Supplementary comparison APMP.RI(I)-S1 of standards for absorbed dose to water in ^{60}Co gamma radiation at radiation processing dose levels

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Abstract

Four 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 0.1 kGy to 50 kGy using alanine dosimeters of the Office of Atoms for Peace (OAP) as transfer dosimeters. The comparison was piloted by the OAP who also participated. Two laboratories from the original six were forced to withdraw due to equipment problems. The results at low doses (0.1 kGy) showed a much wider spread (up to 17%) than at the other doses, most likely as a result of random variations in the alanine readout at OAP at these dose levels. Results in the 0.1 kGy range were excluded from the analysis because the variation between the laboratories' doses is overshadowed by the variation in the readout of the alanine. Above 1 kGy the results indicated reasonable agreement between the laboratories, with the majority of results within 2 % of the reference value. All of these results were within two combined standard uncertainties of the reference value, with the exception of the INER at 50 kGy point which was within three combined standard uncertainties. Within the stated uncertainties, the results establish the equivalence of the laboratories at radiation processing levels, for the range in which they participated: NIS (3 - 10) kGy, NIM (3 - 30) kGy, INER (3 - 50) kGy, OAP (3 - 50) kGy.

1. Introduction

The purpose of the comparison was to establish equivalence between ^{60}Co absorbed dose to water standards at radiation processing levels (of order kGy) in the Asia Pacific region. The comparison was piloted by the Office of Atoms for Peace (OAP), Thailand, with initially six participants (Table 1), four of whom completed the comparison. OAP provided the transfer dosimeters, alanine pellets in water-tight holders, which were sent to the participants, irradiated, and returned to be read out at OAP. The readout was used as the reference value for the comparison, against which all the laboratories (including OAP) were compared. Irradiations took place in 2010 and reaout was completed early in 2011.

Table 1: List of the participants

Laboratory	Full name	Economy
BARC[1]	Bhabha Atomic Research Centre	India
INER	Institute of Nuclear Energy Research	Chinese Taipei
NIM	National Institute of Metrology	China
NIS	National Institute for Standards	Egypt
MNA[2]	Malaysian Nuclear Agency	Malaysia
OAP[3]	Office of Atoms for Peace	Thailand

[1] Withdrawn without performing irradiations

[2] Previously Nuclear Malaysia. Withdrawn following discovery of an error in the irradiation procedure.

[3] Pilot laboratory

2. Dose to water standards

NIM and OAP used primary methods of absorbed dose determination to calibrate their irradiators. INER used alanine irradiated at the National Institute of Standards and Technology (NIST), USA, to calibrate their ESR reader which was used to determine the dose to water rate from their source. NIS used a secondary standard ionisation chamber (NE 2561) calibrated at the BIPM and realised their standard using a radiotherapy unit.

INER use a custom-built pool irradiator with some 3,000 TBq of ^{60}Co. The dose rate from the irradiator was determined using INER's alanine dosimetry system. This EPR system was calibrated using dosemeters in a cylindrical plastic build-up cap of wall thickness 3.0 mm and irradiated at NIST in their Co-60 Gammacell 220-232 to a known dose to water. During the irradiation the dosimeters (in their INER build-up cap) were held in a 5-hole polystyrene cup with a wall thickness of 4.2 mm. Upon return to INER the EPR system was calibrated. For the comparison, a second set of INER's alanine was irradiated concurrently with the transfer alanine, and the INER alanine was read out to obtain the INER value of dose to water. These irradiations were performed in air, but with enough buildup to ensure electronic equilibrium (3 mm of plastic for INER and 3.2 mm of PMMA for the transfer alanine).

NIM use Fricke system as a primary standard to determine absorbed dose in their 480 TBq (2010) pool-type irradiator. Samples were irradiated in a water phantom at 5 cm depth, at 25 cm from the centre of the source to the phantom surface.

The OAP absorbed dose to water rate is determined using a Fricke dosimetry system, established following the ASTM 1026 standard [1]. The OAP irradiations were performed with a Gammacell 220 Excel ^{60}Co irradiator (MDS Nordion, Canada) with an activity of 376 TBq in March 2010. For quality assurance, the absorbed dose ranges from 0.1 kGy to 50 kGy at the OAP is compared annually with the National Physical Laboratory (NPL), UK.

Table 2: Data on irradiation facilities provided by the participants who completed the comparison

NMI	^{60}Co irradiator type	Irradiation phantom material and size	Nominal dose rate (Gy/s)	Traceability	u_{lab} (%)
INER	Custom pool irradiator (3,000 TBq in 2010)	Irradiated in air* with 3 mm of buildup	0.98	NIST	1.7
NIM	480 TBq (2010) pool irradiator	Polystyrene water phantom, 30 cm x 30 cm x 30 cm	0.33	NIM	1.0
NIS	Theratron 780E radiotherapy unit	PTW water phantom 30 cm x 30 cm x 30 cm	0.06	BIPM, via NE 2561 chamber	1.8
OAP	Gammacell 220 Excel, MDS Nordion	Polymethyl methacrylate, 7 cm in diameter, 8.5 cm in length	2.1	OAP	2.0

*See explanation in Section 2

3. Comparison procedure

The comparison was conducted using alanine pellets in holders which were prepared by the pilot laboratory and sent to each of the participants (Figure 1). The alanine pellets were irradiated in the holders at each of the participating laboratories, and returned to the pilot, where the pellets were read using the pilot's EPR (electron paramagnetic resonance) facility (Section 4).

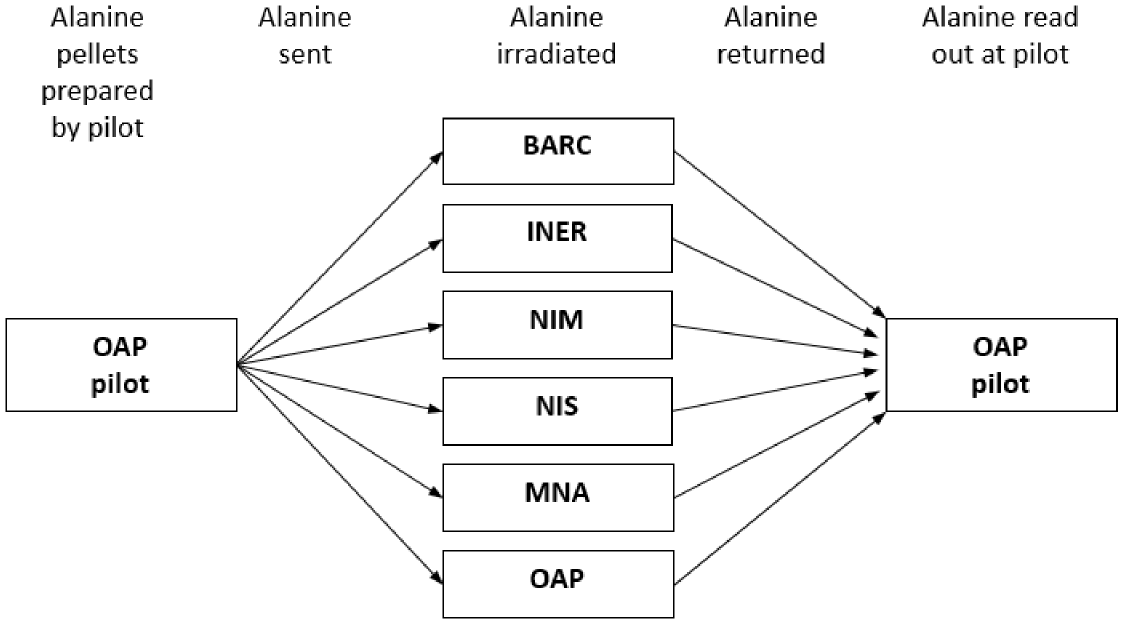

Figure 1: Planned workflow of the comparison, with alanine pellets prepared by the pilot, irradiated at each laboratory, and then returned to the pilot for readout. Irradiations took place in 2010.

The pilot laboratory prepared six groups of eleven holders, with each holder containing four individual alanine pellets (Figure 2) (total number of pellets used in the comparison = 264). A group of eleven holders was sent to each laboratory, where ten holders were available for irradiation using the laboratory's ^{60}Co gamma irradiator, and one was used as a control. The absorbed dose to water was requested to be 0.1, 3, 10, 30 and 50 kGy (with two holders irradiated at each dose level), however participants were allowed to choose other doses between 0.1 and 50 kGy if it suited their irradiation facilities.

The irradiation temperature was requested to be controlled by each laboratory to be in the range 25-35°C, and not to vary from the chosen value by more than ±2°C during the irradiations, and the relative humidity not to exceed 55%. The dosimeters were returned to OAP within three weeks of the irradiation to avoid fading effects [2]. The participant laboratories informed OAP of the irradiated dose (as determined by their laboratory), the date of irradiation, the temperature during irradiation, the source type, the irradiation phantom material and size, the uncertainty in the dose and traceability [3].

The Supplementary Comparison Reference Value (SCRV) was taken to be the EPR readout by OAP. While this value is calibrated by OAP in terms of absorbed dose, it does not have to be calibrated for the purposes of the comparison. Instead, it is enough to know the random variation and the linearity between doses, which are discussed in Section 4.

For the analysis the reading was treated as an independent reference which is used to make the comparison between the irradiating laboratories. For each dose level, all of the laboratories' stated doses were compared to the corresponding EPR readout. That is, the result R_i for each laboratory i, for each dose level D, was the stated dose delivered to each alanine holder $D_{i,j}$ divided by the EPR readout result $E_{i,j}$, averaged over the n pellets given that dose. Here j refers to the pellet in the dose group and n=4 (one holder).

$$R_{i,D} = \frac{1}{n}\sum_{j=1}^{n}\frac{D_{i,j}}{E_{i,j}} \tag{1}$$

The uncertainty in $R_{i,D}$, $u(R_{i,D})$, was calculated from the uncertainty in the laboratory-stated dose provided by the laboratory, *u_lab*, and the statistic uncertainty in the EPR readout, *u_stat*, using equation 2, where we have chosen to ignore uncertainties in the readout which are common to all results. The choice of *u_stat* is discussed later.

$$\left[u(R_{i,D})\right]^2 = [u\_lab]^2 + [u\_stat]^2 \tag{2}$$

4. Alanine specifications and readout

Alanine dosimeters were obtained from Bruker BioSpin AG, Thailand. The pellets were cylindrical, with a height of 3 mm, diameter of 4.5 mm and a weight of (64.5 ± 0.5) mg. The dosimeters were sealed into cylindrical holders nominally 12 mm in diameter and 22 mm in length, with four pellets in each holder (Figure 2). The wall material was polymethyl methacrylate (PMMA) and the internal diameter 5.5 mm. The holders conform to ISO/ASTM 51607:2004 [4].

Figure 2: Four alanine pellets were sealed into a cylindrical holder. One holder was used for each irradiation, and each laboratory received 11 holders.

The pellets were read out at room temperature at OAP within three days after receipt using a Bruker BioSpin model A300 EPR spectrometer. The free radical signal in all of the alanine dosimeters was recorded using a high sensitivity standard rectangular cavity, with an operating frequency of 9.8 GHz. Spectral acquisition details are listed in Table 3. A microwave power of 4 mW was selected after performing a power saturation study for the radical in this cavity. Under these conditions the EPR signal amplitude was measured using the peak-to-peak procedure as described in [4].

Table 3: EPR measurement parameters at OAP for alanine readouts in the dose range of (0.1 - 50) kGy.

Parameters	Dose range of (0.1 - 50) kGy
Microwave power	4 mW
Center field	3514 G
Sweep width	200 G
Modulation frequency	100 kHz
Modulation amplitude	1 G
Conversion time	50.00 ms
Time constant	163.84 ms
Resolution	1024 points
Number of scans per pellet	3

The EPR system is calibrated by OAP using their primary standard Fricke system, described in Appendix I, which also contains an uncertainty budget for the Fricke system. The Appendix also gives the uncertainty budget for the readout of an alanine pellet. For the analysis of the uncertainty in the reference value (the EPR readout) [5,6], only the repeatability of the system is required, and this was assessed from the statistical variation of the readings of the four pellets in each holder. An addition component due to fading was ignored due to the short periods involved. If doses at different dose levels are to be compared, the linearity of the system is also relevant, and a standard uncertainty of 2 %, derived from a curve-fitting method used to calibrate the output for different doses, should be added in quadrature.

The variability of the ESR readout of a dosemeter is shown in Figure 3, which depicts the relative standard deviation of the readings of the four pellets in each holder, as a function of dose. We note that the variation is considerable at very low doses (< 1 kGy). A value of 2 % was used for the standard uncertainty in the mean of the ESR readouts of four pellets, for the region (1 – 50) kGy.

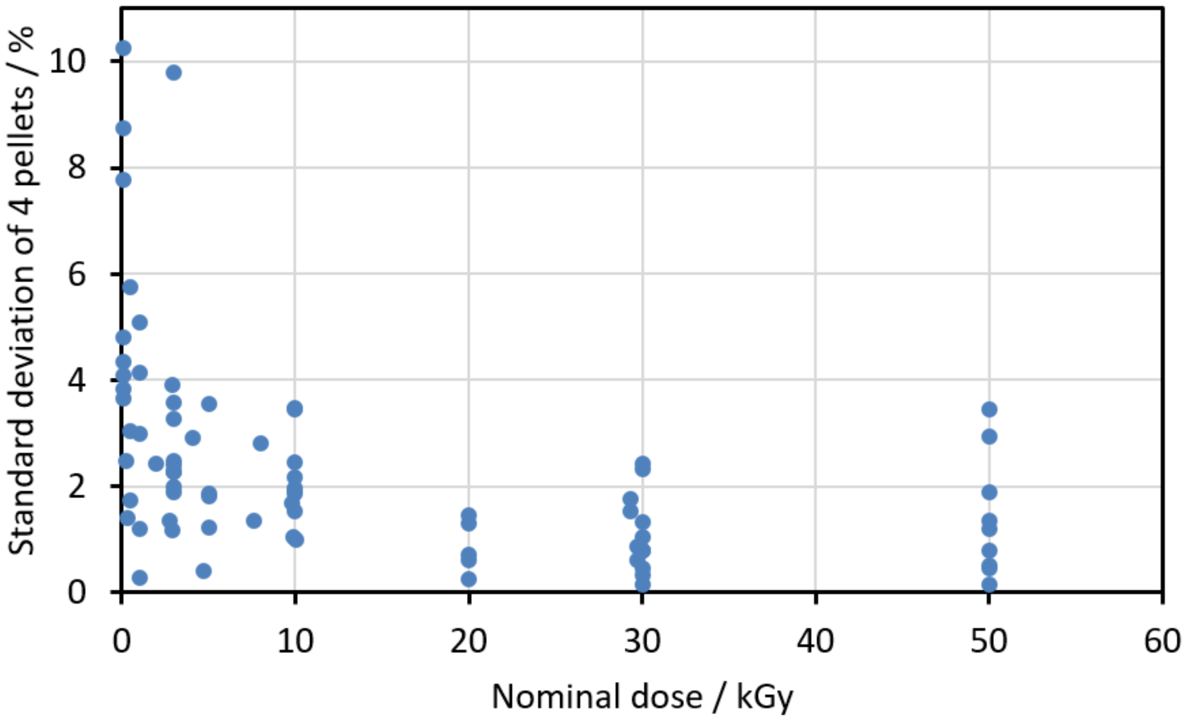

Figure 3: The relative standard deviation of the OAP ESR readout of the 4 pellets of the dosimeters used in the comparison, plotted against the nominal dose.

5. Deviations from the comparison protocol

(a) BARC were unable to perform the irradiations at the scheduled time and withdrew before the comparison started.

(b) The ^{60}Co gamma irradiator at MNA malfunctioned at the time of the comparison, and so a second system designed for the continuous irradiation of liquid latex (PURIDEC Irradiation Technologies) was used instead. However, upon notification of their results, MNA checked the setup and concluded that an error had occurred and asked for their results to be withdrawn. For nominal doses of 0.1, 3, 10, 30 and 50 kGy, the ratios of MNA to the reference value $R_{MNA,D}$ were 1.05, 1.10, 1.23, 1.19 and 1.18, respectively.

(c) For NIM, only 8 of the 10 irradiated holders irradiated at (1-30) kGy were analysed. This was because the temperature in the water phantom varied by around 4 ^{o}C during the 50 kGy exposure, and the laboratory therefore requested that these holders not be assessed.

(d) For INER, although two holders were irradiated at each dose level as per the protocol, only one holder was analysed for each dose level because the second set was missing when the package was received by OAP.

(e) In 2020 INER discovered an administrative error that occurred during the submission of the results: the form sent to OAP contained the nominal doses and not the delivered doses. The original laboratory records were located, and the INER-determined doses are shown in

Table 4. The analysis was revised as this was viewed as the correction of an administrative error and not a change to the measured values.

Table 4: Doses originally submitted by INER on the comparison form, and the INER-determined delivered doses, as determined at the time of irradiation, submitted later.

Alanine capsule code	Delivered dose submitted on form / kGy	Delivered dose determined by INER / kGy	Relative difference / %
31	0.1	0.104	4.2
32	3	2.814	-6.2
33	10	9.270	-7.3
34	30	27.97	-6.8
35	50	50.14	0.3

6. Results

The EPR readouts in kGy from the irradiated alanine dosimeters are given in Table 5. The readouts were corrected using the temperature coefficient of 0.048 %/°C [7,8] with the irradiation temperatures provided by the participants. The absorbed dose to water as determined by the irradiation laboratory was normalized to the alanine readout determined by OAP (the SCRV), and the results are displayed in Figure 4, where the error bars represent the standard uncertainty of the participants combined with the reproducibility of the holder readout (determined from the 4 individual pellet readouts).

Table 5. Laboratory-stated delivered doses D_i and readout results for each holder E_i (each line in the table is a single irradiation: the result is the average of four individual alanine pellets). Uncertainty budgets are given in Appendix I and included here as standard uncertainties.

NMI	$D_{i,D}$ / kGy	*u_lab* [a] /%	E_i / kGy	*u_stat* [b] /%	$R_{i,D}$	*u* [c] /%	Irradiation temp / °C
INER	0.104	1.8	0.106	-	0.983	-	27.0
	2.814		2.75	2	1.023	2.7	27.0
	9.270		9.17	2	1.011	2.7	27.5
	27.97		27.48	2	1.018	2.7	27.5
	50.14		47.09	2	1.065	2.7	29.0
NIM	0.101	1.4	0.095	-	1.063	-	24.5
	0.099		0.090	-	1.100	-	24.5
	2.97		2.86	2	1.038	2.5	24.0
	2.93		2.82	2	1.039	2.5	24.0
	9.90		9.64	2	1.027	2.5	24.0
	9.78		9.60	2	1.019	2.5	24.0
	29.70		30.35	2	0.979	2.5	24.1
	29.34		29.99	2	0.978	2.5	24.1
NIS	0.098	1.8	0.084	-	1.167	-	27.0
	0.101		0.096	-	1.052	-	27.0
	0.500		0.45	2	1.111	2.7	25.3
	0.500		0.47	2	1.064	2.7	25.3
	2.78		2.77	2	1.004	2.7	22.5
	2.90		2.91	2	0.997	2.7	22.5
	4.79		4.65	2	1.030	2.7	25.2
	4.08		4.26	2	0.958	2.7	25.2
	7.98		7.87	2	1.014	2.7	24.6
	7.58		7.58	2	1.000	2.7	24.6
OAP	0.10	1.4	0.112	-	0.893	-	35.0
	0.10		0.104	-	0.962	-	35.0
	3.00		3.08	2	0.974	2.4	35.0
	3.00		3.07	2	0.977	2.4	35.0
	10.0		9.72	2	1.029	2.4	35.0
	10.0		9.88	2	1.012	2.4	35.0
	30.0		29.6	2	1.014	2.4	35.0
	30.0		30.63	2	0.979	2.4	35.0
	50.0		48.82	2	1.024	2.4	35.0
	50.0		48.82	2	1.024	2.4	35.0

[a] *u_lab* = the laboratory-stated standard uncertainty in the absorbed dose to water delivered to each holder.

[b] u_stat = the statistical uncertainty in the readout of a holder (the average of 4 pellets), as estimated by the pilot OAP (left blank at 0.1 kGy).
[c] u = combined standard uncertainty of the ratio $R_{i,D}$.

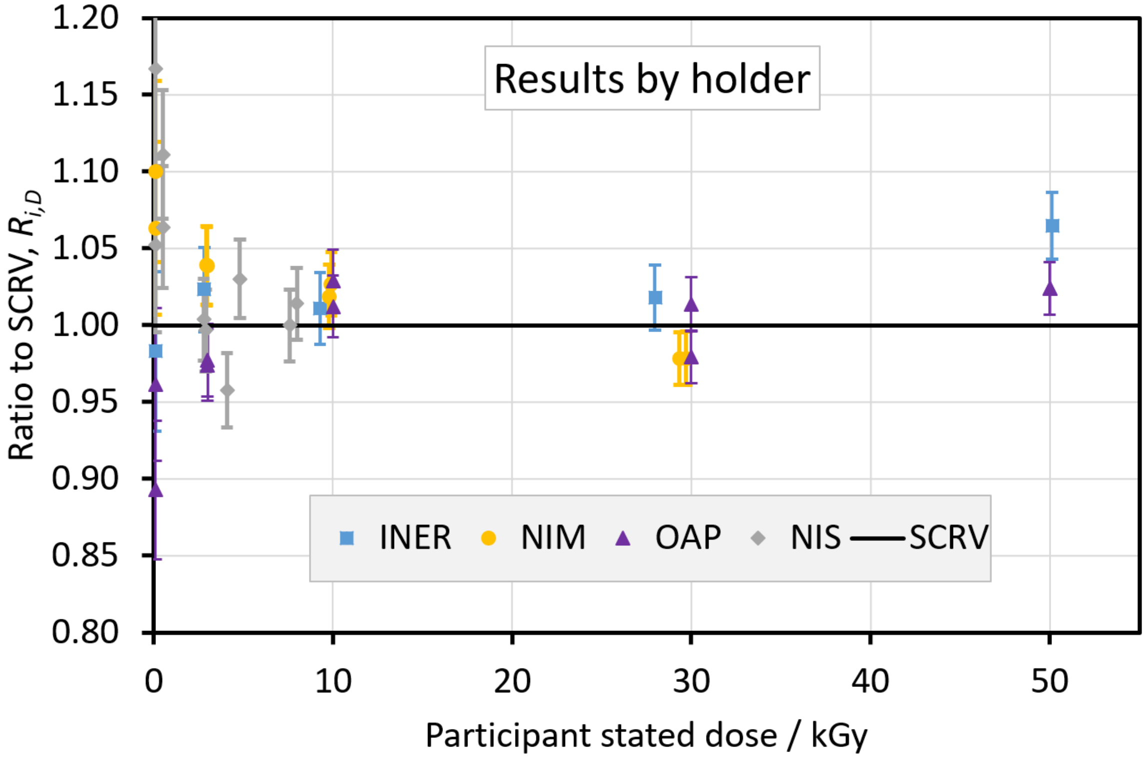

Figure 4. Ratio of stated dose to the SCRV for each irradiated holder, from Table 5. The error bars represent the combined standard uncertainty of the $R_{i,D}$.

These results were then combined for holders irradiated in each of the nominal dose ranges, to obtain a single ratio for each laboratory in the dose ranges at which they participated. These results are given in Table 6 and Figure 5.

Table 6: Results for each laboratory by combining exposures, and the combined and expanded uncertainty associated with the average ratio at the given dose range, excluding the 0.1 kGy range.

NMI	Nominal dose / kGy	R_D	R_D-1 %	$u_c(R_D)$ %	$U_c(R_D)$ %
INER	3	1.023	2.3	2.7	5.4
	10	1.011	1.1		
	30	1.018	1.8		
	50	1.065	6.5		
NIM	3	1.039	3.9	2.0	4.0
	10	1.023	2.3		
	30	0.978	-2.2		
NIS	0.5	1.087	8.7	2.3	4.5
	3	1.000	0.0		
	5	0.994	-0.6		
	10	1.007	0.7		
OAP	3	0.976	-2.4	2.0	4.0
	10	1.020	2.0		
	30	0.996	-0.4		
	50	1.024	2.4		

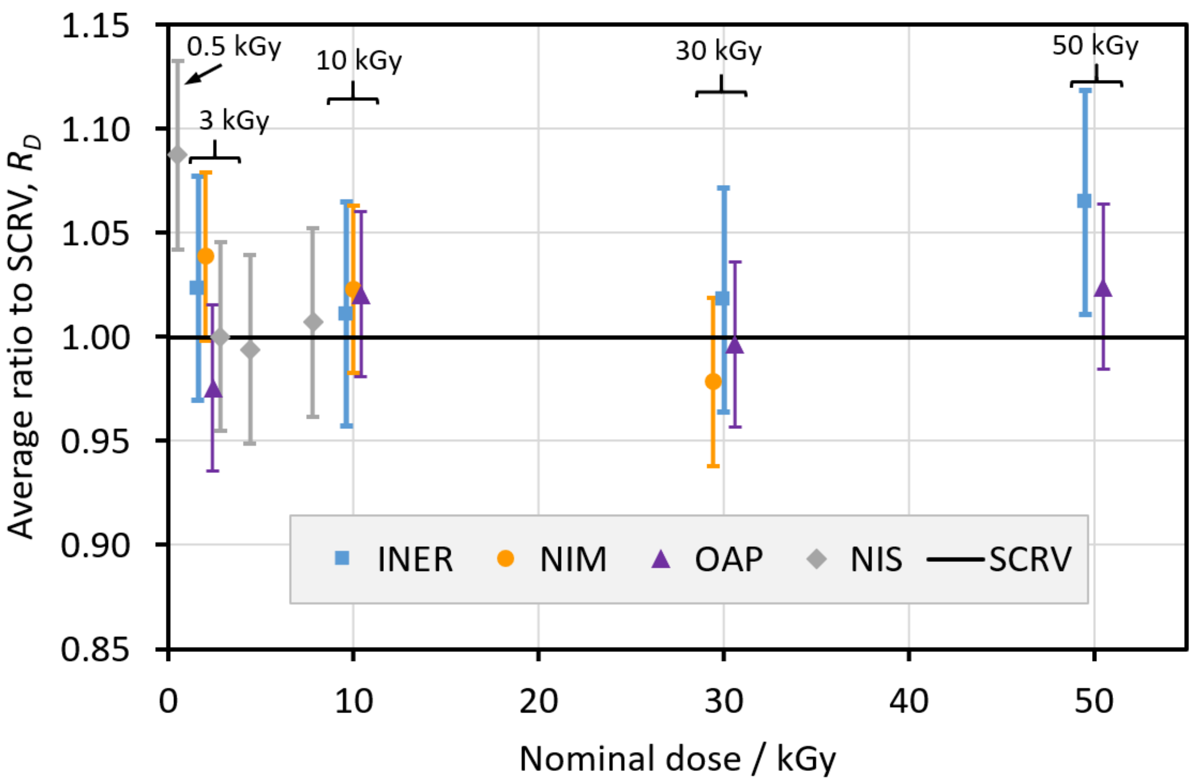

Figure 5. Ratio of each laboratory to the SCRV, from Table 6. The nominal dose has been adjusted in this graph to prevent the results from overlapping. The error bars indicate the combined expanded uncertainty in the ratio. The 0.1 kGy results are omitted.

5. Discussion

The results indicate a level of consistency between the laboratories OAP, NIS, NIM and INER over the range of (3 – 10) kGy, between OAP, NIM and INER over the range of (10 – 30) kGy and between INER and OAP at 50 kGy, as discussed in more detail in the following sections.

5.1 Doses below 1 kGy

The results below 0.1 kGy show a greater spread than at high doses. The standard deviation of all the results $R_{i,D}$ in the range 0.1 kGy is some 0.1, or 10 %. We note that the pilot laboratory results at 0.1 kGy are 0.89 and 0.96, which are also consistent with a large random uncertainty for this low dose range.

Because the variation between laboratories at 0.1 kGy appears to be dominated by random variations in the alanine readout, these points were excluded from the analysis of equivalance, and from the following discussion.

5.2 INER results

The INER results in the (3 – 30) kGy range are within one standard uncertainty of the reference value. At 50 kGy the result lies some 2.4 times the standard uncertainty from the reference value, suggesting a possible outlier. However, we note that if the average of all participants was used as the SCRV (some 1.2 % higher than the actual SCRV), then every result agrees within the k=2 uncertainties.

5.3 OAP results

The OAP results in the nominal (3 – 50) kGy range all lie within two standard uncertainties of unity, with the largest deviation being 2.4 % (1.2 times the standard uncertainty). We note that a ratio of unity is to be expected for OAP, as the EPR readout (while given only relative status in this comparison) is calibrated in terms of absorbed dose to water by OAP.

5.4 NIS results

The NIS ratios in the nominal (3 – 10) kGy range are all within a single standard uncertainty of the reference value. The highest dose delivered was around 8 kGy, due to the time required with a radiotherapy unit. The NIS results below 1 kGy were all within 3 standard uncertainties of unity, but the 0.1 kGy point was excluded from the analysis due to the large statistical variation of the transfer dosimeters.

5.5 NIM results

The NIM ratios in the nominal (3 – 30) kGy range are all within twice the standard uncertainty of unity. The highest dose delivered was 30 kGy.

NIM also took part in the comparison CCRI(I)-S2 [9]. In that comparison the ratio of the absorbed dose to water from NIM to the reference value was (0.988, 0.992, 1.000 and 1.011) at dose levels (1 kGy, 5 kGy, 15 kGy and 30 kGy) respectively, with an expanded uncertainty of 3.2%, providing a link between the two comparisons.

5.6 Recommendations for future comparisons

The comparison was complicated by deviations from the protocol and the loss of laboratory staff. Together these issues meant that additional details required to revise the report could not be obtained in a timely manner, and contributed to long delay completing the report. In addition the transfer dosimeters may have contributed to some of the spread between the results at low dose rates, beyond the expected behaviour which had been characterized by the pilot laboratory.

To help avoid these issues in future, we make the following suggestions:

- Participants should register more than one contact person with the pilot to ensure that they are able to respond to questions and approve the final report by email.
- Details of each laboratory's irradiation should be obtained at the time that the results are submitted (the protocol should provide a list of these details, many of which could be supplied when registering for the comparison, and the pilot should evaluate the responses when they are submitted – even to the point of drafting the report – to ensure that the questions have been understood and answered).
- Means to assess whether the alanine has been compromised should be considered (for example, doing two postal rounds with each laboratory, so that their consistency can be evaluated).
- A tamper-proof system for delivering alanine dosemeters may be desirable.
- The protocol should include a discussion of the random uncertainty in the transfer dosimeters and a definition of the SCRV.
- The protocol should also consider the minimum uncertainty component of the degrees of equivalence that could be established between two laboratories with the proposed transfer dosimeters and ensure that this meets the needs of the participants.

6. Conclusion

A comparison of ^{60}Co absorbed dose to water in the kGy range was carried out by the APMP. The measurements were completed on schedule, although two of the six laboratories were affected by equipment problems and withdrew. The majority of results for the four remaining laboratories were within 4 % of the reference value (around twice the standard uncertainty), and were broadly consistent within the combined standard uncertainty of any two laboratories. However there were several exceptions, including the 0.1 kGy point which deviated by up to 17 % from the reference value, apparently due to larger than expected statistical variations in the readout at this dose level. Doses at 0.1 kGy were subsequently removed from the evaluation of the results. The INER results at 50 kGy was some 6.5 % from the SCRV. The results nevertheless support the equivalence of between the four laboratories within the following subsets of the kGy range: NIS (3-10) kGy, NIM (3-30) kGy, INER (3-50) kGy, and OAP (3-50) kGy, within the stated uncertainties.

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References

[1] American Society for Testing and Materials, Standard Practice for Using the Fricke Reference Standard Dosimetry System, Designation ASTM E1026-95 (1995)

[2] T. Kojima, L. Chen, Y. Hanuyama, H. Tachibana and R. Tanaka. Fading characteristics of an alanine-polystyrene dosimeter. International Journal of Radiation Applications and Instrumentation. Part A. Applied Radiation and Isotopes 43, 863-867 (1992).

[3] K. Mehta and R. Girzikowsky, IAEA high-dose intercomparison in ^{60}Co field, Appl. Radiat. Isot. 52, 1179-1184 (2000).

[4] American Society for Testing and Materials, Standard Practice for Use of Estimating Uncertainties in Dosimetry for Radiation Processing, International Standards Organisation & American Society for Testing and Materials, Designation ISO/ASTM 51707:2005(E).

[5] American Society for Testing and Materials, Standard Practice for Use of an Alanine-EPR Dosimetry System, International Standards Organisation & American Society for Testing and Materials, Designation ISO/ASTM 51670: 2004(E).

[6] E.S. Bergstrand, E.O. Hole and E. Sagstuen. A simple method for estimating dose uncertainty in ESR/alanine dosimetry. Appl. Radiat. Isot. 49, 845-854 (1998).

[7] M.F. Desrosiers, S.L. Cooper, J.M. Puhl, A.L. McBain and G.W. Calvert, A study of the alanine dosimeter irradiation temperature coefficient in the -77°C to + 50°C range, Radiat. Phys. Chem. 71, 363-368 (2004).

[8] M.F. Desrosiers, M. Peters and J.M. Puhl, A study of the alanine dosimeter irradiation temperature coefficient from 25 to 80°C, Radiat. Phys. Chem..78, 465-467 (2009).

[9] D.T. Burns, P.J Allisy-Roberts, M.F. Desrosiers, P.H.G. Sharpe, M. Pimpinella, V. Lourenço, Y.L. Zhang, A. Miller, V. Generalova and V. Sochor. Supplementary comparison CCRI(I)-S2 of standards for absorbed dose to water in ^{60}Co gamma radiation at radiation processing dose levels, Metrologia. 48, 1-18 (2011).

Appendix I. Uncertainty budgets from participants

Information on the uncertainty budgets from the participants is presented below.

Institute of Nuclear Energy Research (INER)

The INER irradiator is a custom-built pool type, of nominal activity 3,000 TBq. The absorbed dose rate was determined using INER's alanine system, which was calibrated using irradiations performed at NIST.

Table A1: Uncertainty budget for absorbed dose to water delivered to alanine pellets at INER

Components of uncertainty	Relative standard uncertainty	
	Type A %	Type B%
Dose rate of irradiator system	-	1.1
Calibration of alanine	-	0.87
Stability of EPR	0.87	-
Mass difference of alanine	-	0.50
Repeatability of EPR	-	0.25
Temperature coefficient to irradiation	0.21	-
Fitting curve	0.10	-
Partial combined uncertainty	**0.90**	**1.5**
Combined uncertainty (1σ)	**1.8**	
Expanded uncertainty at 95 % confidence level (k=2)	**3.6**	

National Institute of Metrology (NIM)

NIM use a Fricke dosimetry system as a primary standard to realise absorbed dose to water for high irradiations using ^{60}Co. The irradiator is of the pool type, where the source is raised inside a 20 cm diameter barrel in the centre of a room. There is no collimator. The surface of the water phantom was placed at a distance of 25 cm from the centre of the source, and the alanine was irradiated at a depth of 5 cm in water. Hollow Perspex tubes with 0.5 mm thick walls were used to hold the transfer dosimeters in position for irradiation.

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.

Table A2: Uncertainty budget for absorbed dose determination at NIM

Components of uncertainty	**Relative standard uncertainty**	
	Type A %	**Type B %**
$G_{(Fe3+)}$=1.61(mol·J^{-1})	--	0.65
$\varepsilon_{(F3+)}$25°C	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
Combined uncertainty (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.

Table A3: Uncertainty budget for absorbed dose to water delivered to alanine pellets at NIM

Components of uncertainty	**Relative standard uncertainty**	
	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
Combined uncertainty (1σ)	**1.44**	
Expanded uncertainty at 95 % confidence level (*k*=2)	**2.9**	

National Institute for Standards (NIS)

Absorbed dose to water at the NIS is determined by an NE 2561 ionization chamber calibrated at the BIPM. The chamber is placed in a water phantom and used to determine the absorbed dose rate at 5 cm depth and 60 cm source-surface distance, in the NIS ^{60}Co radiotherapy unit.

Table A4: Uncertainty budget for the absorbed dose to water delivered to each dosimeter at NIS

Components of uncertainty	Relative standard uncertainty	
	Type A %	Type B %
1. Absorbed dose to water using secondary standard system		
Repeatability	0.23	
Reproducibility	0.2	
Calibration		0.3
Field size	0.1	
Stability	0.24	
Gantry rotation	0.1	
Reference condition		0.5
Temperature		0.1
Pressure		0.1
Time error		0.1
Resolution		0.01
Drift	0.03	
Correction factor		0.2
2. Alanine ⁄ESR dosimetry		
Repeatability	0.33	
Reproducibility	0.6	
Distance	0.32	
Long-term stability	0.25	
Short-term stability	0.33	
Angle	0.1	
Calibration of Alanine		1.1
Fading	0.2	
Noise		0.2
Calibration fitting	0.45	
Time error	0.5	
Humidity	0.25	
Combined uncertainty (1σ)	**1.77**	
Expanded uncertainty at 95 % confidence level (*k*= 2)	**3.54**	

Office of Atoms for Peace (OAP)

The absorbed dose to water in the range of 0.1 kGy to 50 kGy was specified a dose rate from the Fricke dosimetry system as a primary standard. The Fricke dosimeter obtains from the mixing a ferrous ammonium sulfate and a sodium chloride in 0.4 M sulfuric acid. The dosimetric solution was aerated and stored in the room that controls the light and maintains the temperature for two weeks. The Fricke solution was transferred to the ampoules and pre-condition before irradiation in an incubator at a temperature of (25.0 ± 0.5) °C for one hour.

The Fricke dosimeters were contained in a polymethyl methacrylate cylinder phantom, which has a 7 cm in diameter and 8.5 cm in height with a wall thickness of 5. The dosimeters were exposed using ^{60}Co source (Gammacell 220 excel, MDS Nordion, Canada) at the time of 60, 120, 150, 200, and 300 sec. The temperature necessary to record for calculation the variations during exposure to radiation.

The irradiated Fricke solution was evaluated using UV-VIS double beam spectrophotometer (Lambda 650, Perkin Elmer, USA). The absorbance measurements were performed at the wavelength of 303 nm with a spectral bandwidth of 1.0 nm and maintain the sample holder including a dosimeter solution at (25.0 ± 0.5) °C during measurement. The absorbed dose to water of the Fricke solutions was calculated from the absorbance and the temperature according to the ISO/ASTM E 1026:2004. The dose rate of Gammacell 220 Excel ^{60}Co irradiator was specified using the relationship between irradiation time and absorbed dose to water.

The combined uncertainty of alanine measurement estimated from curve fitting from Fricke, repeatability, reproducibility, system drift, alanine response from curve fitting and alanine fading is 2.0 % and 1.9 % for low dose and high dose respectively. The uncertainty of absorbed dose to water is 4.0 % in low dose range and 3.9 % in the high dose range for coverage factor k=2, which corresponds approximately to a 95 % level of confidence.

Table A5: Uncertainty budget for the absorbed dose to water delivered to each dosimeter at OAP

Components of uncertainty	Relative standard uncertainty	
	Type A %	**Type B %**
Fricke solution		
Repeatability of Fricke solution measurement	0.19	-
Calibration of balance	0.0008	-
Calibration of volumetric flask	0.0070	-
Temperature coefficient	0.85	-
Irradiation using Gammacell		
Decay factor	-	0.01
Timing	0.058	-
Reproducibility of positioning	1.1	-
Combined uncertainty (1σ)		**1.4**
Expanded uncertainty at 95% confidence level (*k* = 2)		**2.9**

Table A6: Uncertainty budgets for OAP EPR readout system (0.1 kGy)

Components of uncertainty	Relative standard uncertainty	
	Type A %	**Type B %**
Curve fitting from Fricke	0.52	-
Repeatability of alanine measurement	0.11	-
Reproducibility of alanine measurement	5*	-
System drift	-	0.2
Alanine response from curve fitting (0.1-1 kGy)	-	2.3
Alanine fading	-	1.0
Partial combined uncertainty	**5**	**2.5**
Combined uncertainty (1σ)	**5.6**	
Expanded uncertainty at 95% confidence level (*k* = 2)	**11.2**	

*The random statistical component u_{stat} of the ESR readout for the average reading of 4 pellets irradiated together in a single holder

Table A7: Uncertainty budgets for OAP EPR readout system (1-50 kGy)

Components of uncertainty	**Relative standard uncertainty**	
	Type A %	**Type B %**
Curve fitting from Fricke	0.52	-
Repeatability of alanine measurement	0.11	-
Reproducibility of alanine measurement u_{stat}*	2	-
System drift	-	0.2
Alanine response from curve fitting (1-50 kGy)	-	2.1
Alanine fading	-	1.0
Partial combined uncertainty	2.1	2.3
Combined uncertainty (1σ)	3.1	
Expanded uncertainty at 95% confidence level (k = 2)	6.2	

*The random statistical component u_{stat} of the ESR readout for the average reading of 4 pellets irradiated together in a single holder