPL}}$ from Figure 2, as a function of the irradiation dose. These values for S are plotted as a function of the irradiation dose rate relative to the alanine calibration dose rate. While the use of simple linear fits over the range from 1 kGy to 30 kGy to derive values for S is appropriate in view of the statistical uncertainties, it should not be inferred that the effect continues linearly at higher dose levels.

It is clear from Figure 5 that a systematic effect is present, although the statistical uncertainties do not permit one to distinguish the functional form of the effect. In particular, while it is tempting to postulate an effect that progressively increases as the irradiation dose rate is reduced with respect to the calibration dose rate, the proposition of Desrosiers and Puhl [17] of a threshold effect cannot be excluded. In this scenario, a threshold exists in the region of 1 Gy s^{-1} to 2 Gy s^{-1}. If both dose rates are above or both are below this region, no effect will be observed. However, if this threshold region falls between the irradiation and calibration dose rates, an effect will be observed. For the lowest irradiation dose rates in the present work, around 0.2 Gy s^{-1}, the dose-rate effect can produce systematic errors of up to 4 % for irradiations at the 30 kGy level.

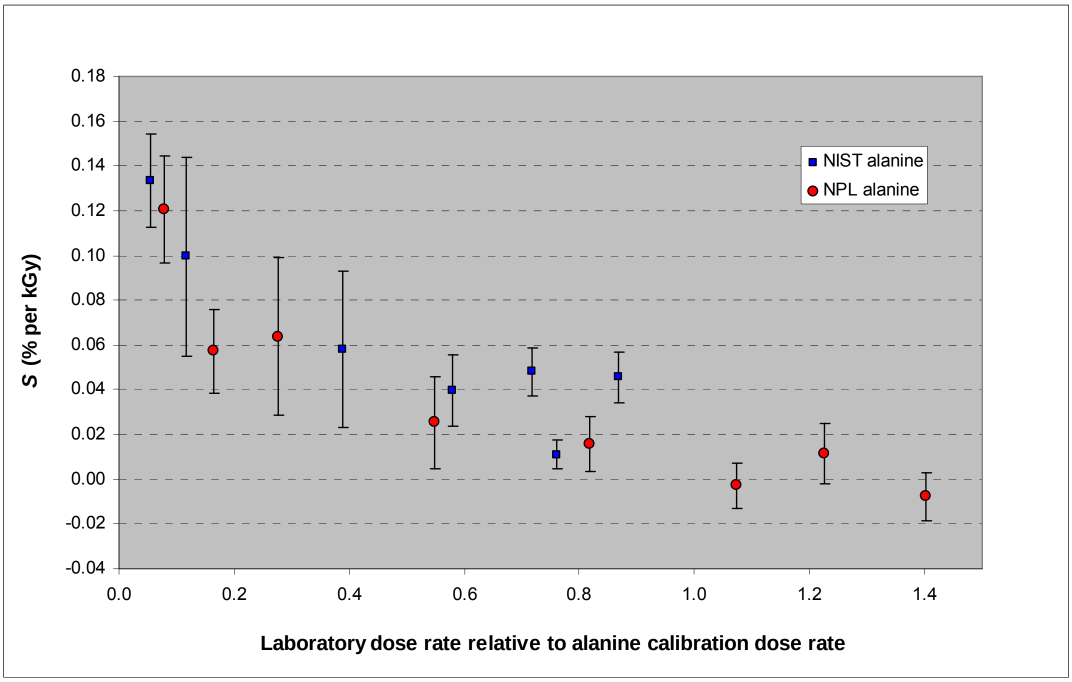

Figure 5. The slope S of the laboratory results $R_{i,\mathrm{NIST}}$ and $R_{i,\mathrm{NPL}}$ as a function of irradiation dose, plotted with respect to the laboratory dose rate relative to the alanine calibration dose rate. The uncertainty bars represent the standard uncertainty of S resulting from the linear regression. The results of the NIST irradiations of the NPL alanine at two dose rates are shown as separate points.

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Appendix I. Uncertainty budgets submitted by the participants

The following information is presented essentially as it was received from the participants.

BIPM

Uncertainty budget

Relative standard uncertainties expressed in parts in 10^2.

	Type A	Type B
Reference dose rate [a]	0.20	0.21
Dosimeter positioning	-	0.02
Radial non-uniformity	-	0.03
Presence of envelope	-	0.03
Presence of rod	-	0.01
Air gap inside envelope	-	0.10
Quadrature sum	0.20	0.24
Combined	**0.31**	

a The uncertainty budget for the reference dose rate is given Table 9 (page 15) of the BIPM report *Rapport* BIPM-2009/04 available on the BIPM website.

CMI-IIR

Calculated data:

Ionization current $I = (I_M-(I_{B1}+I_{B2})/2)$ [A]: $7.759.10^{-9}$
Correction factor for the ambient conditions k_{tp}: 1.0182
Recombination correction factor k_{sat}: 1.0018
Correction factor for the irradiation field non-homogeneity k_{unh}: 1.0041

Uncertainty components and values (k=1):

Ion. chamber position:	type A: n.a.	type B: 1.34%
Ion. chamber calibration factor:	type A: n.a.	type B: 0.31%
Ion. current measurement:	type A: 0.03%	type B: 0.4 %
k_{tp}:	type A: n.a.	type B: 0.5 %
k_{sat}:	type A: n.a.	type B: 0.1 %
k_{unh}:	type A: n.a.	type B: 1.23%

Dose rate determination:

$$D_w = N_{Dw} * I * k_{tp} * k_{sat} * k_{unh}$$

$$D_w = 0.3611 \text{ Gy/s}$$

Expanded uncertainty (k=2):

$u = 3.91$ %

Uncertainty budget (k=1):

Dose rate at the reference point:	type A: n.a.	type B: 1.96%
Dosimeter position:	type A: n.a.	type B: 0.67%
Non-uniformity of the gamma field:	type A: n.a.	type B: 0.62%
Irradiation time:	type A: n.a.	type B: 0.37%
Combined uncertainty:	**2.19%**	

Pressure and temperature correction:	type A: n.a.	type B: 0.25%

(this uncertainty does not contribute to the combined uncertainty of absorbed dose).

ENEA-INMRI

Uncertainties in absorbed dose delivered to the alanine dosimeters.

	Relative standard uncertainty	
Component of uncertainty	Type A (%)	Type B (%)
Step A: ferrous sulphate dosimeter calibration in the reference Co-60 gamma beam (I.U. 1)		
Primary standard (D_w)		
Reference D_w at 5 g cm^{-2}		0.4
Ferrous sulphate dosimeter		
Dosimeter positioning		0.2
Absorbance reading	0.2	0.3
Irradiation temperature		0.2
Absorbance reading temperature		0.1
Stability of ferrous sulphate solution		0.2
Transfer dosimeter intra-batch variability	0.4	
Step B: dichromate dosimeter calibration in the pool-type Co-60 irradiation facility (irradiation condition 1, I.U. 2)		
D_w determination by ferrous sulphate dosimeter		
Dosimeter and source positioning		0.5
Absorbance reading	0.2	0.3
Irradiation temperature		0.3
Absorbance reading temperature		0.2
Transfer dosimeter intra-batch variability	0.4	
Irradiation time	0.2	
Dichromate dosimeter		
Dosimeter and source positioning		0.5
Absorbance reading	0.2	0.3
Irradiation temperature		0.2
Absorbance reading temperature		0.1
Stability of dichromate solution		0.1
Dosimeter intra-batch variability	0.4	
Irradiation time	0.1	
Step C: D_w measurements by dichromate dosimeter in the pool-type Co-60 irradiation facility (irradiation condition 2, I.U. 2)		
Dosimeter and source positioning		0.5
Absorbance reading	0.2	0.3
Irradiation temperature		0.2
Absorbance reading temperature		0.1
Stability of dichromate solution		0.1
Dosimeter intra-batch variability	0.4	
Irradiation time	0.1	
Field non-uniformity		0.5
Alanine irradiation in the pool-type Co-60 irradiation facility (irradiation condition 2, I.U. 2)		
Dosimeter and source positioning		0.8
Irradiation time	0.1	
Field non-uniformity		0.3
Quadratic sum	0.9	1.6
Combined standard uncertainty	**1.9**	

LNE-LNHB

The calculation of the uncertainty associated with the dose delivered using the high dose irradiator is detailed in the following table.

Component of uncertainty (k=1) for dose delivered to dosimeters using Gammacell 220

Source of uncertainty	Type A (%)	Type B (%)
Dose rate of the Gammacell derived from :		0.85%
- Dose delivered at the reference beam (dose rate, decay corrections, irradiation time, positioning, non-uniformities of the irradiation field)		(0.49%)
- Derivation of the absorbed dose to each dosimeter (ESR readings, pellet mass, system drift, fading , non-uniformity of the gamma field over the dosimeter volume, temperature correction)		(0.70%)
Transition dose	0.0012%	
Irradiation time	3.10^{-5}%	
Decay corrections		0.02%
Irradiation temperature correction		0.09%
Relative combined standard uncertainties (1σ)	**0.86%**	

NIM

The full statement of the standard uncertainties of water absorbed dose determined by Fricke dosimetry system is 0.94%. The list of uncertainty components for absorbed dose measurement in terms of type A and B uncertainties are given in the table below.

Components of uncertainty (k = 1) for absorbed dose measurement

Component	Type A %	Type B%
$G_{(Fe3+)}$=1.61(mol·J^{-1})	--	0.65
$\varepsilon_{(Fe3+)}$ at 25.0 ℃	0.27	0.21
D_{Fricke} to D_{water}	--	0.20
Radiation spectrum	--	0.20
Variation in spectrophotometer Abs	0.33	0.25
other	--	0.30
Type A and Type B combined in quadrature (1σ)	0.94	

The list of uncertainty components for derivation of the absorbed dose to each dosimeter in terms of type A and B uncertainties are given in the following table.

Components of uncertainty (k=1) for derivation of the absorbed dose to each dosimeter

Component	Type A %	Type B%
Response of Fricke dosimeter	--	0.94
Source position repeatability	0.50	--
Irradiation time	0.10	--
Irradiation temperature	--	0.20
Decay corrections	0.01	0.03
The beam uniformity over dosimeter	0.8	---
Corrections for attenuation and geometry	---	0.50
Type A and Type B combined in quadrature (1σ)	1.44	

NIST

GC207 Calibration Geometry Dose Rate

Uncertainty Source	Type A (%)		Type B (%)
Water Calorimetry in Vertical Beam	0.16		0.51
GC207/Pool Source Ratio Data	0.08		
Pool/B036 Source Ratio Data	0.17		
Field Uniformity			0.01
Timer Error (irrad time > 8 min)			0.20
Co-60 Decay Correction			0.02
sqrt(sum)	0.25		0.55
combined in quadrature		0.60	
t-factor for 16 degrees of freedom at 95.45%		2.17	
Expanded Uncertainty at 95.45% confidence		1.3	

NPL

Uncertainty Budget for Irradiations in NPL Gammacell 220 High Dose Rate Co-60 Irradiator.

Source of uncertainty	Relative uncertainty	Probability Dist.	Divisor	Relative standard uncertainty u_i	ν_i
Calibration of secondary standard ionisation chamber in terms of absorbed dose to water in Co-60 radiation.	1.2% (from certificate)	N	2	0.6%	∞
Use of chambers to calibrate alanine dosimeters in low dose rate (therapy) irradiator.	0.3%*	N	1	0.3%	10
Use of alanine to calibrate high dose rate irradiator.	0.5%*	N	1	0.5%	10
Use of high dose irradiators to irradiate dosimeters.	0.7%**	N	1	0.7%	16
Combined uncertainty.				**1.1%**	64

* - Values based on statistics of calibration lines between 20 and 120 Gy.

** - Value derived by dose mapping volume using alanine dosimeters (NPL type G holders, 4 positions, 3 layers).

Timing uncertainties are negligible.

Risø-HDRL

Statement of uncertainty

Uncertainty of the specified absorbed dose for irradiation at cobalt-60 gamma cell 3.

1 Transfer dosimeter measurement uncertainty (NPL certificate):
  Calibration: 2.4% (A)
  Measurement: 1.0% (A)
2 Timing of the irradiation:
  0.01% (A)
3 Transient dose: 0.01% (A)
4 Temperature during irradiation, effect on dosimeter response:
  0.23% (A)
5. Geometry. Variation of dose measured within dosimeter holder:
  0.3% (A).
6. Determination of dose rate (fitting of irradiation time and dose data):
  0.2% (A)

Combined uncertainty of dose rate: **2σ: 2.6%**

7 Source decay: 0.05% (B)

8 Transient dose: 0.01% (A)

9 Timing of the irradiation 0.01% (B)

10 Geometry 0.5% (B).

Combined uncertainty of given dose: **2σ: 2.7%**

1σ: 1.35%

VNIIFTRI

Full statement of the standard uncertainty (1 σ) including:

- absorbed dose measurement:

The dose to water for each dosimeter was calculated from:
$D_W = P_W(T_{rad} + T_{trans})$;
P_W – dose rate to water: $P_W = (\mu_{en}/\rho)_W/(\mu_{en}/\rho)_{ps} * P_{PS} = 1.023 * P_{PS}$;
P_{PS} - dose rate to polystyrene;
T_{rad} and T_{trans} – time of irradiation and effective transit time;
The value of P_{PS} was measured by calorimeter with cylindrical polystyrene absorber Ø 22 x 22 mm (with effective mass $M_{eff} = 9.118$ g). Signal is measured by copper-constantan thermal battery which surrounds the absorber. The calorimeter has a wire heater for electrical calibration.
$P_{PS} = U_{tb} / (K(1 - \xi))$, where
U_{tb} – signal of thermo battery,
ξ - thermal defect (for polystyrene $\xi = (0{,}4 \pm 0{,}3)$ %),
K – calorimeter sensitivity which is determined at calibration using electrical wire heater:
$K = U_{tb} / (U_H * I_H) = U_{tb} / (U_H * U_o / R_o)$, where
U_H – voltage on the heater,
U_o - voltage on the standard resistor R_o.

The budget of standard uncertainties of dose measurement is presented in table below:

Source of uncertainty	Standard uncertainty, 1 σ, %	
	Type A	Type B
U_{tb} at calibration, n = 12	0.1	0.05
U_{tb} at measurement, n = 12	0.1	0.05
U_H	0.01	0.02
U_o	0.01	0.02
R_o		0.002
M_{eff}	0.01	0.3
$(\mu_{en}/\rho)_W/(\mu_{en}/\rho)_{ps}$		0.2
ξ		0.2
non-uniformity of the gamma field over the calorimeter volume		0.5
Correction on source decay		0.1
Transit time	0.5 s 0.1 % at 1 kGy	1 s 0.2 % at 1 kGy
Irradiation time	0.01	0.01

Combined standard uncertainty: 0.71 % at 1 kGy, 0.68 % at 30 kGy;

Taken as 0.7 % for all dose levels.