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Original Article

The first KREDOS-EPR intercomparison exercise using alanine pellet dosimeter in South Korea

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ABSTRACT

This paper presents the results of the first intercomparison exercise performed by the Korea retrospective dosimetry (KREDOS) working group using electron paramagnetic resonance (EPR) spectroscopy. The intercomparison employed the alanine dosimeter, which is commonly used as the standard dosimeter in EPR methods. Four laboratories participated in the dose assessment of blind samples, and one laboratory carried out irradiation of blind samples. Two types of alanine dosimeters (Bruker and Magnettech) with different geometries were used. Both dosimeters were blindly irradiated at three dose levels (0.60, 2.70, and 8.00 Gy) and four samples per dose were distributed to the participating laboratories. Assessments of blind doses by the laboratories were performed using their own measurement protocols. One laboratory did not participate in the measurements of Magnettech alanine dosimeter samples. Intercomparison results were analyzed by calculating the relative bias, E_n value, and z-score. The results reported by participating laboratories were overall satisfactory for doses of 2.70 and 8.00 Gy but were considerably overestimated with a relative bias range of 10–95% for 0.60 Gy, which is lower than the minimum detectable dose (MDD) of the alanine dosimeter. After the first intercomparison, participating laboratories are working to improve their alanine-EPR dosimetry systems through continuous meetings and are preparing a second intercomparison exercise for other materials.

1. Introduction

In South Korea, there are currently more than 20 nuclear reactors are in operation, and the number of industries using radioactive material is steadily increasing. Moreover, as a divided nation, there is a risk of nuclear terrorism. In this situation, there is a strong need to prepare various countermeasures for protecting the public from radiation accidents. In case of radiation accident, rapid and accurate assessment of the exposed dose is important to determine the prognosis for the medical condition of exposed patients and to establish treatment plans.

Retrospective dosimetry is a dose assessment method, usually at the level of the individual, carried out after an exposure using methods other than with conventional radiation dosimeters [1]. It can be used when there is suspicion of chronic overexposure to the public, exposure accidents when not wearing a personal dosimeter or partial exposure of the body other than where the personal dosimeter is worn, and reconstruction of occupational exposure doses. Various techniques of retrospective dosimetry are being studied internationally by laboratories related to radiological emergency response, and systematic quality control of these assessment methods is required.

In South Korea, the Korea retrospective dosimetry (KREDOS) working group was founded in 2016 to improve the capability of dosimetry techniques and to offer prompt joint assistance during radiation emergencies. There are three methodology groups in KREDOS: biodosimetry [2], electron paramagnetic resonance (EPR)

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dosimetry [3], and thermoluminescence (TL)/optically stimulated luminescence (OSL) dosimetry [4]. Currently, intercomparison exercises are ongoing in each methodology group.

EPR dosimetry is one of the physical dose assessment methods. It can be used for retrospective dosimetry for external radiation exposure, detection of irradiated food [5–7], and dating [8]. In a radiation accident, various biological samples and personal belongings of overexposed patients may be used in EPR dosimetry. In particular, EPR dosimetry using tooth enamel is widely recognized and used [9]. However, EPR dosimetry using extracted tooth samples is difficult to apply immediately in case of a radiation emergency. Therefore, ex vivo tooth-EPR dosimetry is limited to survivors of large-scale radiation events such as the Chernobyl accident [10] and atomic bomb explosions in Hiroshima and Nagasaki [11]. Recent EPR dosimetry studies have been performed using nails [12], which are relatively easy to collect among biological samples, and personal belongings such as smart phones.

Many intercomparison programs using EPR dosimetry have been conducted internationally [13–15]. In 1993, a series of international intercomparisons involving tooth-EPR dosimetry were started based on the framework of research projects carried out by the European Commission in cooperation with the IAEA; four intercomparison exercises have been conducted till now [16–19]. Recently, intercomparison programs using the cover glass of smart phones have also been performed [20]. However, South Korea has not yet participated in the intercomparison exercise using the EPR method. Therefore, the KREDOS-EPR group has planned a gradational domestic intercomparison program to reach international levels.

Alanine-EPR dosimetry systems have been used in reference or transfer-standard or routine dosimetry systems in radiation applications that include sterilization of medical devices and pharmaceuticals, food irradiation, polymer modifications, medical therapy, and radiation damage studies in materials [21]. In general, the range of absorbed doses for which the alanine dosimeter can be used is between 1 and 1.5×10^5 Gy for photons and electrons irradiation. This dosimeter is used at relatively high dose compared to TL dosimeter (TLD) or radio-photoluminescence glass dosimeter (RPLGD). It is also suitable for long-term accumulated dose assessment because it has very low fading and repeated measurements are possible. Therefore, the alanine dosimeter, which is well known as the standard dosimeter in EPR dosimetry, was selected as the first intercomparison sample even though it is not an appropriate sample for retrospective dosimetry in radiation emergencies.

This paper presents the results of alanine dosimeter intercomparisons performed in the KREDOS-EPR group. Previous literature mainly used standard deviation or relative bias when analyzing intercomparison results. Also, the E_n value or z-score are commonly used for the statistical evaluation of reported results by participating laboratories in various accredited international intercomparison programs [22]. Therefore, the results of this intercomparison were analyzed by calculating the relative bias, E_n value, and z-score.

2. Materials and methods

2.1. Participants and intercomparison schema

Five laboratories participated in this alanine-EPR intercomparison. The Korea Institute of Radiological and Medical Sciences (KIRAMS), Dongnam Institute of Radiological and Medical Sciences (DIRAMS), Korean Association for Radiation Application (KARA), and Radiation Health Institute (RHI) participated in the dose assessment of blind samples. A fifth laboratory, the Korea Atomic Energy Research Institute (KAERI) was in charge of irradiation of the intercomparison samples to maintain the neutrality of the blind doses.

The dose ranges of the blind samples were divided into three levels: low dose level (0–2 Gy), medium dose level (2–5 Gy), and high dose level (5–10 Gy). Four alanine dosimeters for each dose level were distributed to participants. The irradiated blind samples were received by each participant on the day of irradiation. Dose assessments of the blind samples were carried out by the participating laboratories using their own measurement protocols. Dosimetry results were reported as a single value using the average of the four samples. At the KREDOS-EPR group meeting held after two months following the irradiation, the participating laboratories presented their measurement protocol and dosimetry results, including uncertainties and KAERI revealed the reference values of the blind doses. In this paper, the randomly assigned laboratory numbers were used instead of the laboratory names in analyzing the methods and results.

2.2. Sample preparation

Two commercially available L-α-alanine dosimeters purchased from Bruker and Magnettech (manufactured by Aerial CRT, France) were used in this intercomparison exercise, as shown in Fig. 1. Both dosimeters are pellet-shaped and have similar characteristics except for their geometry. The Bruker alanine dosimeter has a diameter of 4.8 mm, thickness of 3 mm, and mass of 64.5 ± 0.5 mg, while the Magnettech alanine dosimeter has a diameter of 4 mm, thickness of 2.45 mm, and mass of 37.95 ± 0.06 mg. Intercomparison samples used dosimeters of the same lot number stored in the same environmental conditions. Four laboratories participated in the analysis of the Bruker alanine sample, and three laboratories participated in the analysis of the Magnettech alanine sample.

2.3. Irradiation conditions

Irradiation of blind samples was performed with an OB40 irradiator (Buchler, Germany) using a ^{137}Cs gamma ray source at ambient temperature (approximately 22 °C). The gamma ray irradiator was calibrated with respect to air kerma using a standard ionization chamber, and the irradiation dose rate was controlled at 10 mGy min^{-1}. The nominal values of the irradiated reference doses are 0.60 (low dose level), 2.70 (medium dose level), and 8.00 Gy (high dose level).

2.4. Dosimetry methods

The dosimetry method used by each laboratory is described below and summarized in Table 1. Table 2 presents the EPR measurement parameters. In the dosimetry procedures of all laboratories, X-band EPR spectrometers were used and the spectra were recorded at room temperatures (22–25 °C). The peak-to-peak value of the alanine spectrum was applied to the determination of the signal intensity. Participating laboratories reported the final results for the blind samples as air kerma values.

- Technique used by laboratory 1 (Lab 1)

Lab 1 performed dosimetry with a calibration method using an EXEXSYS E500 spectrometer (Bruker, Germany) and an exclusive alanine pellet tube (5 mm I.D., Bruker). Lab 1 has been using its own alanine-EPR dosimetry protocol, which was created using Bruker alanine, for various radiation studies since 2016. Therefore, intercomparison samples were measured using this procedure. The calibration samples were irradiated with 1, 5, 10, 20, and 30 Gy calibrated with respect to absorbed dose to water using the

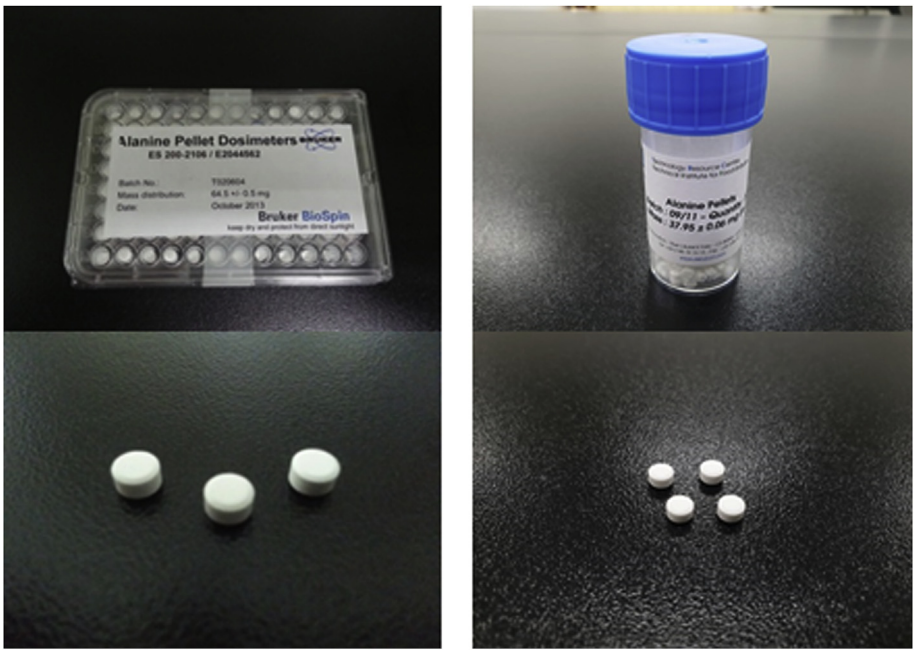

Fig. 1. The alanine dosimeter samples used in this intercomparison exercise (left: Bruker alanine dosimeter; right: Magnettech alanine dosimeter).

Table 1
Characteristic features of methods used by participating laboratories.

	Lab 1	Lab 2	Lab 3	Lab 4
EPR Spectrometer	Bruker EXEXSYS E500	Bruker EMX	Magnettech MS-5000	Bruker EXEXSYS E500
Cavity	ER4122SHQE	Dual cavity ER-4105DR	Rectangular TE 102	ER4122SHQE
Reference for EPR signal	Bruker reference marker	Not used	Magenettech Reference Marker (Ruby Crystal)	Not used
Subtracted background	Not used	Not used	Not used	Not used
Dose assessment method	Cal. curve	Additive dose	Cal. curve	Cal. curve
Calibration source	^{60}Co (dose to water)	^{137}Cs (air kerma)	^{137}Cs (air kerma)	^{60}Co (air kerma)

Table 2
Measurement parameters used by participating laboratories.

	ISO/ASTM 51607	Lab 1	Lab 2	Lab 3	Lab 4
Microwave frequency (GHz)	9 - 10	9.85	–	–	9.82
Microwave power (mW)	0.1 - 10	1.002	6.35	2.0	5.024
Center field (mT)	350	350	350	331	350
Field Sweep width (mT)	20	20	20	2	20
Modulation amplitude (mT)	0.1 - 1.5	0.7	1	1	0.5
Receiver gain (dB)	adjustable according to absorbed dose	51	15	10	50
Time of sweep (s)		30.72	20	60	30.73
Conversion time (ms)		30	327	–	30.01
Time constant (ms)		–	20	–	163.84
Number of scan		10	20	40	10

approved ^{60}Co irradiation system of Korea Research Institute of Standards and Science (KRISS). The regression equation of the calibration curve was obtained using linear fitting, and the coefficient of determination (R^2) was 0.99991. The signal intensity was corrected based on the Bruker reference marker value and the dosimeter mass. Since the influence of gamma-ray energy is negligible, the correction between calibration source (^{60}Co) and blind irradiation source (^{137}Cs) was not considered [21], and doses below 1 Gy were calculated using extrapolation. The determination of blind doses used the mean value of four samples that was calculated after eight measurements per sample; the doses of Magnettech alanine samples were reported using the mean value of three replicated measurements obtained employing the same procedure. The final dose values were reported by converting the absorbed dose to water into the air kerma using conversion factor (0.902 abosorbed dose to water/air kerma) [9].

• Technique used by laboratory 2 (Lab 2)

Dosimetry in Lab 2 was performed using an EMX spectrometer (Bruker, Germany) and the additive dose method (back-extrapolation technique). Irradiation of samples were done in the air kerma using a ^{137}Cs irradiator (Gammacell 40 Exactor, Best Theratronics). The additive dose method generally estimates the initial dose in the process of obtaining a specific response curve for the same incrementally irradiated sample. Optimal spacing of the applied dose and the number of spectra were decided by referring to related literature [23,24]. The estimated initial dose was far from the center of the calibration range, so this method increased the confidence interval. The single high point distribution method was applied to diminish the error of the x-intercept using least square analysis and 10 times the estimated initial dose (initially estimated as 5 Gy) was supplied to the alanine pellet samples to ensure a small relative error. However, these trials were not very efficient in decreasing the relative error because the measurement uncertainty at low dose ranges is much higher than that at high dose ranges. This unusual situation could be caused by extremely low dose ranges for dose estimation of alanine dosimeters.

• Technique used by laboratory 3 (Lab 3)

Lab 3 performed this intercomparison using an MS-5000 bench top spectrometer (Magnettech, Germany). The calibration method was used to determine the irradiated dose of blind samples. Irradiation of the calibration samples was carried out using a ^{137}Cs irradiation system in their laboratory. The calibration curve was prepared using samples irradiated with 0.8, 1, 3, 7, and 10 Gy calibrated with respect to the air kerma. The ruby crystal was used to correct the variation of signal intensity by the measurement environments. And to efficiently measure low dose samples in the range of 1–10 Gy, one and four-pellet setups were used, as shown in Fig. 2. The detection point was set in the center of the four alanine samples to obtain the maximum sensitivity. In the case of the four-pellet setup, measurements were performed by changing the order of samples to minimize the uncertainty due to the deviation of each sample.

EPR measurements at Lab 4 were carried out using a Bruker EXEXSYS E500 spectrometer and an alanine pellet tube. The calibration method was used to determine the irradiated dose of blind samples. Irradiation of the calibration samples was carried out using a ^{60}Co irradiator (Gamma beam X200, Best Theratronics Ltd., Canada) in their laboratory.

The air kerma value for the ^{60}Co irradiator was measured using an ionization chamber (TM30011, PTW, Germany) and an electrometer (6517B, KEITHLEY, USA) at a distance of 100 cm from the cobalt source to the center of the ionization chamber. Standard irradiation was performed for four alanine dosimeters in a build-up cap.

The calibration curve was prepared using samples irradiated with 1, 2, 3.5, 5, 7.5, and 10 Gy calibrated with respect to the air kerma. Regression equations were determined using linear fitting for the Bruker alanine and a 2nd order polynomial fitting for the Magnettech alanine, respectively. The mean value of four samples was used for determining the blind doses.

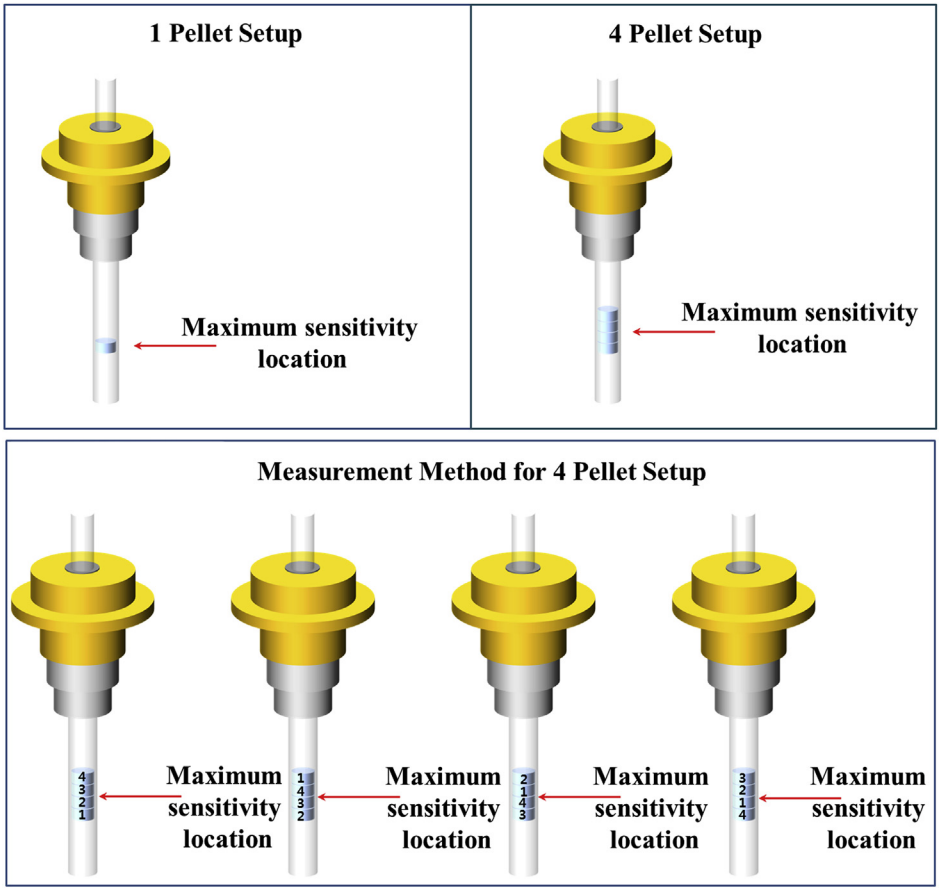

Fig. 2. Schematic of the one-pellet (left) and four pellets (right) setups.

• Technique used by laboratory 4 (Lab 4)

Table 3
Uncertainty budgets of irradiation for blind samples.

Relative uncertainties ($k = 1$)		
Uncertainty source	Type A (%)	Type B (%)
Reference dose	1.65	–
Irradiation time	0.00	–
Distance correction factor	0.12	–
Decay correction factor	–	0.01
Field size of beam	1.44	–
Combined uncertainty of irradiation	2.19	
Relative expanded uncertainty ($k = 2$),	4.38	

Table 4
Measurement uncertainty for blind samples in participating laboratories.

	Relative expanded uncertainty ($k = 2$), U (%)					
	low dose level		medium dose level		high dose level	
Laboratory	Bruker	Magnettech	Bruker	Magnettech	Bruker	Magnettech
Lab 1	11.38	11.38	6.64	6.64	5.65	5.65
Lab 2	–	–	16.55	–	19.79	–
Lab 3	5.68	6.45	5.82	6.34	5.29	5.86
Lab 4	14.78	11.52	13.12	10.30	13.12	9.52

2.5. Uncertainty

The uncertainties of irradiation of the blind samples are given in Table 3, and the measurement uncertainties of the participating laboratories are presented in Table 4. The uncertainties were reported as the relative expanded uncertainty at a confidence level of 95% ($k = 2$).

3. Results and discussion

Table 5 and Fig. 3 present the dosimetry results obtained by all participating laboratories, including uncertainties. In Table 5, uncertainties are expressed by converting the relative expanded uncertainties into doses.

For the low dose level (0.60 Gy), Lab 2 did not report the measurement results owing to equipment performance issues. The measurement values of the three laboratories that reported the results were considerably overestimated with a relative bias range of 10–95% compared to the reference dose. This is because the EPR signal is more affected by noise ,since 0.60 Gy is lower than 1 Gy, which is the general minimum detectable dose (MDD) of the alanine dosimeter [20]. It should also be taken into account that extrapolation was used for dose assessment as the lowest dose of the calibration samples for all laboratories is greater than 0.6 Gy. In the medium dose level (2.70 Gy), the relative biases of all measurement doses were evaluated within ±8%, except for the Magnettech samples of Lab 3, which were evaluated at approximately −12%. This bias occurred because the result for one sample among four samples was out of range. This problem appeared to be caused by the integrity of the alanine sample. In the high dose level (8.00 Gy), the result obtained in Lab 2 was approximately 15% lower than the reference dose, and the results in the other labs were within ±7%.

The E_n value and z-score are standard values can be used to perform conformity analysis of results of intercomparison exercise or proficiency testing. Generally, the E_n value is mainly used when the reference value is clearly known, whereas the z-score is mainly used when there is no reference value or there are many participating laboratories. Therefore, the intercomparison results were analyzed by calculating the E_n value and z-score to avoid the issues found through this analysis in the second intercomparison. The measurement results of the 0.60 Gy reference dose were excluded from the analysis.

The equation for determining E_n value is as follows:

$$E_n = \frac{x - X}{\sqrt{U_{lab}{}^2 + U_{ref}{}^2}}, \quad (1)$$

where x and U_{lab} are the result and expanded uncertainty reported by the participating laboratories, and X and U_{ref} are the reference value and expanded uncertainty assigned by reference laboratory, respectively. If $|E_n| > 1$, the result is "unsatisfactory" and if $|E_n| \leq 1$, the result is considered "satisfactory".

The equation for calculating the z-score is as follows:

$$z = \frac{x - X}{s}, \quad (2)$$

where x is the result reported by the participating laboratories, and X and s are the mean value and standard deviation of the results reported by all participating laboratories, respectively. If $|z| \geq 3$, the result is "unsatisfactory", if $2 < |z| < 3$, it turns out to be "questionable", and if $|z| \leq 2$, the result is considered "satisfactory".

The results of calculated E_n value and z-score are presented in Table 6 and Fig. 4. All E_n values except for the result of the medium dose level for Magnettech samples of Lab 3 were judged "satisfactory". However, as the E_n value has a limitation that those values decrease with the increasing uncertainties of the result reported by the participant, it is not recommended to judge the conformity of intercomparison results by only the E_n value. This experiment also showed that the E_n value was lower even though the relative bias of Lab 2 was higher than that of Lab 3. In the conformity analysis using the E_n value, better results will be obtained if standardization for uncertainty budgets of participants is performed. In case of the z-score, all the results of the participants were found to be "satisfactory" although the number of participants was relatively small.

When comparing the results of the Bruker and Magnettech alanine dosimeters, the relative biases of the Magnettech alanine

Table 5
Dosimetry results of participating laboratories for blind samples.

Reference Doses		0.60 ± 0.03 Gy (low dose level)		2.70 ± 0.12 Gy (medium dose level)		8.00 ± 0.35 Gy (high dose level)	
Dosimetry results		Dose (Gy, $k = 2$)	Relative Bias, %	Dose (Gy, $k = 2$)	Relative Bias, %	Dose (Gy, $k = 2$)	Relative Bias, %
Bruker alanine dosimeter	Lab 1	0.72 ± 0.08	+20.00	2.84 ± 0.19	+5.19	8.18 ± 0.46	+2.25
	Lab 2	[a]N.R.	–	2.90 ± 0.48	+7.41	6.82 ± 1.35	−14.75
	Lab 3	0.66 ± 0.04	+10.00	2.89 ± 0.17	+7.04	8.55 ± 0.45	+6.88
	Lab 4	0.94 ± 0.14	+56.67	2.61 ± 0.34	−3.33	7.82 ± 1.03	−2.25
Magnettech alanine dosimeter	Lab 1	0.81 ± 0.09	+35.00	2.89 ± 0.19	+7.07	7.92 ± 0.45	−0.99
	Lab 3	0.79 ± 0.05	+31.67	2.37 ± 0.15	−12.22	8.47 ± 0.50	+5.88
	Lab 4	1.16 ± 0.13	+93.33	2.62 ± 0.27	−2.96	7.56 ± 0.72	−5.50

[a] N.R: Not Reported.

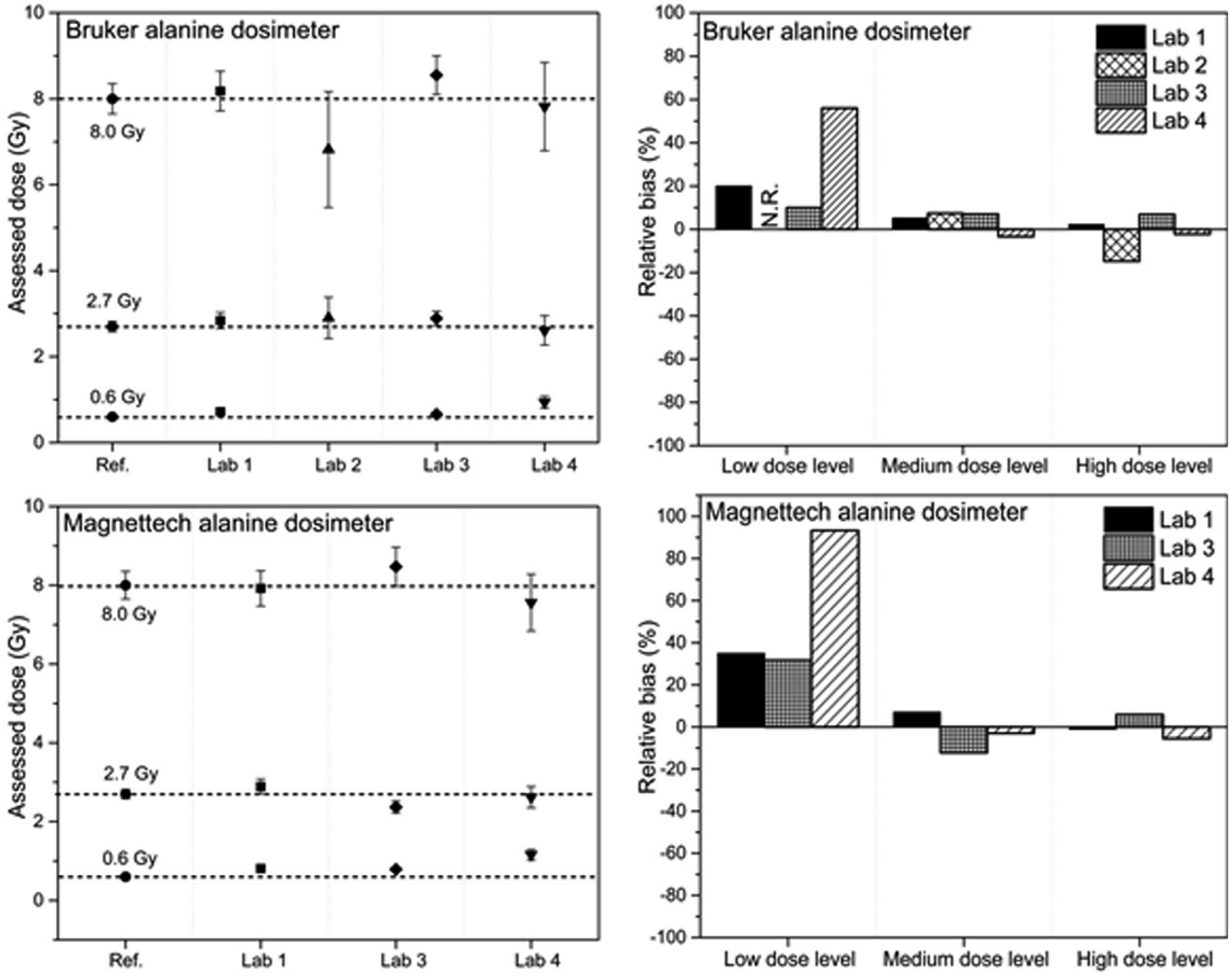

Fig. 3. Results of assessed dose values and relative bias obtained by each laboratory for the two alanine dosimeters (top: Bruker alanine dosimeter; bottom: Magnettech alanine dosimeter).

dosimeters were observed to be slightly higher at the low dose level, but similar results were obtained at other dose levels. This was attributed to the difference in the mass of the two dosimeters.

In this intercomparison exercise, it was a minor mistake to irradiate the same blind doses in both the dosimeters. This was because participating laboratories could compare each other's

Table 6
Results of conformity assessment obtained using E_n values and z-scores of the intercomparison results.

Reference Dose		Medium dose level		High dose level	
		E_n value	conformity assessment	E_n value	conformity assessment
Bruker alanine	Lab 1	0.63	satisfactory	0.31	satisfactory
dosimeter	Lab 2	0.40	satisfactory	−0.85	satisfactory
	Lab 3	0.92	satisfactory	0.96	satisfactory
	Lab 4	−0.25	satisfactory	−0.17	satisfactory
Magnettech	Lab 1	0.85	satisfactory	−0.14	satisfactory
Alanine dosimeter	Lab 3	−1.73	unsatisfactory	0.77	satisfactory
	Lab 4	−0.27	satisfactory	−0.55	satisfactory
		z-score	conformity assessment	z-score	conformity assessment
Bruker alanine	Lab 1	0.22	satisfactory	0.45	satisfactory
dosimeter	Lab 2	0.66	satisfactory	−1.37	satisfactory
	Lab 3	0.59	satisfactory	0.95	satisfactory
	Lab 4	−1.47	satisfactory	−0.03	satisfactory
Magnettech	Lab 1	1.01	satisfactory	−0.14	satisfactory
Alanine dosimeter	Lab 3	−0.99	satisfactory	1.06	satisfactory
	Lab 4	−0.03	satisfactory	−0.92	satisfactory

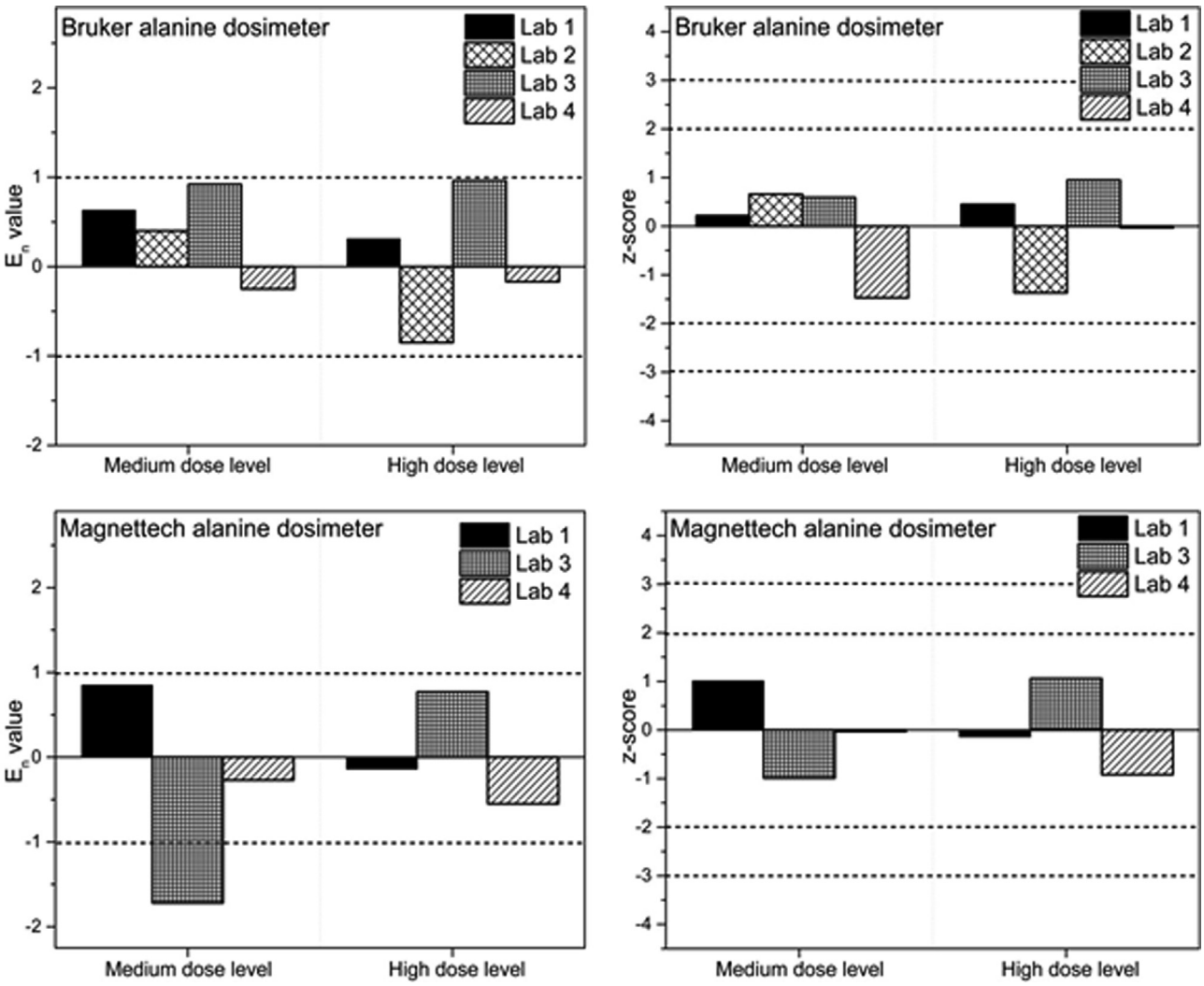

Fig. 4. Intercomparison results between participating laboratories in terms of E_n values and z-scores (top: Bruker alanine; bottom: Magnettech alanine).

results when measuring two types of alanine dosimeters. Also, it was impossible to discuss the results based on relative precision or root mean square error (RMSE) as the final results were reported as a single dose value at each dose level. Additionally, it is necessary to optimize the various data processing technique of laboratories such as correction using reference samples, extrapolation and fitting of spectrum. Therefore, the next intercomparison exercise will be planned and performed considering these issues. However, when looking at the overall results of this intercomparison exercise in terms of the relative bias, E_n value, and z-score, it was considered very satisfactory.

4. Conclusions

The first EPR-intercomparison exercise in South Korea was performed using two types of alanine dosimeters. Intercomparison was carried out for samples irradiated by three blind doses at less than 10 Gy. The doses below 10 Gy are considerably lower doses in the alanine dosimetry, but overall satisfactory results were obtained for the doses above MDD. This intercomparison is especially meaningful as it is the first attempt toward establishing a cooperation system among the laboratories using EPR dosimetry methods in South Korea. This was also an opportunity to improve the reliability of the EPR measurement system in each laboratory.

After the first intercomparison, participating laboratories are having continuous meetings discussing various aspects, such as standardization of EPR measurement uncertainties, sharing measurement results of various dosimetry samples, and the next intercomparison exercise, to prepare for a nationally coordinated response in case of radiation emergency. Hydroxyapatite was determined as the second intercomparison sample, and each laboratory is currently preparing to build a measurement procedure for the sample. In addition, the KREDOS-EPR group is looking for other laboratories which can participate in the second intercomparison, and participating in international intercomparison programs is also under consideration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] International Organization for Standardization (ISO), Radiological Protection — Minimum Criteria for Electron Paramagnetic Resonance (EPR) Spectroscopy for Retrospective Dosimetry of Ionizingradiation — Part 1: General Principle. ISO 13304-1, 2011.
[2] International Atomic Energy Agency (IAEA), Cytogenetic Dosimetry: Applications in Preparedness for and Response to Radiation Emergencies, 2011.
[3] M. Desrosiers, D.A. Schauer, Electron paramagnetic resonance (EPR) biodosimetry, Nucl. Instrum. Methods Phys. Res. B 184 (2001) 219–228, https://doi.org/10.1016/S0168-583X(01)00614-0.
[4] C. Bassinet, F. Trompier, I. Clairland, Radiation accident dosimetry on electronic components by OSL, Health Phys. 98 (2010) 440–445.
[5] Committee European de Normalisation(CEN), Detection of Irradiated Food Containing Bone, Method by ESR Spectroscopy, European Committee for Standardization EN 1786, 1996.
[6] Committee European de Normalisation(CEN), Detection of Irradiated Food Containing Cellulose, Method by ESR Spectroscopy, European Committee for Standardization EN 1787, 2000.
[7] Committee European de Normalisation(CEN), Detection of Irradiated Food Containing Crystalline Sugar, Method by ESR Spectroscopy, European Committee for Standardization EN 13708, 2001.
[8] R. Grun, Electron spin resonance dating and the evolution of modern humans, Archaeometry 33 (1991) 153–199, https://doi.org/10.1111/j.1475-4754.1991.tb00696.x.
[9] International Atomic Energy Agency (IAEA), Use of Electron Paramagnetic Resonance Dosimetry with Tooth Enamel for Retrospective Dose Assessment. IAEA-TECDOC-1331, 2002.
[10] V.G. Skvortsov, A.I. Ivannikov, V.F. Stepanenko, A.F. Tsyb, L.G. Khamidova, A.E. Kondrashov, D.D. Tikunov, Application of EPR retrospective dosimetry for large-scale accidental situation, Appl. Radiat. Isot. 52 (2000) 1275–1282, https://doi.org/10.1016/S0969-8043(00)00083-X.
[11] N. Nakamura, C. Miyazawa, M. Akiyama, S. Sawada, A. Awa, A close correlation between electron spin resonance (ESR) dosimetry from tooth enamel and cytogenetic dosimetry from lymphocytes of Hiroshima atomic-bomb survivors, Int. J. Radiat. Biol. 73 (1988) 619–627, https://doi.org/10.1080/095530098141870.
[12] Abbas Noori, Mojtaba Mostajaboddavati, Farhood Ziaie, Retrospective dosimetry using fingernail electron paramagnetic resonance response, Nucl. Eng. Technol. 50 (2018) 526–530, https://doi.org/10.1016/j.net.2018.01.014.
[13] V. Gancheva, N.D. Yordanov, F. Callens, G. Vanhaelewyn, J. Raffi, E. Bortolin, S. Onori, E. Malinen, E. Sagstuen, S. Fabisiak, Z. Peimel-Stuglik, An international intercomparison on "self-calibrated" alanine EPR dosimeters, Radiat. Phys. Chem. 77 (2008) 357–364, https://doi.org/10.1016/j.radphyschem.2007.06.004.
[14] C. De Angelis, V. De Coste, P. Fattibene, S. Onori, E. Petetti, Use of alanine for dosimetry intercomparisons among Italian radiotherapy centers, Appl. Radiat. Isot. 62 (2005) 261–265, https://doi.org/10.1016/j.apradiso.2004.08.019.
[15] E. Haskell, G. Kenner, R. Hayes, S. Sholom, V. Chumak, AN EPR intercomparison using teeth irradiated prior to crushing, Radiat. Meas. 27 (1997) 419–424, https://doi.org/10.1016/S1350-4487(96)00131-X.
[16] V. CHUMAK, et al., The first International Intercomparison of EPR-dosimetry with teeth: first results, Appl. Radiat. Isot. 47 (1996) 1281–1286, https://doi.org/10.1016/S0969-8043(96)00231-X.
[17] A. Wieser, et al., The second international intercomparison on EPR tooth dosimetry, Radiat. Meas. 32 (2000) 549–557, https://doi.org/10.1016/S1350-4487(00)00060-3.
[18] A. Wieser, et al., The 3rd international intercomparison on EPR tooth dosimetry: Part 1, general analysis, Appl. Radiat. Isot. 62 (2005) 163–171, https://doi.org/10.1016/j.apradiso.2004.08.027.
[19] P. Fattibene, et al., The 4th international comparison on EPR dosimetry with tooth enamel Part 1: report on the results, Radiat. Meas. 46 (2011) 765–771, https://doi.org/10.1016/j.radmeas.2011.05.001.
[20] P. Fattibene, et al., EPR dosimetry intercomparison using smart phone touch screen glass, Radiat. Environ. Biophys. 53 (2014) 311–320, https://doi.org/10.1007/s00411-014-0533-x.
[21] International Organization for Standardization (ISO), Practice for Use of an Alanine-EPR Dosimetry System. ISO/ASTM 51607, 2013.
[22] International Organization for Standardization (ISO), Conformity Assessment – General Requirements for Proficiency Testing. ISO/IEC 17043, 2010.
[23] R.B. Hayes, E.H. Haskell, G.H. Kenner, A mathematical approach to optimal selection of dose values in the additive dose method of EPR dosimetry, Radiat. Meas. 27 (1997) 315–323, https://doi.org/10.1016/S1350-4487(96)00117-5.
[24] V. Nagy, Accuracy consideration in EPR dosimetry, Appl. Radiat. Isot. 52 (2000) 1039–1050, https://doi.org/10.1016/S0969-8043(00)00052-X.