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Feasibility Study of the Radiophotoluminescent Glass Dosimeter for High-energy Electron Beams

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Our goal is to assess the suitability of a glass dosimeter on detection of high-energy electron beams for clinical use, especially for radiation therapy. We examined the dosimetric characteristics of glass dosimeters including dose linearity, reproducibility, angular dependence, dose rate dependence, and energy dependence of 5 different electron energy qualities. The GD was irradiated with high-energy electron beams from the medical linear accelerator andgamma rays from a cobalt-60 teletherapy unit. All irradiations were performed in a water phantom. The result of the dose linearity for high-energy electron beams showed well fitted regression line with the coefficient of determination; R^2 of 0.999 between 6 and 20 MeV. The reproducibility of GDs exposed to the nominal electron energies 6, 9, 12, 16, and 20 MeV was ±1.2%. In terms of the angular dependence to electron beams,GD response differences to the electron beam were within 1.5% for angles ranging from 0° to 90° and GD's maximum response differencewas 14% lower at 180°. In the dose rate dependence, measured dose values were normalized to the value obtained from 500 MU/min. The uncertainties of dose rate were measured within ±1.5% except for the value from 100 MU/min. In the evaluation of the energy dependence of the GD at nominal electron energies between 6 and 20 MeV, we obtained lower responses between 1.1% and 4.5% based on cobalt-60 beam. Our results show that GDs have a considerable potentiality for measuring doses delivered by high-energy electron beams.

Key Words: Glass dosimeter, Dosimetric characteristics, Electron beam

INTRODUCTION

To obtain a higher degree of accuracy and precision, variousradiation detectorsare being used such as ionization chambers, diode detectors, films, metal-oxide-semiconductor field effect transistors (MOSFETs), optically stimulated radiation detectors (OSDLs), and thermoluminescent dosimeter (TLD). Ionization chambers and semiconductor diode detectors measure absorbed dose with high accuracy and precision.However, detection uncertainties increase on small radiation fields and also the characteristic of non-tissue equivalence and angular dependence are problematic, respectively.[1-3] Although films provide best spatial resolution, they offer only relative dose measurements. Absolute dose delivery requires that the relationship between delivered dose and film optical densitybe determined. However, optical density is influenced by time elapsed after exposure, room temperature, relative humidity, and the film processing procedure.[2,4,5] MOSFETs can provide immediate dose information, but it presents energy dependence andlifetime limited.[6] OSLDs offer not only the advantages of minimal signal loss for repeated readout measurementsbut alsosimpler readout process using light instead of heat and stable signal after 8 minute post irradiation and optical bleaching to remove radiation-induced effects. On the other hand, one disadvantage of these devices that differs from TLDs is that they accumulate a residual signal due to the filling of deeper en-

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ergy traps that cannot be emptied by simply optical bleaching with fluorescent light.[7] TLDs have smaller effective volumes than ionization chambers, and have lower energy dependence,[8-10] but readout values are not reproducible and fading effects are encountered due to thetimeelapsed after irradiation.[11]

Glass dosimeter (GD) is used a lot recently and has many benefits. Commercially available radiophotoluminescent (RPL) GD have been used to measure a radiation doses such as diagnostic and environmental X-ray exposure and high-energy photon beams during radiation therapy.[8,12] GDs have many advantages of high sensitivity, low energy dependence, low fading effects, excellent dose linearity, and readout repeatability in photon beams.[13] The purpose of this study is to investigate the suitability of GD-based dosimetric systems for high-energy electron beams for clinical use. We measured the dosimetric features of GD such as dose linearity, reproducibility, angular dependence, dose rate dependence, and energy dependence for electron beams applications at therapeutic electron beam qualities.

MATERIALS AND METHODS

1. Principle and consists of GD system

The GD system consists of glass detectors and a reader unit. Dose measurements are performed based on the formation of fluorescence centers in silver-activated metaphosphate caused by an incoming electron or photon beam. The ground state of silver activated metaphosphate in GDs is normally Ag^{+}. When a GD is exposed to ionizing radiation, an electron/PO_4 (hole) pair is formed. Both Ag^0 and Ag^{++} are stable states and namedradiophotoluminescence (RPL) centers.[3] When radiation-irradiated GD is exposed to ultraviolet (UV) light, a radiation-induced photoluminescent orange light is emitted; the intensity of which is proportional to the radiation dosage. The elemental composition of the GD (Asahi Techno Glass Corporation, Shizuoka, Japan) used was; P: 31.55%, O: 51.16%, Na: 11.00%, Al: 6.12%, and Ag: 0.17%. The GD-302M modelused in this study had a diameter of 1.5 mm and a length (without its holder) of 12 mm. The effective atomic number and density of the GD were 12.04 and 2.61 g/cm^3, respectively.

The reader unit (FGD-1000, Asahi Techno Glass Corporation, Shizuoka, Japan) is used to detect the intensity of the orange luminescence. After an exposure to the UV stimulation level, the stable RPL centers remains at the exposed level.[12,14,15] The GD reader unit consists of a N_2 laser oscillator, a photomultiplier, a photodiode, a readout magazine (moving table), a reference glass, and an internal calibration glass. Measurable doses range from 10 μGy to 10 Gy in standard mode. Also, Measurable doses range from 1 to 500 Gy in high-dose mode.[12,16]

2. Dosimetric characteristics of GD for electron beam

The model of GD-302M was irradiated in a water phantom with high-energy electron beams. We used nominal electron energies of 6, 9, 12, 16, and 20 MeV from a Varian ClinaciX linear accelerator. Premeasured mean electron energies ($\bar{E}_z$) at each d_{max} (d_{max}: depth of maximum dose) point were 3.06, 4.45, 6.22, 8.40, and 15.11 MeV for the ClinaciX.Doses absorbed by water for the ClinaciX electron beams were determined using anionization chamber connected to an UNIDOS electrometer (PTW-Freiburg, Schwarzenbruck, Germany). Absorbed doses delivered to GD were calculated from the ionization chamber calibration factor using the absorbed dose to water in accord with the IAEA TRS-398.[17] All measurements without dose rates dependence were measured at dose rates of 600 MU/min. Also, each factor of evaluation is repeatedly measured to reduce a statistical error.

Dose linearity of GD was evaluated by comparing delivered and absorbed doses. The delivered dose range was from 1 to 15 Gy and GDs were irradiated at nominal energies of 6, 9, 12, 16, and 20 MeV. Measurements were taken 5 times at each delivered dose point to decrease the statistical error. Also, 10 repeated readings were taken.

Reproducibility of GD was measured using 100 GDs for all electron nominal energies mentioned.Measurements were carried out using the source-to-surface distance (SSD) of 100 cm with an applicator size of 10×10 cm^2. The dose delivered to each GD was 2 Gy. GDs were set up on the reference depths ($Z_{ref}=0.6R_{50}-0.1$ cm) in the water phantom for each electron beam energy to decrease the fluctuation error.[17] R_{50} is an index (unit of centimeter) defined as the depth at which the absorbed dose has decreased to 50% of its maximum value.

Angular dependence was measured using a 9 MeV electron beam from the Varian ClinaciX linear accelerator and the spherical PMMA phantom (density 1.19 g/cm^3). This phantom was made for this study (Fig. 1). GD response regarding gantry angle was examined with the GD positioned at the beam isocenter. The effective reading center of the GD was positioned at the center of the spherical phantom. The center of the effective reading volume of the GD was kept at the center of gantry rotation. Measurements were made at angles of 0^o, 30^o, 60^o, 90^o, 120^o, 150^o, and 180^o.

Dose rate dependence was measured with 9 MeV electron beam of 10×10 cm^2 field size of d_{max}. GDs were irradiated by 2 Gy at each of the following dose rates; 100, 200, 300, 400, 500, 600, and 1,000 MU/min. Measurementsare taken 10 times at each delivered dose point and 10 consecutive readings.

To determine the energy dependence of GDs for electron beams, GDs were set uponthe reference depth in the water phantom and measurements were taken 100 times in the nominal energy ranging from 6 to 20 MeV. In this study, the dose correction factor of GDs was determined by comparing measured GD's dose values with the reference condition of the exposure by ^{60}Co γ-rays. GDs were normalized at the Korean Institute of Radiological & Medical Sciences (KIRAMS) using a cobalt-60 teletherapy unit (Theratron 780, AECL, Kanata, Canada), which delivered a dose rate of 112.63 cGy/min at a SSD (Source to Surface Distance) of 80 cm in accord with the IAEA TRS-277.[18] A dose of 2 Gy was delivered to every GD. Absorbed dose measurements were carried out using a water phantomand Farmer type PTW TN 30006 calibrated ionization chamber.

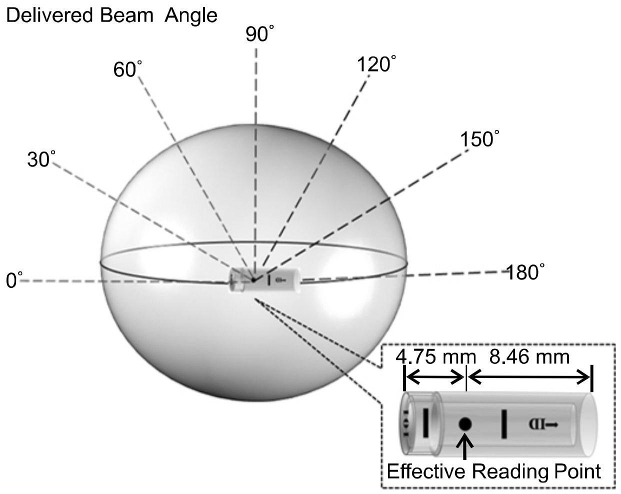

Fig. 1. Schematic diagram of the measurement setup used to determine the angular dependence of the GD-302M. The spherical PMMA phantom was constructed for this study. The diameter of spherical PMMA phantom is 4.0 cm. The effects of angular dependence were measured in total 7 directions for the electron beams and the X-ray photon beams.

RESULTS

The dose linearity response of GD for 5 electron beam qualitiesis presented in Table 1. For high-energy electron beams, the results of dose linearity measurement showed well fitted regression lines with R^2=0.999 for 6 MeV, R^2=0.999 for 9 MeV, R^2=0.999 for 12 MeV, R^2=0.999 for 16 MeV, and R^2=0.984 for 20 MeV (R^2=coefficient of determination). Measured doses were calibrated versus a dose of 1 Gy determined using an ionization chamber.

The reproducibility of GDs exposed to nominal electron energies of 6, 9, 12, 16, and 20 MeV is presented in Fig. 2. The reproducibility of the average of dose ranging from 6 to 20 MeV was within ±1.2% (one standard deviation). Relative responses were normalized with respect to average readout values at each energy point.

The angular dependence of the GD is shown in Fig. 3.

Table 1. Dose linearity of GD for high-energy electron beams. Doses are measured ranging from 1 to 15 Gy. The values of percentage are calculated by dividing absorbed dose of readout value of GD by each value of delivered dose on the basis of absorbed dose of 1 Gy. The uncertainty was estimated to be one standard deviation for 5 measurements. (unit: %)

Delivered dose	1 Gy	2 Gy	4 Gy	6 Gy	8 Gy	10 Gy	15 Gy
6 MeV	100±1.3	98.7±1.0	97.9±1.5	97.0±1.3	96.5±1.4	96.1±1.4	95.6±1.4
9 MeV	100±0.9	98.9±0.7	98.4±1.2	97.7±1.4	98.1±1.6	98.5±1.4	98.3±1.3
12 MeV	100±1.3	98.8±0.9	98.2±0.7	98.5±0.9	97.1±1.4	97.0±1.3	98.6±1.4
16 MeV	100±1.1	99.1±1.2	98.4±1.4	97.2±1.5	98.0±1.5	98.4±1.0	98.9±1.5
20 MeV	100±1.4	99.3±1.1	98.8±0.9	98.4±0.9	97.1±1.2	98.3±1.1	99.0±1.4

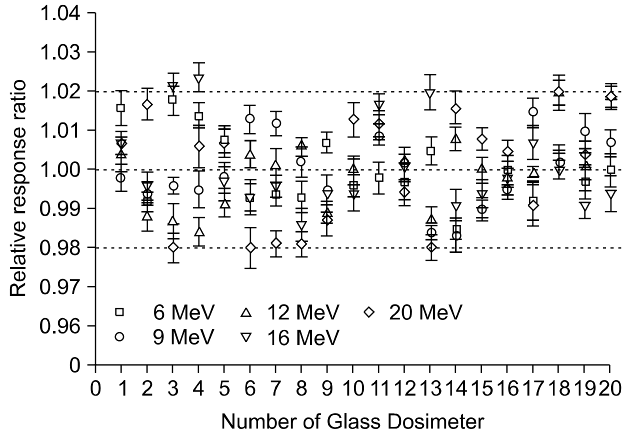

Fig. 2. Reproducibility of GD for electron beams of 6, 9, 12, 16, and 20 MeV. The error bars represent one standard deviation of 5 consecutive readings.

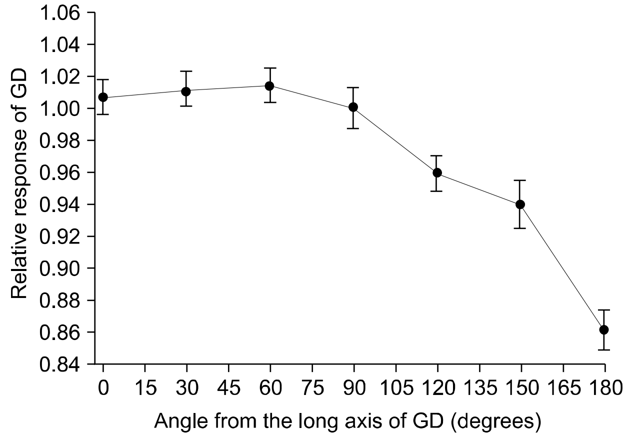

Fig. 3. Angular dependence of GDs measured using 9 MeV electron beams. The effects of angular dependence were measured in total 7 angle directions between 0° and 180°. The data at the different angles are presented as average values and one standard deviation for 5 GDs.

Response was normalized versus GD readout value at 90° (perpendicular to the long axis of the effective GD reading point). GD response differences to the electron beam were within 1.5% for angles ranging from 0° to 90° and GD response difference of maximum was 14.0% lower at 180°. Each data point represents an average value and one standard deviation for 5 GDs. GD responses to the photon beam were within 2.0% for angles between 0° to 90° and GD response difference of maximum was 12.0% lower at 180°.

In dose rate dependence, measured values were normalized to the value obtained from 500 MU/min. The uncertainties were measured within ±1.5% except the value from 100 MU/min (Fig. 4).

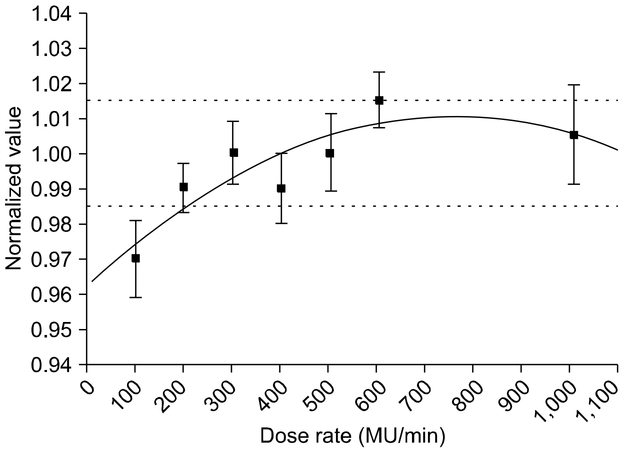

Fig. 4. Dose rate dependence of GDs is measured using electron beams. Measurements were taken 10 times at each delivered dose point and 10 consecutive readings are conducted. Error bars represent one standard deviation of 10 measurements.

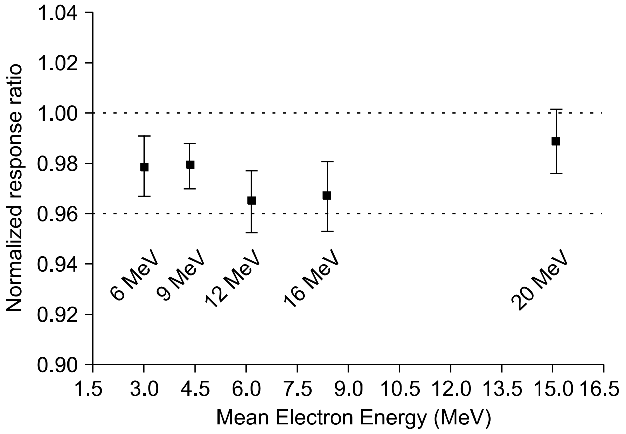

Fig. 5. Energy dependence of the electron beams ranging from 6 to 20 MeV of GD. Response for beams is normalized versus the response of irradiated GDs to a ^{60}Co beam. Mean electron energy were determined using absorbed doses measured using an ionization chamber. The error bars represent one standard deviation of 20 measurements.

The energy dependence of the GD for electron beams between 6 and 20 MeV is shown in Fig. 5. The GD responses to each beam were normalized versus responses to a ^{60}Co beam. The energy dependence on average showed with a variation of 0.975±0.012% (one standard deviation).

DISCUSSION

In this study, we measured the characteristics of GD for high-energy electron beams. Dose linearity was examined at doses ranging from 1 to 15 Gy. It shows good dose linearity in each of 5 energies ranging from 6 to 20 MeV as R^2= 0.999. GD reproducibility differences for electron beams were almost the same as those for photon beams.In published report, reproducibility of photon beam was within ±1.1% for 50 GDs.[3] Regarding the angular dependence experiment, the variation of sensitivity at an angle of 0^o was 1.0% and 180^o was almost 14.0% for the electron beam, which are lower and higher than electron beams at an angle of 90^o. In a study by Araki et al.,[3] the difference of the GD response in photon beam is within 1.5% for the angle ranging from 0^o to 120^o, and it shows the same asymmetrical trend that is the same as the result of this study based on 90^o. It is considered that variation of RPL centers occurs due to self-attenuation according to the different beam direction when electron beams are passed through GD. Dose rate dependence shows ±1.5% ranging from 200 MU/min to 1,000 MU/min excluding 100 MU/min, so it is considered that present electron beam therapy using high dose rate doesn't have great influence on measuring absorbed dose. In a reported data,[6] dose rate dependence in photon beam between 100 MU/min to 600 MU/min shows ±2.0%. The energy dependence of GD was measured for 5 electron beam qualities. At all electron energies, we observed that the energy dependence of GDs to electron beams were lower than for ^{60}Co γ-ray beams. According to this study, responses of electron energies between 6 and 20 MeV were lower by between 3.8% and 4.6%;[19] we obtained responses between 1.1% and 4.5% from 6 to 20 MeV. As compared with the energy dependence to photon beams, energy dependence to electron beams was approximately 2 times higher. The energy dependence of GDs for photon beams was within ±2.0%, which is good agreement with published data.[3] Thus, a correction factor should be determined for high-energy electron beams used in evaluations, assessments, or for absorbed dose determination.

ICRU report No. 24[20] recommends a dosimetric accuracy within 5.0% for radiation therapy. In the present study, we followed this recommendation. The combined uncertainty of GD for electron beams with dose linearity up to 15 Gy (within 1.7%), taking into account reproducibility (±1.2%), angular dependence from 0^o to 90^o (within 1.5%), dose rate 500 MU/min and energy dependence (2.5%, average value of 5 electron beam qualities), was calculated to be less than 3.6%. From this point of view, GD was found to be suitable for dosimetry of high-energy electron beam in the radiotherapy field.In the near future, it is considered that more accurate dose evaluation by GD could be possible if fading effect in the long term and the effect of beam direction including arc-techniqueare additionally evaluated with various beam qualities.

CONCLUSION

In this study, we examined the dosimetric characteristics of a glass dosimetry system for clinical use, especially for radiotherapy. Our results show that GD has considerable potential for the dosimetry of high-energy electron beam.

REFERENCES

1. **Rah JE, Shin DO, Jang JS, Kim MC, Yoon SC, Suh TS**: Application of a glass rod detector for the output factor measurement in the CyberKnife. Appl Radiat Isot 66:1980-1985 (2008)
2. **Araki F, Ikegami T, Ishidoya T, Kubo HD**: Measurements of Gamma-Knife helmet output factors using a radiophotoluminescent glass rod dosimeter and a diode detector. Med Phys 30:1976-1981 (2003)
3. **Araki F, Moribe N, Shimonobou T, Yamashita Y**: Dosimetric properties of radiophotoluminescent glass rod detector in high-energy photon beams from a linear accelerator and Cyber-Knife. Med Phys 31:1980-1986 (2004)
4. **Heydarian M, Hoban PW, Beddoe AH**: A comparison of dosimetry techniques in stereotactic radiosurgery. Phys Med Biol 41:93-110 (1996)
5. **Ertl A, Zehetmayer M, Schoggl A, et al**: Shuttle dose at the Vienna Leksell Gamma Knife. Phys Med Biol 43:1567-1578 (1998)
6. **Rah JE, Hwang UJ, Jeung H, et al**: Clinical application of glass dosimeter for *in vivo* dose measurements of total body irradiation treatment technique. Radiat Meas 46:40-45 (2011)
7. **Chester S**: The energy dependence and dose response of a commercial optically stimulated luminescent detector for kilovoltage photon, megavoltage photon, and electron, proton, and carbon beams. Med Phys 36:1690-1699 (2009)
8. **Kirby TH, Hanson WF, Jhonston DA**: Uncertainty analysis of absorbed dose calculations from thermoluminescence dosimeters. Med Phys 19:1427-1433 (1992)

9. **Mobit PN, Mayles P, Nahum AE**: The quality dependence of LiF TLD in megavoltage photon beams: Monte Carlo simulation and experiments. Phys Med Biol 41:387-398 (1996)
10. **Mizuno H, Kanai T, Kusano Y, et al**: Feasibility study of Glass dosimeter postal dosimetry audit of high-energy radiotherapy photon beams. Radiol Oncol 86:258-263 (2008)
11. **Araki F, Ishidoya T, Ikegami T, Moribe N, Yamashita Y**: Application of radiophotoluminescent glass plate dosimeter for small field dosimetry. Med Phys 32:1548-1554 (2005)
12. **Ashahi Techno Glass Corporation (ATG)**: Explanation material of RPL glass dosimeter: Small element system. Tokyo, Japan (2004)
13. **Fan S, Yu C, He D, Li K, Hu L**: Gamma rays induced defect centers in phosphate glass for radiophotoluminescence dosimeter. Radiat Meas 46:46-50 (2011)
14. **Hoshi Y, Nomura T, Oda T**: Application of a newly developed photoluminescence glass dosimeter for measuring the absorbed dose in individual mice exposed to low-dose rate 137CS γ-rays. J Radiat Res 41:129-137 (2000)
15. **Ihara Y, Kishi A, Kada W**: A compact system for measurement of radiophotoluminescence of phosphate glass dosimeter. Radiat Meas 43:542-545 (2008)
16. **Hsu SM, Yang HW, Yeh TC**: Synthesis and physical characteristics of radiophotoluminescent glass dosimeters. Radiat Meas 42:621-624 (2007)
17. **IAEA, International Atomic Energy Agency**: Absorbed Dose Determination in External beam Radiotherapy, An International Code of Practice for Dosimetry based on Standards of Absorbed dose to Water, Technical Reports Series TRS-398, IAEA, Vienna, Austria (2000)
18. **IAEA, International Atomic Energy Agency**: Absorbed Dose Determination in Photon and Electron Beams, an International Code of Practice, Technical Reports Series TRS-277, IAEA, Vienna, Austria (1987)
19. **Rah JE, Hong JY, Kim GY, Kim YR, Shin DO, Suh TS**: A comparison of the dosimetric characteristics of a glass rod dosimeter and a thermoluminescent dosimeter for mailed dosimeter. Radiat Meas 44:18-22 (2009)
20. **ICRU, International Commission on Radiation Units & Measurements**: Determination of Absorbed Dose in a Patient Irradiated by Beams of X or Gamma Rays in Radiotherapy Procedures, Report No. 24, ICRU, Bethesda, Maryland (1976)

유리선량계를 이용한 고에너지 전자선 측정 이용 가능성에 관한 연구

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본 연구에서는 유리선량계를 이용하여 전자선 치료빔의 선량평가 이용 가능성을 판단하고자 하였다. GD-302M 유리선량계에 선형가속기를 이용한 전자선과 ^{60}Co 방사선조사기로부터 감마선을 조사하였다. 유리선량계의 전자선에서의 선량 선형성, 재현성, 방향성, 선량률의존성, 에너지의존성의 총 5개 항목에 대해서 평가를 하였다. 측정은 물팬톰 40×40×40 cm^{3}을 이용하여 유리선량계의 흡수선량을 측정하였다. 명목상 전자선에너지 6, 9, 12, 16, 20 MeV에서의 선량 1 Gy부터 15 Gy까지 유리선량계의 반응도를 평가해 본 결과 5개 전자선 에너지에서 같은 R^2=0.999의 선형계수를 확인할 수 있었다. 또한 5개의 에너지에서 총 100개의 유리선량계를 판독한 결과, 재현성은 5개 전자선에너지 평균 ±1.2% (1SD) 이내에서 잘 일치함을 확인할 수 있었다. 유리선량계의 방향성은 유리선량계의 수직방향인 90°를 기준으로 하였을때 0°에서 90°사이에서 빔방향에 따라 1.5% 이내의 차이를 나타내었다. 선량률의존성은 500 MU/min을 기준으로 200 MU/min에서 1,000 MU/min 사이에서 ±1.5%의 차이를 나타내었다. 유리선량계의 에너지 의존성은 원통형 전리함으로 측정한 선량과 비교했을때 5개의 명목상 전자선에너지(6 MeV에서 20 MeV) 각각에 대해 ^{60}Co 감마선의 반응도로 일반화시킨 결과 1.1%에서 3.5% 사이에서 낮은값을 나타내었다. 본 연구결과를 통하여 측정환경에 따라 결과값을 적절히 환산인자로 활용한다면 유리선량계를 이용한 전자선치료빔 선량평가가 가능하리라 사료된다.

중심단어: 유리선량계, 선량특성평가, 전자선