Investigation of the dosimetric characteristics of radiophotoluminescent glass dosimeter for high-energy photon beams

Puntiwa Oonsiri\textsuperscript{a}, Sakda Kingkaew\textsuperscript{a}, Chulee Vannavijit\textsuperscript{a} and Sivalee Suriyapee\textsuperscript{b}

\textsuperscript{a}Radiation Oncology Division, King Chulalongkorn Memorial Hospital, The Thai Red Cross Society, Bangkok, Thailand; \textsuperscript{b}Radiation Oncology Division, Radiology Department, Faculty of Medicine, Chulalongkorn University, Bangkok, Thailand

ABSTRACT

The aim of this work was to investigate the dosimetric characteristics of radiophotoluminescent glass dosimeter (RPLGD) for high energy photon beams in both flattening filter mode and flattening filter free (FFF) mode. The dosimetric characteristics of RPLGD model GD-302M were studied in 6 MV photon beams for the reproducibility of dosimeter reader, uniformity and reproducibility of RPLGD, dose linearity (range from 1 to 20 Gy), repetition rate, and angular dependence. In addition, the energy responses were observed in flattening filter mode (6 MV, 10 MV, and 15 MV) from Varian Clinac C-series and FFF mode (6 MV_FFF and 10 MV_FFF) from Varian TrueBEAM system. The FGD-1000 reader system exhibited stable readout. The entire number of 100 RPLGDs showed good uniformity and reproducibility within ±1.5%. Furthermore, the signal from RPLGD demonstrated a linear proportion to the radiation dose (r = 0.999), and no energy dependence was observed. For repetition rate response of flattening filter mode and FFF mode, the maximum error of relative response to 400 MU/min were 0.977 ±0.006 and 0.986±0.017, respectively. The response of RPLGD reached 1.00 at ±30° gantry angle while at +90° gantry angle, the RPLGD response was 8% lower compared to -90° gantry angle because the attenuation effect was more pronounced. We conclude that the RPLGD is capable to measure radiation dose since it provides desirable dosimetric properties such as good uniformity and reproducibility of RPLGD including the reader system. Besides, RPLGD is available with small active readout area which adds benefit for clinical implementation in radiotherapy, especially for advanced techniques.

1. Introduction

The use of radiophotoluminescent glass dosimeter (RPLGD) for radiation dose measurement has been introduced since 1951. However, it was still unfamiliar at that time due to the limitation associated with high residual dose. Recent development in glass materials and readout system of RPLGD has made this dosimeter becomes more accurate to measure radiation dose until low dose within 10 μGy. Nowadays, interest to employ RPLGD rather than thermoluminescent dosimeter (TLD) is increasing for such reasons related to the better dosimetric properties. Hsu, Yeh, Lin, and Chen (2006) reported the dosimetric properties of RPLGD were superior to TLD regarding energy response, fading effect, and readout reproducibility. The glass component of RPLGD is fabricated from high melting point material which contributes to small variation among RPLGDs (Huang & Hsu, 2017). This reflects the use of RPLGD requires no individual sensitivity correction factors as TLD does.

Unlike TLD, RPLGD can repeatedly be readout. After RPLGD is exposed to radiation, the luminescent materials inside the glass component will form the color center. Then, ultraviolet light with 337.1 nm length will stimulate the electrons in the color center to emit the fluorescence light (600–700 nm) before electrons return to the electron traps. This enables RPLGD to be re-readout unlimited times for single irradiation until the annealing procedure is performed. The RPLGD comes in a cylindrical shape with three different models: GD-302M, GD-352M, and GD-301. The size of both GD-302M and GD-352M is similar where the length is 12 mm, and the diameter is 1.5 mm. For GD-301, the diameter remains similar with other models, except its length. GD-301 possesses a smaller length of 8.5 mm. Furthermore, the existence of the filter also distinguishes those models of RPLGD. Both GD-302M and GD-301 contains no filter and typically used to measure high-energy photon beams such as in radiotherapy, while GD-352M possess Tin filter to measure the low energy of...
photon beams without the energy dependence, for instance, in diagnostic radiology.

Although several studies have reported the dosimetric properties of RPLGD for high-energy photon beams (Araki, Moribe, Shimonobou, & Yamashita, 2004; Mizuno et al., 2008, 2009a; Rha et al., 2008). Due to the lack of study pays attention to evaluate the characteristics of RPLGD for high-energy photon beams in flattening filter free (FFF) mode. The present study focuses on the investigated RPLGD characteristics model GD-302M available in our department. Our observations emphasize on the repetition rate (Rep. rate) and the energy dependence for two different high-energy photon beams in FFF mode (6 MV and 10 MV).

2. Materials and methods

2.1. The RPLGD system

The same batch number of 100 RPLGDs model GD-302M series FD-7 was utilized in this study where the element of glass luminescent materials by its weight composed of Na (11%), P (31.5%), O (51.2%), Al (6.1%), and Ag (0.2%). The shape of this model is cylindrical with 1.5 mm diameter and 12 mm length (without holder) or 2.5 × 13 mm² (with holder). The density and effective atomic number of glass dosimeter is 2.61 g/cm³ and 12.04, respectively. Before irradiation, the residual signal was removed by an annealing process at 400°C for 1 h using the electric furnace. After irradiation, the luminescent signal was stabilized by the preheat process at 70°C for 30 min. The automatic reader FGD-1000 (AGC Techno Glass Co., LTD, Shizuoka, Japan) was used to readout the signal. The readout system can automatically category the dose from low dose (< 5 Gy) to high dose (5–20 Gy) according to the types of readout magazine. Each RPLGD was repeatedly read for five times which automatically set by FGD-1000 software.

2.2. Dosimetric characteristics evaluation

The RPLGD was calibrated with an ionization chamber FC-65G (IBA Dosimetry GmbH, Schwarzenbruck, Germany) where the chamber was connected to DOSE-I electrometer (IBA Dosimetry GmbH, Schwarzenbruck, Germany). The 6 MV photon beams from Varian Clinac 21EX (Varian Oncology System, Palo Alto, CA, USA) delivered the dose at 200 cGy to 5 cm depth in a solid water phantom (RMI-Gammex, Inc., Middleton, WI, USA) with 100 cm source to surface distance (SSD) and 10 × 10 cm² field size. Then, the same condition was set for the RPLGD. The sensitivity of the RPLGD readout which related with the absolute dose as measured by the FC-65G was converted to the dose readout when the RPLGD was utilized in dose measurement.

For setup condition of RPLGD characteristic studies, the field size and SSD were adjusted to 20 cm × 20 cm and 100 cm, respectively, while the depth of measurement in solid water phantom was set to 5 cm. To reduce the air gap effect of the solid water phantom, 1 cm thickness of bolus was placed on the superior and inferior part of glass dosimeter as illustrated in Figure 1. All of the characteristics study except for energy response was undertaken on 6-MV photon beams from Varian Clinac 21EX (Varian Oncology System, Palo Alto, CA, USA). To study the energy response, three different Linear Accelerators were employed: Varian Clinac 21EX (Varian Oncology System, Palo Alto, CA, USA).
2.2.1. Reproducibility of the dosimeter reader

To examine the reproducibility of FGD-100 reader system, 10 RPLGDs were exposed to 100 cGy of radiation dose. The FGD-1000 reader system was turned on approximately 15 min before the reproducibility test. For single readout, each RPLGD was re-readout for 5 times where the software has been computerized to do so. The readout process was run continuously for 4 times on the same day which means each glass dosimeter was read entirely 20 times. In each session, the setup of readout magazine was made independently from the previous readout procedure and followed by resetting the FGD-1000 system. Afterward, the readout magazine was pulled in and out to ensure no residual signal was left and affecting the next reading of glass dosimeter.

2.2.2. Uniformity and reproducibility of RPLGD

All RPLGDs (totally 100 RPLGDs) were exposed to 100 cGy of radiation dose. To minimize the statistical error, measurement was repeated three times, started from the annealing process to the readout process. The batch uniformity of all RPLGDs was determined in the relative response; the average signal of 15 readouts per each RPLGD (five times readout per measurement and entirely three times of measurement) divided by the average signal for all 100 RPLGD. The reproducibility of RPLGD was defined by the average of the standard deviation of each RPLGD for 3 times of measurement.

2.2.3. Dose linearity

To investigate the dose linearity, 10 RPLGDs were employed to measure various doses at 1, 3, 5, 10, 50, 100, 500, 1000, 1500, and 2000 cGy from 6 MV photon beams. The radiation doses from 1 to 500 cGy were read in the standard mode. For doses higher than 500 cGy, readout process was performed in the high dose mode (the system automatically recognized from the types of the magazine). Readout of each RPLGD was averaged for 5 times to obtain the signal response as per the dose setting.

2.2.4. Repetition rate response (rep. rate)

Observation of repetition rate response (Rep.rate) was performed in 10 RPLGDs at normal Rep. rate and high Rep. rate from 6 MV and 6 MV_FFF high-energy photon beams, respectively. The single prescribed dose of 100 cGy was delivered. For standard Rep. rate, the responses of 6 MV were observed at 40, 80, 100, 200, 300, 400, 500, and 600 MU/min. Meanwhile, for high Rep. rate of 6 MV_FFF, the responses were varied at 400, 600, 800, 1000, 1200, and 1400 MU/min. The Rep. rate response in each step was normalized to 400 MU/min according to our clinical usage.

2.2.5. Energy response

The RPLGDs were irradiated with a similar dose level of 100 cGy under flattening filter mode from 6, 10, and 15 MV photon beams and FFF mode from 6 MV_FFF and 10 MV_FFF photon beams. The average signal response of 10 RPLGDs in each beam quality was normalized to the average signal response of 6 MV. The beam quality of photon beams was defined by TPR\text{20,10} value (the ratio of absorbed dose at 20 cm to 10 cm depth with constant source-detector distance). TPR\text{20,10} of 6 MV, 10 MV, 15 MV, 6 MV_FFF, and 10 MV_FFF were 0.67, 0.74, 0.76, 0.63, and 0.71, respectively.

2.2.6. Fading effect

To explore the fading effect, 100 RPLGDs were exposed to 100 cGy of radiation dose. Then, the glass detectors were separated into 10 RPLGDs for readout process for

Figure 2. (a) The RPLGD direction setup inside the CTDI phantom, (b) The CTDI phantom setup on the treatment couch.
10 consecutive weeks. The unread RPLGDs were stored in the unexposed radiation area under a room temperature of 25°C. Fading effect was defined as the relative response of glass dosimeter to the initial readout.

2.2.7. Angular dependence
For angular dependence test, the RPLGD response was examined concerning the gantry angle of 0° toward a cylindrical Computed Tomography (CT) head phantom. This phantom is fabricated from polymethyl-methacrylate (PMMA). One glass dosimeter was inserted into the middle hole of the phantom. The RPLGD was positioned in a horizontal and perpendicular direction to the incident beam axis as displayed in Figure 2. In each step of the gantry angle, measurement was repeated for 3 times.

Figure 3. The relative response of FDG-1000 reader system from 10 RPLGDs.

Figure 4. The uniformity of 100 RPLGDs for 6-MV photon beams. The readout for each RPLGD was normalized to the average readout of 100 RPLGDs. The error bars show the standard deviation from 3 times of repeated measurement.

Figure 5. The linearity response of RPLGD for standard and high dose range mode (a). Similar linearity response was exhibited by low dose setting from 0.01 to 1 Gy (b).
3. Results and discussion

3.1. Reproducibility of the dosimeter reader

The reproducibility of FDG-1000 reader system was examined for 20 times readout (each RPLGD readout for 5 times and entirely 4 sessions of reading) was explored in 10 RPLGDs as can be seen in Figure 3. Overall, the standard deviation of the relative response was ±0.5% which indicated that the FGD-1000 reader system was very stable.

3.2. Uniformity and reproducibility of RPLGD

The uniformity reading from 100 RPLGDs is presented in Figure 4. The relative response of each RPLGD was normalized to the average signal of 100 RPLGDs which were measured 3 times on a separate day. The standard deviation for each RPLGD from 3 times of measurement was exhibited by the error bars. The lowest relative response was 0.83 in glass number 8. The reason was due to the position of splinter where located at the edge of the dosimeter. Then, this dosimeter was omitted from the remaining experiments. Our research found the uniformity was 1.5% which consistent with previous work conducted by Hsu et al. (2007).

Meanwhile, the reproducibility (average of the standard deviation of each RPLGD for 3 times of measurement) of RPLGD in our study was ±1.5% which agreed well with previous work conducted by Araki, Moribe, Shimonobou, and Yamashita (2004) where they discovered the value of ±1.1%.

3.3. Dose linearity

As shown in Figure 5, the response of RPLGD yielded a linear proportion across both standards, and high doses ranged from 1 to 2000 cGy. Both standard dose range and high dose range presented R² of 0.999. This value was agreeable with a study by Son et al. (2011) where they found R² of doses from 1 to 500 Gy was 0.998. The ratio between RPLGD readout dose versus dose setting was within ±2%, where Araki, Moribe, Shimonobou, and Yamashita (2004; Son et al., 2011) published an identical outcome with our study.

3.4. Repetition rate (Rep. rate) response

The average readout of 10 RPLGDs in each Rep. rate was divided by the readout of 400 MU/min, which is the standard treatment in our department. The Rep. rate response is depicted in Figure 6. The maximum error of relative response to 400 MU/min was 0.977 ± 0.006 and 0.986 ± 0.017 for flattening filter mode and FFF mode, respectively. It was considered that the high Rep. rate photon beams did not affect the color center of RPLGD forming.

3.5. Energy response

Table 1 summarizes the energy response of RPLGD from various high-energy photon beams relative to 6 MV photon beams. The maximum relative response was 1.017 ± 0.011 for 6 MV_FFF, indicating that RPLGD is energy independence to high-energy photon beams.

| Energy (MV) | TPR 20,10 | Relative response to 6 MV |
|-------------|-----------|--------------------------|
| 6 MV        | 0.67      | 1.000 ± 0.018             |
| 10 MV       | 0.74      | 1.002 ± 0.008             |
| 15 MV       | 0.76      | 0.992 ± 0.015             |
| 6 MV_FFF    | 0.63      | 1.017 ± 0.011             |
| 10 MV_FFF   | 0.71      | 0.993 ± 0.009             |

Figure 6. The Rep. rate response of RPLGD for flattening filter mode and FFF mode. The error bars demonstrate the standard deviation over 10 RPLGDs.
photon beams in both flattening filter mode and FFF mode. According to published data by Rah et al. (2009b), the energy response of RPLGD for high-energy photon beams with flattening filter mode was 1.5% which closely matched to our result.

3.6. Fading effect

The fading effect was observed for 10 consecutive weeks. The range of relative response to the first readout was from 0.973 to 1.003 as depicted in Figure 7. The trend of the relative response in fading between week number 5–7 and 8–10 was rising due to the uncertainty of the RPLGD sensitivity while the difference PRLGD was read in each week. However, this result was not affected by our measurement since the readout was completed during each session. Furthermore, we did not apply fading correction factors in all measurements Wesolowska et al. (2017) also confirmed that the fading correction of RPLGD was negligible once the readout process was within two weeks after irradiation. Rah et al. (2009b) evaluated the fading effect of RPLGD for 19 weeks and reported the number of 1.6%.

3.7. Angular dependence

As shown in Figure 8, the angular dependence of RPLGD across ± 90° gantry angles. The relative response was normalized to the RPLGD readout of the central axis at 0° gantry angle. Each point displays the outcome from average three repeated measurements and five times readout in each RPLGD. The response of RPLGD reached a value of 1 at ±30° gantry angle which was in an excellent agreement to the previous observation by Son et al. (2011) where they reported the relative response of 1.0% for gantry angles between 60° and 105°, while 90° gantry angle, beam direction was parallel to the longitudinal axis of the cylindrical RPLGD. Since the readout area of RPLGD model GD-302M is located at 0.7 mm from its edge, the relative response at ± 90° gantry angle in our study

![Figure 7. The fading response of RPLGD over 10 weeks. The error bars represent the standard deviation of relative response from 10 RPLGDs.](image1)

![Figure 8. The angular dependence of RPLGD at various gantry angles.](image2)
became not symmetry. In comparison to the response at −90° gantry angle, the response at +90° gantry angle was 8% which attributed to higher attenuation effect. Araki, Moribe, Shimonobou, and Yamashita (2004) confirmed the angular dependence of RPLGD where the response was almost 6% lower compared to the normalization beam angle. This implies that beam direction to the effective point of RPLGD should be made parallel to obtain precise dose readout. Otherwise, the angular correction factors should be applied.

The present work also estimates the uncertainty that is defined as the square root of the quadratic summation of individual uncertainties from several factors. The RPLGD uncertainties for high-energy photon beams with flattening filter mode and FFF mode are listed in Table 2. Overall, the combined uncertainty was 3.45%. The uncertainty for each value was 1 SD of relative response with 68.3% confidence level.

Overall, the evaluation of all dosimetric characteristics in this research presented good outcomes. In addition to that, RPLGD possesses small active readout area of 1 mm diameter and 0.6 mm in length (Araki, Moribe, Shimonobou, & Yamashita, 2004; Rha et al., 2009b), which increases the potential use for postal dosimetry audit as previously mentioned by Mizuno et al. (2008) and Rha et al. (2009b) showed linear proportion to the radiation dose. Another good point from RPLGD is the ID number located at the edge of each RPLGD allows the user to identify glass dosimeter easily.

4. Conclusion

Evaluation of RPLGD dosimetric characteristics in this work confirms that this dosimeter could be regarded as the prospective dosimeter for high-energy photon beams in flattening filter mode and FFF mode. No energy dependence was found in both modes when RPLGD was employed. Stable repetition rate response was discovered. The combined uncertainty for all factors was 3.45%.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Araki, F., Moribe, N., Shimonobou, T., & Yamashita, Y. (2004). Dosimetric properties of radiophotoluminescent glass rod detector in high-energy photon beams from a linear accelerator and CyberKnife. Medical Physics, 31, 1980–1986.

Hsu, S. M., Yang, H. W., Yeh, T. C., Hsu, W. L., Wu, C. H., Lu, C. C., ... Huang, D. Y. C. (2007). Synthesis and physical characteristics of radiophotoluminescent glass dosimeters. Radiation Measurement, 42, 621–624.

Hsu, S. M., Yeh, S. H., Lin, M. S., & Chen, W. L. (2006). Comparison on characteristics of radiophotoluminescent glass dosemeters and thermoluminescent dosemeters. Radiation Protection Dosimetry, 119(1–4), 327–331.

Huang, D. Y. C., & Hsu, S. M. (2017). Radiophotoluminescence glass dosimeter (RPLGD). Retrieved from 23 October 2017 http://cdn.intechopen.com/pdfs/23935/InTechRadio_Photoluminescence_glass_dosimeter_rplgd_.pdf.

Mizuno, H., Kanai, T., Kusano, Y., Ko, S., Ono, M., Fukumura, A., ... & Ishikura, S. (2008). Feasibility study of glass dosimeter postal dosimetry audit of high-energy radiotherapy photon beams. Radiotherapy and Oncology, 86(2), 258–263.

Rah, J., Hong, J., Kim, G., Kim, Y., Shin, D., & Suh, T. (2009a). A comparison of the dosimetric characteristics of a glass rod dosimeter and thermoluminescent dosimeter for mailed dosimeter. Radiation Measurement, 44, 18–22.

Rah, J., Shin, D., Jang, J., Kim, M., Yoon, S., & Suh, T. (2008). Application of glass rod detector for the output factor measurement in the CyberKnife. Applied Radiation and Isotopes, 66, 1980–1985.

Rah, J. E., Kim, S., Cheong, K. H., Lee, J. W., Chung, J. B., Shin, D. O., Suh, T.-S. (2009b). Feasibility study of radiophotoluminescent glass rod dosimeter postal dose intercomparison for high energy photon beam. Applied Radiation and Isotopes, 67, 324–328.

Son, K., Jung, H., Shin, S. H., Lee, H. H., Kim, M. S., Ji, Y. H., & Kim, K. B. (2011). Evaluation of the dosimetric characteristics of a radiophotoluminescent glass dosimeter for high-energy photon and electron beams in the field of radiotherapy. Radiation Measurement, 46(10), 1117–1122.

Wesolowska, P. E., Cole, A., Santos, T., Bokulic, T., Kazantsev, P., & Izewska, J. (2017). Characterization of three solid state dosimetry systems for use in high energy photon dosimetry audits in radiotherapy. Radiation Measurement, 106, 556–562.

Table 2. The uncertainty of RPLGD for high-energy photon beams with flattening filter mode and FFF mode. All uncertainties are expressed with 1 SD.

| Characteristic                        | Uncertainty (%) |
|--------------------------------------|-----------------|
| Uniformity                           | 1.5             |
| Reproducibility                      | 1.5             |
| Linearity                            | 1.2             |
| Reproducibility of the dosimeter reader | 0.5            |
| Rep. rate                            | 0.9             |
| Energy dependence                    | 1.0             |
| Fading                               | 1.0             |
| Angular dependence                   | 1.7             |
| Combined uncertainty                 | 3.45            |