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Original article

Measurement uncertainty analysis of radiophotoluminescent glass dosimeter reader system based on GD-352M for estimation of protection quantity

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ABSTRACT

At the Korea Institute of Radiological and Medical Sciences, physical human phantoms were developed to evaluate various radiation protection quantities, based on the mesh-type reference computational phantoms of the International Commission on Radiological Protection. The physical human phantoms were fabricated such that a radiophotoluminescent glass dosimeter (RPLGD) with a Tin filter, namely GD-352M, could be inserted into them. A Tin filter is used to eliminate the overestimated signals in low-energy photons below 100 keV. The measurement uncertainty of the RPLGD reader system based on GD-352M should be analyzed for obtaining reliable protection quantities before using it for practical applications. Generally, the measurement uncertainty of RPLGD systems without Tin filters is analyzed for quality assurance of radiotherapy units using a high-energy photon beam. However, in this study, the measurement uncertainty of GD-352M was analyzed for evaluating the protection quantities. The measurement uncertainty factors in the RPLGD include the reference irradiation, regression curve, reproducibility, uniformity, energy dependence, and angular dependence, as described by the International Organization for Standardization (ISO). These factors were calculated using the Guide to the Expression of Uncertainty in Measurement method, applying ISO/ASTM standards 51261(2013), 51707(2015), and SS-ISO 22127(2019). The measurement uncertainties of the RPLGD reader system with a coverage factor of $k = 2$ were calculated to be 9.26% from 0.005 to 1 Gy and 8.16% from 1 to 10 Gy. A blind test was conducted to validate the RPLGD reader system, which demonstrated that the readout doses included blind doses of 0.1, 1, 2, and 5 Gy. Overall, the E_n values were considered satisfactory.

1. Introduction

With the increasing use of radiation, the interest in the effects of the exposed doses on human health is also increasing [1–3]. Considering radiation protection quantities, methods for dose assessment have to be developed, using which the effects of exposed doses on human health can be determined. Recently, physical human phantoms were fabricated such that various types of in vivo dosimeters could be inserted into the phantoms for measuring radiation. The results of these radiation measurements can be used to evaluate the protection quantities [4–6]. In vivo dosimeters such as radiochromic film dosimeters, thermoluminescent dosimeters (TLDs), optically stimulated luminescent dosimeters (OSLDs), and radiophotoluminescent glass dosimeters (RPLGDs) have various characteristics applicable for evaluating protection quantities using physical human phantoms.

Gafchromic films have low thicknesses of 300 μm and can be cut to the required sizes. These films are not only used as in vivo

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dosimeters but also as alternative dosimeters for surface dose measurements in certain conditions [7]. For measurements within the 30–80 cGy range, an uncertainty of 3.6% was obtained for a Gafchromic EBT3 film (Ashland, USA) in precise dosimetry used for clinical applications [8]. However, for very-low-energy photons (e.g., 50 keV), a variation of more than 11% owing to the energy dependence is observed, depending on the absorbed dose, spatial resolution, and color channel used [9]. In addition, Gafchromic EBT3 films have a relatively small dynamic dose range of 0.2–10 Gy compared to other in vivo dosimeters [10].

TLD-100 (Thermo Fisher Scientific, USA) has already been used to determine the absorbed dose in the external audit programs of radiotherapy for several decades [11,12]. TLD-100 contains a reader made of LiF:Mg, Ti in the form of a square ($3.2 \times 3.2 \times 0.38$ mm^3) manufactured by Harshaw, and the measurable dose ranges are from 1 μGy to 10 Gy. The measurement uncertainty of a TLD used for high-energy photon dosimetry audits in radiotherapy was evaluated by 1.60% at 1 Gy [13]. However, sunlight has a substantial effect on stored radiation-induced TL intensity, which could significantly influence the accuracy of delayed dose assessments [14]. Furthermore, the readout values are not reproducible, and fading effects of 4% after 100 days were observed for the TLD [13].

The nanoDot™ OSLD (Landauer, USA) offers the advantages of minimal signal loss during repeated readout measurements and a simple readout process using light; it can measure doses ranging from 50 μGy to 15 Gy according to the NanoDot™ dosimeter (Landauer, USA). NanoDot™ comprises Al_2O_3:C in the form of a chip ($10 \times 10 \times 2$ mm^3), and the measurement uncertainty of nanoDot™ in high-energy photon dosimetry audits for radiotherapy was evaluated to be 1.46% at 2 Gy [13]. However, OSLDs accumulate residual signals owing to the filling of deeper energy traps that cannot be emptied by simple optical bleaching with fluorescent light [15]. Furthermore, OSLDs can induce the distortion of signals by absorbing visible light when they are not stored in light-tight containers [13].

The characteristics of RPLGDs (ASAHI Techno Glass Corporation, Japan) as in vivo dosimeters have been researched for several years to evaluate their measurement uncertainty under high-energy photon beams [16–18]. RPLGDs have several advantages such as a wide dose measurement range from 10 μGy to 500 Gy, a small fading effect of 0.4% after 100 days, and repeatable readouts [13]. RPLGDs are classified according to whether they contain filters. In particular, the RPLGD without a Tin filter called GD-302 M has been generally used in the quality assurance (QA) processes of radiotherapy units. The radiation used in radiotherapy has high energy and is used under strict conditions. In this case, the Tin filter is not used to compensate for the low-energy photons. The measurement uncertainty of GD-302M in high-energy photon dosimetry audits for radiotherapy units is 1.51% at 1 Gy [13]. In contrast, the RPLGD with a Tin filter called GD-352M has been used to decrease the energy dependence in radiation diagnoses. The Tin filter decreases the energy dependence in the energy range below 100 keV [19]. Therefore, GD-352M is a suitable in vivo dosimeter to evaluate the protection quantities in various radiation sources without signal distortion.

In the Korea Institute of Radiological and Medical Sciences (KIRAMS), physical human phantoms were developed based on the mesh-type reference computational phantoms of the International Commission on Radiological Protection. Physical human phantoms were fabricated such that the GD-352M could be inserted in them for evaluating the various protection quantities. However, the measurement uncertainty of the RPLGD reader system should be evaluated based on the dosimetric characteristics of the GD-352M before its using it in radiation protection applications. In previous studies regarding the measurement uncertainty of dosimeters, the RPLGD reader system based on GD-352M was not evaluated for applications in estimating the protection quantities [15–18]. The uncertainty factors associated with the RPLGD reader system were referenced from the International Standard for Organization (ISO) and calculated using the Guide to the Expression of Uncertainty in Measurement (GUM) method [20]. Additionally, a blind test was conducted to validate the RPLGD reader system. The results of the blind test were analyzed by evaluating the relative bias and E_n values.

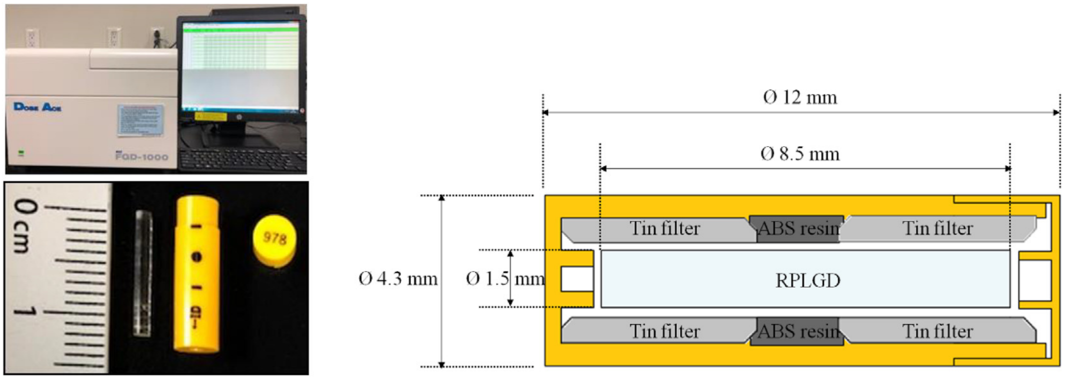
2. Materials and methods

2.1. Composition of RPLGD reader system

The RPLGD reader system comprises RPLGD and the FGD-1000 automatic reader unit (ASAHI Techno Glass Corporation, Japan). The RPLGD has a diameter of 1.5 mm and a length of 12 mm. The effective atomic number and density of the RPLGD were 12.04 and 2.61 g/cm^3, respectively [21]. A holder of GD-352 M having a diameter of 4.33 mm and a length of 14.52 mm was made of acrylonitrile butadiene styrene resin. A Tin filter compensates for the high response in low-energy photons. Fig. 1 shows the RPLGD reader system and the geometry of GD-352 M.

2.1.1. Reference irradiation

The uncertainty of reference irradiation is caused by the irradiation setup for the ^{60}Co γ-ray teletherapy unit (Best Theratronics,



(a) (b)

Fig. 1. RPLGD reader system and geometry of GD-352M: (a) FGD-1000 automatic reader unit and GD-352M and (b) geometry of GD-352M.

Canada). It is combined by the uncertainty of the irradiation dose rate, irradiation time, sample position, and nonuniformity of the beam. The absorbed dose to water by ^{60}Co γ-rays was determined using a TM 30011−1 farmer chamber approved ionization chamber at the Korea Research Institute of Standard and Science. GD-352 M was set at a reference depth of 5 cm in a water phantom at a source-to-surface distance of 100 cm, and a field size of 10 × 10 cm^2 [22]. The reference irradiation of GD-352Ms was conducted at the Dongnam Institute of Radiological and Medical Sciences to calculate the measurement uncertainty of the RPLGD reader system.

2.1.2. Regression curve

The regression curve indicates the relationship between the responses of GD-352 M and irradiated doses. The confidence interval of the regression curve was used to determine the uncertainty of the curve fit. The regression curves were separated by low- and high-dose ranges to evaluate the accurate uncertainty of regression curve. If the regression curve was not distinguished according to dose range, the uncertainty of regression curve would be overestimated in high-dose range. GD-352Ms were irradiated by the low dose range from 0.005 to 1 Gy for ^{60}Co γ-rays (0.005, 0.007, 0.01, 0.015, 0.02, 0.03, 0.05, 0.07, 0.1, 0.2, 0.3, 0.5, 0.7, and 1 Gy). For the high-dose range from 1 to 10 Gy, GD-352Ms were irradiated with ^{60}Co γ-rays (1, 2, 3, 5, 7, and 10 Gy) under the same irradiation conditions. The dose points of irradiated doses in the regression curve were determined as follows:

$$Q = log_{10}(D_{max} \,/\, D_{min}) \tag{1}$$

D_{max} = maximum dose,
D_{min} = minimum dose.

If Q is equal to or greater than 1, Q is multiplied by 5, and the round calculated result is up to the nearest integer value. These results represent the minimum number of irradiated doses to be used in dose ranges. If Q is less than 1, five dose points are applied to determine the irradiation point [23]. Furthermore, the uncertainty of the regression curve can be estimated at a single dose as the ratio of the one half the dose range, defined by the confidence interval to the dose estimate shown below (ISO/ASTM 51261(2013)):

$$U_{\widehat{X}fit}\% = \left(\frac{(D_{UCL} - D_{LCL})/2}{\widehat{x}}\right) \times 100 \tag{2}$$

$\widehat{x}$ = dose estimate
D_{UCL} = dose at the upper confidence level
D_{LCL} = dose at the lower confidence level.

2.1.3. Reproducibility

Reproducibility is the closeness of the agreement between the results of measurements of the same measurand carried out under changed measurement conditions [24]. The uncertainty of reproducibility includes the principle of measurements, method of measurement, observer, measuring instrument, reference standard, location, conditions of use, and time. To evaluate the reproducibility of the RPLGD reader system, the deviation in the changed measurement condition was evaluated for 10 days. Each GD-352Ms was irradiated by an identical method with reference irradiation, in the low- and high-dose range from 0.005 to 1 Gy and from 1 to 10 Gy, respectively. The uncertainty of reproducibility was determined by the largest deviation for 10 days in the irradiated dose range.

2.1.4. Uniformity

The RPLGD corresponding to the manufacturing standard is manufactured from the same production process. The quality properties are guaranteed by the manufacturer with regard to their response [25]. The uncertainty of uniformity was referred to in the manufacturer's technical report.

2.1.5. Energy dependence

Energy dependence is the response of GD-352 M to radiation quality [25]. In a previous study, GD-302 M was used to calibrate the high-energy photon in the quality assurance of the radiotherapy unit. Therefore, the uncertainty of energy dependence in GD-302 M did not have to be considered in the range of low energy. However, to apply evaluating protection quantities in the physical human phantoms, the response of RPLGDs should be evaluated in the low energy range under 100 keV [26]. GD-302 M and GD-352 M were irradiated in the reference radiation field of the Korea Atomic Energy Research Institute. The X-ray field is designed to produce and use 20 different types of beams [27]. The energies from 35 to 118 keV for X-rays (35, 48, 65, 73, 83, 100, and 118 keV) were applied to evaluate the energy dependence under an identical irradiated dose to the air kerma.

2.1.6. Angular dependence

Directional dependence is the response of a GD-352 M on the direction of radiation incidence [25]. In this case, the directional dependence is identical to the meaning of angular dependence. Because GD-352 M is an anisotropic structure, it can cause a different response depending on the incidence angle. Angular dependence was evaluated using ^{60}Co γ-rays of 2 Gy at a field size of 5 × 5 cm^2. The reading point of the GD-352M was positioned at the center of the spherical polymethylmethacrylate (PMMA) phantom (density 1.19 g/cm^3) and was kept at the beam isocenter and axis parallel to the incident beam axis. By rotating the ^{60}Co γ-ray radiotherapy unit gantry, readout values were made at intervals of 15° from −90° to 90°. Fig. 2 shows the experimental setup for the GD-352 M response according to the change in the irradiation

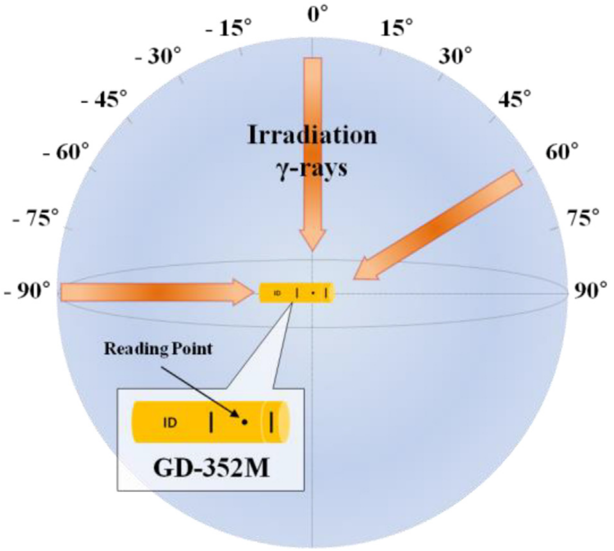


Fig. 2. Experimental setup for angular dependence of GD-352 M using the spherical PMMA phantom.

angle.

3. Results and discussion

3.1. Reference irradiation

The uncertainties of irradiation dose rate, irradiation time, sample position, and non-uniformity of the beam were applied to evaluate the combined uncertainty of the reference irradiation. The uncertainty of the ion-chamber was included in the uncertainty of the irradiation dose rate. Each uncertainty factor was evaluated; irradiation dose rate was 1.95%, the irradiation time was 0.42%, sample position was 0.05%, and non-uniformity of beams was 1.44%. The combined uncertainty of the reference irradiation was evaluated as 2.46%, i.e., a Type B uncertainty.

3.2. Regression curve

The regression curves of GD-352M according to the irradiated doses are shown in Fig. 3(a) and (b). The irradiated doses were determined using 14 and 6 dose points, based on Eq. (1). Each of the dose points was measured using five RPLGDs. It was found that GD-352M exhibits a linear relationship with the irradiated dose at low- and high-dose ranges, with coefficients of determination (R^2) of 0.9995 and 0.9990, respectively. R^2 can be used to explain the curve fit between the readout values and irradiated doses. The uncertainties of the regression curves were 2.86% and 1.85%, and it is a Type A uncertainty. The largest deviation of the readout values in the measured dose range was applied to conservatively evaluate the uncertainty of the regression curve.

3.3. Reproducibility

The reproducibility of GD-352Ms according to different irradiated doses is shown in Fig. 4(a) and (b). The responses for each dose were normalized with respect to the response of GD-352M. The uncertainties of reproducibility for 10 days were evaluated to be 0.47% and 0.40%, with respect to the irradiated dose ranges, and they were Type A uncertainties. The uncertainty of reproducibility was evaluated using the largest measurement deviation in the irradiated dose ranges.

3.4. Uniformity

The uncertainty of uniformity, a Type B uncertainty, was obtained as 1.15% for a single lot number. If GD-352M dosimeters with different lot numbers are used in the experiment, the correction factor provided in the manufacturer's technical report will be applied to the calibrated readout value.

3.5. Energy dependence

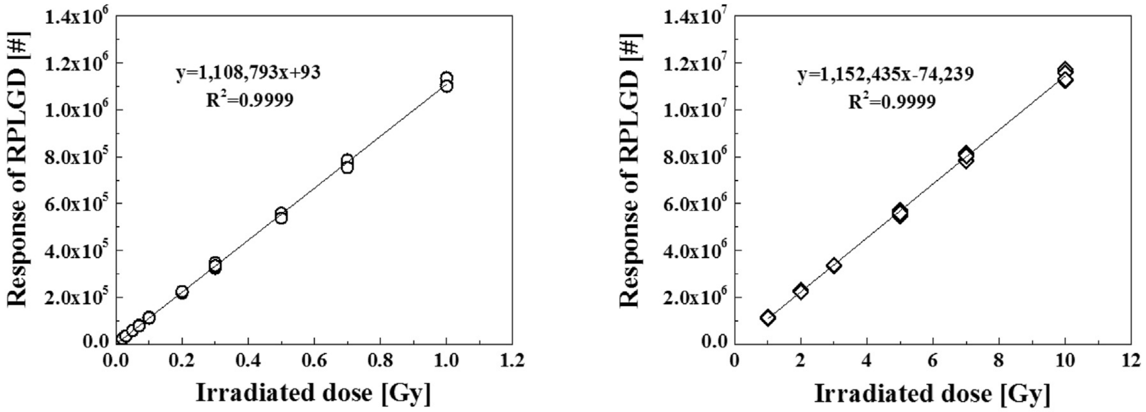
The response of RPLGD with respect to various energies depends on whether the energy compensated filter is used. The responses of GD-302M and GD-352M are presented in Fig. 5, and each response was normalized with respect to the response to 662 keV. Each readout value was evaluated from an average of five repeated measurements, and ten readout values were evaluated for each dosimeter.

The readout values in GD-302M were overestimated in the energy range from 35 to 100 keV. The energy range includes X-ray and gamma ray energies of 35, 48, 65, 73, 83, 100, 118, and 662 keV. The readout values of GD-302M and GD-352M have a constant response in the dose range from 100 to 662 keV [19]. The response of energy dependence from 35 to 118 keV was between 23.69% and 262.22% for GD-302M and between −5.56% and 12.73% for GD-352M. The uncertainties of energy dependence in GD-302M and GD-352M were evaluated at 15.16% and 2.29%, respectively, as Type A uncertainties. These results show that GD-352M can be used to analyze X-rays with an energy lower than 100 keV without a distorted signal.

3.6. Angular dependence

The result of angular dependence in GD-352 M is shown in Fig. 6. The relative response is obtained by normalizing the response to the vertical axis at 0°.

Each of the readout values was averaged three times to obtain the response as per the angle. The uncertainty of angular dependence in GD-352 M was evaluated at 0.65%, as a Type An uncertainty. The response of GD-302 M steadily decreased on both sides of GD-302M mainly due to the γ-ray self-attenuation within the RPLGD [17]. However, the response of GD-352M is influenced by the Tin filter as well as self-attenuation. Fig. 6 shows that GD-352M has no effect on self-attenuation at −90° and 90° because γ-rays were attenuated by the tin filter except for −90° and 90°. It was



(a) (b)

Fig. 3. Regression curves of GD-352 M according to the irradiated dose ranges: (a) 0.005–1 Gy and (b) 1–10 Gy.

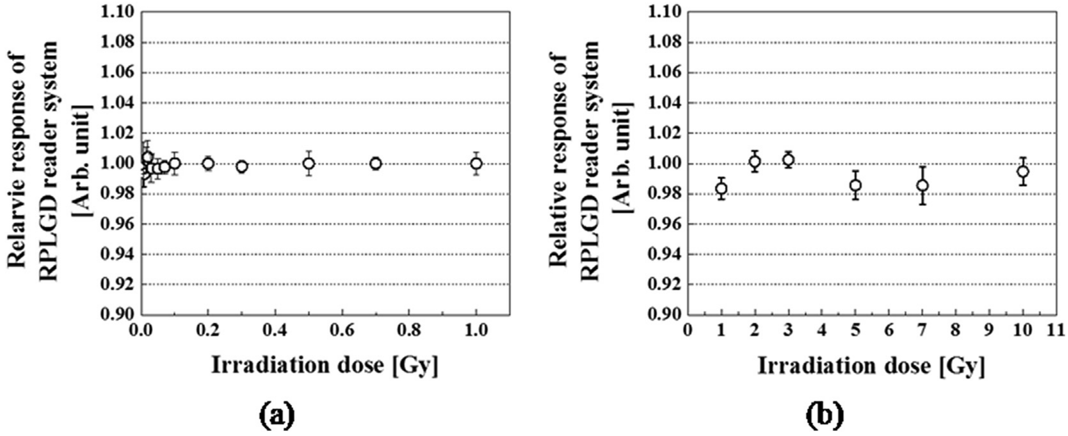


Fig. 4. Reproducibility of GD-352Ms according to the irradiated doses ranges for 10 days: (a) 0.005–1 Gy and (b) 1–10 Gy.

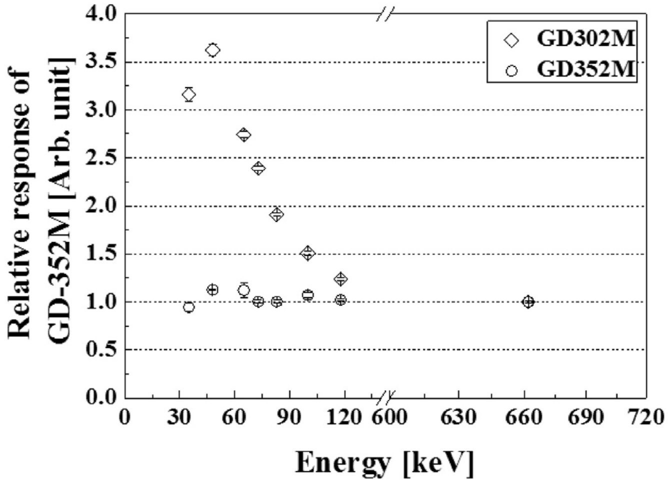


Fig. 5. Relative responses of GD-302M and GD-352M to different energies, from 35 to 662 keV.

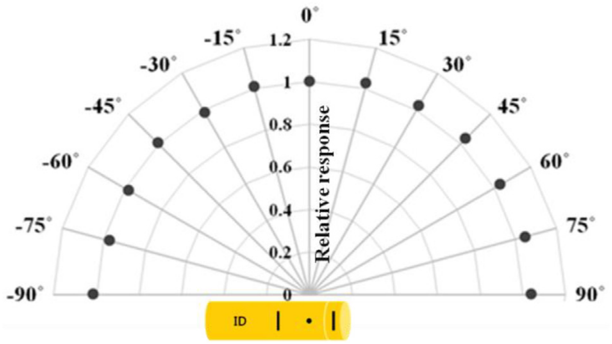


Fig. 6. Responses of GD-352 M in spherical PMMA phantom according to change of irradiation angle.

anticipated that the results of angular dependence would be affected by the geometric properties of GD-352M.

3.7. Measurement uncertainty

The measurement uncertainty of the RPLGD reader system was evaluated by considering various uncertainties based on the dosimetric characteristics of GD-352M. For this study, the uncertainty factors are expressed with a 68.3% confidence interval. The combined uncertainty of the RPLGD reader system is defined as the square root of the quadratic sum of the individual uncertainties. Each uncertainty and the corresponding level of contribution in the RPLGD reader system are listed in Table 1. The expanded uncertainties for low- and high-dose ranges were evaluated at 9.26% and 8.16% with a confidence interval of 95% ($k = 2$). By analyzing the level of contribution according to each dose range, it is observed that the uncertainties of the regression curve and energy dependence account for the largest portion of the measurement uncertainty of GD-352M, except for the reference irradiation.

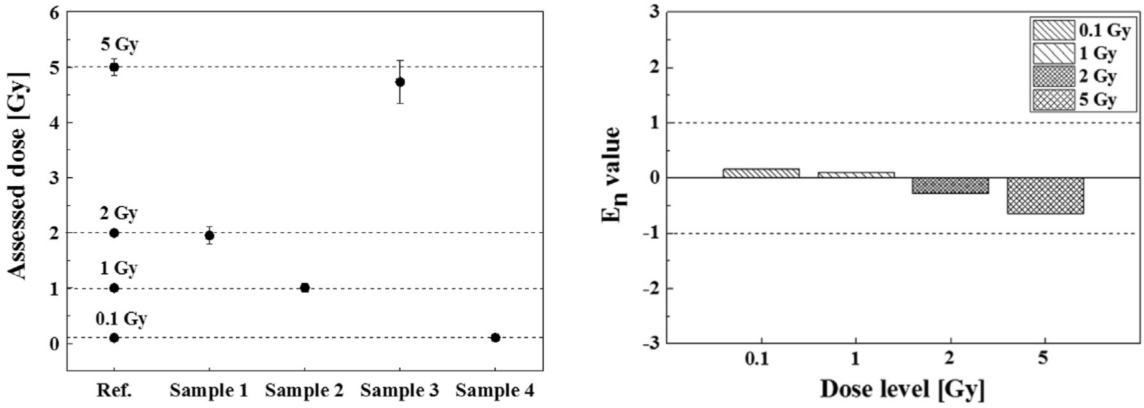
Additionally, a blind test was performed in KIRAMS to validate the RPLGD reader system. The irradiation of blind samples was performed with a ^{60}Co γ-ray teletherapy unit (Best Theratronics, Canada), calibrated with respect to the absorbed dose in the case of water, using a TM 30013 farmer chamber. GD-352 M was set at a reference depth of 5 cm in a water phantom, at a source–axis distance (SAD) of 100 cm with a field size of 10 × 10 cm^2 (IAEA TRS-398 (2002)). The uncertainty of reference irradiation for blind samples was 2.97%. The blind samples of GD-352Ms were irradiated with four unknown doses between 0.005 and 10 Gy. Fig. 7 and Table 2 show a comparison between the readout doses provided by the RPLGD reader system and the blind doses, which are 0.1, 1, 2, and 5 Gy. The relative bias between the readout and blind doses was evaluated to be within 6%. Furthermore, the E_n value was applied to analyze the results of the blind test. The E_n value can be used to perform conformity assessment for proficiency testing and intercomparison exercises. If $|E_n| > 1$, the result is "unsatisfactory" and if $|E_n| \leq 1$, the result is considered "satisfactory" [28]. Overall, the E_n values were $|E_n| \leq 1$, and these results were considered satisfactory. Based on these validation results, the RPLGD reader system is expected to be applicable for evaluating radiation doses as an in vivo dosimeter in the dose range of 0.005–10 Gy.

4. Conclusion

GD-352 M exhibits several advantages—such as small size, good reproducibility, low energy dependence, outstanding dose linearity, and low angular dependence—as an in vivo dosimeter for evaluating protection quantities in physical human phantoms. In this research, the measurement uncertainty of the RPLGD reader system based on GD-352 M was evaluated using dosimetric

Table 1
Measurement uncertainty of RPLGD reader system according to dose ranges.

Dose range	0.005–1 (Gy)		1–10 (Gy)	
	Uncertainty (%)	Contribution (%)	Uncertainty (%)	Contribution (%)
Reference irradiation	2.46	28.24	2.46	36.44
Regression curve	2.86	38.18	1.85	20.61
Reproducibility	0.47	1.03	0.40	0.96
Uniformity	1.15	6.22	1.15	8.03
Energy dependence	2.29	24.47	2.29	31.57
Angular dependence	0.63	1.85	0.63	2.39
Combined uncertainty and contribution	4.63	100	4.08	100
Expanded uncertainty at $k = 2$	9.26		8.16	



(a) (b)

Fig. 7. Results of conformity assessment for measurement uncertainty of RPLGD reader system based on GD-352M: (a) readout doses according to samples and (b) the result of calculated E_n value.

Table 2
Readout doses of blind samples for validation of RPLGD reader system.

Sample number	Reference dose (Gy, $k = 2$)	Readout dose (Gy, $k = 2$)	Relative bias (%)	E_n value
S1	0.1 ± 0.003	0.102 ± 0.009	+1.549	0.156
S2	1 ± 0.029	1.009 ± 0.082	+0.860	0.098
S3	2 ± 0.06	1.950 ± 0.159	−2.426	−0.285
S4	5 ± 0.149	4.732 ± 0.386	−5.352	−0.646

uncertainty factors by referring to ISO standards. The measurement uncertainties with a coverage factor of $k = 2$ were evaluated as 9.26% and 8.16% according to the dose ranges from 0.005 to 1 Gy and from 1 to 10 Gy, respectively. The results of the blind test indicated that the RPLGD reader system can be used to evaluate various protection quantities. In future studies, the RPLGD reader system should be validated complementarily in various situations using the Monte Carlo method, but not at the laboratory level. The validation using physical human phantoms will be the first step toward realizing practical applications of the RPLGD reader system.

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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