Original Article

Dosimetric Characteristics of Radiophotoluminescent Glass Dosimeters for Proton Beams

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Abstract

Purpose: The purpose of the study was to investigate the dosimetric characteristics of radiophotoluminescent glass dosimeters (RGDs) for pencil beam scanning proton therapy. The RGD's end-to-end testing of intensity-modulated proton therapy (IMPT) plans was also evaluated. **Materials and Methods:** The dosimetric characteristics of the GD-302M type glass dosimeter were studied in terms of uniformity, short-term and long-term reproducibility, stability of the magazine position readout, dose linearity in the range from 0.2 to 20 Gy, energy response in 70–220 MeV, and fading effect. The reference conditions of the spot scanning beam from the Varian ProBeam Compact system were operation at 160 MeV, a 2 cm water-equivalent depth in a solid water phantom, a 10 cm × 10 cm field size at the isocenter, and 2 Gy dose delivery. End-to-end testing of IMPT plans for the head, abdomen, and pelvis was verified using the Alderson Rando phantom. The overall uncertainty analysis was confirmed in this study. **Results:** The relative response of RGDs for the uniformity test was within 0.95–1.05. The percentages of the coefficients of variation for short-term and long-term reproducibility were 1.16% and 1.50%, respectively. The dose ACE glass dosimetry reader FGD-1000 showed a stable magazine position readout. The dose was found to be linear with $R^2 = 0.9988$. The energy response relative to 160 MeV was approximately within 4.0%. The fading effect was within 2.4%. For the end-to-end test, the difference between the treatment plan and RGD measurement was within 1.0%. The overall uncertainty of the RGD measurement for the proton beam was 4.6%, which covered all energy ranges in this study. **Conclusion:** The experimental study indicates that the RGDs have the potential to be used in the dosimetry of therapeutic proton beams, including end-to-end dosimetry.

Keywords: End-to-end test, proton therapy, radiophotoluminescent glass dosimeter, uncertainty analysis

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Introduction

Proton beam therapy has been increasingly used in the state of the art for various types of tumors. Passive scattering gives excellent dose conformity for the distal part of the target; however, it lacks proximal dose conformity.[1,2] Pencil beam scanning (PBS) involves magnetic scanning across the target volume, which can achieve both distal and proximal dose conformities, thus potentially further improving the therapeutic ratio.[3] The major basis of proton therapy is a sharp and rapid distal falloff, known as the Bragg peak.[4] The adjustable beam energy affects the beam range and renders the dosimetric characteristics to be achieved in the target volume.[5]

Various types of detectors are used for proton dosimetric verification, such as an ionization chamber, a radiochromic film, a metal-oxide-semiconductor field-effect transistor (MOSFET) detector, a thermoluminescent dosimeter (TLD), an optically stimulated luminescence dosimeter (OSLD), a diamond detector, and a radiophotoluminescent glass dosimeter (RGD). The Gafchromic EBT3 film and MOSFET show dose accuracy when the linear energy transfer (LET) correction factor was applied.[6] The TLD and OSLD exhibit an over-response and under-response, except in the distal region.[7,8] The diamond detector is nonreproducible in terms of stability, sensitivity, and LET dependence.[9]

The RGD exhibited excellent dosimetric characteristics and clinical applications in our previous study on photon beams.[10-12] Limited studies have applied RGDs in the clinical

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usage of proton beams. The aim of this study was to investigate the dosimetric characteristics of RGDs for PBS proton therapy. The feasibility of using an RGD in end-to-end testing of intensity-modulated proton therapy (IMPT) plans at various treatment sites was also evaluated.

Materials and Methods

Beam delivery system

The Varian ProBeam Compact spot scanning system (Varian Medical Systems, Palo Alto, California, USA) was utilized in this study. The accelerator produces a proton energy range that can vary from 70 to 220 MeV. The spot scanning beam was operated at 160 MeV for the reference conditions in this study, which is the middle range of energy for the machine. The dose was calibrated following the IAEA TRS-398[13] guidelines at Z_{ref} 2 cm.

Dosimetry system

A GD-302M glass dosimeter model and an FGD-1000 automatic reader (AGC Techno Glass Co., LTD, Shizuoka, Japan) were utilized in this study. The glass element materials by weight were Na (11%), *P* (31.5%), O (51.2%), Al (6.1%), and Ag (0.2%). The RGD without the holder was 1.5 mm in diameter and 12 mm in length with a cylindrical shape. The effective atomic number and density of the glass dosimeter were 12.04 and 2.61 g/cm^3, respectively. The residual signal of the RGD was removed before measurement by annealing at 400°C for 1 h. Preheating at 70°C for 0.5 h was performed before readout to stabilize the fluorescence. The readout area was 1 mm in diameter and 6 mm in length, which was located opposite to the serial number. The cutoff dose reading for the standard dose range was 10 Gy. For doses higher than 10 Gy, the readout system can automatically categorize them in high-dose-range mode according to the type of readout magazine. The reader was set to read out five times for each RGD.

Dosimetric characteristics of the glass dosimeter

The reference conditions for each RGD exposure experiment were as follows: a proton beam energy of 160 MeV, a 2 cm water-equivalent depth in a solid water phantom, and a 10 cm × 10 cm field size at the isocenter. The RGDs were embedded with 1 cm boluses in the superior and inferior parts to prevent cracking of the glass elements. The delivered dose was 2 Gy.

The uniformity was determined by exposing 200 RGDs to the beam under the reference conditions. The percentages of coefficients of variation (%CV) were defined as the standard deviation of the readout signal of all detectors divided by the average signal of the RGDs.

The short-term reproducibility was evaluated by splitting the RGDs into 10 RGDs per set. Each set of RGDs was consecutively exposed to the beam under the reference conditions 10 times. The signal response for each set relative to the average for all sets was observed. In addition, only one set of RGDs was used to check the stability of the magazine position readout by putting the magazine in, taking it out, and reading out the signal 10 times. Each average readout was normalized to the average for all 10 readouts. For long-term reproducibility, the process for one set of RGDs, from irradiation to readout, was repeated weekly for 10 weeks.

The dose linearity was checked for various doses of 0.2, 0.5, 1, 2, 5, 8, 10, 12, 15, 18, and 20 Gy for each set of RGDs according to the reference conditions. The high-dose-range readout mode was applied for dose readings 8 Gy and higher, and the system was automatically recognized based on the type of magazine inserted. The responsibility of the signal readout to the dose setting was plotted in a relation curve.

For the energy response, the RGD set was irradiated at 70, 100, 130, 160, 190, and 220 MeV. The average signal for each energy was normalized to 160 MeV. The proton beam quality was defined by R_{80}, which was equivalent to 4.07, 7.72, 12.29, 17.65, 23.77, and 30.54 cm according to beam scanning during the commissioning process.

For the fading effect, 100 RGDs were exposed to proton beams under the reference conditions. A set of 10 RGDs was separated and read out weekly for a total of 10 consecutive weeks. The unread RGDs were stored in an area without radiation exposure at a room temperature of 25°C. The fading effect was defined as the response for each week readout relative to the initial readout.

Clinical dosimetric verification

A simple plan, with a box volume, was verified for depths of 5, 8, and 10 cm in a solid water phantom. The prescribed dose in the box volume was 2 Gy. The beam arrangement was only along one direction at 0° from the gantry.

The point dose measurement of an RGD was utilized to verify the dose to the center of the target in an end-to-end test. The female adult Alderson Rando phantom (Alderson Research Labs, Stanford, CA, USA) was imaged by GE Revolution 256-slice (GE HealthCare, Illinois, United States) computed tomography simulation with a 3-mm slice thickness. The verification plans of the IMPT technique were created by the Eclipse treatment planning system version 16.1.0 (Varian Medical Systems Inc., Palo Alto, CA, USA).

The studied regions of interest were the head, abdomen, and pelvis. The RGD measurement point was within the clinical target volume (CTV). The gantry rotation and monitor units were retained the same as those in the plans. The two parallel opposing fields were undergone for the head and pelvis, but the anterior and right lateral were performed for the abdomen. The plans and RGD placement in the Alderson Rando phantom are illustrated in Figure 1. The RGD measurement was performed three times for each experiment.

Results

The uniformity of the responses of the 200 RGDs is shown in Figure 2. Each signal response was relative to the average of all the signals. The minimum and maximum relative responses

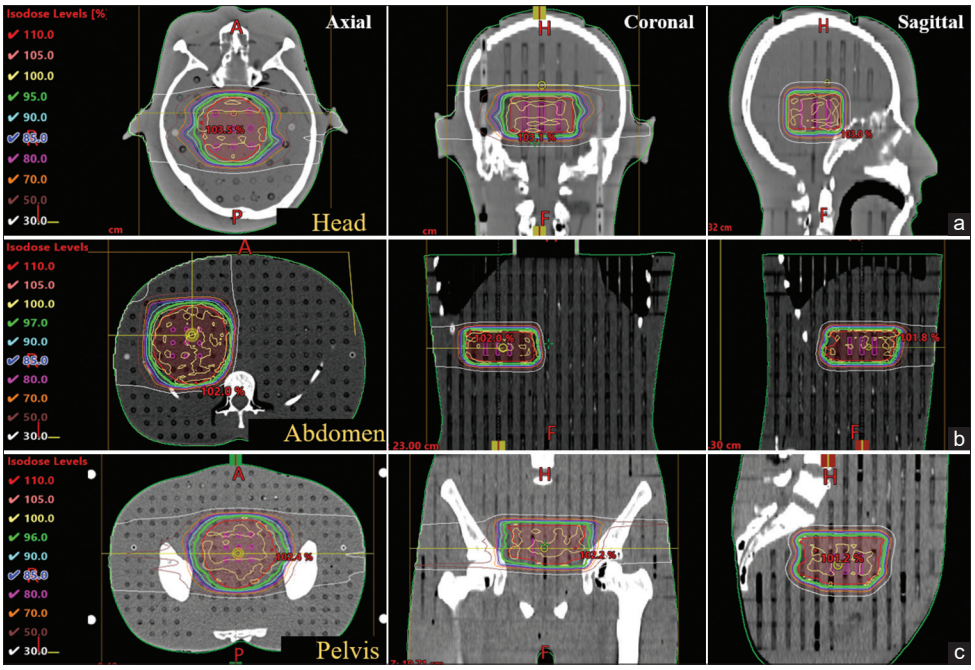

Figure 1: Clinical plans for end-to-end testing with the Alderson Rando phantom (a) head; (b) abdomen; and (c) pelvis

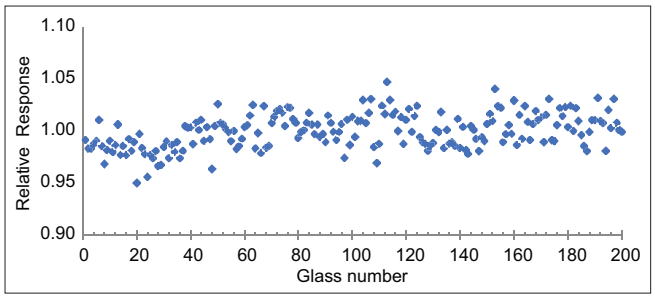

Figure 2: Relative response uniformity of 200 radiophotoluminescent glass dosimeters

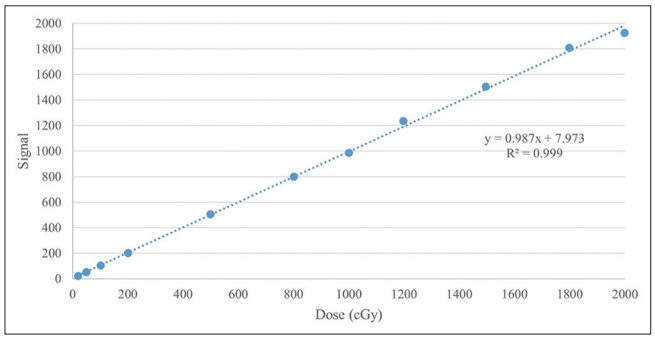

Figure 3: Radiophotoluminescent glass dosimeters response linearity in the dose range of 0.2–20 Gy

were 0.950 and 1.048, respectively. The %CV of this group of RGDs was 1.66%.

The short-term reproducibility was evaluated by the relative response of the RGD readout signal. The %CV of the short-term reproducibility was 1.16%. The stability of the magazine position readout showed high consistency. The range of the relative responses for the stability test of the magazine position readout was from 0.997 to 1.002. For long-term stability, the relative response of RGDs varied from 0.977 to 1.032. The %CV was 1.50%.

The dose–response linearity for the RGD signal readout is shown in Figure 3. Each step-dose data point represents the average value for five readouts. The RGDs for proton beams were found to have an obviously good linear relationship, with $R^2 = 0.999$.

The RGD readout for the proton energy range of 70–220 MeV normalized to that at 160 MeV is depicted in Figure 4. The graph showed more deviation for the lowest and highest energies, 0.966 and 1.043, respectively, due to the LET dependence.[5] However, the overall response exhibited %CV = 2.15%.

For the RGD fading effect, the range of responses relative to the first readout was from 0.976 to 1.003.

Clinical dosimetric verification

The details of the RGD dose measurement for the simple plan and clinical plans in each region are summarized in Table 1. The maximum difference between the treatment planning system calculation and RGD measurement showed a very good result that was within 1%. These results confirmed that RGDs are appropriate for end-to-end testing in proton therapy.

Uncertainty analysis

The uncertainty analysis of RGDs is shown in Table 2. The combined uncertainty was obtained as the square root of the quadratic sum of the individual uncertainties in RGD dose measurement. For the first step, the calibration procedure included the dose and machine instability and the setup uncertainty based on the positioning accuracy and readout system of the RGDs. The typical uncertainty of the dose

Table 1: Summary of radiophotoluminescent glass dosimeter dose measurements compared with treatment planning system calculations

Plans	Prescribed dose to CTV (cGy)	Mean±SD (cGy)		Average percentage difference
		TPS	RGDs measured	
Simple plan				
5 cm depth	200.0	197.5±0.8	197.6±3.2	0.2
8 cm depth	200.0	197.0±1.2	198.1±3.3	−0.1
10 cm depth	200.0	198.0±1.2	198.3±3.6	−0.1
Head	200.0	199.5±0.7	199.0±2.5	0.2
Abdomen	500.0	513.7±1.2	516.1±9.0	−0.4
Pelvis	300.0	312.1±0.6	309.1±4.4	1.0

RGDs: Radiophotoluminescent glass dosimeters, SD: Standard deviation, CTV: Clinical target volume, TPS: Treatment planning system

Table 2: Uncertainty analysis for radiophotoluminescent glass dosimeter measurement

Physical quality of the procedure	Uncertainty (%)
Step 1: Calibration procedure	
Dose measurement with the ionization chamber	1.0
Reading uniformity	1.7
Short-term reproducibility	1.2
Magazine position readout	0.2
Step 2: Dose correction factors	
Energy dependence	2.2
Long-term reproducibility	1.5
Fading	1.9
Step 3: Clinical measurement	
Combined uncertainty	2.0
Overall uncertainty (k=1)	4.6

measurement with the ionization chamber for the clinical proton beam was approximately 2%. All correction factors that we could determine for RGD dosimetric characteristics for proton beams were combined in the second step. In the last step, the conditions of the patient setup for clinical treatment were determined based on the anthropomorphic Rando phantom measurement in this study. The overall uncertainty of the RGD end-to-end test with the proton beam was approximately 4.6%. Our result corresponded to that of Rah *et al*.[14]

Discussion

In this study, the dosimetric characteristics of RGDs were evaluated for proton beams. The uniformity results showed good agreement, within 1.66%, which corresponded to other studies.[4,10] The RGDs were found to have a good linear relationship in the applied dose range of 0.2–20 Gy. The dose rate response was negligible, which was the same as the result from Rah *et al*.[14] The fading effect was relatively stable for 10 weeks of storage, within 2.4%. Rah *et al*.[15] supported that the response of RGDs did not exceed a 2% loss after 150 days of storage.

Although, various reports have shown that the RGD response is strongly dependent on LET.[4,16,17] Our results showed the difference in the CTV dose between the Eclipse calculation and

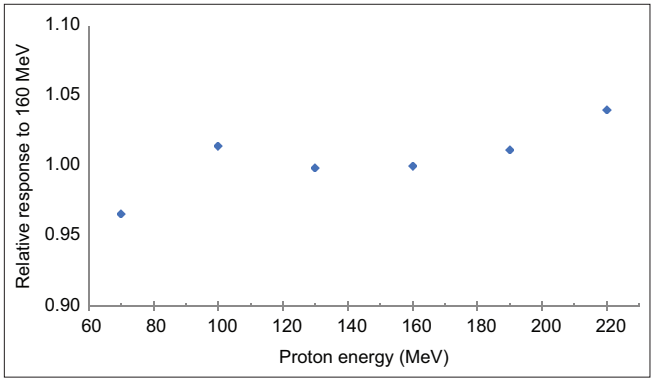

Figure 4: Relative energy response for 70–220 MeV proton beams normalized to 160 MeV

RGD measurements was within approximately 1%. The overall uncertainty of the RGD measurement for the proton beam was 4.6%. Our study proves that RGDs can be confidently applied for proton dose measurement.

Conclusion

The dosimetric characteristics of the RGDs in terms of uniformity, short-term and long-term reproducibility, stability of the magazine position readout, dose linearity, energy, and fading effect have the potential to be used in the dosimetry of therapeutic proton beams, including end-to-end dosimetry for clinical cases. The overall uncertainty is approximately 4.6%.

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Nil.

Conflicts of interest

There are no conflicts of interest.

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