Nuclear Engineering and Technology 55 (2023) 2283–2287

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

A formalism for the absorbed dose evaluation of the glass dosimeter

Ka-Young Park [a], Hyun-Chul Kim [a], Byoung-Chul Kim [b, *]

[a] Department of Physics, Inha University, Incheon, 22212, Republic of Korea
[b] Ionizing Radiation Metrology Group, Korea Research Institute of Standards and Science, Daejeon, 34113, Republic of Korea

ARTICLE INFO

Article history:
Received 26 January 2023
Accepted 9 March 2023
Available online 18 May 2023

Keywords:
Radiophotoluminescent glass dosimeter
Absorbed dose
Dose evaluation formalism

ABSTRACT

We propose in the present work how the reference glass dosimeters can be introduced, which reflects the user irradiation condition. The reference glass dosimeters are used for correcting the reader fluctuation by reading it with sample glass dosimeters at the same time. Since they can be used without annealing after irradiation for long periods, one should consider both the fading effect and the natural background dose accumulation quantitatively. We construct an empirical but practical formalism of evaluating the absorbed dose on the glass dosimeter with the fading effect and the natural background dose accumulation considered.

1. Introduction

A radiophotoluminescent glass dosimeter (RPLGD) has been widely used in various fields, since it provides good dosimetric properties, such as high sensitivity, good linearity, low fading effects, repeatability, reusability, and so on [1–5]. The typical small size of the RPLGD provides additional advantages of the glass dosimeter over other methods. This smallness is exceptionally useful for the small field or in-vivo dosimetry [6–8].

Most of the glass dosimeter readout systems determine the absorbed dose based on the batch properties of glass dosimeters. A group of glass dosimeter manufactured from the same production process is a batch. All glass dosimeters in a batch are expected to have the same properties with respect to response and environmental effect, and this is called a batch property. It is well known that the typical batch uniformity of the glass dosimeters lies within about 2% for the dose range over 1 mGy [9]. Dose values of the systems are evaluated generally by utilizing a single internal calibration glass dosimeter and a standard glass one supplied by a manufacturer [10].

Both glass dosimeters, the internal calibration glass dosimeter and the standard glass dosimeter, are irradiated under specific conditions, usually under Cs-137 beam with several mGy. On the other hand, the user irradiation conditions such as the beam type and the dose level may become different, given conditions. A systematic discrepancy was found when the internal calibration one was irradiated under different conditions other than the user irradiation condition [6]. This error was attributed to the internal calibration glass being calibrated in the low dose range with a calibration factor that was not sufficiently accurate to be applied to the high dose range. In addition, it was reported that the glass dosimeter response had a good linear relationship for dose, but the difference in the dose was within ±2% for dose ranging from 0.5 to 30 Gy [2], and 5% for dose ranging from 0.1 mGy to 100 mGy [9].

When the glass dosimeters are read within a few weeks after irradiation, the fading effect and the natural background dose accumulation can be neglected. However, if the period between the irradiation and the reading becomes prolonged, the fading effect and the natural background dose accumulation come into play. In particular, the fading effect on the glass dosimeter stored at room temperature for 150 days can be up to 1.7% [11]. The environmental effects should be evaluated to determine the absorbed dose reliably.

In the present work, we first review critically two different known formalisms for dose evaluations. The first one relies on the internal calibration glass dosimeter and the second one does not explicitly consider environmental effects. To improve them, we introduce the reference glass dosimeters that reflects the user irradiation condition. This condition contains information on the user beam type and the dose range of interest. The reference glass dosimeter enables one to correct the fluctuation of the read systems. Since the reference glass dosimeter is maintained without being annealed, one has to take into account the daily variation of the dose due to the fading effect and the natural background dose accumulation in calculating the absorbed dose. We propose an

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* Corresponding author.
E-mail address: bchkim@kriss.re.kr (B.-C. Kim).

https://doi.org/10.1016/j.net.2023.03.014

empirical but practical formalism of evaluating the absorbed dose on the glass dosimeter with the fading effect and the natural background dose accumulation considered.

The present work is organized as follows: we first review two existing formalisms for dose evaluation. Then, we introduce the new formalism of evaluating the absorbed dose of the glass dosimeter and carry out a case study applying the new formalism. Finally, we summarize the present work and draw conclusions.

2. Existing dose evaluation formalisms

2.1. Formalism A

Commercial glass dosimetry systems (FGD-1000, Chiyoda Technol Corporation, Japan) provide users with methods of evaluating the absorbed dose. In Ref. [10], the following method was suggested as to how the absorbed dose can be determined for the glass dosimetry systems. It is given by

$$D_i = R_i \bullet k_{rd} \bullet N_{std} \tag{1}$$

where R_i denotes the readout value of the i-th sample glass dosimeter. The readout value is only related to the fluorescence by the radiophotoluminescent. k_{rd} stands for the reader correction factor. This is evaluated by using the internal calibration glass dosimeter that is installed in the glass dosimeter reader. The readout value should be corrected by taking into account this factor, since the effect of the output variation of UV laser pulses influences the readout value. The process of the correction of the reader is called ‘internal calibration’. The reader correction factor is defined as:

$$k_{rd} = \frac{R_{IC,0}}{R_{IC,r}} \tag{2}$$

where $R_{IC,0}$ represents the readout value of the internal calibration glass dosimeter of the system at the date of the calibration, and $R_{IC,r}$ does the readout value at the date of the sample reading. N_{std} designates the calibration coefficient of the internal calibration glass dosimeter determined by the standard glass dosimeter:

$$N_{std} = \frac{D_{std}}{R_{std,0}} \tag{3}$$

where D_{std} is the standard irradiation dose with the correction of the natural background dose accumulation and $R_{std,0}$ denotes the readout value of the standard glass dosimeter at the calibration time for the internal calibration glass dosimeter. D_{std} reflecting the natural background dose accumulation, d_b, over time is expressed as:

$$D_{std} = D_{std,0} + d_b \bullet n \tag{4}$$

where $D_{std,0}$ is the irradiation dose to the standard glass dosimeter and n is the number of days between readout and irradiation of the standard glass dosimeter.

The internal calibration glass dosimeter plays a crucial role in this formalism. It can be calibrated by the standard glass dosimeter for a specific irradiation condition of users.

2.2. Formalism B

Formalism B is suitable to determine the water absorbed dose of high energy photons [12]. It has been developed for the external audit program in MV X-ray radiotherapy. The absorbed dose to water is obtained from the i-th glass dosimeter as follows:

$$D_i = \left(R_i \bullet S_i - R_{i',0} \bullet S_{i'}\right) \bullet N_{ref} \bullet f_{en} \bullet f_p \bullet f_{lin} \tag{5}$$

where R_i denotes the mean value of multiple readings of the i-th dosimeter and $R_{i',0}$ represents the background (non-irradiated) value of the i'-th one. S_i stands for the individual dosimeter sensitivity correction factor of the i-th one. The sensitivity correction factor redresses the difference in the sensitivity for each glass dosimeter, which is defined as:

$$S_i = \frac{\overline{R}_{uniform}}{R_{uniform,i}} \tag{6}$$

where $R_{uniform,i}$ is the readout value of an individual dosimeter under the uniform irradiation whereas $\overline{R}_{uniform}$ denotes the mean of each $R_{uniform,i}$ from the same batch. This correction factor relies on the sample variation of the batch, and it is recommended to be checked periodically and should be revised when it is necessary.

N_{ref} in Eq. (5) means the calibration coefficient determined by using reference glass dosimeters that are exposed to a known dose close to that which is supposed to be delivered to the sample glass dosimeters in the reference condition. The reference glass dosimeters are read with the sample glass dosimeters for compensating the daily fluctuation of the reader. N_{ref} is defined as follows:

$$N_{ref} = \frac{D_{ref}}{R_{ref}\,S_{ref} - R_{i',0}\,S_{i'}} \tag{7}$$

where D_{ref} designates the absolute absorbed dose measured by ionization chamber under the same beam condition with the reference irradiation condition. R_{ref} and $R_{i',0}$ denote the mean values for the readout of the reference glass dosimeter and the background one, respectively.

Note that f_{en}, f_p and f_{lin} represent respectively the correction factors for the radiation quality, the phantom material, and the nonlinearity. The fading effect and the natural background dose accumulation on the absorbed dose are not considered apparently.

3. A new formalism for the absorbed dose evaluation

We propose a new formalism that introduces the reference glass dosimeters and uses the calibration coefficients for each glass dosimeter while both formalisms in the previous section are based on the batch properties of the glass dosimeters. The reference glass dosimeters are taken from the same batch with the sample glass dosimeter, which play a role of the internal calibration glass dosimeter as in formalism A. The internal calibration glass dosimeter may not come from the same batch with the sample glass dosimeters. The dosimetry property of the internal calibration glass dosimeter may be distinguished from the sample glass dosimeters, so that additional corrections may be considered. Moreover, it is difficult to precisely determine the absorbed dose of a sample glass dosimeter, since the beam condition for the irradiation of the internal calibration glass dosimeter may be different from what we intend to irradiate the sample one. Thus, we suggest to select the reference glass dosimeter group from the same batch with the sample glass dosimeters and to irradiate them in the same beam condition and the similar dose range of interest. Note that the reference glass dosimeters are read in the reading tray at the same time with the sample glass dosimeters to correct the reader fluctuation. The usage of the reference glass dosimeter is almost the same as that in formalism B.

The proposed formalism determines the absorbed dose by considering the dose of the individual glass dosimeter other than the dose of the batch in formalism B. Thus, this formalism requires several plausible assumptions as follows.

- All glass dosimeters in the same batch have the same dosimetry properties such as the dose linearity, the energy dependency, and so on.
- The dose reading does not affect the written dose in the glass dosimeter. The effect of the readout on the glass dosimeter is a temporal loss of the signal, not a permanent loss [13].
- The annealing process does not change the property of the glass dosimeter.
- The natural background dose accumulation is constant. The environmental condition does not undergo changes. If the environmental condition is varied, then it is treated as an additional irradiation.
- The settings of the glass dosimeter reader are not modified for all readings.
- The residual dose is taken to be zero after the annealing in the calibration process. When the standard irradiation and the reading for the calibration process of the glass dosimeter are carried out in a few days, the fading effect and the natural background dose accumulation for this period are ignored.

3.1. Absorbed dose determination for a glass dosimeter

The absorbed dose of a single glass dosimeter can be evaluated as:

$$D = N k_{RD} R \prod_{\nu} k_{\nu} \tag{8}$$

where N denotes the individual calibration coefficient of the glass dosimeter and k_{RD} designates the reader correction factor. Since the reader performance varies every time, the readout value should be corrected whenever measurements are performed. R stands for the mean value of the successive readout values for the single dosimeter whereas $\prod_{\nu} k_{\nu}$ represents the product of other correction factors such as the nonlinearity, the energy dependency, and so on. N is determined for each dosimeter as follows:

$$N = \frac{D_Q}{R_c} \tag{9}$$

where D_Q stands for the known irradiated dose under the well-defined beam condition with the radiation quality Q such as the reference conditions for the high energy photon beam in IAEA TRS-398 [14]. The irradiated dose should be evaluated by using a more accurate device such as an ionization chamber than the glass dosimetry system. R_c represents the readout value of each glass dosimeter at the calibration reading.

3.2. A daily change of the absorbed dose in a single glass dosimeter

We propose a method to describe a daily dose variation of a single glass dosimeter due to the natural background dose accumulation and the fading effect as follows:

$$\text{Day 0} \quad D_0$$

$$\text{Day 1} \quad (D_0 + d_B)(1 - f_F)$$

$$\text{Day 2} \quad [(D_0 + d_B)(1 - f_F) + d_B](1 - f_F)$$

$$= D_0(1 - f_F)^2 + d_B(1 - f_F)^2 + d_B(1 - f_F)$$

$$\text{Day 3} \quad \left[D_0(1 - f_F)^2 + d_B(1 - f_F)^2 + d_B(1 - f_F) + d_B\right](1 - f_F)$$

$$= D_0(1 - f_F)^3 + d_B(1 - f_F)^3 + d_B(1 - f_F)^2 + d_B(1 - f_F)$$

$$\vdots \qquad \qquad \vdots$$

$$\text{Day n} \quad D_0(1 - f_F)^n + d_B \sum_{k=1}^{n} (1 - f_F)^k \tag{10}$$

$$= D_0(1 - f_F)^n + d_B \frac{(1 - f_F)[1 - (1 - f_F)^n]}{f_F}$$

where D_0 stands for the initial dose, d_B designates the natural accumulated background dose per day, and $f_F\ (>0)$ denotes the daily dose fading factor. n is the number of days past from the initial dose. The first term in Eq. (10) expresses the change of the initial dose, and its second term does the change of the natural accumulated background dose due to the fading effect.

3.3. A case study using the new formalism

We are now able to carry out a case study. We consider a simple case that can be usually happened in the field to apply the new formalism developed above. Fig. 1 shows the timeline of the dose evaluation of the sample glass dosimeter at a given time t_{rs} with the reference glass dosimeter. t_{proc} represents the time of the process. $D_{i,proc}$ and $R_{i,proc}$ describe respectively the dose value and the readout value of the i-th glass dosimeter (for *ref*, reference glass) at each process (proc). Each process is exhibited in terms of the following abbreviations written in the parentheses, i.e., the calibration of reference glasses (cr), the calibration of sample glasses (cs), the annealing (a), the reading of background after the annealing (rb), the irradiation of an unknown dose (x), and the reading of the sample glasses (rs). These symbols are also used to denote the process of the calibration (◉), the annealing (//), the reading (•), and the irradiation (⚡).

In this formalism, $N_{i,proc}$ means the calibration coefficient of the i-th glass dosimeter (for *ref*, reference glass) at each process, which is defined as

$$N_{i,proc} = \frac{D_{i,proc}}{R_{i,proc}}. \tag{11}$$

We should evaluate the calibration coefficients for all dosimeters, samples and reference glass dosimeters before using them.

To determine the dose of the sample glass dosimeter at a given time t_{rs}, the reader correction factor at this point should be obtained. By using Eq. (10), the dose of the reference glass dosimeter at the time t_{rs} is given as follows:

$$D_{ref,rs} = D_{ref,cs}(1 - f_F)^{n_r} + d_B \sum_{k=1}^{n_r} (1 - f_F)^k, \tag{12}$$

where $n_r = t_{rs} - t_{cs}$. $D_{ref,rs}$ can be also expressed as:

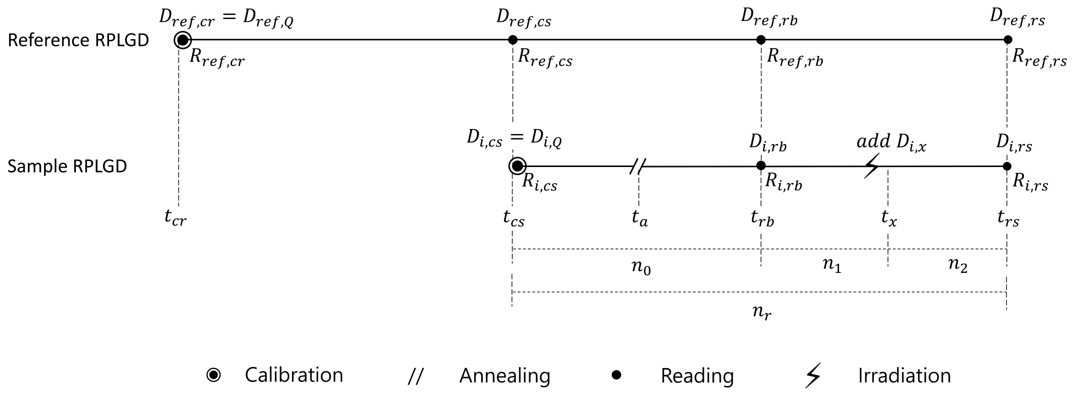

Fig. 1. The timeline of the dose evaluation using RPLGD.

$$= \left[N_{i,cs}R_{i,rs}\frac{R_{ref,cs}}{R_{ref,rs}}\left\{(1-f_F)^{n_r}+\frac{d_B}{D_{ref,cs}}\sum_{k=1}^{n_r}(1-f_F)^k\right\}-d_B\sum_{k=1}^{n_2}(1-f_F)^k\right](1-f_F)^{-n_2}-\left[(1-f_F)^{n_1}N_{i,cs}R_{i,rb}\frac{R_{ref,cs}}{R_{ref,rb}}\left\{(1-f_F)^{n_0}\right.\right.$$
$$\left.\left.+\frac{d_B}{D_{ref,cs}}\sum_{k=1}^{n_0}(1-f_F)^k\right\}+d_B\sum_{l=1}^{n_1}(1-f_F)^l\right].$$

$$D_{ref,rs} = N_{ref,cs}k_{RD,rs}R_{ref,rs}\prod_{v}k_v, \tag{13}$$

which is taken from Eq. (8). For the simplicity, it is assumed that $\prod_{v} k_v = 1$. Combining Eqs. (12) and (13), we are able to derive the reader correction factor as

$$k_{RD,rs} = \frac{R_{ref,cs}}{D_{ref,cs}R_{ref,rs}}\left[D_{ref,cs}(1-f_F)^{n_r}+d_B\sum_{k=1}^{n_r}(1-f_F)^k\right]. \tag{14}$$

The dose of the i-th sample glass dosimeter, $D_{i,rs}$, at the reading time can be written by using the reader correction factor, Eqs. (8), (10) and (14) turn out to be:

$$D_{i,rs} = N_{i,cs}R_{i,rs}\frac{R_{ref,cs}}{R_{ref,rs}}\left[(1-f_F)^{n_r}+\frac{d_B}{D_{ref,cs}}\sum_{k=1}^{n_r}(1-f_F)^k\right] \tag{15}$$

$$D_{i,rs}=\left[D_{i,x}+D_{i,rb}(1-f_F)^{n_1}+d_B\sum_{l=1}^{n_1}(1-f_F)^l\right](1-f_F)^{n_2}+d_B\sum_{k=1}^{n_2}(1-f_F)^k, \tag{16}$$

where $n_1 = t_x - t_{\mathrm{rb}}$, $n_2 = t_{rs} - t_x$.

Then the unknown irradiated dose, $D_{i,x}$, can be obtained from Eqs. (15) and (16):

$$\begin{aligned} D_{i,x} = & \left[D_{i,rs}-d_B\sum_{k=1}^{n_2}(1-f_F)^k\right](1-f_F)^{-n_2} \\ & -\left[D_{i,rb}(1-f_F)^{n_1}+d_B\sum_{l=1}^{n_1}(1-f_F)^l\right] \end{aligned} \tag{17}$$

The dose value and the reader correction factor at the background reading time, t_{rb}, is also derived in the same manner. When the dose evaluation period from the annealing time (t_a) to reading time (t_{rs}) is brief enough or when the dose level irradiated to the sample glass dosimeter exceeds several Gy, Eq. (17) can be approximated as

$$D_{i,x} \sim D_{i,Q}\frac{R_{ref,cs}}{R_{i,cs}}\left[\frac{R_{i,rs}}{R_{ref,rs}}-\frac{R_{i,rb}}{R_{ref,rb}}\right](1-f_F)^{n_r-n_2}. \tag{18}$$

Eq. (18) is similar to Eq. (5) except for the fading effect that is not considered in formalism B. The fading factor, $(1-f_F)^{n_r}$, is related to the reader correction. That of the reference glass dosimeters should be considered when the period between the calibration of sample glass dosimeter and the readout becomes prolonged.

4. Summary

Table 1 summarizes the main characteristics of formalisms for determining the dose of the glass dosimeter.

In formalism A, the calibration coefficient of the standard glass dosimeter is used as a representative value for all glass dosimeters considering the batch property. Only the natural background dose accumulation is considered for the change in dose of the standard glass dosimeter in obtaining the calibration coefficient. The correction for the reader is taken into account through the readout value of one internal calibration glass dosimeter based on the batch property.

In formalism B, the reference glass dosimeter is utilized to calculate the calibration coefficient and offset the fluctuation of the reader, but all environmental effects on the change in absorbed dose of the reference glass dosimeter are not regarded.

The proposed formalism assessed the calibration coefficient for each glass dosimeter to reflect variation between individuals. The

Table 1
The main characteristics of formalisms for determining the dose of the glass dosimeter.

Formalism	Calibration coefficient	Reader correction factor
A	• Use the calibration coefficient of the standard glass dosimeter (N_{std}) • Consider only the natural background dose accumulation • Batch properties applied	• Use an internal calibration glass dosimeter irradiated with a known dose • Batch properties applied
B	• Use the calibration coefficient of the reference glass dosimeter selected from the same batch of the sample glass dosimeter (N_{ref}) • No explicit consideration on the natural background dose accumulation and the fading effect • Batch properties applied	• Use multiple reference glass dosimeters selected from the same batch of the sample glass and read them in the same session • Batch properties applied
Proposed	• Use the calibration coefficients for individual glass dosimeters (N_i)	• Use multiple reference glass dosimeters selected from the same batch of the sample glass dosimeter and read them in the same session • Consider both the natural background dose accumulation and the fading effect in the formalism itself • Batch properties applied

reader correction factor was obtained using a reference glass dosimeter group selected from the same batch as the sample glass dosimeter and irradiated with a known dose. The reader correction factor was calculated from the dose value and the readout value of the reference glass dosimeter, and both natural background dose accumulation and fading effects are considered.

5. Conclusion

In the present work, we aimed at developing a new dose evaluation formalism for the determination of the absorbed dose of the glass dosimeters. The proposed formalism introduced the reference glass dosimeter to correct the daily stability of the reader. The reference glass dosimeter was selected from the same batch as the sample glass dosimeter and irradiated under the same conditions as the user irradiation condition to reflect the user environment for evaluating the absorbed dose of the sample glass dosimeter. The fading effect and the natural background dose accumulation of the glass dosimeters were considered in this formalism when the glass dosimeters were used over a long period without annealing processes. Individual calibration coefficients are evaluated to reflect the sensitivity of the sample glass dosimeter, which distinguishes the proposed formalism from others. Relevant applications to the measurement of the absorbed doses for glass dosimeters are underway.

Disclaimer

The authors clarify that this paper does not stand for the opinions of the Dosimetry Metrology Team at Korea Research Institute of Standards and Science. In addition, the corresponding author does not represent any opinions of the Dosimetry Metrology Team at the Korea Research Institute of Standards and Science.

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.

Acknowledgements

The present work is supported by Inha University Grant in 2023.

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