EURAMET.RI(I)-S7 comparison of alanine dosimetry systems for absorbed dose to water measurements in gamma- and x-radiation at radiotherapy levels

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Abstract

The National Physical Laboratory (NPL), the Physikalisch-Technische Bundesanstalt (PTB) and the Laboratoire National Henri Becquerel (LNE-LNHB) are involved in the European project "External Beam Cancer Therapy", a project of the European Metrology Research Programme. Within this project, the electron paramagnetic resonance (EPR)/alanine dosimetric method has been chosen for performing measurements in small fields such as those used in IMRT (Intensity Modulated Radiation Therapy). In this context, these three national metrology institutes (NMI) wished to compare the result of their alanine dosimetric systems (detector, *modus operandi* etc) at radiotherapy dose levels to check their consistency. This EURAMET.RI(I)-S7 comparison has been performed with the support of the Bureau International des Poids et Mesures (BIPM) which collected and distributed the results as a neutral organization, to ensure the comparison was "blind".
Irradiations have been made under reference conditions by each laboratory in a ^{60}Co beam and in an accelerator beam (10 MV or 12 MV) in a water phantom of 30 cm × 30 cm × 30 cm in a square field of 10 cm × 10 cm at the reference depth. Irradiations have been performed at known values of absorbed dose to water (D_w) within 10 % of nominal doses of 5 Gy and 10 Gy, i.e. between 4.5 Gy and5.5 Gy and between 9 Gy and 11 Gy, respectively. Each participant read out their dosimeters and assessed the doses using their own protocol (calibration curve, positioning device etc) as this comparison aims at comparing the complete dosimetric process.
The results demonstrate the effectiveness of the EPR/alanine dosimetry systems operated by national metrology institutes as a method of assuring therapy level doses with the accuracy required. The maximum deviation in the ratio of measured to applied dose is less than 1 %.

Keywords: Comparison, dosimetry, alanine, EPR, radiotherapy

1. Introduction

The National Physical Laboratory (NPL), the Physikalisch-Technische Bundesanstalt (PTB) and the Laboratoire National Henri Becquerel (LNE-LNHB) are involved in the European project "External Beam Cancer Therapy", a project of the European Metrology Research Programme. Within this project, the electron paramagnetic resonance (EPR)/alanine dosimetric method has been chosen for performing measurements in small fields such as those used in IMRT. In this context, these three national metrology institutes wished to compare the results of their alanine dosimetric systems (detector, *modus operandi* etc) at radiotherapy dose levels to check their consistency. This comparison (EURAMET.RI(I)-S7) was performed in 2010 using two beams (^{60}Co and one accelerator (Linac) beam) in each laboratory. The Bureau International des Poids et Mesures (BIPM) collected and distributed the results as a neutral organization, to ensure that the comparison was "blind". For each set of data, the results from the irradiating laboratory and the measuring laboratory were sent to the BIPM for distribution once the results from all parties had been received.

2. Comparison procedure

2.1. Irradiation geometries

A protocol for the comparison was issued in early 2010 and each national laboratory sent information on its irradiation protocol to the others before the irradiations started.
Each laboratory provided one batch of 20 dosimeters (Table 1) and their associated positioning system as well as information such as storage conditions, irradiation temperature range, etc. to the two other participants.
Each laboratory irradiated at a given absorbed dose to water a batch of dosimeters, coming from each of the two others laboratories, in a ^{60}Co beam and a Linac Beam.

Table 1. Number of dosimeters to be sent by each NMI to each of the two other participants.

Nominal Doses		Cobalt 60	Accelerator
5 Gy		4	4
10 Gy		4	4
Control dosimeters	unirradiated	2	
	pre-irradiated	2	
TOTAL		**20**	

Irradiations have been made under the reference conditions of each laboratory in a ^{60}Co beam and in an accelerator beam (10 MV or 12 MV) in a water phantom of 30 cm × 30 cm × 30 cm, or larger. The dosimeters were irradiated using a square field of 10 cm × 10 cm (at the reference depth) (Table 2). Irradiations were performed at known doses, within 10 % of the two nominal dose values of 5 Gy and 10 Gy. The doses were specified in terms of absorbed dose to water (D_w).

Table 2. Irradiation conditions used by each NMI.

	NPL		PTB		LNHB	
Beam	Cobalt 60	Accelerator (10 MV)	Cobalt 60	Accelerator (10 MV)	Cobalt 60	Accelerator (12 MV)
Depth in water / cm	5	5	5	10	5	10
Source to detector distance / cm	100	100	100	110	80	100
Dose rate / (Gy.h^{-1})	41	120	76	l 20	27	93

2.2. Dosimeters and positioning systems of each participant

2.2.1. NPL dosimeters and positioning systems

Each dosimeter consists of four alanine pellets from Harwell Dosimeters Ltd, UK, enclosed in a cylindrical holder of 11.5 mm external diameter and 17 mm long. The holder is made of Delrin (polyacetal / polyoxymethylene). For irradiation in a water phantom, a polymethylmethacrylate (PMMA) sheath was provided to hold the dosimeter (Figure 1).

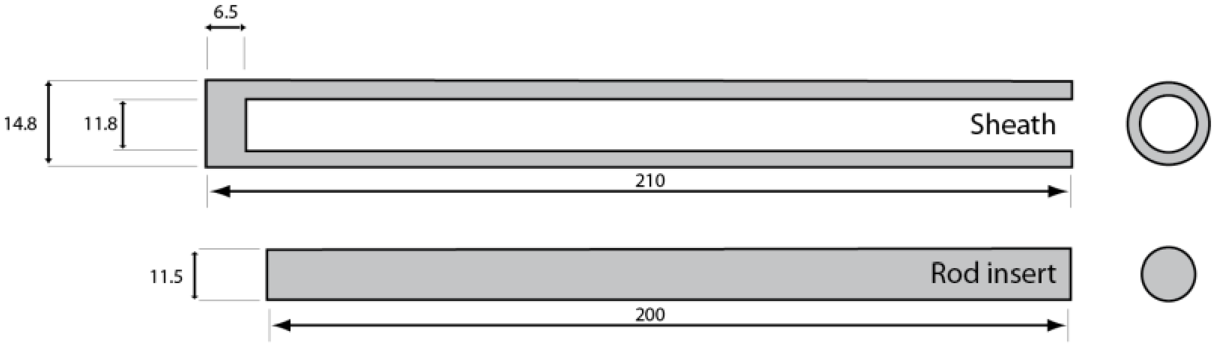

Figure 1. NPL positioning system. Dimensions in mm. Not to scale.

2.2.2. PTB dosimeters and positioning systems

Each dosimeter is composed of 4 pellets from Harwell Dosimeters Ltd, UK, shrink-wrapped in a polyethylene foil 0.2 mm thick. The foil is spanned in a frame made from PMMA (Figure 2). The frame is attached to a PMMA rod for positioning in the water phantom.

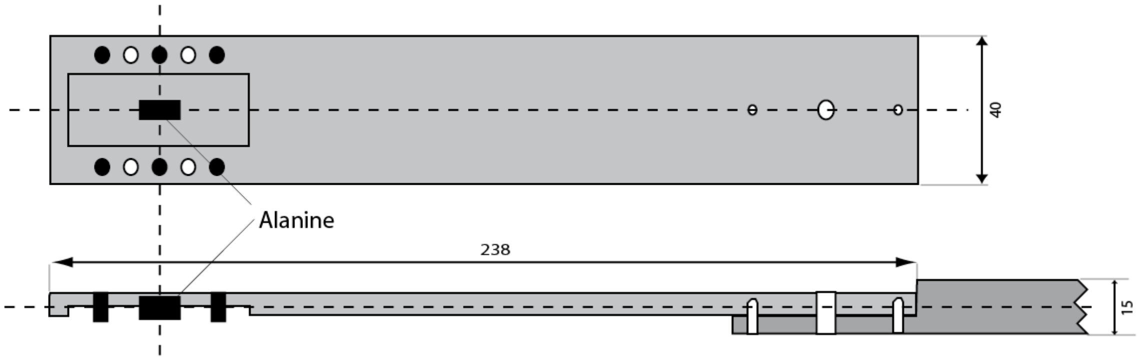

Figure 2. Holder for irradiation of the PTB dosimeters. Dimensions in mm. Not to scale.

2.2.3. LNE-LNHB dosimeters and positioning systems

Each dosimeter is composed of 4 pellets from GammaService, Germany. They are encapsulated in a waterproof cylindrical holder (11.3 mm in diameter and 18 mm in length) made of polyoxymethylene (POM). Moreover, holders have at one end, a small cylindrical rod (2 mm in diameter and 4 mm in length) for clipping on the top of a bigger, reticulated polystyrene rod 440 mm long (Figure 3) to hold the dosimeter in the water phantom.

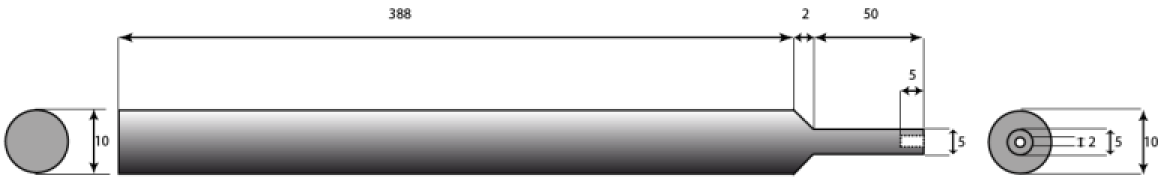

Figure 3. LNE-LNHB positioning system. Dimensions in mm. Not to scale.

2.3. Irradiations performed by each participant

The dosimeters were irradiated to doses within 10 % of two nominal values of 5 Gy and 10 Gy (Table 3). The relative standard uncertainty, quoted *u*(%), is the uncertainty in delivered dose reported by the irradiating laboratory.

Table 3. Absorbed dose to water delivered to each dosimeter.

	NPL irradiations					
	PTB dosimeters			LNE-LNHB dosimeters		
	Dosimeter	D_w /Gy	u /%	Dosimeter	D_w /Gy	u /%
Cobalt-60 beam	GB-17	4.992	0.64	NPL-1	4.992	0.64
	GB-02	4.992	0.64	NPL-2	4.992	0.64
	GB-03	4.992	0.64	NPL-3	4.992	0.64
	GB-04	4.992	0.64	NPL-4	4.992	0.64
	GB-05	9.984	0.64	NPL-5	9.984	0.64
	GB-06	9.984	0.64	NPL-6	9.984	0.64
	GB-07	9.984	0.64	NPL-7	9.984	0.64
	GB-08	9.984	0.64	NPL-8	9.984	0.64
Accelerator beam	GB-09	4.683	0.74	NPL-9	4.683	0.74
	GB-10	5.006	0.74	NPL-10	5.006	0.74
	GB-11	5.010	0.74	NPL-11	5.010	0.74
	GB-12	5.012	0.74	NPL-12	5.012	0.74
	GB-13	10.019	0.74	NPL-13	10.019	0.74
	GB-14	10.047	0.74	NPL-14	10.047	0.74
	GB-15	10.039	0.74	NPL-15	10.039	0.74
	GB-16	10.039	0.74	NPL-16	10.039	0.74

	PTB irradiations					
	NPL dosimeters			LNE-LNHB dosimeters		
	Dosimeter	D_w /Gy	u /%	Dosimeter	D_w /Gy	u /%
Cobalt-60 beam	NPL 681	4.71	0.22	L.CO.5.1	4.68	0.22
	NPL 682	5.32	0.22	L.CO.5.2	5.26	0.22
	NPL 683	5.19	0.22	L.CO.5.3	4.91	0.22
	NPL 684	4.94	0.22	L.CO.5.4	5.34	0.22
	NPL 685	9.48	0.22	L.CO.10.1	10.68	0.22
	NPL 686	9.63	0.22	L.CO.10.2	9.94	0.22
	NPL 687	10.20	0.22	L.CO.10.3	9.23	0.22
	NPL 688	10.46	0.22	L.CO.10.4	10.21	0.22
Accelerator beam	NPL 689	4.76	0.33	L.MV.5.1	5.01	0.33
	NPL 690	5.22	0.35	L.MV.5.2	5.36	0.33
	NPL 691	4.77	0.33	L.MV.5.3	5.22	0.33
	NPL 692	5.36	0.35	L.MV.5.4	5.13	0.33
	NPL 693	10.71	0.35	L.MV.10.1	9.62	0.33
	NPL 694	9.54	0.43	L.MV.10.2	9.85	0.33
	NPL 695	9.93	0.43	L.MV.10.3	10.35	0.33
	NPL 696	10.33	0.39	L.MV.10.4	10.33	0.33

	LNE-LNHB irradiations					
	NPL dosimeters			PTB dosimeters		
	Dosimeter	D_w /Gy	u /%	Dosimeter	D_w /Gy	u /%
Cobalt-60 beam	65/1145	4.81	0.50	F1	4.81	0.50
	65/1146	5.41	0.50	F2	5.41	0.50
	65/1147	5.01	0.50	F3	5.01	0.50
	65/1148	5.61	0.50	F4	5.61	0.50
	65/1149	11.02	0.50	F5	11.02	0.50
	65/1150	10.21	0.50	F6	10.22	0.50
	65/1151	9.52	0.50	F7	9.51	0.50
	65/1152	10.52	0.50	F8	10.52	0.50
Accelerator beam	65/1153	5.03	0.99	F9	5.01	0.99
	65/1154	5.33	0.99	F10	5.32	0.99
	65/1155	5.15	0.99	F11	5.15	0.99
	65/1156	5.15	0.99	F12	5.15	0.99
	65/1157	9.61	0.99	F13	9.60	0.99
	65/1158	9.82	0.99	F14	9.80	0.99
	65/1159	10.44	0.99	F15	10.42	0.99
	65/1160	10.44	0.99	F16	10.43	0.99

2.4. EPR measurement protocols of each participant

Each participant read out their dosimeters and assessed the doses using their normal protocol (calibration curve, positioning device etc.) as this comparison aims at comparing the complete dosimetric process.

2.4.1. NPL measurement protocol

Measurements at NPL were made using a Bruker EMX spectrometer with a rectangular st4102 cavity. The pellets are positioned using a quartz holder consisting of two concentric tubes. The pellets are held on the top of the inner tube by a weak vacuum, which keeps the pellet in place during rotation. For doses below 20 Gy, measurements are made over a field scan width of 20 mT, encompassing the full alanine radical spectrum. A measurement consists of six scans of 20 s each, with rotation of the pellet by 90° between the third and fourth scan. Measurements are also made of unirradiated pellets, to establish the instrument / pellet background, and of a pellet irradiated to 100 Gy, to establish a “template” for the analysis procedure. The spectrometer parameters for the 100 Gy pellet are identical to those for the lower dose pellets, with the exception of the signal channel amplifier gain. A least-squares fitting procedure is used to determine the amount of the “template” spectrum present in the measured lower dose spectrum, and this quantity is used as the effective “dosimeter response” in subsequent calculations. The fitting procedure is iterative and allows account to be taken of pellet-dependent background variations.

An individual calibration curve is prepared for each day’s measurements using a set of dosimeters irradiated to known doses and covering a dose range greater than that of the pellets whose dose is to be determined. These “calibration dosimeters” are measured in dose order at intervals throughout the day. Comparison of the resultant first order (linear) calibration function with expected values enables the detection of spectrometer drift and allows an estimation of measurement related components of uncertainty. The calibration dosimeters were irradiated within a few days of the irradiation at PTB or LNE-LNHB, in order to minimize uncertainty due to fading effects. Details of the measurement and analysis procedure are given in [5] and [8].

2.4.2. PTB measurement protocol

For the ESR measurements of the dosimeters irradiated at NPL and LNE-LNHB, each set required three days of measurement; one for the cobalt data, one for the MVX measurements and one for the controls. For the calibration (base functions), probes irradiated in the cobalt reference field of PTB to a dose of 25 Gy were used. The irradiations could be organized in such a way that the base function probes were irradiated during the same week as the test probes at LNE-LNHB and NPL (*i.e.* there were two different sets of base function probes required). Thus, no corrections for fading had to be taken into account. The measurements of the LNE-LNHB data were carried out between June 17th and June 23rd while the measurements of the NPL probes were performed between August 10th and August 12th, 2010.

General description of the measurement procedure

The measurement procedure was modified recently and is described in detail in the technical report PTB-Dos-55 [1]. The major difference to the procedure described in earlier publications [2] is that no calibration curve is measured; instead, the so-called dose-normalized amplitude A_D is used directly as an estimate for the calculated dose D_{calc}.
Each probe consists of four alanine pellets. For each pellet, five ESR spectra are acquired, where the pellet is rotated by 72° after registration of a spectrum. The spectrum of alanine is measured simultaneously with the spectrum of a reference substance which remains fixed in the resonator. The five spectra per pellet are fitted separately, using the alanine and the reference base functions (see the above mentioned publications). From the fit parameters, *i.e.* from the coefficients A^{ala} (for the alanine contribution) and A^{ref} (for the contribution of the reference substance), the five relative amplitudes

$$A = \frac{A^{ala}}{A^{ref}}$$

are calculated and then averaged. Four values A_i, (i = 1…4) corresponding to the four pellets which constitute one probe, are then averaged to yield the mass-normalized amplitude

$$A_m = M.\frac{1}{n}\sum_{i=1}^{n}\frac{A_i}{m_i}$$

where m_i is the individual mass and M is the average mass of the n pellets (here n = 4).
The quantity which is used for the dose determination is the dose-normalized amplitude A_D derived from A_m which is defined by

$$A_D = \frac{A_m}{M}.M^b.D^b.K_T.K_Q.K_F$$

Index b refers to the base function from which these amplitudes have been calculated. The meanings of the terms on the right of the previous equation are as follows:

$A_m = M.\frac{1}{n}\sum_{i=1}^{n}\frac{A_i}{m_i}$	Average mass-normalized ESR-amplitude, n is the number of pellets irradiated simultaneously (usually n = 4)
$M = \frac{1}{n}\sum_{i=1}^{n} m_i$	Average mass of the simultaneously irradiated pellets
M^b	Same for the pellets used to construct the (alanine) base function
D^b	Dose applied to the pellets used to construct the (alanine) base function
$K_T = \frac{k_T}{k_T^b}$	Correction factor for the irradiation temperature $k_T = 1-c_T.(T-T_0)$: c_T: temperature coefficient
$K_Q = \frac{k_Q}{k_Q^b}$	Correction factor for the radiation quality
$K_F = \frac{k_F}{k_F^b}$	Fading correction

The above list contains only those corrections that are relevant to the present comparison. A detailed description of the correction factors and the estimation of their associated uncertainties can be found in PTB-Dos-55 [1]. The procedure is encoded in a Matlab routine dose_AD_plus_a.m which generates an EXCEL sheet with the individual uncertainty contributions, which is also detailed in the PTB report. The value of the calculated dose D_{calc} is identical to A_D as given above.

2.4.3. LNE-LNHB measurement protocol

The central peak spectrum amplitude measurement was chosen in accordance with different authors [3], [4], [5]. The alanine dosimeters signals were measured on a Bruker ELEXSYS E500 EPR spectrometer with an ER 4119 HS resonator, which operates in X-band. The EPR measurements were performed at controlled room temperature (23 ± 1) °C and (50 ± 5 %) RH. Readouts were made 7 and 14 days after irradiation of the dosimeters. Tubes in Suprasil quartz with 5 mm internal diameter were used to maintain the pellet in the readout cavity. The EPR readout process consisted of measurements at different angles (0, 120 and 240°) in order to take into account a possible variation of the response with angle. The EPR readout parameters are the ones described by Garcia et al [6] except that 5 sweeps per angle were performed instead of 7. The gain was set according to the signal.
The final readout of a dosimeter is the mean value of the amplitudes of the central peak for the three angles. Correction factors due to pellet mass, the gain and the irradiation temperature were applied.
This procedure was used to establish a calibration curve between 4 Gy and 12 Gy using dosimeters irradiated in the LNE-LNHB Cobalt-60 reference beam according to the International Code of Practice IAEA TRS-398 under reference conditions. This curve was used to determine the dose received by each dosimeter irradiated by the NPL and PTB laboratories.

3. Results

Table 4 shows the EPR measurement results data for all dosimeters. In every sub-table, the column “Dosimeter” lists the identifier of each dosimeter also referred to in Table 3. The following two columns show the calculated dose in Gy and its relative standard uncertainty as a percentage.

Table 4. EPR measurements results of each participant.

	NPL irradiations					
	PTB analysis			LNE-LNHB analysis		
	Dosimeter	D_w / Gy	u / %	Dosimeter	D_w /Gy	u / %
Cobalt-60 beam	GB-17	4.97	0.6	NPL-1	4.98	1.8
	GB-02	4.98	0.6	NPL-2	5.00	2.3
	GB-03	5.00	0.6	NPL-3	5.03	1.6
	GB-04	4.99	0.6	NPL-4	5.00	2.0
	GB-05	9.95	0.4	NPL-5	10.04	1.0
	GB-06	9.96	0.4	NPL-6	10.04	1.3
	GB-07	10.00	0.4	NPL-7	10.09	1.5
	GB-08	9.99	0.4	NPL-8	9.97	1.5
Accelerator beam	GB-09	4.67	0.7	NPL-9	4.65	2.5
	GB-10	5.01	0.7	NPL-10	5.08	2.9
	GB-11	5.03	0.7	NPL-11	5.05	1.6
	GB-12	5.03	0.7	NPL-12	5.02	2.8
	GB-13	10.06	0.5	NPL-13	10.14	1.2
	GB-14	10.06	0.5	NPL-14	10.08	1.5
	GB-15	10.09	0.5	NPL-15	10.18	1.3
	GB-16	10.06	0.5	NPL-16	10.21	2.0

	PTB irradiations					
	NPL analysis			LNE-LNHB analysis		
	Dosimeter	D_w / Gy	u / %	Dosimeter	D_w /Gy	u / %
Cobalt-60 beam	NPL 681	4.69	1.06	L.CO.5.1	4.83	1.9
	NPL 682	5.32	1.06	L.CO.5.2	5.42	1.9
	NPL 683	5.21	1.06	L.CO.5.3	5.05	2.4
	NPL 684	4.96	1.06	L.CO.5.4	5.55	2.3
	NPL 685	9.45	0.83	L.CO.10.1	11.05	1.2
	NPL 686	9.59	0.83	L.CO.10.2	10.29	1.2
	NPL 687	10.14	0.83	L.CO.10.3	9.57	1.2
	NPL 688	10.39	0.83	L.CO.10.4	10.58	1.4
Accelerator beam	NPL 689	4.79	1.12	L.MV.5.1	5.05	2.3
	NPL 690	5.23	1.12	L.MV.5.2	5.34	2.1
	NPL 691	4.80	1.12	L.MV.5.3	5.14	1.6
	NPL 692	5.40	1.12	L.MV.5.4	5.14	2.2
	NPL 693	10.64	0.90	L.MV.10.1	9.61	1.9
	NPL 694	9.51	0.90	L.MV.10.2	9.83	1.5
	NPL 695	9.95	0.90	L.MV.10.3	10.33	1.1
	NPL 696	10.31	0.90	L.MV.10.4	10.34	0.9

	LNE-LNHB irradiations					
	NPL analysis			PTB analysis		
	Dosimeter	D_w / Gy	u / %	Dosimeter	D_w /Gy	u / %
Cobalt-60 beam	65/1145	4.83	1.06	F1	4.87	0.6
	65/1146	5.42	1.06	F2	5.43	0.6
	65/1147	5.00	1.06	F3	5.07	0.6
	65/1148	5.60	1.06	F4	5.69	0.5
	65/1149	10.97	0.83	F5	11.10	0.4
	65/1150	10.13	0.83	F6	10.28	0.4
	65/1151	9.49	0.83	F7	9.62	0.4
	65/1152	10.46	0.83	F8	10.61	0.4
Accelerator beam	65/1153	5.03	1.12	F9	5.02	0.7
	65/1154	5.33	1.12	F10	5.32	0.6
	65/1155	5.18	1.12	F11	5.16	0.7
	65/1156	5.17	1.12	F12	5.16	0.7
	65/1157	9.60	0.90	F13	9.61	0.5
	65/1158	9.75	0.90	F14	9.77	0.5
	65/1159	10.46	0.90	F15	10.44	0.5
	65/1160	10.36	0.90	F16	10.44	0.5

4. Comparison

All the results have been compiled and are represented in Figures 4, 5 and 6 in order to visualize the differences between the dose measured (D_{meas}) and the dose applied (D_{appl}). In the figures, data points represent the ratio of measured to applied dose, i.e. $D_{\mathrm{meas}}/D_{\mathrm{appl}}$. Open circles and triangles correspond to dosimeters irradiated at 5 Gy whereas filled circles and triangles correspond to those irradiated at 10 Gy. The uncertainties illustrated in all of the figures are relative standard uncertainties.

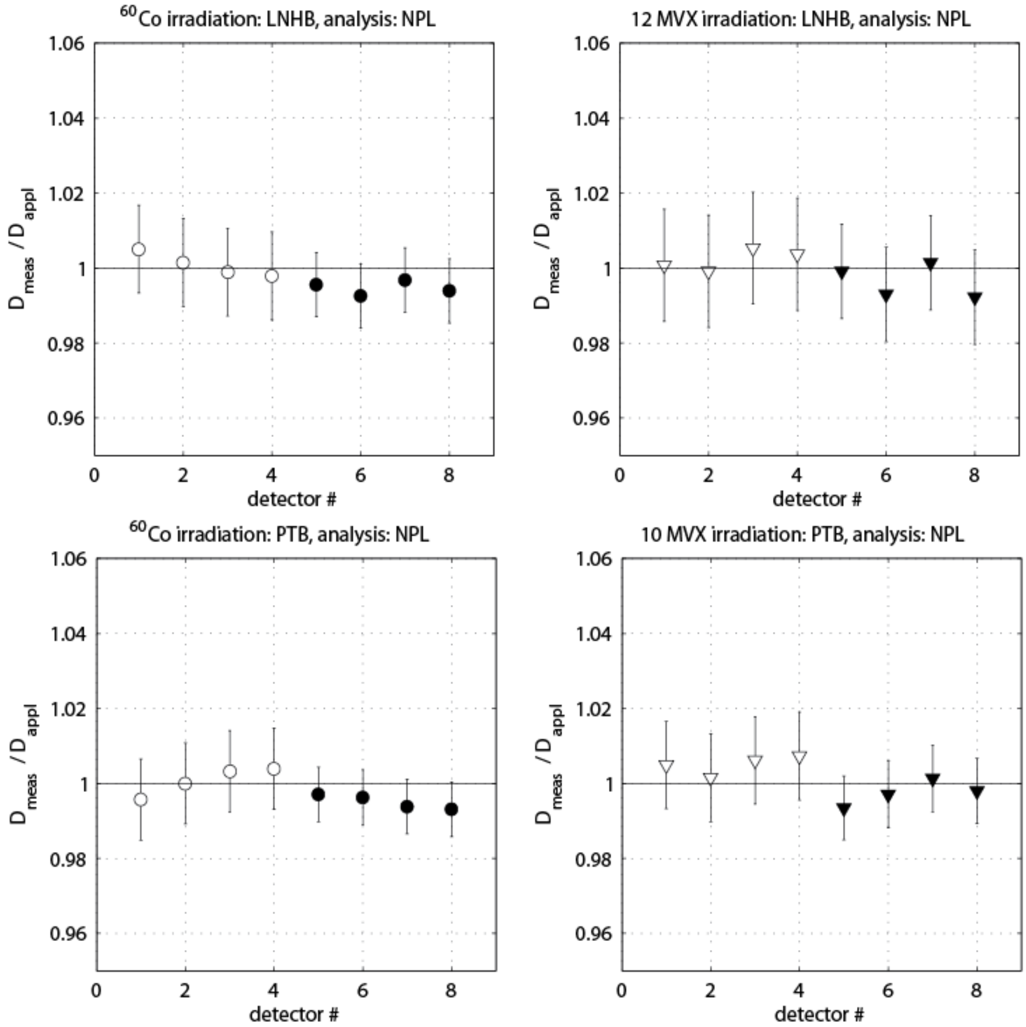

Figure 4. *NPL measurement results: Ratio of the dose measured by NPL and the dose stated by LNE-LNHB (top two frames) and by PTB (lower two frames), respectively. Detector # 1:4 corresponds to a nominal dose of 5 Gy whereas detector # 5:8 corresponds to 10 Gy.*

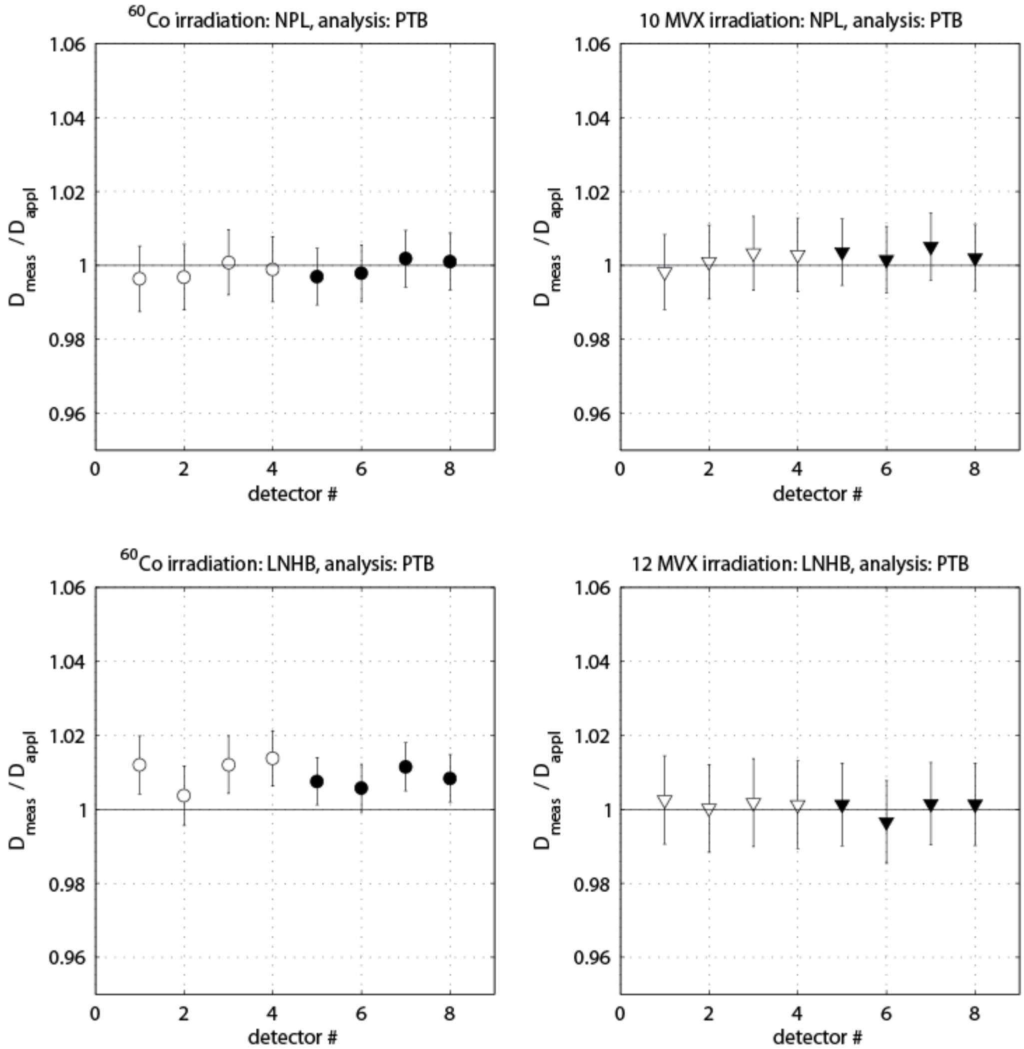

Figure 5. PTB measurement results: Ratio of the dose measured by PTB and the dose stated by NPL (top two frames) and by LNE-LNHB (lower two frames), respectively. Detector # 1:4 corresponds to a nominal dose of 5 Gy whereas detector # 5:8 corresponds to 10 Gy.

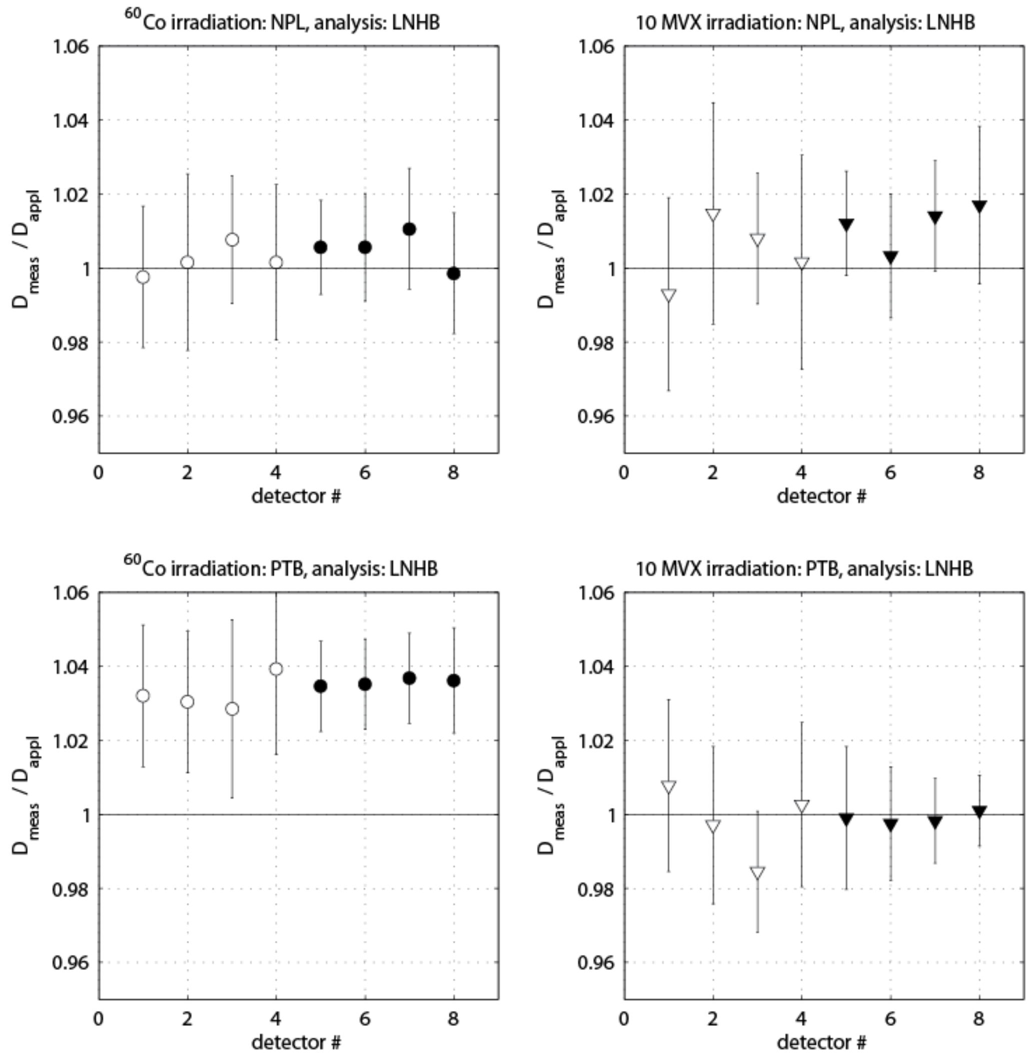

Figure 6. LNHB measurement results: Ratio of the dose measured by LNE-LNHB and the dose stated by NPL (top two frames) and by PTB (lower two frames), respectively. Detector # 1:4 corresponds to a nominal dose of 5 Gy whereas detector # 5:8 corresponds to 10 Gy.

The mean values of the ratio D_{meas}/ D_{appl} for each pair of laboratories and for each beam are given in Table 5.

A problem for the LNE-LNHB measurement of the PTB ^{60}Co irradiations occurred due to a very low humidity value in the EPR laboratory during the assessment (around 30 % RH while it should have been around 50 % RH). However, a second measurement of these particular dosimeters has been made (Figure 7) and the new results are much more in line with expectations.

Table 5. Summary of the EURAMET.RI(I)-S7 comparison: mean values of the ratio D_{meas}/D_{appl} for each pair of laboratories and each beam separately along with its relative standard uncertainty.

Beam quality	Irradiation	Analysis		Mean ratio	u (ratio)	Analysis		Mean ratio	u (ratio)
^{60}Co	LNE-LNHB	1	NPL	0.9959	0.0091	2	PTB	1.0087	0.0062
^{60}Co	NPL	3	LNE-LNHB	1.0043	0.0098	4	PTB	0.9992	0.0073
^{60}Co	PTB	5	LNE-LNHB	1.0348	0.0080	6	NPL	0.9962	0.0079
^{60}Co	PTB	7	*LNE-LNHB, 2nd*	*1.0099*	*0.0068*				
12 MVX	LNE-LNHB	8	NPL	0.9976	0.0129	9	PTB	1.0005	0.0109
10 MVX	NPL	10	LNE-LNHB	1.0094	0.0109	11	PTB	1.0027	0.0088
10 MVX	PTB	12	LNE-NHB	0.9983	0.0079	13	NPL	0.9991	0.0090

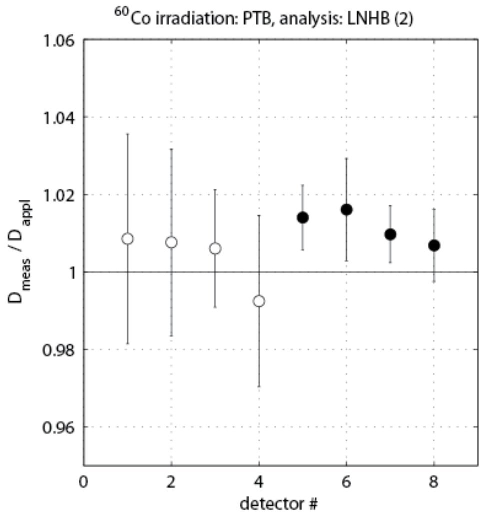

Figure 7. Ratio of the 2nd LNHB dose measurement to the stated dose of PTB ^{60}Co irradiated dosimeters.

5. Uncertainty budgets

5.1. NPL uncertainty budget:

The uncertainty budget shown in Table 6 lists the various components of uncertainty associated with the dose measurement of a single alanine pellet when operated as a mailed dosimeter. It therefore includes components associated with the travel and shipment of the dosimeter as well as the underlying uncertainties of the calibration irradiation and the measurement procedure. All data presented in this work is the mean of four pellets enclosed in a single dosimeter and therefore the “dosimeter-to-dosimeter” reproducibility will be the “pellet-to-pellet” reproducibility divided by √4. The uncertainties given in Tables 3 and 4 have been derived by combining the relevant components of Table 6.

Table 6. Uncertainty budgets for the EPR measurements by NPL.

Component	Distribution	Relative standard uncertainty	Degrees freedom	Comments
Delivery of dose to calibration set of alanine (Co-60)	Gaussian Type B	0.65%	Inf	From calibration certificate
Difference in alanine response (Co-60 / MV x-ray)	Rectangular Type B	0.35%	Inf	± a (a = 0.6%) (100% of correction i.e. overestimate)
Correction for dose received during transport	Gaussian Type A	0.4% at 5 Gy 0.2% at 10 Gy	7	Mean of 8 travelled unirradiated controls
Correction for fading	Gaussian Type A	0.2%	7	Mean of 8 travelled controls irradiated to 10 Gy.
Correction for irradiation temperature	Rectangular Type B	0.3%	Inf	Current coeff. 0.143% / ºC may be in error by up to 0.1% / ºC. Assume max correction from ref temp of 5 ºC.
Statistical uncertainty associated with calibration line	Gaussian Type A	0.4% at 5 Gy 0.2% at 10 Gy	6	Based on uncertainties of predicted points (“jackknife” method)
Pellet-to-pellet reproducibility	Gaussian Type A	1.0% at 5 Gy 0.5% at 10 Gy	31	From reproducibility of replicates 0.05 Gy

5.2. PTB uncertainty budget:

The following Table 7 lists typical values of the components of the uncertainty budget as obtained for the probes under investigation. For the definitions, see previous section 2.4.2. The values are relative standard uncertainties in percent.

For the amplitude A_m, an equivalent of 5 Gy is assumed. The standard measurement uncertainty for the ESR amplitude is independent of dose (in the range between 2 Gy and 25 Gy, approximately) and is equivalent to a dose of 25 mGy. Therefore, the relative uncertainty contribution due to the amplitude determination is 0.5% for 5 Gy or 0.25% for 10 Gy, respectively, which explains the different uncertainty values listed in the tables of section 4.

The amount of data communicated concerning the temperature of the water phantom during irradiations was different for LNE-LNHB and NPL. For the LNE-LNHB data, an uncertainty of the irradiation temperature of 0.1 K was assumed, while in the case of the NPL data 0.5 K was taken into account which is the reason for the higher uncertainty of the temperature correction K_T for the latter. All other uncertainty components are identical for LNE-LNHB and NPL. The actual value of $u_r(A_m)$ depends on the value of A_m as explained above.

For the quality correction K_Q, an experimental value determined at PTB using the water calorimeter for 10 MVX (yet unpublished, apart from [1]) was used for the NPL data. There are at present no experimental data available for 12 MVX (LNE-LNHB); therefore a value interpolated between the known values for 10 MVX and 16 MVX was used in that case [1], [7].

The calculation of the uncertainties for the masses M of the test probes and the masses M^b of the base function probes is straightforward. The uncertainty contribution named D^b contains the uncertainty of the primary standard (PTB) and the uncertainty for the reproducibility for irradiating the base probes in the reference field (compare the section above on irradiation in PTB's cobalt reference field). The contribution A^b finally is the contribution of the amplitudes of the base functions for the alanine and the reference signal. Due to the careful scheduling for the irradiation of the test probes and the probes used for the base functions (calibration) no correction for fading (and no uncertainty contribution due to fading) had to be taken into account [2].

The uncertainty values listed in Table 7 are given in percent and for $n = 4$, i.e. for four probes per dose value. They are valid for a dose of 5 Gy. In two cases, only three probes per dose could be evaluated which increased the corresponding uncertainties slightly. The first column of Table 7 lists the name of the contribution as explained above and in [1], the second and the third columns list the relative uncertainty contributions for the LNE-LNHB data (in percent) for cobalt and MVX irradiations, respectively. The fourth and fifth columns give the same data as the second and third columns, but for the NPL data.

Table 7. Uncertainty budgets for the EPR measurements by PTB for a nominal dose of 5 Gy. The figures are relative uncertainties in percent. For further explanations see text.

	LNHB/Co	LNHB/MVX	NPL/Co	NPL/MVX
Am	0.5	0.5	0.5	0.5
M	0.04	0.04	0.04	0.04
A^b	0.25	0.25	0.25	0.25
M^b	0.04	0.04	0.04	0.04
D^b	0.22	0.22	0.22	0.22
K_T	0.03	0.03	0.09	0.09
K_Q	-	0.3	-	0.3
Total	0.6	0.67	0.61	0.68

5.3. LNE-LNHB uncertainty budget

All uncertainty values reported are relative standard uncertainties in percent (k = 1). They have been calculated following the Guide to the Expression of Uncertainty in Measurement.

Table 8. Uncertainty budgets for the EPR measurements by LNE-LNHB.

Categories	Components	Type A / %	Type B / %	Comments
Dose (delivered at LNE-LNHB)	Reference standard for dose rate determination		0.470	
	Correction for temperature and pressure		0	negligible
	Irradiation time (counting)		0	negligible
	Time to open-close the beam	0.007		
	Distance from the source to the reference point		0.032	
	Depth in water		0.100	
	Source decay		0.020	
	Non-equivalence of delrin to water		0.100	
	Uncertainty on the dose (u_{Di})	**0.492**		
ESR response	ESR readout(RSD of the 4 pellets)	0.980		for each dosimeter (here: example of LNHB-L.CO.10.1 dosimeter)
	Correction for irradiation temperature		0.024	
	Spectrometer drift		0.391	within 2 weeks after irradiation
	Cavity positioning		0.298	
	Mass of the pellets		0.190	
	Uncertainty on the ESR Response (u_{Sk})	**1.113**		
Evaluation of dose measurement	Calibration curve + ESR response (u_{reg})	1.124*		done for each dosimeters (here LNHB-L.CO.10.1) See explanations in text below
	Uncertainty of the dose (u_{Di})	0.492		same as for the dose delivered at LNHB
Combined standard uncertainty of the measured dose of a dosimeter $\sqrt{(u_{Di}^2+u_{\text{reg}}^2)}=u(D_k)$		**1.3**		

* The absolute uncertainty on the measured dose of a dosimeter k is:

$$\Delta D_k = \sqrt{\sum_i \left[\left(\frac{\partial a}{\partial S_i} + \frac{\partial a}{\partial S_i} \times S_k \right)^2 u(S_i)^2 \right] + \sum_i \left[\left(\frac{\partial a}{\partial D_i} + \frac{\partial b}{\partial D_i} S_k \right)^2 u(D_i)^2 \right] + b^2 \times u(S_k)^2}$$

where:

a and b are respectively the parameters of the calibration curve ($y = bx+a$),

S_i is the EPR signal of a calibration dosimeter i and $u(S_i)$ its uncertainty,
D_i is the corresponding dose received by the calibration dosimeter,
S_k is the EPR signal of the dosimeter k,
a and b are the calibration curve coefficients.

Therefore, the relative uncertainty of a measured dosimeter is $u(D_k) = \Delta D_k/D_k$.

6. Conclusions

The results demonstrate the effectiveness the EPR/alanine dosimetry systems operated by national metrology institutes as a method of assuring therapy level dose with the accuracy required. The three different approaches to positioning the dosimeters in a water phantom have been shown to be equally effective and convenient to use.

The maximum deviation in the ratio of measured to applied dose is less than 1% (ignoring the LNE-LNHB first measurements of PTB ^{60}Co irradiated dosimeters) (fig. 8).

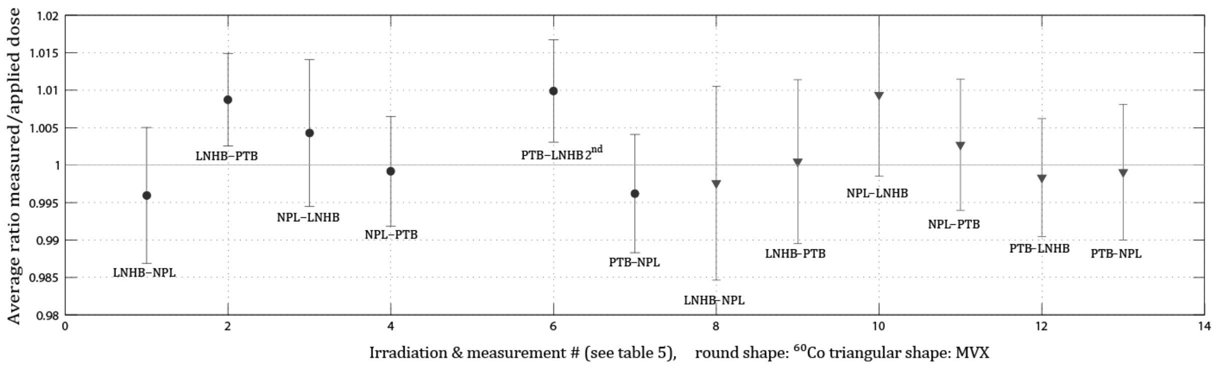

Figure 8. Mean ratios D_{meas}/D_{appl} between each laboratory for ^{60}Co and MVX beams.

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